The human performance envelope:

Past research, present activities and future directions
Agenda

• Human performance envelope?

• Past research:
  – Research motivation & overview
  – Initial findings

• Present activities: Confirmation and extension
  – What happens when controllers are working with automation? Overview

• Future directions

• Conclusions

• Applications
Human performance envelope

Normal operations: ATC is working effectively within this workload and scenario space.

At edges, due to difficulty, complexity, overload etc., performance/safety may be temporarily compromised; but situation normally recovered before loss of separation event.

Here a loss of separation will occur.
Motivation

• ATM is an ‘ultra-safe’ industry

• ATM remains highly ‘human-centric’ – real-time operations

• Mitigations defend against incidents, but still occur

• Need to know when controllers are approaching the edges of acceptable performance
Research overview

• Overall Aims
  – Identify factors
  – Identify and verify interactions that threaten performance
  – Develop markers of performance limits or boundaries

• Potential Outcomes
  – Better understanding of ‘difficult’ human performance factors in Air Traffic Control (ATC)
  – Signs and symptoms that performance is threatened
Study approach

2009
- Literature review
- Incident reports
- Survey
- Sim. trials

2012
- Controller interview

Factor identification
- Interacting factors
- Markers of performance limits
Method: ATC exercise

- **Design**
  - **IV:** Taskload (low/high)
  - **Covariates:** Arousal, Fatigue, SA, Stress, Workload
  - **DV:** (Performance): STCA, route directs, time to respond

- **Measures**
  - **Covariate** | Arousal | Fatigue | SA | Stress | WL
  - **Measure**  | Stress–Arousal Check List | Visual Analogue | Situation Present Assessment Method | SACL | Instantaneous Self Assessment
  - **Interval (Mins)** | 20 | 20 | 4 | 20 | 4

- **Participants**
  - 29 male students aged between 18-30
  - All received a 4 hour training session
  - Score of ≥80% on a simulation-related competency test
Results: Factors occur together

- Stress
- Fatigue
- WL
- Arousal
- SA

Graph shows the relationships between these factors with significance levels indicated.

- Black lines: Significance of p<0.001
- Pink lines: Negatively related, significance level of p<0.001
- Gray lines: Significance of p<0.005

Graph inset:
- X-axis: Workload (ISA)
- Y-axis: Stress (SACL)
Factors may combine in a cumulative way and associate with poorer performance.
Results (2) Time on task: Less resilient performance

![Bar chart showing time on task for different conditions]

- Low WL, Low Stress (n=10) = 59.55
- Low WL, High Stress (n=3) = 62.63
- High WL, Low Stress (n=5) = 65.31
- High WL, High Stress (n=11) = 109.9

![Bar chart showing time on task for different conditions]

- High WL, Low Stress (n=5) = 55.37
- Low WL, Low Stress (n=10) = 74.49
- Low WL, High Stress (n=5) = 125.66
- High WL, High Stress (n=9) = 128.22
Apparent link between some behaviours and self reported measures
  – Example: Indicators associated with fatigue
    – Yawning
    – Looking away from screen
    – Posture changes

Interviews
  – 22 ATCOs took part (17 males, 5 female)
  – What markers have you used that informed you about your performance?

Edwards et al., 2014
Key findings

• Controllers use internal and external markers

“If someone’s getting stressed they can get louder or sit closer to the screen or something so if you see these things then you pay more attention yourself.”

Edwards et al., 2014
Markers are used to indicate edges of performance

- **Indicators**
  - Internal – subjective to the controller
  - External – overt, observable indicators
    - Compensation strategy
    - Physical change
    - Performance decline
Key findings

• Controllers use internal and external markers

• Markers are similar between controllers

Edwards et al., 2014
Key findings

• Controllers use internal and external markers

• Markers are similar between controllers

• Developed from experience

“You start to know that you’ve been burning your fingers before on this kind of situation and you really have to pay attention”

Edwards et al., 2014
Key findings

- Controllers use internal and external markers
- Markers are similar between controllers
- Developed from experience
- Markers are used to support performance

“I’d say 300%, if you know that you’re not being top performing today then that’s fine, just adapt your working style. But if you don’t know it, it might end in tears”

Edwards et al., 2014
Key findings (2) Markers are used to support performance

Edwards et al., 2014
Conclusions at the end of this research...

