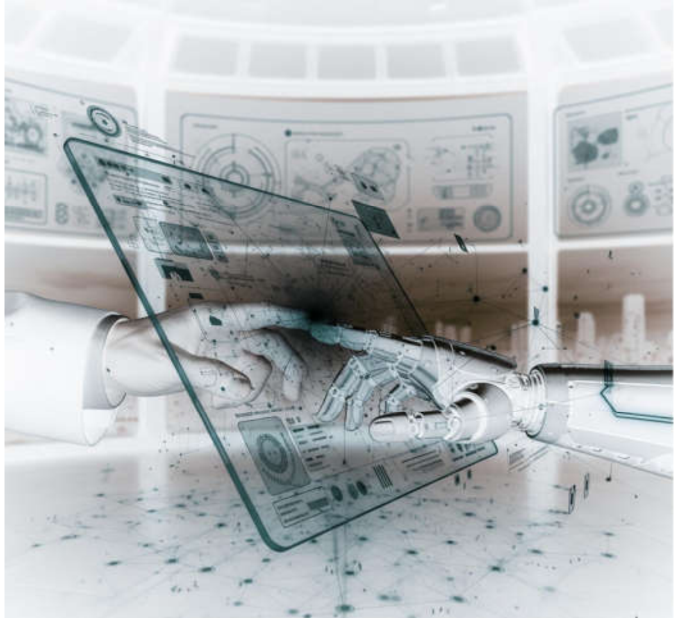


Human-Machine Interaction

Interaction Modalities & Technologies

Visual and Auditory Interaction

Dr. Patrick Chan
patrickchan@scut.edu.cn
South China University of Technology

Human Visual Dominance

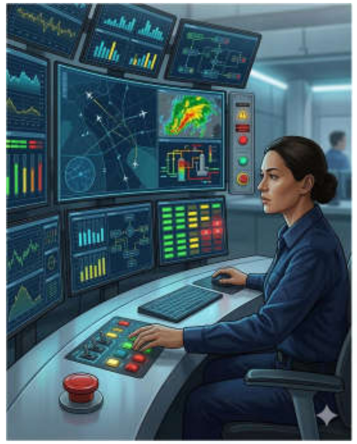
- Rely heavily on vision for environmental awareness
  - Afraid in dark environments
  - Sleeping at night in ancient times
- Vision Characteristics:
  - High detail and sharpness
  - Strong ability to recognize patterns
  - Quick detection of unusual changes

Visual Information Characteristic

- **High Bandwidth**
  - Simultaneous processing of multiple elements
  - Parallel perception of shape, color, motion, depth
- **Persistence**
  - Unlike audio, visual information can remain stable
  - Information remains visible
  - Supports comparison over time
  - Allows scanning and re-checking

Vision in Safety-Critical Systems

- Visual displays are **commonly used in Safety-Critical Systems**, e.g. aviation, nuclear plants, medical systems, and autonomous vehicles
  - Monitor system state
  - Detect abnormal conditions
  - Anticipate failures
  - Execute corrective actions



Poor Visual Design

- Cognitive load increases
  - Slower reaction time
  - Mode confusion
  - Missed alarms
  - Loss of trust
- Not usability issues but also escalate into safety failures

Communication Channel

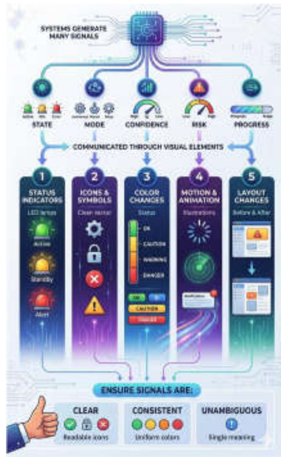
- Visual interfaces are **communication channels** between the system and the human
  - Continuously communicates through visual signals
    - Current system state
    - Mode of operation
    - Progress of tasks
    - System confidence in decisions

Communication Channel

- It is a **language spoken by the system**
  - Not decoration
  - Let's user to Interpret system states and detect change
- Examples
  - Smartphone: Loading spinner → system is processing
  - Autonomous vehicle: Blue light → autonomous mode active
  - Medical monitor: Red alarm → abnormal patient status

System-to-Human Signaling

- **Systems generate many signals** showing different state, mode, confidence, risk, progress
- Communicated through visual elements
  - status indicators
  - icons and symbols
  - color changes
  - motion and animation
  - layout changes



Visual Cues

- **Explicit Cues**
  - Text warnings
  - Highlighted alerts
  - Clear labels and messages
  - Suitable for critical events
- **Implicit Cues**
  - Subtle color variation
  - Animation speed
  - Spatial emphasis
  - Icon transformation
  - Support background awareness
- **Balance** prevents overload or invisibility

Feedback vs Feedforward

- **Feedback**
  - Communicates what has already happened
  - Examples:
    - Button changes color after activation
    - Status updates to “Completed”
- **Feedforward**
  - Communicates what will happen next
  - Examples:
    - Preview of system trajectory
    - Countdown to threshold
    - Highlighting consequences before confirmation

Temporal Behavior

- Visual information **is shown over time**
- Timing is critical and part of interface design
  - **Too slow** → perceived unresponsiveness
  - **Too fast** → missed signals
- Should show intermediate feedback
  - **< 100 ms** → feels instantaneous
  - **> 3 seconds** → user attention drops

UI Design

- Must support **safe, efficient, and understandable interaction, not** only about appearance
- Example
  - Aircraft cockpit displays prioritize **readability and function over decoration**

Goal

- **Clarity and predictability**
  - What the system is doing and what will happen next
- **Minimizing cognitive load**
  - Reduce mental effort and avoid unnecessary complexity
- **Supporting fast and correct decisions**
  - Easy to interpret under time pressure

Monitoring vs Control

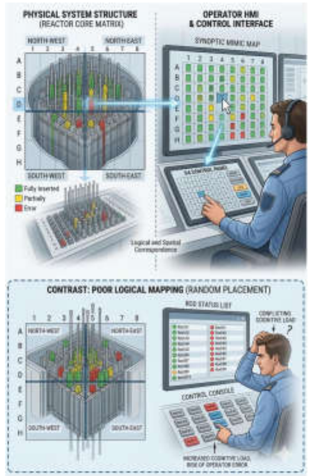
- Two roles in HMI should be supported:
  - **Monitoring**
    - Observing system behavior
    - Detecting anomalies
    - Maintaining situational awareness
  - **Control**
    - Issuing commands
    - Adjusting parameters
    - Intervening in system behavior

