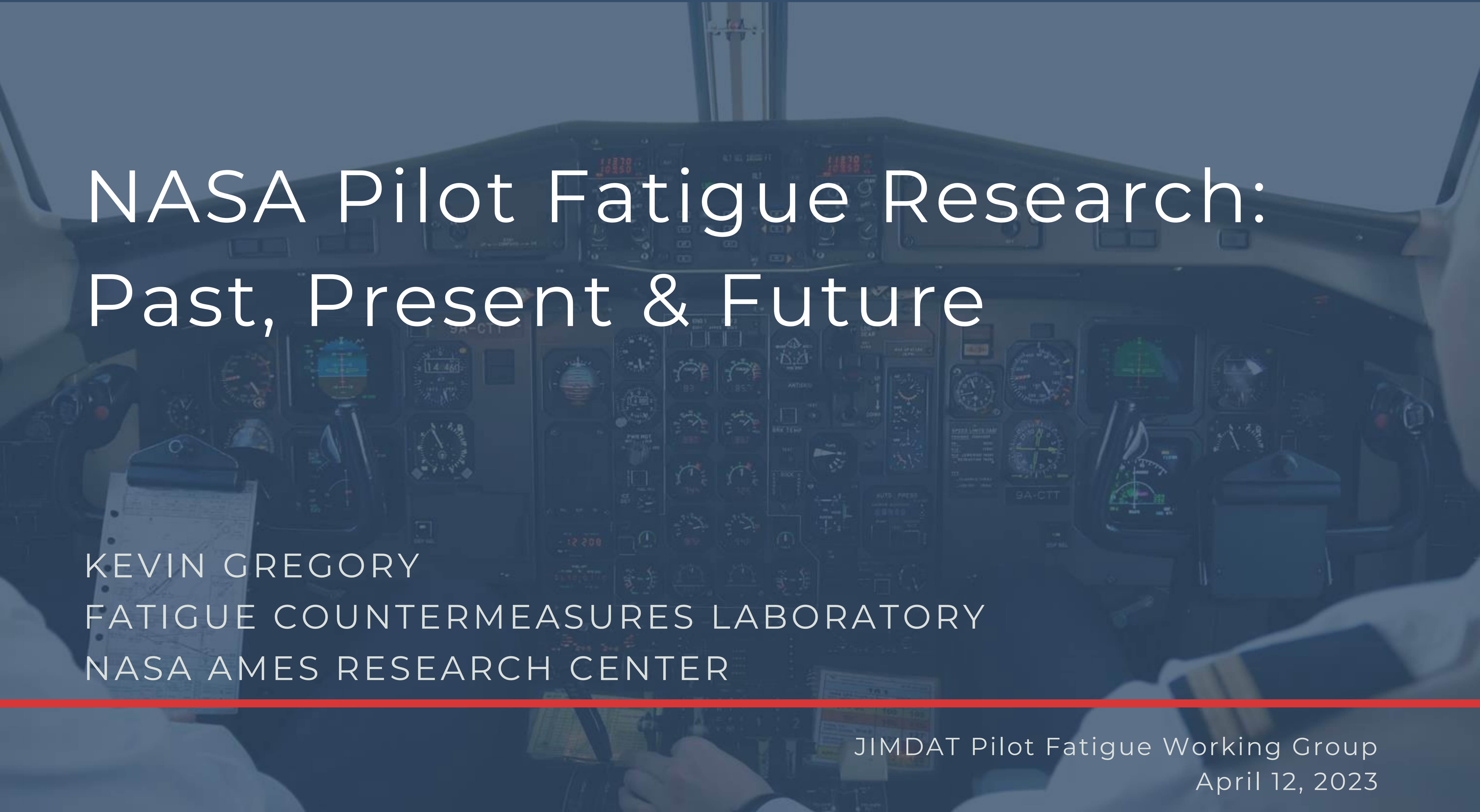

# NASA Pilot Fatigue Research: Past, Present & Future

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JIMDAT Pilot Fatigue Working Group
April 12, 2023

# Defining Fatigue

"A physiological state of reduced mental or physical performance capability <u>resulting from sleep loss or extended wakefulness, circadian phase, or workload</u> (mental and/or physical activity) that can impair a crew member’s alertness and ability to safely operate an aircraft or perform safety-related duties."   -ICAO

# Defining Fatigue: Sleep

## Cumulative Sleep Debt

Sleep loss accumulated when sleep is insufficient for multiple nights (or 24-hr days) in a row. As cumulative sleep debt builds up, performance impairment and objective sleepiness increase progressively, and people tend to become less reliable at assessing their own level of impairment.