• Multiple factor relationships:
  – Multiple factors co-occur to influence controller performance
  – Interactions between factors may create a cumulative influence on performance
  – But limitations of study challenge generalisability of results

• Behavioural markers:
  – Markers indicate limits of performance
  – Controllers use markers to support performance

Edwards et al., 2014
Research overview

• Overall Aims
  – Identify the effect of automation in the ATC task on:
    • Workload
    • SA
    • Performance
  – Identify and verify interactions that threaten performance

• Potential Outcomes
  – Better understanding of ‘difficult’ human performance factors in Air Traffic Control (ATC)
  – Signs and symptoms that performance is threatened
Method: Simulation

- Human in the loop, en-route high fidelity simulation (Part task)
  - Single high-altitude sector in Cleveland ARTCC (79)
  - Mix of level flight and transitioning aircraft
  - No winds
  - All aircraft CPDLC equipped
  - All aircraft FMS and ADS-B equipped
Method: Design (1)

- Within subjects design
- Conducted as part of a larger study
- 4 task sets, Decreasing levels of automation:
  - Task set 1: Conflict detection only (CD)
  - Task set 2: Conflict detection and routine tasks (CD+RT)
  - Task set 3: Conflict detection, coordination and pilot requests – decision making (CD+DM)
  - Task set 4: Conflict detection, routine tasks, coordination's and pilot requests (CD+RT+DM)
- Conflict probe running, but hidden
Method: Design (2)

• Measures:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Workload</th>
<th>SA</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure</td>
<td>ISA</td>
<td>SPAM</td>
<td>Time to correctly detect conflicts</td>
</tr>
<tr>
<td>Interval (Mins)</td>
<td>3</td>
<td>3</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

• Participants
  
  – 8 retired controllers from ZOA staffing the test sector
  
  – Age range 50-69
  
  – Experience in en-route ATC ranged from 23 – 29.5 years (M=24.94 SD=2.54)
Results

• Workload significantly different between conditions
  – Task 1 – lowest workload
  – Tasks 2 and 4* highest
• SA response times significantly different between conditions
  – Times slowest task 1 and task 3
  – Fastest task 2* and task 4
• Time to detect conflicts significantly different between conditions
  – Slowest in task 1, fastest in task 2
Results (1): Automation significantly affects controller workload

- (1) Conflict Detection (CD): 3.09
- (2) CD + Routine Tasks (RT): 3.46
- (3) CD + Decision Making (DM): 3.39
- (4) CD + RT + DM: 3.71
Results (2) Automation significantly affects controller situation awareness

Average time to respond (secs)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Average Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Conflict Detection (CD)</td>
<td>6.77</td>
</tr>
<tr>
<td>(2) CD + Routine Tasks (RT)</td>
<td>5.33</td>
</tr>
<tr>
<td>(3) CD + Decision Making (DM)</td>
<td>7.29</td>
</tr>
<tr>
<td>(4) CD + RT + DM</td>
<td>5.38</td>
</tr>
</tbody>
</table>
Results (3) Automation significantly affects controller performance

![Bar chart showing time (secs) to correctly detect conflicts for different conditions.](chart.png)

- **(1) Conflict Detection (CD)**: 340.39 seconds
- **(2) CD + Routine Tasks (RT)**: 282.06 seconds
- **(3) CD + Decision Making (DM)**: 326.22 seconds
- **(4) CD + RT + DM**: 301.38 seconds
Results (3) Automation significantly affects controller performance

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time (Secs) to correctly detect conflicts</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Conflict Detection (CD)</td>
<td>340.39</td>
</tr>
<tr>
<td>(2) CD + Routine Tasks (RT)</td>
<td>282.06</td>
</tr>
<tr>
<td>(3) CD + Decision Making (DM)</td>
<td>326.22</td>
</tr>
<tr>
<td>(4) CD + RT + DM</td>
<td>301.38</td>
</tr>
</tbody>
</table>
Results – Factor interactions: Task set 1

<table>
<thead>
<tr>
<th>Factor dyad</th>
<th>Time to detect aircraft (secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low WL, Good SA</td>
<td>307.74</td>
</tr>
<tr>
<td>High WL, Good SA</td>
<td>289.50</td>
</tr>
<tr>
<td>Low WL, Poor SA</td>
<td>323.97</td>
</tr>
<tr>
<td>High WL, Poor SA</td>
<td>291.80</td>
</tr>
</tbody>
</table>
Results(2) – Factor interactions: Task set 2

![Bar chart showing time to detect aircraft (secs) for different factors: Low WL, Good SA = 206.33, High WL, Good SA = 264.00, Low WL, Poor SA = 274.04, High WL, Poor SA = 325.06.](image-url)
Factors that influence controller performance (e.g. workload, fatigue) co-vary and appear to interact to create cumulative effect on performance.

