Situation Awareness and Other Cross-Domain Constructs:
Lessons Learned from 110 Years of Aviation Human Factors Research

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Larger Themes

- Technology-Driven or Operator-Driven?
- Science vs. Engineering?

- False dichotomies!

Science/ Theory → **Methodology/ Analytics** → **Design/ Engineering**

Operators → **Methodology/ Analytics**

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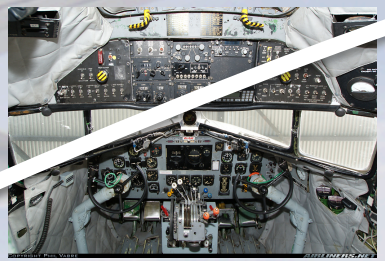
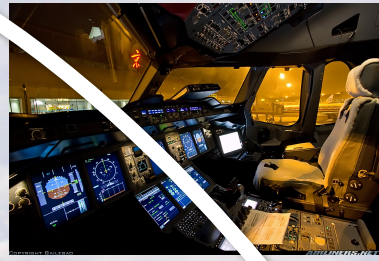
Evolution of the number of cockpit displays





1926: Ford Tri-Motor 1935: DC-3 1955: Sud Aviation Caravelle 1972: Locheed L-1011 2005: Airbus A-380

Correspondence and Coherence

- The hybrid ecology of a modern flight deck (Mosier, 2010)

Naturalistic World	**Electronic World**
Sensory and kinesthetic	Cognitive
Correspondence strategies and goals	**Coherence** strategies and goals
Ambiguity	Reliability
Intuitive processes	**Analytical** processes
Probabilistic cues	Deterministic data and information**
Expertise affords intuitive “shortcuts”	Analysis required at all levels of exprtise

Correspondence Errors

- Difficulty of competent correspondence judgments from ambiguous, missing, or misleading cues
  - USAir 1016 accident in Charlotte, NC, July 2, 1994
  - Colgan Air Flight 340 in Buffalo, NY, February 12, 2009

- Spatial Disorientation

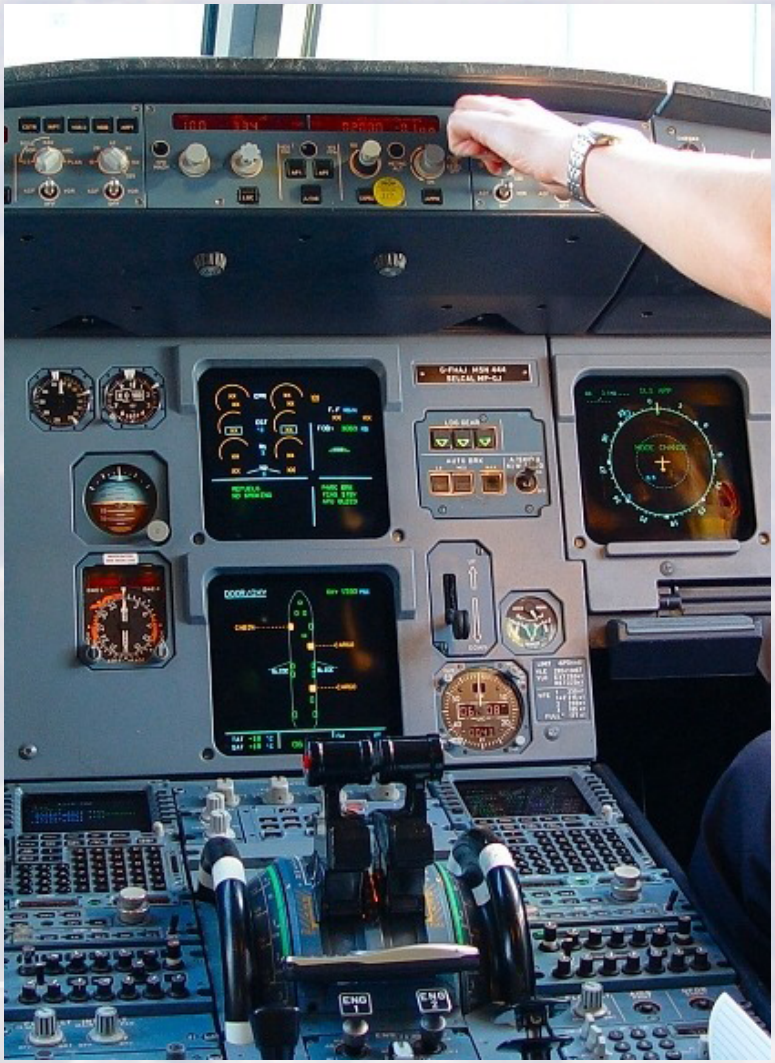
Coherence Errors

- **Coherence**: The electronic "story"
- **Automation surprises** result from inaccurate judgment of coherence, misinterpretation of misassessment of data on system state and functioning.
- **Mode confusion** or **mode errors** result from forgetting what state the interface is in, or performing actions that are appropriate for a different mode.
- Many accidents involving modern, highly automated aircraft have resulted from mode confusion.

January 20, 1992, Strasbourg, France: Air Inter Flight No. 148, Airbus A320-111; Fatalities: 87:96

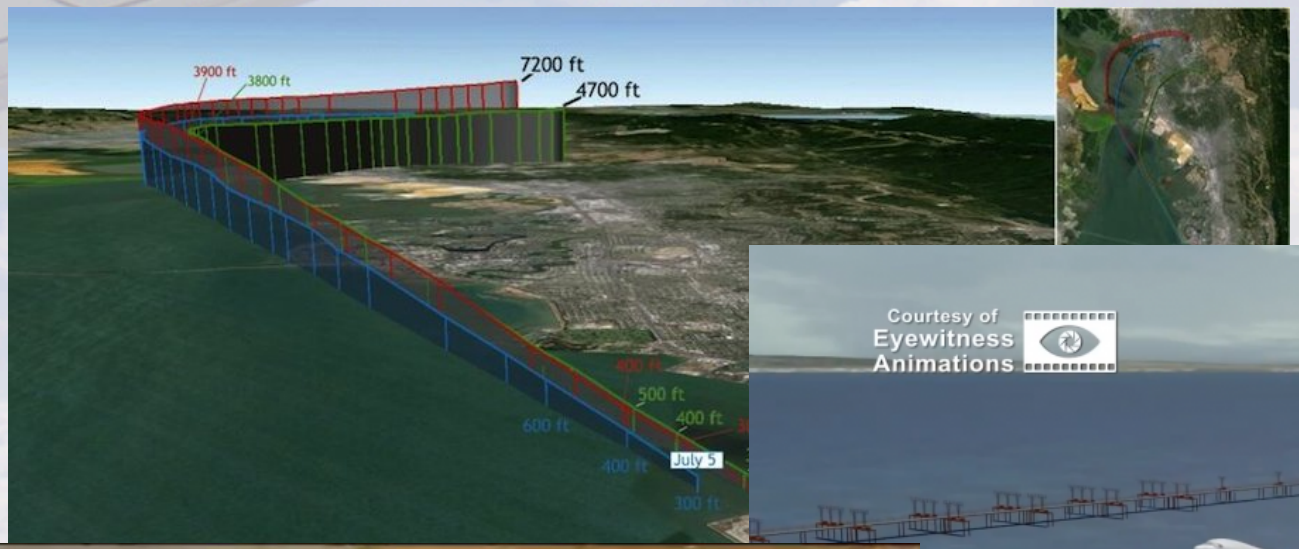
January 20, 1992, Strasbourg, France: Air Inter Flight No. 148, Airbus A320-111; Fatalities: 87:96