## Sleep Quality

Capacity of sleep to restore waking function. Good quality sleep has minimal disruption to the non-REM/REM cycle. Fragmentation of the non-REM/REM cycle by waking up, or by brief arousals that move the brain to a lighter stage of sleep without actually waking up, decreases the restorative value of sleep.

## Acute Sleep Loss

Staying awake for longer than 16 hours in a row. Performance impairment worsens with increasing time awake, interacting with the circadian drive for sleep and wake.

## Recovery Sleep

Sleep required for recovery from the effects of acute sleep loss (in one 24-hour period) or cumulative sleep debt (over multiple consecutive 24-hour periods).

# Defining Fatigue: Circadian

| WINDOW OF CIRCADIAN LOW | EVENING WAKE MAINTENANCE ZONE | JET LAG<br>(A FORM OF CIRCADIAN MISALIGNMENT) |
| --- | --- | --- |
| Time in the circadian body clock cycle when fatigue and sleepiness are greatest and people are least able to do mental or physical work. The WOCL occurs around the time of the daily low point in core body temperature - usually around 0200-0600 when a person is fully adapted to the local time zone. **However, there is individual variability in the exact timing of the WOCL.** | A period of several hours in the circadian body clock cycle, just before usual bedtime, when it is very difficult to fall asleep. Consequently, going to bed extra early usually results in taking a longer time to fall asleep, rather than getting extra sleep. Can cause restricted sleep and increased fatigue risk with early duty start times. | Desynchronization between the circadian body clock and the day/night cycle caused by transmeridian flight (experienced as a sudden shift in the day/night cycle). Also results in internal desynchronization between rhythms in different body functions. Resolves when sufficient time is spent in the new time zone for the circadian body clock to become fully adapted to local time. |

# Defining Fatigue: Workload

## High Workload

High workload situations may exceed the capacity of a fatigued crew member, resulting in poorer performance. High workload may also have consequences for sleep, due to the time required to “wind down” after demanding work.