State Visibility

- The operator must always understand:
  - What the system is doing
  - Why it is doing it
  - What it will do next
- Situational awareness depends on clear state visibility
  - If the state is unclear, safe cooperation is impossible

Mapping UI & System Functions

- Controls and displays should have **logical relationships** with system functions.
  - Avoid user confusion and errors
  - Control location reflects physical system location
  - Interface structure mirrors system structure

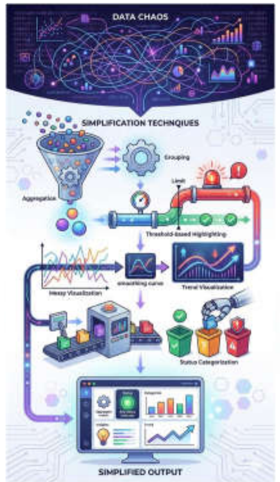


Mapping UI & System Functions

- Example: Car dashboard layout
  - **Left** → vehicle status
  - **Center** → navigation and media
  - **Right** → driver assistance

Meaningful Representation

- Systems
  - Detect **numerical values**
  - Process **raw signals**
- Humans
  - Interpret **patterns**
  - Rely on **visual abstraction**
- The interface must translate internal states into meaningful visual forms



Meaningful Representation

- **Raw data**
  - High dimensional
  - Continuous
  - Numerical
  - Machine-readable
- **Meaningful display**
  - Simplified
  - Structured
  - Contextualized
  - Human-interpretable

- **Core Question**
  What does the operator actually need to see?

Abstraction

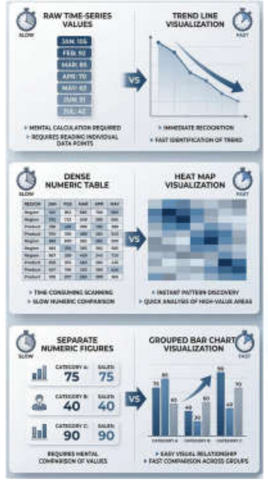
- Reduces complexity without losing critical meaning
- **Goal**: **Rapid understanding**, not detailed computation
- Techniques:
  - Aggregation
  - Threshold-based highlighting
  - Trend visualization
  - Status categorization

Mapping

- Algorithm **outputs** may include:
  - Probability scores
  - Confidence levels
  - Classification labels
  - Trajectory predictions
- These must be **mapped** into:
  - Visual cues
  - Status categories
  - Risk levels
  - Actionable insights
- The mapping must align with **human mental models**.

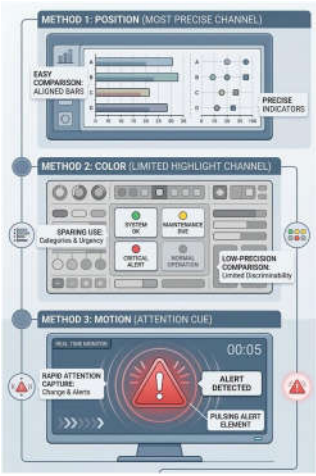
Pattern Recognition vs Numbers

- Humans recognize patterns faster than they read numbers
- Better examples:
  - Trend line instead of raw values
  - Heat map instead of table
  - Bar comparison instead of separate figures
- Visualization reduces mental calculation



Visual Encoding

- Information can be encoded using:
  - **Position:** Most precise visual channel, Good for comparisons
  - **Color:** Highlights categories or urgency, Use sparingly
  - **Motion:** Attracts attention, Suitable for change or alerts
- Encoding choice affects interpretation speed.



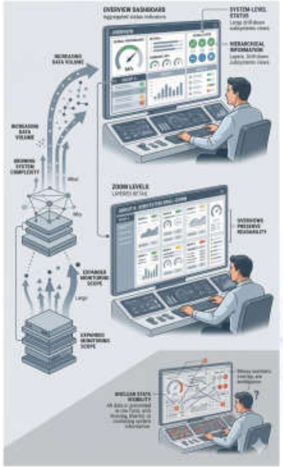
Temporal Consistency

- Visual elements should remain stable over time.
- Avoid:
  - Frequent layout shifts
  - Changing color meanings
  - Inconsistent scales
- Temporal consistency supports memory

UI Design: Meaningful Representation

Scalability

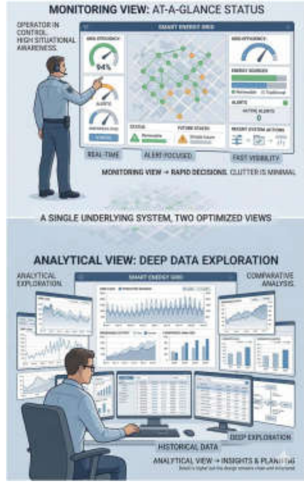
- Clarity must **scale with complexity**.
- Visualization must remain clear as:
  - Data volume increases
  - System complexity grows
  - Monitoring scope expands
- Design for:
  - Aggregation
  - Zoom levels
  - Layered detail



UI Design: Meaningful Representation

Different Views

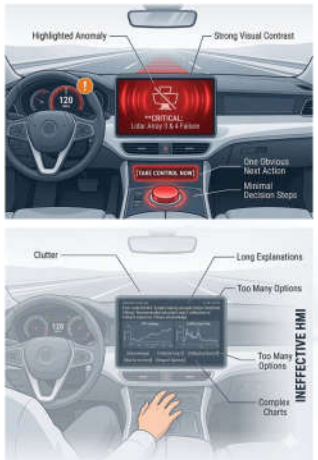
- Different tasks require different visual structures
  - **Monitoring View**
    - Real-time status
    - Simplified
    - Alert-focused
  - **Analytical View**
    - Detailed exploration
    - Historical data
    - Comparative analysis