- While on approach into Strasbourg, the aircraft impacted the side of a mountain.
- The cause of the crash was found to be a **faulty design** in an autopilot mode selector switch which led the flight crew to inadvertently select a 3,300 foot per minute descent rate on the approach instead of the desired 3.3° flight path angle.



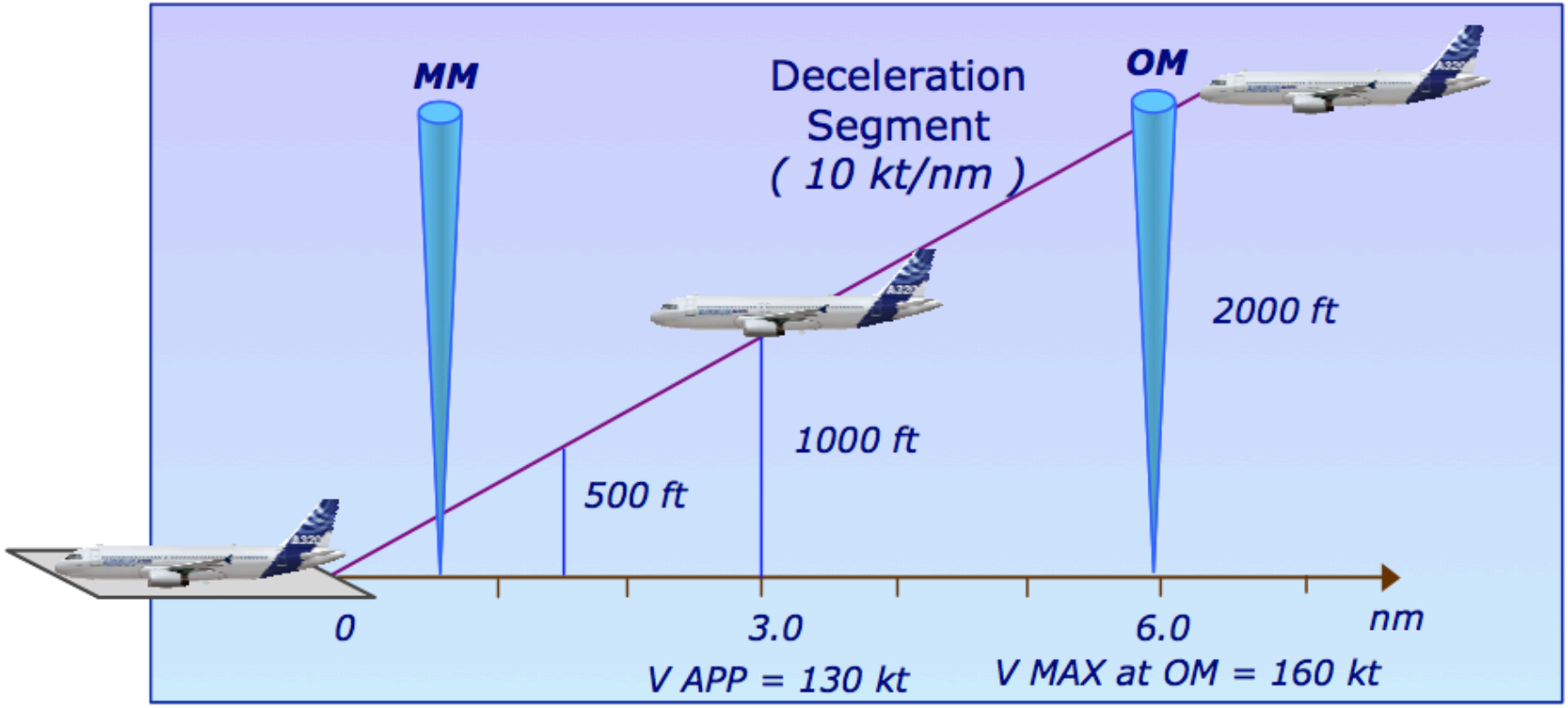
One More Example…

- Asiana Flight 214, San Francisco, CA, July 6, 2013



On First and Second Things

- ~ 70 % of rushed and unstable approaches involve an incorrect management of the aircraft energy level, resulting in being slow and/or low on approach (40 % of events) or being fast and/or high on approach (30 % of events).



Aircraft Energy Management During Approach

- Either a **deficit** of energy (low and/or slow) or an **excess** of energy (high and/or fast) may result in approach-and-landing accidents, such as:
  - Loss of control;
  - **Landing short**;
  - Hard landing;
  - **Tail strike**;
  - Runway excursion;
  - Runway overrun.
- The level of energy of an aircraft is a function of the following primary flight parameters and of their rate of change (trend):
  - Airspeed and speed **trend**;
  - Altitude and vertical speed (or flight path angle);
  - Aircraft configuration (i.e., drag caused by speed brakes, slats/flaps and/or landing gear); and,
  - Thrust level.