Results appear to be confirmed in a second experiment with a small, but expert, sample.

Factor influences on performance may change with control context – e.g. automation.
Future directions

• HF Expert workshop
  – AHFE 2016
  – Concept development and (face) validation
• Collaboration between Future Sky and NASA Ames
  – Parallel development of human performance envelope model for pilots and controllers
  – Collaboration of Europe and US research
• Controlled simulations with expert participants
  – Part task and high-fidelity
• Factor scaling
• Further specification of edges of performance envelope
  – Markers
  – Psychophysiological measures?
Implications

- Findings support a shift towards research investigating multi-factor co-occurrences and performance associations

- Training in markers
  - Predictive measures of human performance and prevention of performance decline

- Multifactor relationships - Performance prediction
  - Mitigation in the control room
  - Prevention of multifactor combinations

- Design of controller workstation/flight deck

- Adaptive automation implications
Thank you!
Back up slides
Back up slides
Conflict Detection Study

• How well can controllers detect conflicts?
  – ...when it’s their only responsibility?
  – Could the addition of a secondary task impact their performance?
    • Routine tasks, such as hand-offs, check-ins, and frequency changes
    • Decision-making tasks, such as responding to flight crew requests or coordination requests from other controllers
  – 4x2x2 within-subjects experiment design
    • Primary independent variables:
      – Task set
      – Traffic density
      – Run length
Conflict Detection Study

- 4x2x2 matrix

<table>
<thead>
<tr>
<th>TASK SET</th>
<th>TRAFFIC DENSITY</th>
<th>SCENARIO LENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>conflict detection</td>
<td>1x</td>
<td>20m</td>
</tr>
<tr>
<td></td>
<td>1.2x</td>
<td>60m</td>
</tr>
<tr>
<td>conflict detection + routine tasks</td>
<td>1x</td>
<td>20m</td>
</tr>
<tr>
<td></td>
<td>1.2x</td>
<td>60m</td>
</tr>
<tr>
<td>conflict detection + requests and coordinations</td>
<td>1x</td>
<td>20m</td>
</tr>
<tr>
<td></td>
<td>1.2x</td>
<td>60m</td>
</tr>
<tr>
<td>conflict detection + routine tasks +</td>
<td>1x</td>
<td>20m</td>
</tr>
<tr>
<td>requests and coordinations</td>
<td>1.2x</td>
<td>60m</td>
</tr>
</tbody>
</table>
Conflict Detection Study

• Simulation backdrop:
  – Single high-altitude sector in Cleveland ARTCC
  – Mix of level flight and transitioning aircraft
  – Constant winds at altitude with forecast error
  – Conflict probe running, but hidden
Conflict Detection Study

• Dependent measures:
  – Controller detections are compared to the conflict probe data, producing:
    • Correctly identified conflicts
    • False alerts
    • Missed alerts
  – Real-time subjective workload ratings
  – Safety (separation violations)
  – Feedback from questionnaires and debrief
Conflict Detection Study

• Participants:
  – 8 retired controllers from ZOA staffing the test sector
  – 4 retired controllers from ZOA staffing the confederate airspace
  – 12 aviation students / general aviation pilots staffing the pseudo pilot positions
Results (3): Markers are used to indicate edges of performance.
Key results

• Factors correlated as expected

• Factor interactions associated with a significantly larger performance decline compared to single factors

• Significant relationships between observed participant behaviours and self-report measures
ATC Exercise: Overview

- **Aims:**
  - Investigate multifactor relationships and association with performance
  - Identify markers of performance edge

- **Experiment:** designed to reflect ATC working session
  - 116 minute task (20 minute break after 60 minutes)
  - Task used real sectors, routes and traffic flow data
  - Taskload varied every 20 minutes between low and high through number of aircraft and complexity

- **Measures:** arousal, fatigue, SA, stress, workload
- Participant behaviours observed and recorded
Behavourial markers of performance limits