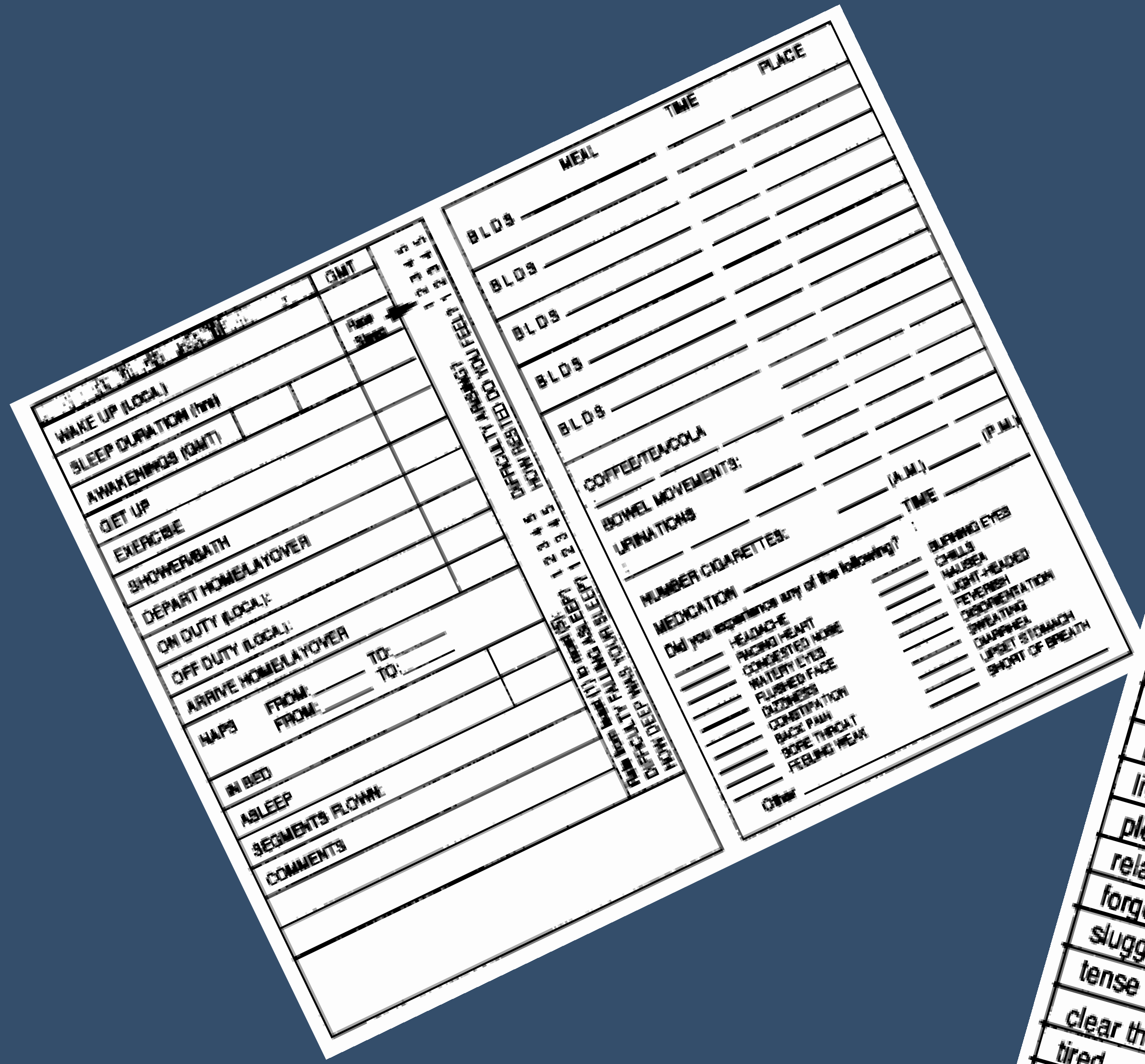
## Low Workload

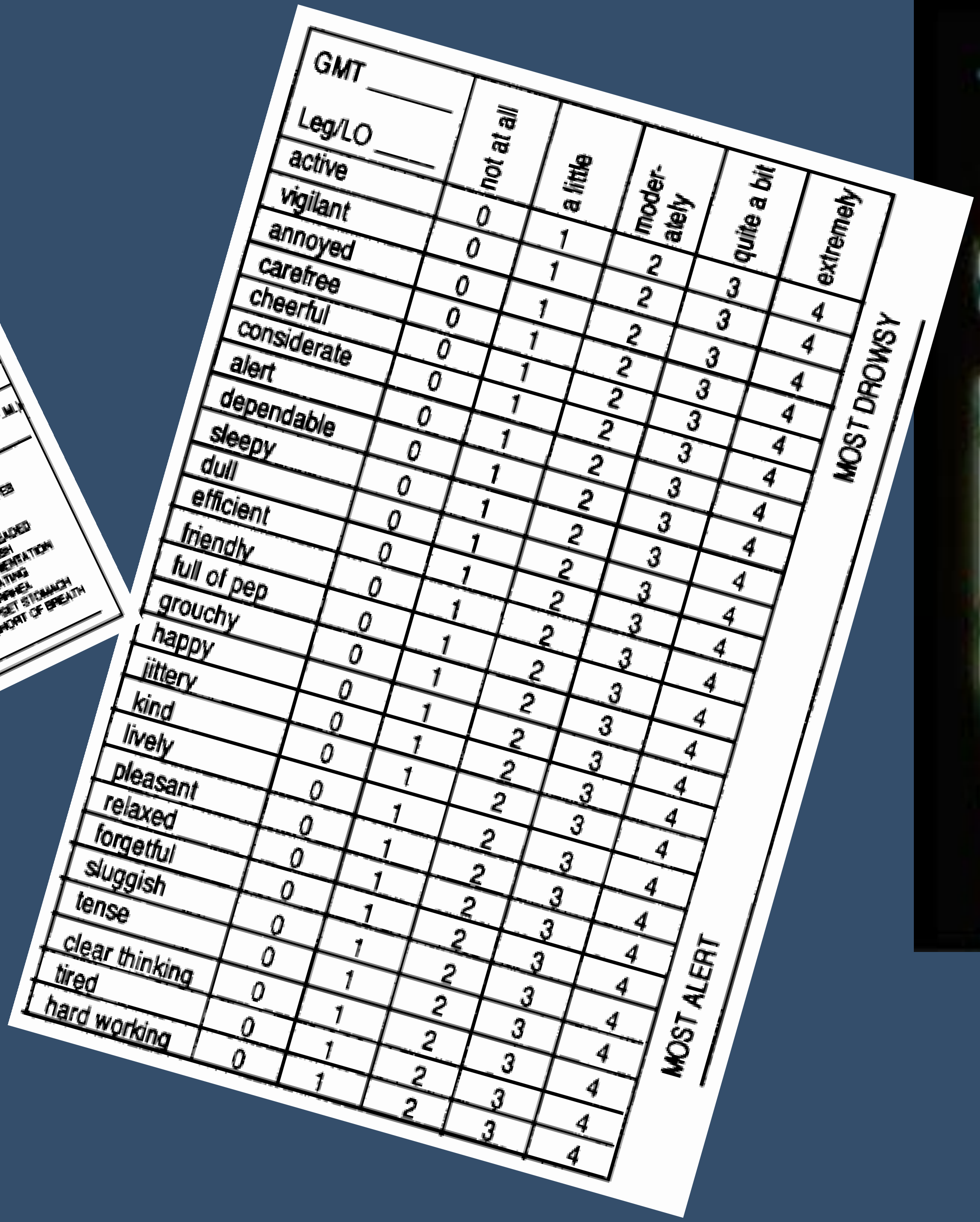
Low workload situations may lack stimulation, leading to monotony and boredom which could expose underlying physiological sleepiness and thus degrade performance.