The Power Curve

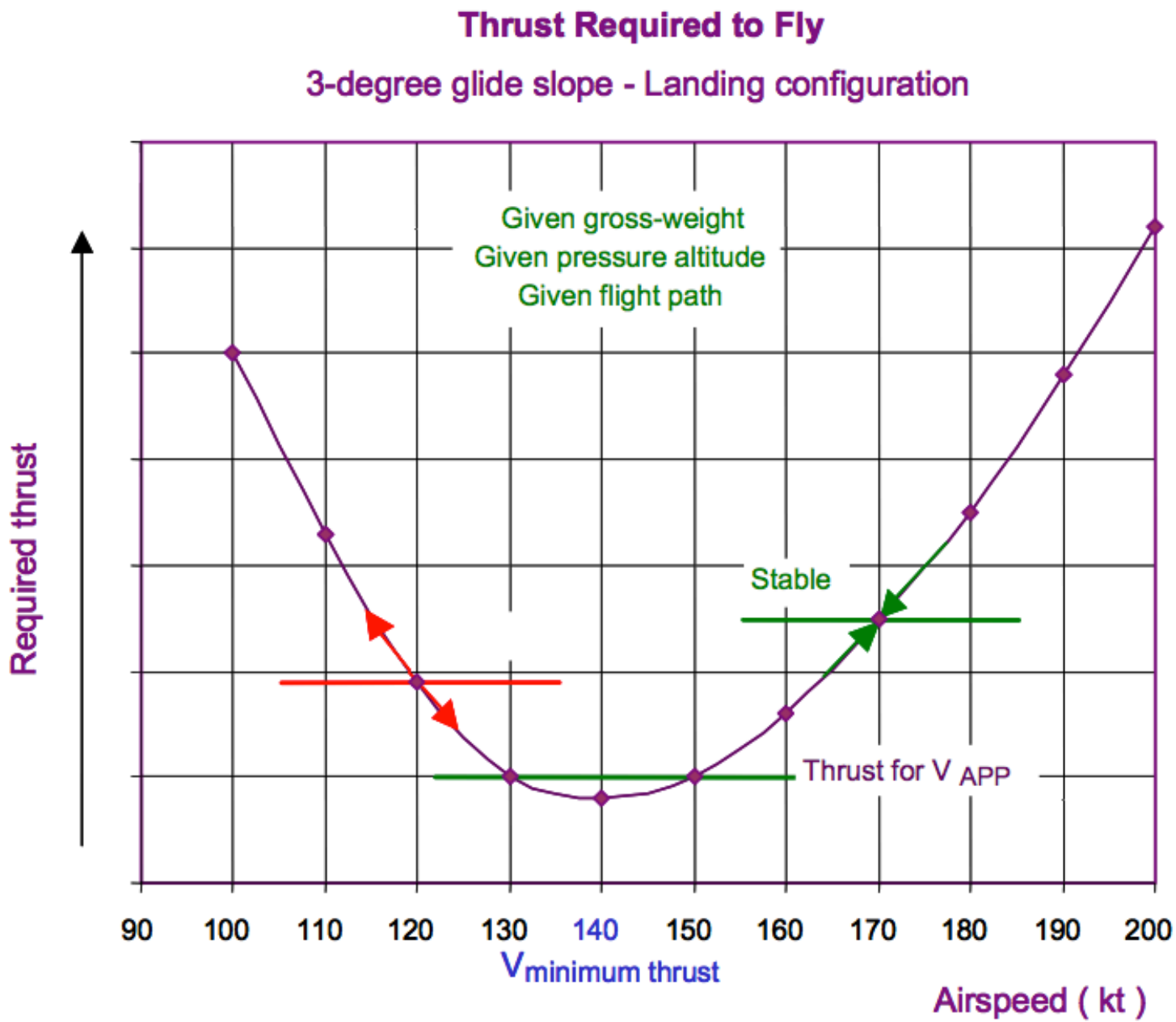
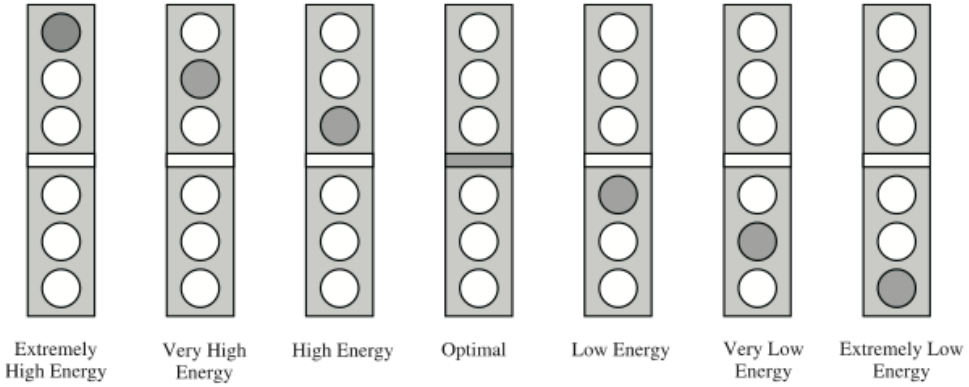
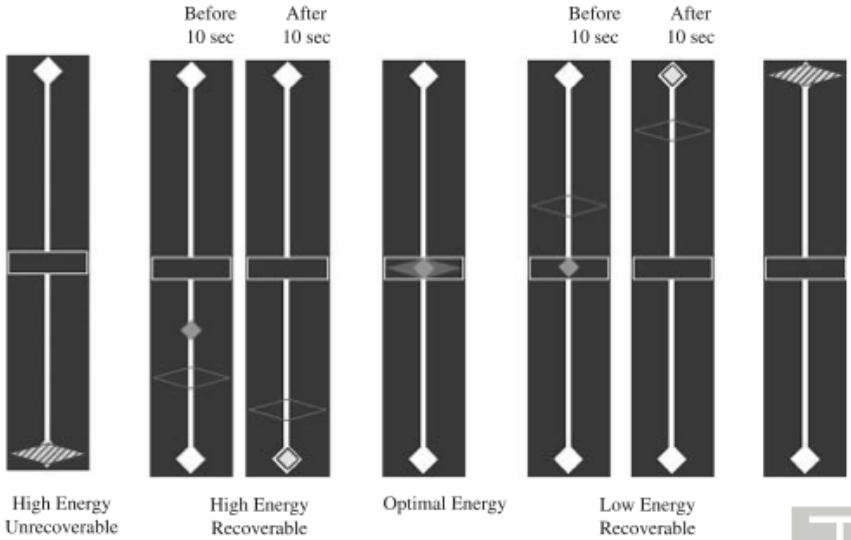