UI Design: Meaningful Representation

Time Pressure

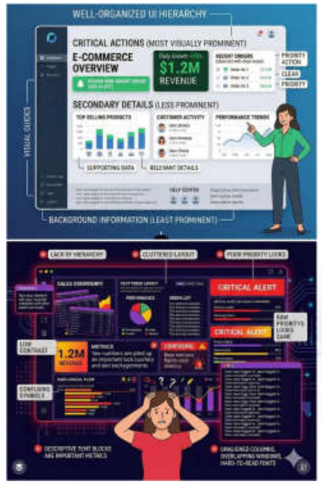
- In urgent situations, **speed** and **clarity** become critical
- Users cannot:
  - Read long explanations
  - Interpret complex charts
- Design must:
  - Highlight anomalies clearly
  - Use strong visual contrast
  - Reduce decision steps



UI Design: Meaningful Representation

Hierarchy

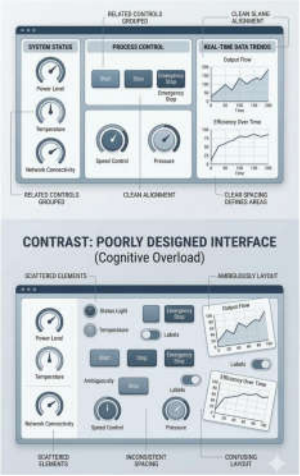
- Information should be organized in a hierarchy to reflect its importance
  - Users should be able to immediately distinguish the importance of information
- Hierarchy is created using Size, Color, Position, Contrast, Motion



UI Design: Meaningful Representation

Grouping, Alignment & Spacing

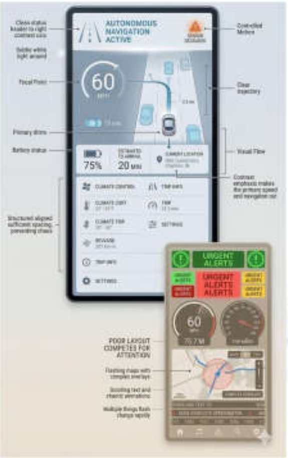
- Human perception naturally groups related elements.
- Good UI design uses
  - **Grouping**: indicate related functions
  - **Alignment**: create structure
  - **Spacing**: separate different information areas



UI Design: Meaningful Representation

Attention Guidance

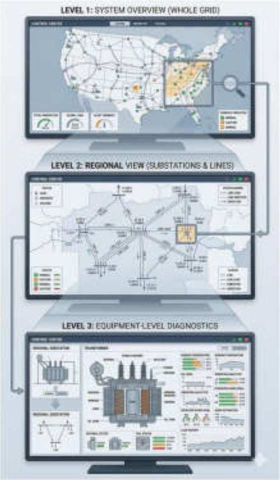
- Guides the user's eyes naturally
  - Guide attention, not compete for it
- Techniques:
  - **Visual flow** (top-to-bottom or left-to-right)
  - Contrast emphasis
  - Clear focal points
  - Controlled use of motion



UI Design: Meaningful Representation

Progressive Disclosure

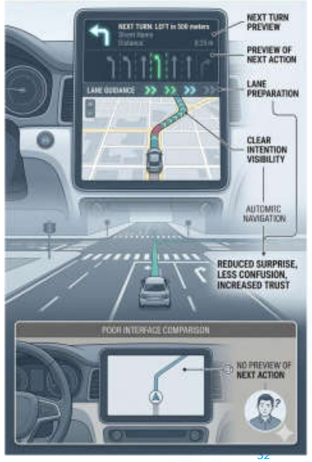
- **Not all information** should be shown at once
  - Show essential information first
  - Reveal more detail when needed
- Benefits
  - Reduces cognitive load
  - Keeps interface clean



UI Design: Meaningful Representation

Intention

- Must inform users that what the system is trying to do
  - Reduces surprise and confusion
  - Build trust
- Common methods
  - Visual previews before execution
  - Animated indicators showing next action

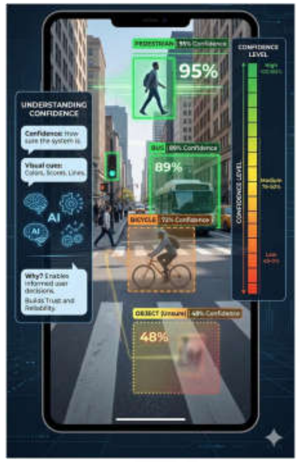


Transparency

- Intelligent systems are often **dynamic** and **unpredictable**
- Non-ideal system conditions should be clearly reflected
- Transparency increases the trust

Confidence

- **How certain** the system is
  - AI outputs may be uncertain
- Good design should
  - Confidence score should be indicated, especially when it is low
    - E.g. Object detection box with confidence
  - Confirmation should be required in uncertain cases
    - E.g. "Did you mean: Call Alex?"



Latency

- Intelligent systems introduce **delays**
  - Sensor latency
  - Network communication
  - AI model processing
  - Cloud inference
- Good design should show
  - Show processing status
  - System mode

Partial or Degraded Information

- Sometimes the received data is **incomplete or degraded**
  - Camera obstruction
  - Sensor failure
  - Poor environmental conditions
- Good design should show
  - Data limitations
  - Reduced reliability
  - System fallback behavior

UI Design: Meaningful Representation: Transparency

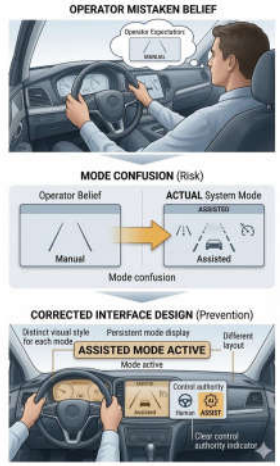
Information Overload

- Transparency usually provide more information
- More information is always better?
  - **Too little information**
    → users cannot trust the system
  - **Too much information**
    → users cannot process it
- Good design provides **the right information at the right time**

UI Design

Mode Transition

- Modern intelligent systems operate in **multiple modes**
  - Users have different responsibility and expectation in modes
- Mode Confusion should be avoided
  - Persistent mode display
  - Distinct visual styles for each mode
  - Clear control authority indicators