• Apparent link between some behaviours and self reported measures
  – Example: Indicators associated with fatigue
    – Yawning
    – Looking away from screen
    – Posture changes

• Interviews
  – 22 ATCOs took part (17 males, 5 female)
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Edwards et al., 2014
Markers of workload

- Different markers for high workload and low workload:

- High workload:

<table>
<thead>
<tr>
<th>Category</th>
<th>Internal Marker</th>
<th>Category</th>
<th>External Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive changes</td>
<td>Don't know the next steps</td>
<td>Perception changes</td>
<td>Can’t talk to executive/ executive doesn’t hear you</td>
</tr>
<tr>
<td></td>
<td>Increased focus</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calls are a surprise</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced self-awareness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subjective feeling</td>
<td>Losing control</td>
<td>Visible cues</td>
<td>Fidgety</td>
</tr>
<tr>
<td></td>
<td>More traffic than can handle</td>
<td></td>
<td>Move closer to screen</td>
</tr>
<tr>
<td></td>
<td>Panic and uncertainty</td>
<td>Verbal cues</td>
<td>Colleagues not talking</td>
</tr>
<tr>
<td></td>
<td>Not comfortable</td>
<td>Performance changes</td>
<td>Miss actions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mixing call signs</td>
</tr>
</tbody>
</table>
Markers of workload

**Low workload:**

<table>
<thead>
<tr>
<th>Category</th>
<th>Internal Marker</th>
<th>Proposed category</th>
<th>External Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive changes</td>
<td>Pay less attention</td>
<td>Perception changes</td>
<td>Incorrect assessment of a situation</td>
</tr>
<tr>
<td></td>
<td>Easily distracted</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced self-awareness</td>
<td>Visible cues</td>
<td>Sit back in chair</td>
</tr>
<tr>
<td>Changes to control</td>
<td>Leave situations develop</td>
<td></td>
<td>Away from radar screen</td>
</tr>
<tr>
<td></td>
<td>Trying to create more complex situations</td>
<td>Performance changes</td>
<td>Talking to colleague</td>
</tr>
<tr>
<td></td>
<td>Less safety buffer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subjective feeling</td>
<td>Boredom</td>
<td></td>
<td>Overlooking aircraft</td>
</tr>
<tr>
<td></td>
<td>Relaxed</td>
<td></td>
<td>Forgetting aircraft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Repeated ‘sloppy’ mistakes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fall behind traffic due to distraction</td>
</tr>
</tbody>
</table>
## Markers of fatigue

<table>
<thead>
<tr>
<th>Cognitive changes</th>
<th>Subjective experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration issues</td>
<td>More effort to control</td>
</tr>
<tr>
<td>Increased assumptions</td>
<td>Don't want to work busy traffic</td>
</tr>
<tr>
<td>Slower</td>
<td>Force self to pay attention</td>
</tr>
<tr>
<td>Mild confusion</td>
<td>Feel tired</td>
</tr>
<tr>
<td>Reduced awareness</td>
<td>Not looking forward to shift</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Markers internal to the controller</th>
<th>Observable markers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Visible cues</td>
</tr>
<tr>
<td>Yawning</td>
<td>Less active</td>
</tr>
<tr>
<td>Laid back</td>
<td>Not as confident</td>
</tr>
<tr>
<td>Eyes closed</td>
<td>Quieter</td>
</tr>
<tr>
<td>Falling asleep</td>
<td>Distracted</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Style of control</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less flexible</td>
<td>Overlook aircraft</td>
</tr>
<tr>
<td>Reduction in efficiency</td>
<td>Multiple, small mistakes</td>
</tr>
<tr>
<td>Less safety buffer</td>
<td>‘Running behind traffic’</td>
</tr>
<tr>
<td>Incorrect plan</td>
<td>Slow to solve problems</td>
</tr>
<tr>
<td>Slower communications</td>
<td>Forget aircraft</td>
</tr>
</tbody>
</table>
### Markers of stress

- Differentiation between positive stress and negative stress

> “It’s almost excited because there is more traffic coming. It’s a different situation if someone is already in a complex situation, you realise he is falling behind”