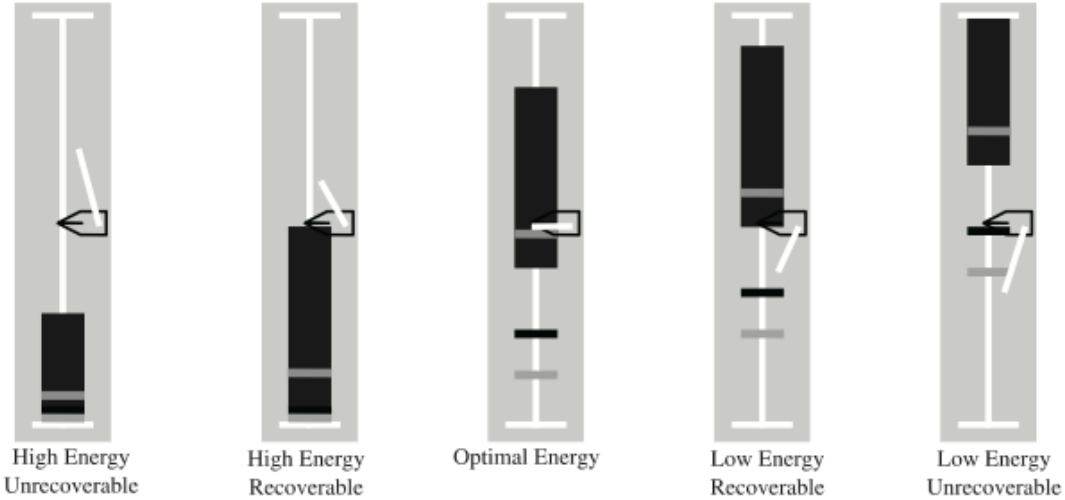
Figure 2

Power Curve – Typical

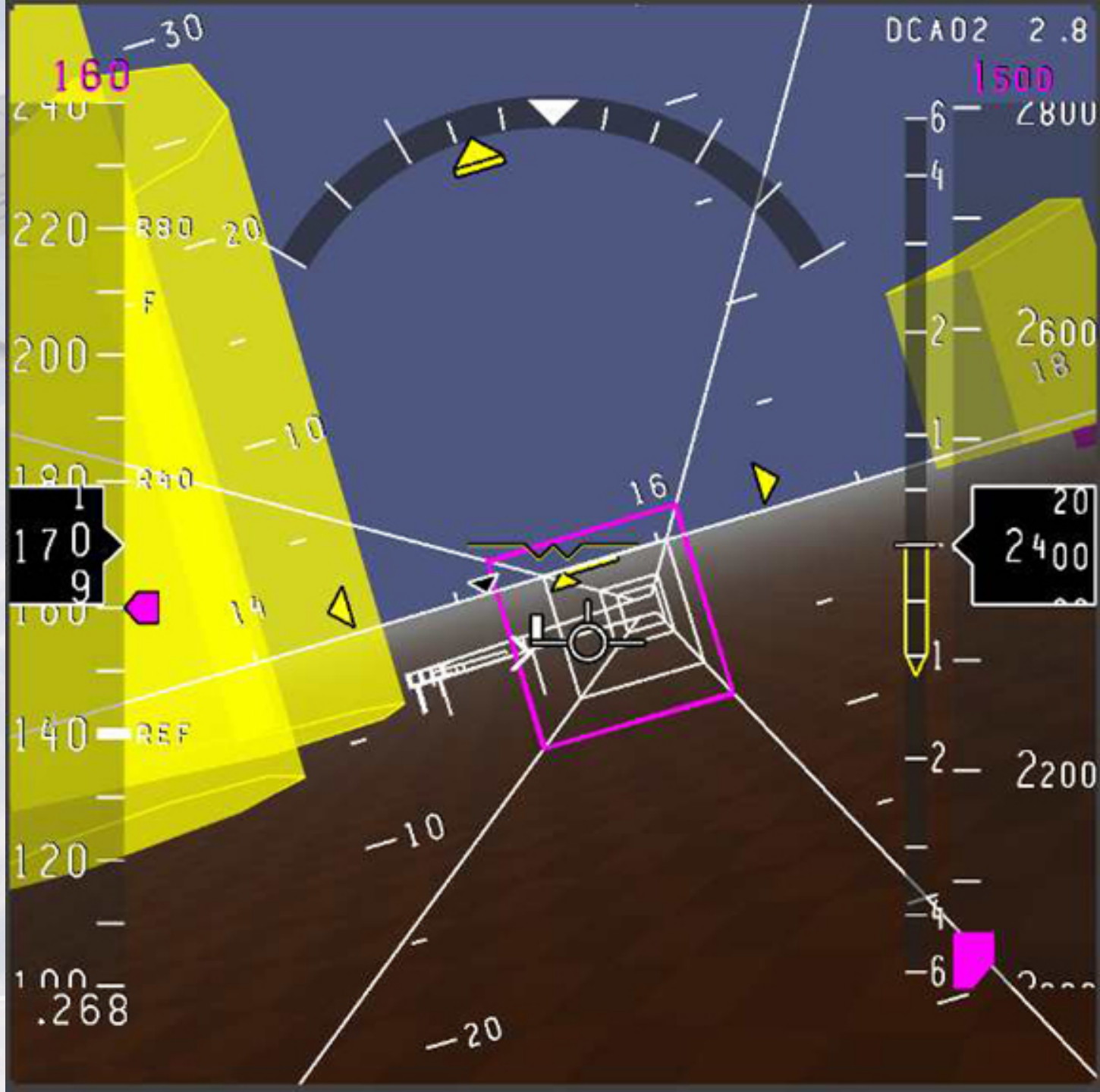




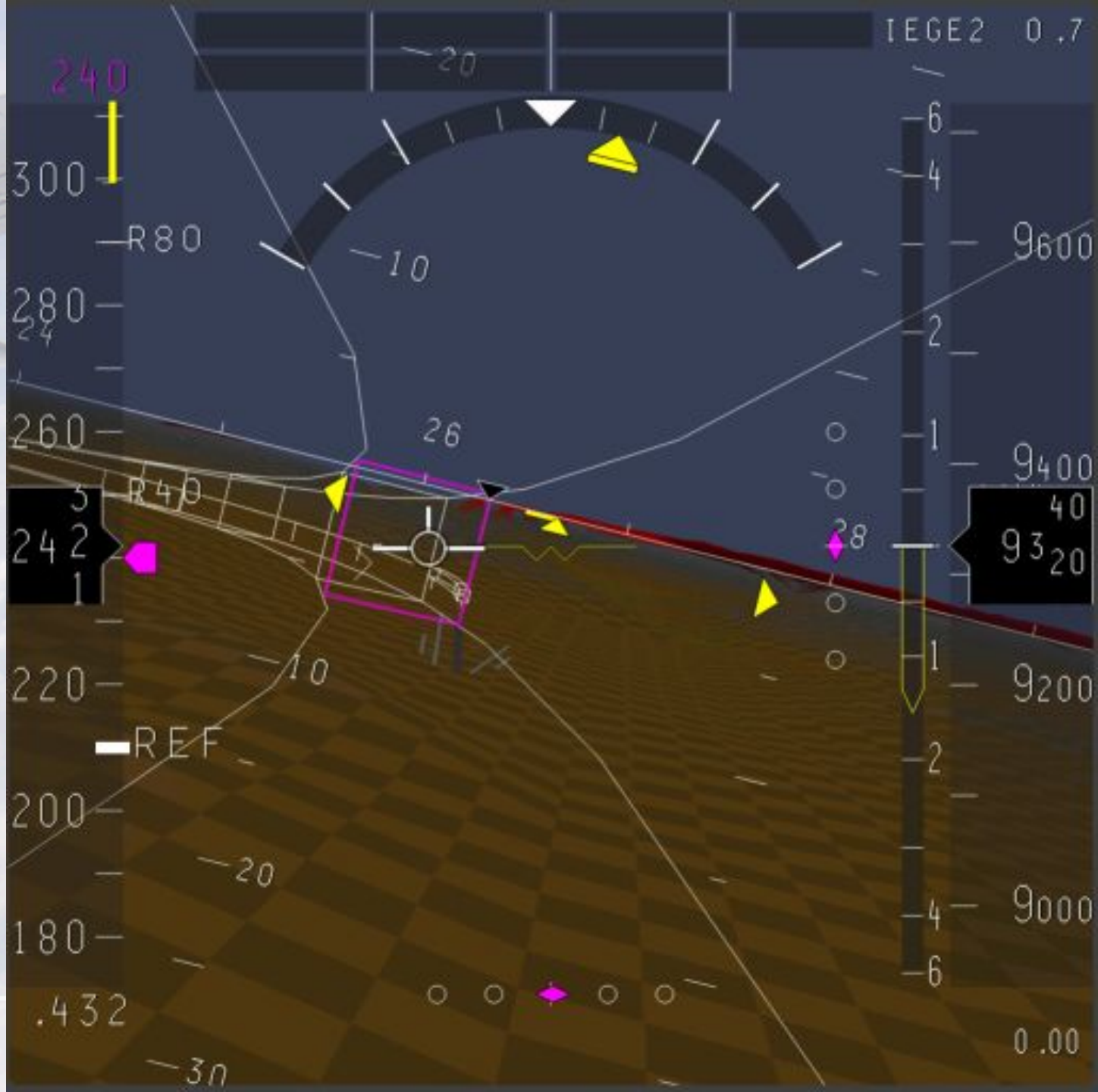
Energy Displays
(Catton, Starr, Noyes, Fisher, & Price, 2007)



Tunnel-in-the-Sky



Tunnel-in-the-Sky

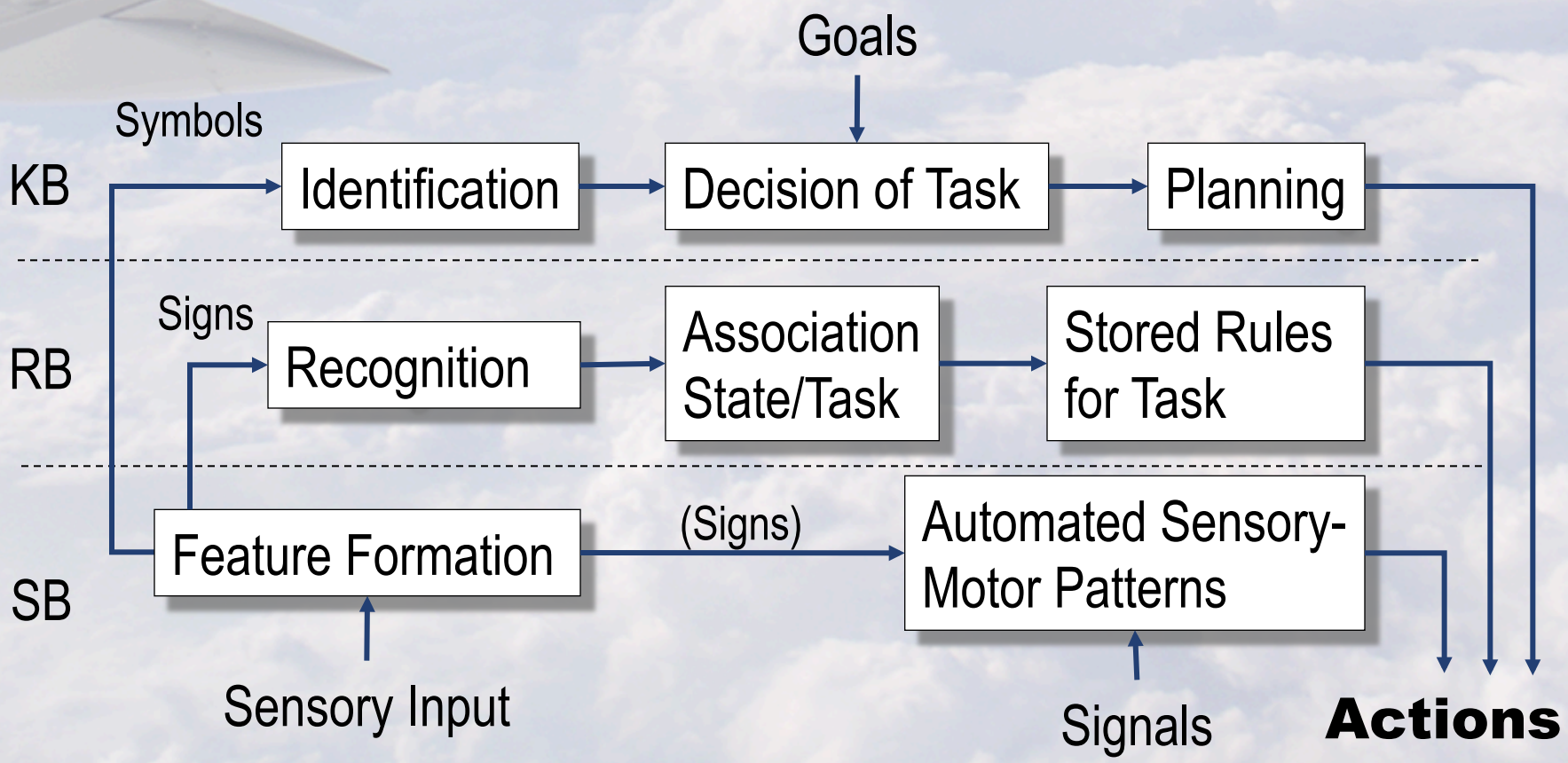


Some Theory

- There are several influential cognitive theories that may be readily used in interface **design**:
  - The Skills, Rules, and Knowledge (SRK) framework of Rasmussen;
  - The Two-System View by Kahneman
  - The Cognitive Continuum Theory by Hammond
- …and some methodology: **Cognitive Work Analysis (CWA)**

Skills-, Rules-, and Knowledge-Based Behavior

(The SRK Framework; Rasmussen, 1986)



The SRK Framework

- The **skill-based (SB)** behavior:
  - Diagnostic troubleshooting by a direct match between the features of the problem observed and patterns previously experienced and stored in the LTM.
  - Fast, requires little cognitive activity, accurate.
- The **rule -based (RB)** behavior*:*
  - Diagnosis done by applying sets of rules stored in LTM, e.g., sequence of steps and the procedures for doing so.
  - Mental 'checklists', mental simulation of 'what if' scenarios.
- The **knowledge-based (KB)** behavior:
  - Explicitly goal controlled performance in unfamiliar situations where no rules or know-how are available; functional reasoning based on mental models.
  - Iterative diagnostic testing and subsequent analyses necessary for problem-solving.