UI Design: Mode Transition

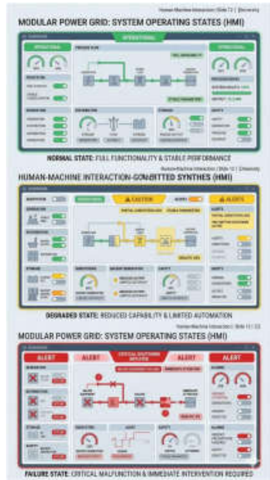
Transition Design

- Transitions must be **explicit**, **noticeable** and **understandable**
  - Clear visual indication
  - Change in color or layout
  - Status confirmation

UI Design: Mode Transition

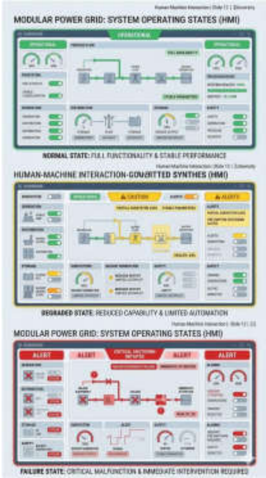
Normal, Degraded, and Failure

- Each state must be clearly **distinguishable**
- Systems may operate in:
  - **Normal State:** Full functionality, Stable performance
  - **Degraded State:** Reduced capability, Limited automation
  - **Failure State:** Critical malfunction, Immediate intervention required



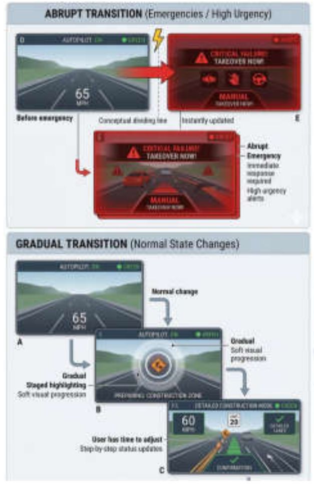
Visual Continuity

- Helps users maintain mental models
- Transitions should preserve:
  - Layout stability
  - Familiar structure
  - Consistent encoding



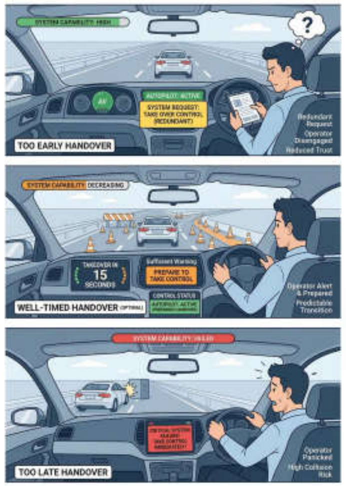
Abrupt vs Gradual Transitions

- Depends on risk level and urgency
  - **Abrupt Transitions**
    - Immediate change
    - Suitable for emergencies
    - High urgency
  - **Gradual Transitions**
    - Progressive visual cues
    - Time for adjustment
    - Suitable for normal state changes



Handover Timing

- Timing must balance **system capability** and **human readiness**
- Human takeover requires:
  - Sufficient warning time
  - Clear responsibility shift
  - Cognitive preparation
- If too **late**, reaction time is insufficient
- If too **early**, trust may decrease



Alerts

- Alerts are not decorative signals
- Mechanism to:
  - Capture attention
  - Signal abnormal conditions
  - Trigger timely action
- Poor alert can cause delay, confusion, or overreaction

UI Design: Alerts

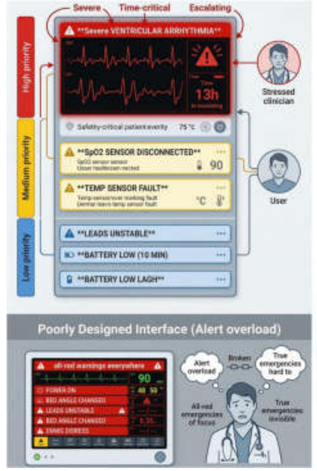
Notification vs Warning vs Alarm

- **Notification**
  - Informational
  - No immediate action required
- **Warning**
  - Potential risk
  - Attention required
  - Possible action needed
- **Alarm**
  - Immediate danger
  - Action required **now**

UI Design: Alerts

Prioritization

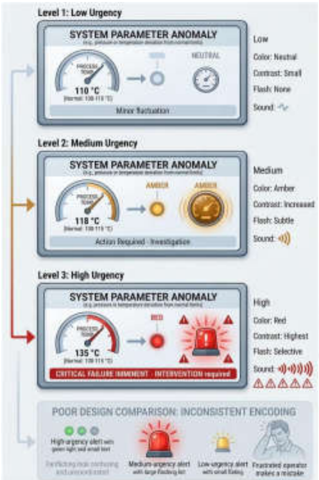
- If everything is urgent, nothing is urgent
  - Not all alerts are equally critical
- Prioritization should be based on:
  - Consequence Severity
  - Time Sensitivity
  - Escalation Probability



UI Design: Alerts

Urgency Encoding

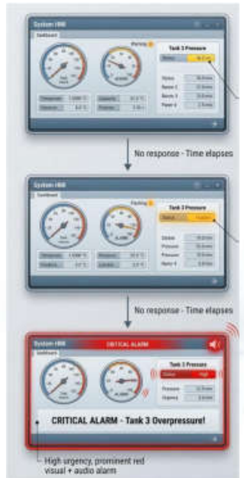
- Urgency can be encoded through:
  - Color (e.g., neutral → amber → red)
  - Size and contrast
  - Flashing or motion
  - Sound intensity and repetition
- Must be consistent and easy to interpret



UI Design: Alerts

Escalation Strategies

- **Increasing visibility** over time if no action is taken
  - Supports timely intervention without immediate overload
- Examples:
  - Static indicator → flashing signal
  - Visual only → visual + audio
  - Warning → alarm