<table>
<thead>
<tr>
<th>Category</th>
<th>Internal Marker</th>
<th>Category</th>
<th>External Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive changes</td>
<td>Start to think slower</td>
<td>Visible cues</td>
<td>Fidgeting</td>
</tr>
<tr>
<td>Physiological changes</td>
<td>Heartbeat</td>
<td></td>
<td>Red cheeks/neck</td>
</tr>
<tr>
<td></td>
<td>Sweat</td>
<td></td>
<td>Flustered</td>
</tr>
<tr>
<td>Subjective feeling</td>
<td>Not coping</td>
<td>Changes to voice</td>
<td>Speaks faster, louder</td>
</tr>
<tr>
<td></td>
<td>Feeling uncomfortable</td>
<td></td>
<td>Speaks higher</td>
</tr>
<tr>
<td></td>
<td>Anxious (negative)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nervous</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tense</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Markers of vigilance

<table>
<thead>
<tr>
<th>Category</th>
<th>Internal Marker</th>
<th>Category</th>
<th>External Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive/perception changes</td>
<td>Not as ‘sharp’</td>
<td>Performance changes</td>
<td>Overlook aircraft</td>
</tr>
<tr>
<td></td>
<td>Surprised</td>
<td></td>
<td>Don't hear/see</td>
</tr>
<tr>
<td></td>
<td>Assume more</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Focused, ‘tunnel vision’</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Donut effect</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not aware</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changes to control</td>
<td>Scan differently</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not leaving a problem</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Markers of losing the picture

- Differentiation between markers that indicate losing the picture, and having lost the picture:

  “It starts off by just falling behind a bit. So you might just be a few steps behind what you’re supposed to be doing and if that builds up too much then you will get to the point where you start to lose the picture”

<table>
<thead>
<tr>
<th>Category</th>
<th>Internal Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive changes</td>
<td>Difficulty selecting priorities</td>
</tr>
<tr>
<td></td>
<td>Thinking whilst giving the clearance</td>
</tr>
<tr>
<td></td>
<td>Tunnel vision/hearing</td>
</tr>
<tr>
<td>Subjective feeling</td>
<td>Under confident</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>External Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible cues</td>
<td>Slow at task</td>
</tr>
<tr>
<td>Performance changes</td>
<td>Running behind</td>
</tr>
<tr>
<td></td>
<td>Time working ahead degrades</td>
</tr>
<tr>
<td></td>
<td>Missing calls</td>
</tr>
</tbody>
</table>
## Markers of having lost the picture

<table>
<thead>
<tr>
<th>Category</th>
<th>Internal Marker</th>
<th>Category</th>
<th>External Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive changes</td>
<td>Lose awareness</td>
<td>Visible cues</td>
<td>Zig zagging head movement of where to look</td>
</tr>
<tr>
<td></td>
<td>Everything a surprise</td>
<td>‘Blacked out’/ silent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No plan</td>
<td>Verbal cues</td>
<td>Asking for confirmation</td>
</tr>
<tr>
<td></td>
<td>Cannot see a solution</td>
<td>Performance changes</td>
<td>Unsafe clearance</td>
</tr>
<tr>
<td>Changes to control</td>
<td>Reactive control</td>
<td></td>
<td>Unexpected decisions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Jumping from one aircraft to another</td>
</tr>
<tr>
<td>Subjective feeling</td>
<td>Panic</td>
<td></td>
<td>Don't know who’s calling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Don't react correctly</td>
</tr>
</tbody>
</table>
Inadequate communications

• Inadequate communications were described in relation to causes and contributory factors such as fatigue, lack of attention, or stress:

  “Mixing call signs happens more if someone’s tired or under pressure”

  “If you have aircraft that aren’t listening and you’re busy...maybe the extra thing that sends you over”

<table>
<thead>
<tr>
<th>Category</th>
<th>External Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Situational issues</td>
<td>Inadequate communications with aircraft</td>
</tr>
<tr>
<td></td>
<td>Equipment failures</td>
</tr>
<tr>
<td>Performance changes</td>
<td>Mixing call signs</td>
</tr>
<tr>
<td></td>
<td>Slip of the tongue</td>
</tr>
</tbody>
</table>
Conclusions

• Multiple factor relationships:
  – Multiple factors co-occur to influence controller performance
  – Interactions between factors may create a cumulative influence on performance

• Behavioural markers:
  – Markers indicate limits of performance
  – Controllers use markers to support performance

*Edwards et al., 2014*