The SRK Taxonomy

- Cognitive control may rely on…

  a) …a repertoire of automated behavioral patterns (SBB)
  b) …a set of cue-action mappings (RBB)
  c) …problem-solving operations on symbolic representations (KBB)

- Application to design:
  - Complex domains have highly skilled and experienced operators
  - Interfaces are system-specific (generality not required)

→ Complex domains afford design for SBB and RBB

The Two-System View

(Kahneman et al.)

Controls

	Perception	Intuition System 1	Reasoning System 2
Process:	• Fast • Parallel • Automatic	• Effortless • Associative • Self-learning	• Slow • Serial • Controlled • Effortful • Rule-governed • Flexible
Content:	Percepts Current stimulation Stimulus-bound	Conceptual representations Past, present, and future Can be evoked by language etc.	

Cognitive Continuum Theory

(Hammond, 2000)

- Two **metatheories**:

1. Coherence
   - Theories about coherence = rationality of judgments and decisions
   - Logical or mathematical consistency, or absence of contradictions
2. Correspondence
   - Theories concerned about correspondence of judgment with empirical facts (i.e., empirical accuracy of judgment; e.g., physicians' diagnoses)
   - Factors leading to empirical accuracy or inaccuracy of the judgment

Psychological Underpinnings of Competence

- Correspondence competence
  - Remarkable perceptual abilities of humans (and other species)
  - Perceiving 3D world projected on 2D retina
  - Shape, size, color, &c. **constancy**
- Coherence competence
  - Unique to humans; acquired (taught!) skill (story telling)
  - Different tasks demand coherence competence than correspondence comptence
- Two aspects of **cognitive** competence
  1. Subject matter (or, domain) competence: Learning, memory, and deduction
  2. Judgment and decision-making competence: Observation and inference

Cognitive Continuum Theory of Judgment
(Hammond, 2000)

- Based on
  1. **Correspondence** and **Coherence** metatheories
  2. Concepts of **Intuition** and **Analysis**

- Both correspondence and coherence can be achieved both by intuition and analysis

Cognitive Continuum: Premises

(Hammond, 2000)

1. Various modes, or forms, of cognition can be ordered in relation to one another on a continuum with intuitive cognition in one end and analytical cognition in the other

2. The forms of cognition that lie on the continuum between intuition and analysis contain elements of both, and is termed quasi rationality (a.k.a. common sense)

3. Cognitive tasks can be ordered on a continuum with regard to their capacity to induce intuition, quasi rationality, or analytical cognition

4. Cognitive activities may move along the intuitive-analytical continuum over time; successful condition in stable environments require stability along the continuum, but changing environments necessitate movement along it (dynamic cognition)

5. Human cognition is capable of both pattern recognition and the use of functional relations

Cognition-Task Interaction

Task Continuum Index \ Cognitive Continuum Index	I	Q	A
I	**Best**	Mediocre	Poor
Q	Mediocre	**Best**	Mediocre
A	Mediocre	Mediocre	**Best (Normal)**

Method: Cognitive Work Analysis

(Lintern, 2009)

- **Stage 1: Functional Work Structure, Work Domain Analysis (WDA):**
  - An Abstraction Hierarchy (AH) extending over the five levels of (1) Domain Purpose, (2) Domain Values and Priorities, (3) Domain Functions, (4) Physical Functions and (5) Physical Objects;
  - **Product**: an Abstraction-Decomposition Space (ADS), an activity-independent representation of the the functional structure of the work domain.

- **Stage 2: Partitioning and Organization of Work, Work Organization Analysis:**
  - Domain Functions, as identified in the Abstraction-Decomposition Space,
  - Work Situations, which are the various situational contexts in which work takes place, and
  - Work Tasks, which are the distinctive outcomes to be achieved.
  - **Product**: a Contextual Activity Matrix.

Method: Cognitive Work Analysis

(Lintern, 2009)

- **Stage 3: Cognitive States and Processes; Cognitive Transformations Analysis:**
  - Cognitive States established during task execution, and
  - Cognitive Processes used to effect the transitions between states.
  - **Product:** a suite of Decision Ladders.

- **Stage 4: Cognitive Strategies; Strategies Analysis:**
  - The categories of task procedure that could be used to transform an initial Cognitive State into another Cognitive State, and
  - **Product:** a detailed description of potential strategies that can be used to execute the Cognitive Processes identified in the Cognitive Transformations Analysis and a description of the factors that will prompt selection of one strategy over another.

Method: Cognitive Work Analysis

(Lintern, 2009)

- **Stage 5: Cognitive Processing Modes; Cognitive Processing Analysis:**
  - A Skill-Based (SB) mode of cognition, which has no conscious processing between perception and action,
  - A Rule-Based (RB) mode of cognition, which is guided by sets of procedural instructions that specify sequences of actions, some of which may be conditional, leading to branches or halts in the sequence, and
  - A Knowledge-Based (KB) mode of cognition, which is grounded in conscious and explicit reasoning, and
  - **Product:** a detailed description of the activity elements associated with the different modes of cognitive processing.

Method: Cognitive Work Analysis

(Lintern, 2009)

- **Stage 6: Work Coordination; Social Transactions Analysis:**
  - The social and collaborative processes that can facilitate peer-to-peer interaction, and
  - The social and collaborative processes that can facilitate management-worker interaction and organizational integration.
  - **Product 1**: a Social Transactions Matrix, which is an adaptation of the Contextual Activity Matrix developed in Stage 2
  - **Product 2**: a Transaction Network in which the transactions between agents (either human or technological) are identified and characterized in terms of fundamental or generic properties relevant to design.