UI Design: Alerts

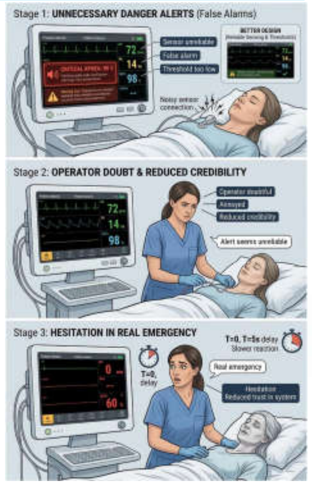
Alarm Fatigue

- **Alert frequency** must be carefully controlled
- Alarm fatigue occurs when:
  - Too many alarms are triggered
  - Low-priority alarms dominate
- Consequences:
  - Ignored critical alerts
  - Delayed response
  - Loss of trust

UI Design: Alerts

False Alarms

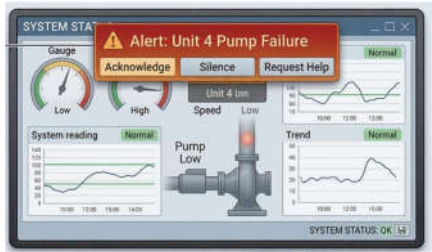
- Happen when:
  - System signals danger unnecessarily
  - Thresholds are poorly set
  - Sensors are unreliable
- Effects:
  - Reduced credibility
  - Hesitation during real emergencies



UI Design: Alerts

Acknowledgment Design

- Users must be able to:
  - Confirm the alert
  - Silence non-critical alarms
  - Escalate or request assistance
- Acknowledgment should:
  - Not hide unresolved problems
  - Clearly show current status



UI Design: Alerts

Human Factors Patterns

- Alert design must align with human cognitive limits
- Common human factors issues:
  - Startle effect from sudden alarms
  - Attention tunneling on flashing signals
  - Overreaction to loud warnings
  - Delay due to unclear instructions

Failures

- **Hidden Modes**
  - Mode changes but the user does not notice
    - E.g. Aircraft autopilot mode changes without clear indication
- **Delayed Feedback**
  - Slow responds without feedback
  - Users may
    - Repeat commands
    - Assume failure
    - Take unnecessary actions
    - Create conflicting inputs

Failures

- **Over-Automation Masking**
  - Automation can hide system complexity
    - Users may not understand what the system is doing
  - Leads to automation complacency
- **Poor State Visibility**
  - If system states are not clearly visible, users cannot maintain situational awareness

Failures

- **Poor Prioritization**
  - Low-risk issues are displayed like high-risk
    - Lose urgency perception
    - Alarm fatigue
  - Prioritization should reflect severity and time sensitivity
- **Misleading Scales**
  - Axis scales are inconsistent
  - Small changes look dramatic
  - Large changes appear minor
  - Context is missing

Failures

- **Missed Critical Alerts**
  - Critical alerts must dominate the visual field
  - Design must ensure:
    - High visibility
    - Strong contrast
    - Clear differentiation
- **Overlapping Alarms**
  - Multiple alarms trigger simultaneously
  - Signals compete for attention
  - Urgency levels are unclear

2D Screen Limitation

- **Traditional Interaction**
  Environment ↔ **Display** ↔ Operator
  - Screens separated from the physical task environment
- Problems:
  - Users must shift gaze between task and display
  - Information must be mentally mapped to real-world locations
  - Spatial relationships may be unclear

Immersive Interface

- Aim to integrate **digital content** with the **user's sensory perception** (vision, hearing, or touch), allowing users to interact with **virtual** or **augmented environments** in a more natural and spatial manner
  - Place digital information directly into the user's perception of the environment
- Extend traditional interfaces with different immersion and risk

Virtual Reality (VR)

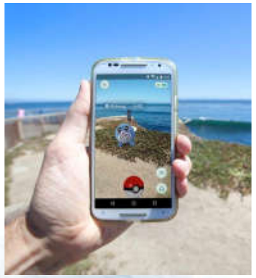
- Creates a **fully simulated digital environment**
  - immersed through a head-mounted display (HMD)
  - interact using controllers, gestures, or body motion
  - Users cannot see the real world during the experience
- E.g. Surgical training, flight simulators

Virtual Reality (VR)

- **Benefits**
  - Fully immersive interaction environment
  - Supports spatial understanding of complex systems
  - Effective for simulation and education
    - Enables safe training for dangerous tasks
- **Limitations**
  - Users lose awareness of the real environment
  - Motion sickness and visual fatigue may occur
  - Requires specialized hardware
  - Not suitable for tasks requiring real-world interaction

Augmented Reality (AR)

- **Overlays digital** information on top of the **real world**,
  - Usually through AR glasses or mobile devices
    - if head-mounted displays is used, it will be Mixed Reality
  - Users can see **both** the physical environment and digital elements simultaneously
- E.g. AR repair instructions, AR navigation systems



Augmented Reality (AR)

- **Benefits**
  - Combines real-world perception with digital guidance
  - Reduces cognitive translation between instructions and action
  - Improves situational awareness
  - Useful for maintenance, navigation, and training
- **Limitations**
  - Requires accurate environment tracking
  - Alignment errors between digital objects and real objects
  - Limited field of view in current AR devices
  - Visual clutter may obstruct real-world information

Mixed Reality (MR)

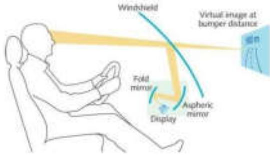
- Blends **digital and physical worlds**, allowing virtual objects to interact with real objects and respond to the environment
  - Digital elements appear anchored in the real environment and can change dynamically
- E.g. Holographic models in engineering design.

Mixed Reality (MR)

- **Benefits**
  - All benefits of AR and VR
  - Enables natural interaction with digital objects
  - Supports collaboration in shared environments
  - Useful for design, engineering, and remote assistance
- **Limitations**
  - High computational and hardware requirements
  - Tracking and environment mapping challenges
  - Limited maturity of current devices
  - Potential visual distractions

Head-Up Display (HUD)

- Projects **essential information** into the **user's line of sight**,
  - allowing users to access information **without looking away** from their primary task
- E.g. Commonly used in vehicles and aircraft



Head-Up Display (HUD)

- **Benefits**
  - Reduces gaze shifts between display and environment
  - Supports faster perception of critical information
  - No wearable devices
  - Improves situational awareness
  - Useful for navigation and safety alerts
- **Limitations**
  - Limited display area
  - Too much information may cause distraction
  - Brightness and visibility challenges under sunlight
  - Risk of visual clutter

Projection-Based Interfaces

- Project digital information **directly onto real-world surfaces**
  - Users interact with the projected information through **gestures** or **touch**
- Examples: Interactive factory workstations, projection-based repair guidance

Projection-Based Interfaces

Projection-Based Interfaces

- **Benefits**
  - Integrates digital information into the physical workspace
  - Enables collaborative interaction
  - Large display area
  - No wearable devices
  - Useful in industrial and educational environments
- **Limitations**
  - Sensitive to lighting conditions
  - Limited interaction precision
  - Requires stable surfaces for projection
  - Occlusion problems when users block the projection

Interface Comparison

Interface	Immersion Level	Ability	Risk
Virtual Reality	Very High	Fully virtual environment for training and simulation	Users lose awareness of the real world; motion sickness
Augmented Reality	Medium	Overlays digital information onto the real world	Misalignment and visual clutter
Mixed Reality	Medium–High	Digital objects interact with the real environment	Complex tracking; distraction
Head-Up Display	Low	Shows critical information in the user’s line of sight	Limited display space; information overload
Projection Interface	Low–Medium	Projects digital information onto physical surfaces	Lighting sensitivity; occlusion

Immersion Levels

- **Higher Immersion ≠ Better Performance**
  - Maintaining awareness of the real world is essential in **safety-critical systems**
- Excessive immersion can:
  - Reduce awareness of surrounding hazards
  - Distract users from the physical task
  - Delay response to unexpected events
- Choose the **appropriate level of immersion** based on the task and safety requirements

Benefits

- Immersive interfaces align digital information with physical objects
  - Reduces the need for mental translation between information and action
- E.g. **AR maintenance system**
  - Repair instructions appear directly on the machine component

Immersive Interface
Benefits

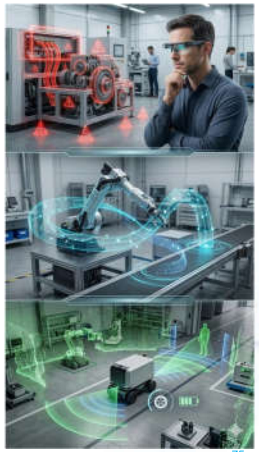
- Reduce switch of attention between the display and the system
    - Reduce the workload and error
- E.g. **Car Head-Up Display (HUD)**
    - Speed and navigation are shown on the windshield
    - The driver does not need to look down at the dashboard

Immersive Interface
Benefits

- Reduce cognitive translation
    - Faster understanding and response
    - Reduced cognitive load
- E.g. **Navigation system**
    - Driver sees a map and need to convert it to real-world direction
    - AR HUD: Arrow appears directly on the road ahead.

Immersive Interface
Benefits

- Integrating system information with environmental perception
- Examples
    - Highlighting hazards in AR
    - Visualizing robot movement paths
    - Displaying vehicle sensor information



Immersive Interface
Interaction Method

- Each method has trade-offs in precision, fatigue, and reliability:
    - Gaze-based selection
    - Gesture control
    - Voice commands
    - Hand controllers
    - Physical buttons

Immersive Interface

Hardware Constraints

- Immersive systems face **physical limitations**:
  - Field of view size
  - Display brightness in outdoor environments
  - Tracking accuracy
  - Latency
  - Weight and ergonomics
- **Hardware constraints** directly affect usability and safety

Immersive Interface

Human Factors

- Unlike traditional screens, immersive interfaces:
  - Share visual space with the real world
  - Compete with physical hazards
  - Depend on tracking and motion
- Will new human factors risks be introduced?

Immersive Interface: Human Factors

Occlusion

- Digital elements **block** real-world objects
  - Hide critical environmental cues
  - Reduce peripheral awareness
- In safety-critical contexts
  - Delay hazard detection
  - Create false confidence

Immersive Interface: Human Factors

Visual Clutter

- **Minimalism** is essential in immersive HMI
- Too many overlays are displayed
  - Multiple layers compete for attention
  - Contrast and hierarchy are weak
- Effects:
  - Slower decision-making
  - Increased cognitive load
  - Missed critical information

Registration Errors

- Digital overlays do not align with physical objects
  - Tracking drifts over time
  - Motion causes instability
- Consequences:
  - Misinterpretation of position
  - Dangerous action based on incorrect alignment

Delayed response

- Latency may occur due to sensor, network, graphics rendering, system processing
- Delayed visual feedback can cause:
  - incorrect perception of object position
  - mismatch between real movement and displayed information
  - slower user reaction and decision-making

Motion Sickness & Fatigue

- Low latency and ergonomic design are mandatory
- Immersive systems may cause discomfort due to:
  - Latency between head movement and display update
  - Mismatch between visual motion and body sensation

Overtrust in Overlays

- Highlighted digital cues may appear **authoritative**
- Users may:
  - Follow overlays without verification
  - Ignore conflicting real-world signals
  - Over-rely on automation
- Immersive design must avoid creating blind trust

Immersive Interface: Human Factors

Attention Diversion

- Overlays can:
  - Pull attention away from hazards
  - Narrow focus excessively
  - Reduce peripheral awareness
- Attention must remain **balanced between**: **Digital** information and **physical** environment

Immersive Interface: Human Factors

Context Switching

- Operators may **switch** between:
  - Immersive view
  - Physical controls
  - External displays
- Frequent switching increases:
  - Cognitive load
  - Error probability
- Immersive interfaces **should reduce**, not increase, **context switching**

Immersive Interface

Design Principles

- Engineering rules
  - Goal: **maximize** safety and reliability
  - Goal: **not maximum** immersion
- Design must prioritize:
  - Safety → Clarity → Stability → Trust

Immersive Interface: Design Principles

Real-World Dominance

- Physical environment must remain **primary**
- Digital information should **support reality**
- Guidelines:
  - Do not block critical objects
  - Preserve peripheral vision
  - Avoid full-screen overlays in operational tasks