Abstraction Hierarchy in System Representation

Means-Ends Relations	Properties Represented
Purposes and values; Environmental constraints	Purpose-based properties and **reasons** for proper functions are propagating from top-down
Priority measures; flow of mass, energy, people, and monetary value	
General work activities and functions	
Specific work processes and physical processes equipment	Physics-based properties and **causes** of malfunction are propagating from bottom-up
Appearance, location, and configuration of material objects	

The Classes Within the Means-Ends Hierarchy

Means-Ends Relations	Properties Represented
Purposes and Constraints	Properties necessary and sufficient to establish relations between the performance of the system and the reasons for its design (i.e., the purposes and constraints of its coupling with the environment)
Abstract Functions and Priority Measures	Properties necessary and sufficient to establish priorities according to the intention behind design and operation; topology of flow and accumulation of mass, energy, information, people, value
General Functions	Properties necessary and sufficient to identify the 'functions' which are to be coordinated irrespective of their underlying physical processes
Physical Processes and Activities	Properties necessary and sufficient to control of physical work activities and use of equipment: To adjust operation to match specifications or limits, to predict response to control action, to maintain and repair equipment
Physical Form and Configuration	Properties necessary and sufficient for classification identification, and recognition of particular material objects and their configuration; for navigation in the system.

1. Work Domain Analysis

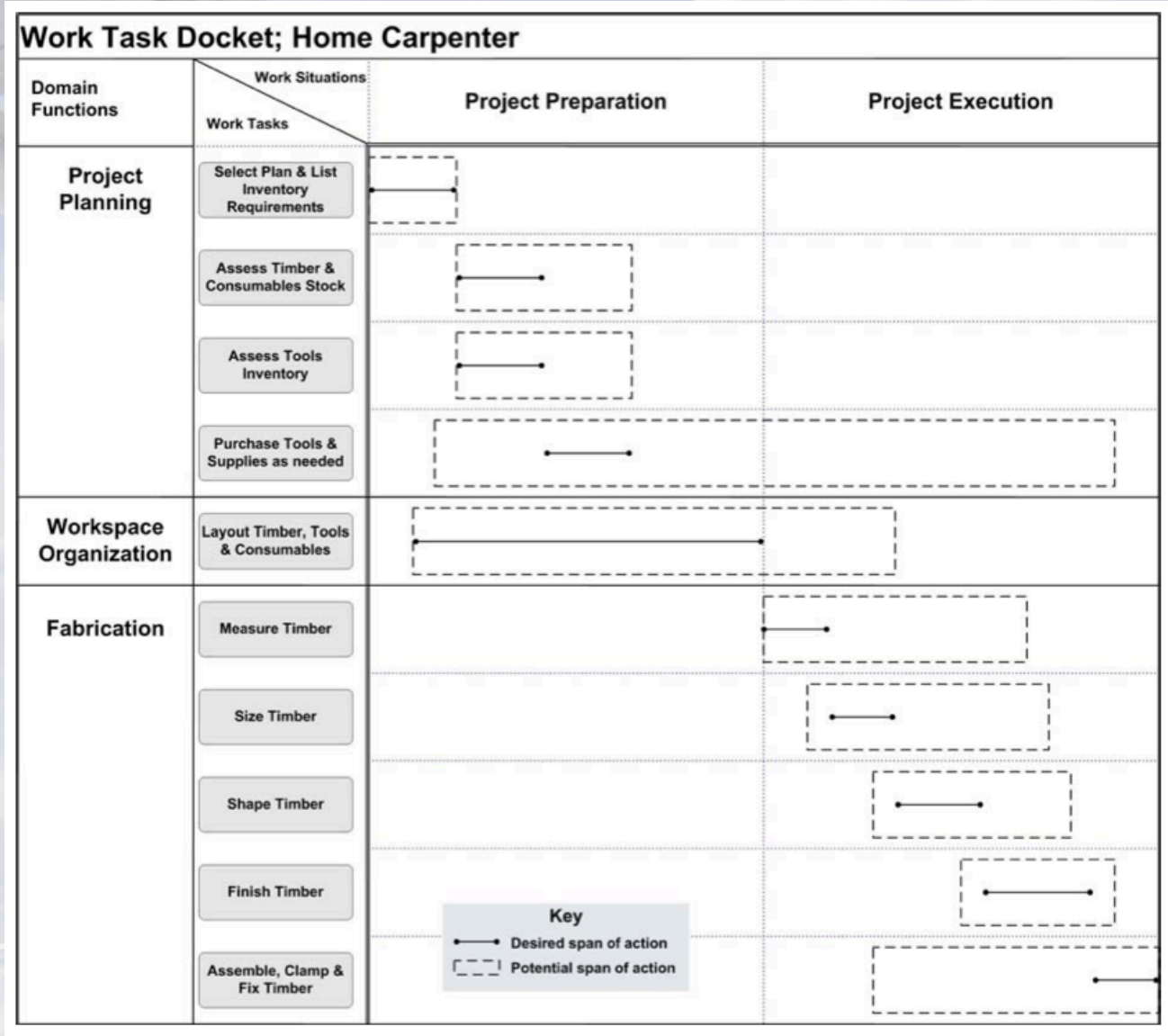
Abstraction-Decomposition Space (ADS)

	System	Unit	Component	Part
Domain Purpose				
Domain Values & Priorities				
Domain Functions				
Physical Functions				
Physical Objects, Material Configuration				