Immersive Interface: Design Principles

Minimal Overlays

- Display **only**:
  - Task-relevant information
  - Time-critical signals
  - Actionable guidance
- **Avoid**:
  - Decorative graphics
  - Excessive annotations
  - Persistent non-essential elements

Immersive Interface: Design Principles

Priority Hierarchy

- Use **hierarchy** to indicate:
  - Critical vs secondary
  - Immediate vs future
  - Risk vs normal state
- Hierarchy must be instantly recognizable
- Priority should be encoded (size, motion, position)

Immersive Interface: Design Principles

Adaptive Visibility

- Adapt display based on:
  - Task phase
  - Environmental condition
  - User workload
  - Risk level
- **Low-risk** state → simplified display
  High-risk state → increased guidance

Immersive Interface: Design Principles

Failure Fallback

- Tracking or sensors may fail
- **Never leave incorrect information visible**
  - Detect failure clearly
  - Remove misleading overlays
  - Notify the operator immediately
- Fallback behavior must be explicit

Safe Degradation

- When system **capability reduces**:
  - Reduce automation level
  - Simplify interface
  - Maintain core functionality
- Graceful degradation prevents sudden confusion
- Avoid abrupt loss of essential information

Trust Calibration

- Immersive interfaces influence trust
- Design should:
  - Show uncertainty
  - Avoid false precision
  - Make automation boundaries visible
  - Indicate confidence levels

Audio

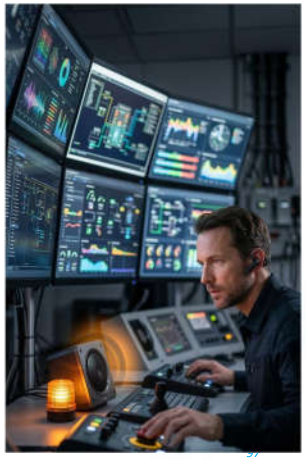
- Vision is dominant, but **audio** is **critical**
- Audio is not secondary decoration
  It is a functional safety channel
- The auditory channel:
  - Complements visual information
  - Captures attention quickly
  - Supports operation in dynamic environments

Complementary Modality

- Audio complements vision by:
  - Providing redundancy for critical alerts
  - Reducing visual overload
    - When visual attention is limited, audio maintains awareness
  - Supporting multimodal feedback
    - Proper coordination between vision and audio improves robustness

Eyes-Busy Scenarios

- Audio is **especially valuable** when:
  - The operator must focus visually on the environment
  - Hands are occupied
  - Movement is required
- Audio supports safe operation
  - E.g. Driving, Surgery, Industrial maintenance



Temporal Advantages

- Sound has **strong temporal properties**:
  - Immediate attention capture
  - Fast perception
  - Effective for urgency signaling
  - Does not require visual fixation
- Unlike visuals, audio can interrupt ongoing tasks effectively

Urgency Encoding

- Which sound feels more urgent?

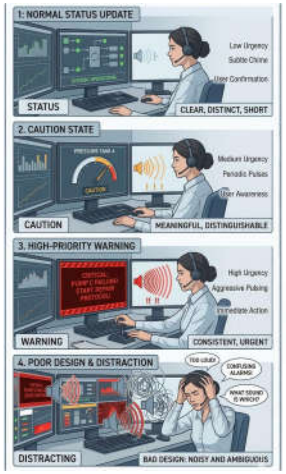
Sound A **Sound B** **Sound C** **Sound D**

Urgency Encoding

- Urgency can be conveyed through:
  - Pitch (higher = higher urgency)
  - Tempo (faster = higher urgency)
  - Rhythm (faster = higher urgency)
  - Volume (larger = higher urgency, used carefully!)
- Encoding must be consistent and easy to distinguish

Effective Feedback

- Sound should communicate state and urgency **without causing distraction**
- Sound Feedback must be:
  - Clear
  - Distinguishable
  - Meaningful
  - Consistent



Meaning of Sound

- Users should not need to guess what a sound means
- Method:
  - **Earcons**
    - Meaning learned through training
    - Abstract tones or musical patterns
    - Example:
      - Windows system notification sound
  - **Auditory Icons**
    - Real-world sounds mapped to events
      - Intuitive and familiar
    - Example
      - Trash delete sound
      - Camera shutter sound
      - Keyboard typing sound

Meaning of Sound

- Effective mapping requires:
  - Clear association between sound and event
  - Consistency across system states
  - Distinct sounds for distinct meanings
- Avoid:
  - Similar tones for different alerts
  - Overly complex sound patterns

Escalation via Sound

- Escalation supports gradual attention capture without immediate overload
- Escalation strategy:
  - Low-priority notification → short tone
  - Warning → repeated tone
  - Alarm → louder, faster repetition
- Sound intensity should match risk level

Audio

Directionality

- Humans can localize sound sources
- Directional sound can guide attention without visual scanning
- Audio can provide:
  - Spatial orientation
  - Directional warnings
  - Source identification

Audio

When Audio Outperforms Visual

- In time-critical situations, sound can reduce response delay
- Audio is superior when:
  - Immediate reaction is required
  - Visual channel is overloaded
  - Visibility conditions are poor
  - Continuous monitoring is impractical

Audio: Effective Design

Overload

- Too many sounds cause stress and desensitization
  - Sound alerts may be ignored
- Design Implication:
  - Limit number of distinct sounds
  - Reserve audio for important events
  - Avoid continuous or unnecessary tones

Audio

Risks of Overuse

- **Silence** can be as important as sound
- Too many sounds reduce effectiveness.
  - Annoyance
  - Distraction
  - Alarm fatigue
  - Desensitization

Audio: Effective Design

Redundancy

- Critical events should use be alerted by both visual and auditory signals
  - **Redundant signals** must be synchronized and non-conflicting
- Redundancy improves reliability

Audio

Speech Interaction

- One of the **most natural forms of human communication**
- Advantages
  - Natural communication (no and little training)
  - Hands-free interaction
  - Eyes-free interaction
  - Faster input for some tasks

Audio: Speech Interaction

Components

- Speech interaction typically includes several stages:
  1. **Speech Recognition**
     Spoken Audio → Text
  2. **Natural Language Understanding (NLU)**
     Interprets meaning
  3. **Dialogue Management**
     Determines how to response
  4. **Speech Synthesis (Text-to-Speech)**
     Text → Spoken Output

Audio: Speech Interaction

Types

- **Command-Based Interaction**
  - Speak predefined commands.
    - E.g. "Turn on the lights."
  - Advantages
    - Reliable
    - Easy to interpret
  - Limitations
    - Limited flexibility
- **Conversational Interaction**
  - Communicate using natural language
    - E.g. "What should I do?"
  - Advantages
    - More natural interaction
    - Supports complex queries
  - Limitations
    - Higher system complexity

Audio: Speech Interaction

User Frustration

- Speech interaction can frustrate users when:
  - Commands must be repeated
  - Misunderstands frequently
  - Responses are unnatural or rigid
- Frustration reduces compliance and increases manual override
  - Should focus on Turn-Taking Determination, Interruption Handling, Feedback Timing, Confirmation Strategy, Error Recovery

Audio: Speech Interaction: Design Principle

Turn-Taking

- Requires clear control of **who is speaking**
- Challenges
  - Interruptions
  - Overlapping speech
  - Delayed system responses
- Design should provide signals such as:
  - Listening indicators
  - Audio feedback
  - Confirmation prompts

Audio: Speech Interaction: Design Principle

Interruptions

- **Interruptions** are **inevitable**
  - User corrects system
  - System and User talk at the same time
  - Multiple commands overlap
  - Emergency situations override normal dialogue
- **Interruption management** is important to avoid:
  - Confusion
  - Missed instructions
  - Unsafe outcomes

Audio: Speech Interaction: Design Principle

Feedback Timing

- **Timing** is part of interaction **quality**
  - Immediate acknowledgment
  - Processing indication
  - Clear response
- **Delayed feedback** may cause:
  - Repeated commands
  - User confusion
  - Loss of trust

Confirmation Strategy

- Critical commands require confirmation
  - E.g. “Confirm shutdown?”
  - Prevents unintended actions
- However, excessive confirmation slows workflow
- **Tradeoff** between safety and efficiency

Error Recovery

- Speech errors are **inevitable**
- **Error handling** must be smooth and predictable.
  - Repetition prompts
  - Clarification questions
  - Alternative suggestions
  - Safe cancellation

Over-Expectation

- Human-like voice can create unrealistic expectations
  - Users may assume more than the system can do:
    - Deep understanding
    - Full reasoning ability
    - Emotional awareness
- Mismatch between expectation and capability leads to frustration and misuse.
- Clearly communicate system limitations

Limitation

- Speech interactions are less visible than graphical interfaces
  - **Cannot** easily **see available options**
  - Users have to remember the commands

Challenges

- **Language Interpretation**
  - Ambiguity
  - Accent and pronunciation variation
- **Environment Issues**
  - Noisy environments
  - Multiple speakers
  - Echo and reverberation
- **Advanced AI**, e.g. LLM, may **help** but **high cost**

Safety Constraints

- In safety-critical systems:
  - Speech should not be the sole control method
  - Critical commands require confirmation
  - Fail-safe alternatives must exist
- Voice control must never reduce system safety
- Redundancy and clear boundaries are essential

Safety Constraints

- E.g. **Voice Misrecognition Caused a Highway Crash in Guangxi Expressway**
  - Lynk & Co Z20, February 25, 2026
  - The driver wanted to use a voice command to turn off the interior reading lights
  - However, the machine turned off all vehicle lights, including the headlights
  - The driver tried to use voice control again to turn the lights back on, but the system failed to recognize the request correctly and reportedly replied, “I still don’t know how.

Human Sensory Integration

- Humans **naturally integrate multiple senses**
- Multimodal interaction aligns with natural perception processes
- Well-designed multimodal systems feel intuitive and robust

Why Not Single Modality?

- **Single-modality** is **fragile**
  - Bright sunlight reduces screen visibility
  - Loud environments reduce speech clarity
  - Physical movement limits visual attention
- **Multimodal systems** adapt to environmental constraints

Why Not Single Modality?

Multimodal Fusion

- **Combining** information from multiple channels to support perception, decision, and action
- There are two types:
  - **Complementary**
    - Each modality provides **different** information
    - Increases richness
    - Example: visual path + auditory warning
  - **Redundant**
    - **Same** critical information delivered via multiple channels
    - Increases safety
    - Example: flashing red + alarm sound

Complementarity

- Combining multiple modalities allows one channel to **compensate** for the limitations of another
- Example
  - **Vision**
    - Pro: Spatial information
Persistent display
High data bandwidth
    - Con: Overload
Occlusion
Limited field of view
  - **Audio**
    - Pro: Temporal alerts
Attention capture
Directional cues
    - Con: Noise
Desensitization
Limited capacity

Redundancy

- Critical information can be presented through different channels
  - If one channel fails, another remains active
- Redundancy increases:
  - Detection probability
  - Reliability
  - Reaction speed

Design Principle

- **Temporal Synchronization**
  - Timing alignment is critical
  - E.g. **Confusion** when
    - Visual alert appears before sound
    - Sound triggers without visual confirmation
- **Conflict Resolution**
  - Multimodality disagrees
  - System must:
    - Detect inconsistencies
    - Prioritize more reliable modality
    - Provide clear clarification

Design Principle

- **Modality Dominance**
  - Dominance should match urgency
  - Maintain balanced awareness in normal situations
- **Reliability-Based Weighting**
  - Not all modalities are equally reliable
  - Emphasize more reliable channel
  - Adaptive reliability improves robustness

Design Principle

- **Attention Management**
  - Multi-signal competes for limited attention
  - Should:
    - Avoid simultaneous overload
    - Sequence signals logically
    - Escalate gradually
    - Prevent startle effects
- **Adaptive Modality Switching**
  - Adapt modality based on:
    - Task phase
    - User workload
    - Environmental condition
    - Risk level
  - Example:
    - Low risk: Visual only
    - High risk: Visual + audio

Failure Handling

- Failure-aware fusion increases safety
  - When one modality fails:
    - Detect the failure
    - Notify the user
    - Increase reliance on remaining modalities
- Never leave users unaware of degraded capability