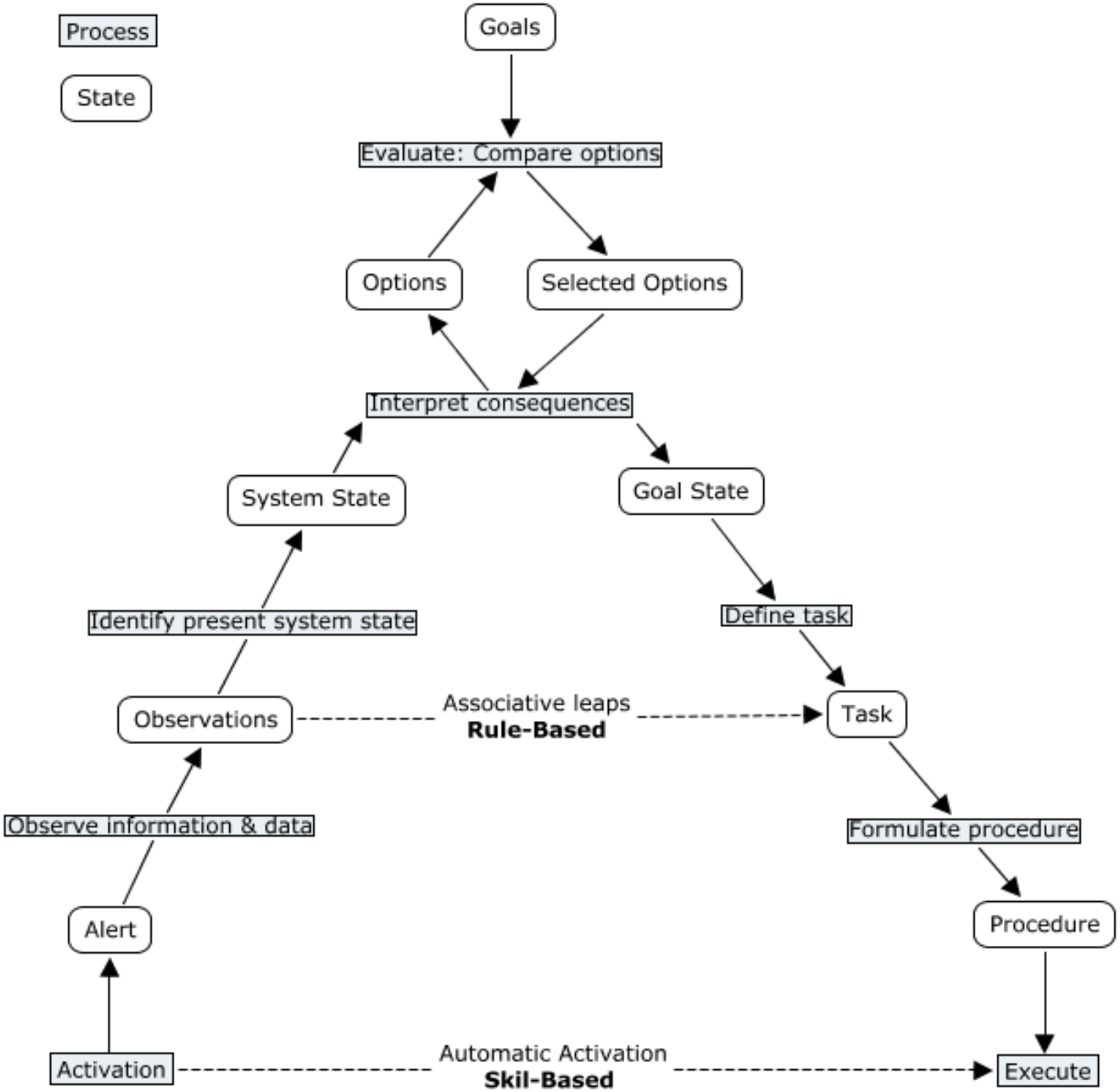
WHY, WHAT, and HOW in the Means-Ends Space

Means-Ends	Whole → Part
Purposes, Constraints	WHY
Abstract Functions	WHY WHAT
General Functions	WHY WHAT HOW
Physical Processes	WHAT HOW
Physical Form	HOW

2. Contextual Activity Matrix



3. Decision Ladders



Human Factors of **Information Visualization**: Issues

- The role of information display in
  - **enhancing human capabilities** and
  - **alleviating their limitations**
- Information Access Cost (IAC)
  - Displays should reduce IAC in particular during emergencies and in situations subjected to time pressure
- The information display should
  - prevent human errors, or
  - help in error detection, or
  - mitigate error consequences
  - **not** introduce new types of errors

Ecological Interface Design (EID)

- A theoretical framework for interface design.
- An attempt to extend the benefits of traditional direct-manipulation interfaces (DMI) to complex human-machine systems.
- Foundational concepts:
  - The Abstraction Hierarchy (AH)
  - The Skills-, Rules-, and Knowledge (SRK) framework

→ Three prescriptive guidelines

Complex Human-Machine Systems

Range of events operators must respond (three classes):

1. **Familiar events** for which they have necessary skills through repeated exposure (most frequently)

2. **Unfamiliar but anticipated events**; lack of operator skill compensated by tools and aids anticipated by the designer (infrequently)

3. **Unfamiliar and unanticipated events**, also by designers; hence, no procedures, tools, or aids are available but solutions must be improvised

The Interface Design Problem

Complex Work Domain

Question: How to describe domain complexity?

Required: A domain representation formalism

Interface…
-content
-structure
-form

Question: How to communicate the information?

Required: A model of the mechanisms that people have for dealing with complexity

Human Operator

EID Principles: SBB

- The operator should be able to act directly on the display
- Structure the display to support SBB
- Manipulation of on-screen elements
  - Direct manipulation device preferred over command-language interface
  - Aggregation of elementary movements to into more complex routines corresponds to concurrent chunking of visual features into higher-level cues for these routines
  - Representation of multiple levels simultaneously

EID Principles: RBB

- Provide consistent one-to-one mapping between the work domain constraints and the cues or signs provided by the interface…
- i.e., provide the operators signs they can use to select appropriate actions

  → Will allow operators operate by relying in perceptual cues instead of having to resort to KBB

  → Will allow operators to take advantage of the economy of RBB while preserving the wide applicability of KBB

EID Principles: KBB

- Support KBB by…

  … revealing the problem space in the form of an AH presentation

  … providing the operators a normative model of the work domain

  … supporting experimentation

  … relieving the operators of the burden of keeping track of causal nets within which they are reasoning

EID Guidelines

1. Support experimentation by making boundaries of acceptable performance visible and their effects observable and reversible.

2. Provide feedback to support understanding and KB monitoring during RB performance, make visible latent constraints upon action.

3. At the RB level, the display should represent cues for action as readily interpretable signs *and* indicate the preconditions to their validity (i.e., signs should have *symbolic* content)

EID Guidelines

4. To assist operators in coping with unanticipated situations at the KB level, provide tools for experimentation and hypothesis-testing without a need to impact the plant, or make these actions reversible

5. Provide users with overview displays by which SB routines can be peripherally monitored

6. At RB level, avoid procedural traps (strong-but-wrong rules) by providing integrated patterns as cues for action

7. At the KB level, support memory by externalized schematics of mental models

EID Guidelines

8. Present information based on available data that is simultaneously suitable for SB, RB, and KB processing

9. Provide an externalized mental model to aid in causal reasoning

10. Provide external memory aids for items, acts, and data that are not part of the present operational 'gestalt.'

Display Design Challenges

- Mapping of system variables to graphical variables
- Follow basic human factors guidelines in display design
- Avoid 'visual noise' (e.g., animation and color)
- Avoid clutter (decluttering functions)
- Display of predicted values
- Display of dynamic information: **Rate of change**
- Display of uncertain (probabilistic) information
- Display of old (unreliable) information

Mapping of System Variables to Graphical Variables

System Variables:

- Voltage magnitude
- Line flow
- Line status

- Capacitor bank status
- Generator output

- Load status

- Load power requirement
- Generator reactive reserves

- Transformer phase shift
- Generator real power reserves
- Phase angles

Mapping?

Graphical Variables:

- Line width
- Contrast
- Color: hue, saturation
- Shape
- Animation
- Transparency
- Symbols (icons)
- Text and numbers (font and size)
- Etc.

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Thank You!

Questions?

Comments?

Discussion?