# NASA Aviation Studies: Beginnings

- Short-haul
- Long-haul
- Long-haul layovers (lab overnight)
- Helicopter
- Overnight cargo

# NASA Aviation Studies: Methods


WAKE UP (LOCAL)
SLEEP DURATION (hrs)
AWAKENINGS (GMT)
GET UP
EXERCISE
SHOWER/BATH
DEPART HOME/LAYOVER
ON DUTY (LOCAL):
OFF DUTY (LOCAL):
ARRIVE HOME/LAYOVER
NAPS FROM: TO:
FROM: TO:
IN BED
ASLEEP
SEGMENTS FLOWN:
COMMENTS
GMT
Rate Sleep
1 2 3 4 5
DIFFICULTY ARISING?
HOW RESTED DO YOU FEEL?
MEAL TIME PLACE
B L D S
B L D S
B L D S
B L D S
B L D S
COFFEE/TEA/COLA
BOWEL MOVEMENTS:
URINATIONS
(A.M.) TIME (P.M.)
NUMBER CIGARETTES:
MEDICATION
Did you experience any of the following?
HEADACHE
RACING HEART
CONGESTED NOSE
WATERY EYES
FLUSHED FACE
DIZZINESS
CONSTIPATION
BACK PAIN
SORE THROAT
FEELING WEAK
BURNING EYES
CHILLS
NAUSEA
LIGHT-HEADED
FEVERISH
DISORIENTATION
SWEATING
DIARRHEA
UPSET STOMACH
SHORT OF BREATH
Other


GMT ____
Leg/LO ____

| | not at all | a little | moder-ately | quite a bit | extremely |
|---|---|---|---|---|---|
| active | 0 | 1 | 2 | 3 | 4 |
| vigilant | 0 | 1 | 2 | 3 | 4 |
| annoyed | 0 | 1 | 2 | 3 | 4 |
| carefree | 0 | 1 | 2 | 3 | 4 |
| cheerful | 0 | 1 | 2 | 3 | 4 |
| considerate | 0 | 1 | 2 | 3 | 4 |
| alert | 0 | 1 | 2 | 3 | 4 |
| dependable | 0 | 1 | 2 | 3 | 4 |
| sleepy | 0 | 1 | 2 | 3 | 4 |
| dull | 0 | 1 | 2 | 3 | 4 |
| efficient | 0 | 1 | 2 | 3 | 4 |
| friendly | 0 | 1 | 2 | 3 | 4 |
| full of pep | 0 | 1 | 2 | 3 | 4 |
| grouchy | 0 | 1 | 2 | 3 | 4 |
| happy | 0 | 1 | 2 | 3 | 4 |
| jittery | 0 | 1 | 2 | 3 | 4 |
| kind | 0 | 1 | 2 | 3 | 4 |
| lively | 0 | 1 | 2 | 3 | 4 |
| pleasant | 0 | 1 | 2 | 3 | 4 |
| relaxed | 0 | 1 | 2 | 3 | 4 |
| forgetful | 0 | 1 | 2 | 3 | 4 |
| sluggish | 0 | 1 | 2 | 3 | 4 |
| tense | 0 | 1 | 2 | 3 | 4 |
| clear thinking | 0 | 1 | 2 | 3 | 4 |
| tired | 0 | 1 | 2 | 3 | 4 |
| hard working | 0 | 1 | 2 | 3 | 4 |

MOST DROWSY
MOST ALERT

Images: Gander, et al, ASEM, 1998

Image: Aviation Safety Journal

# NASA Aviation Studies: Findings

- Sleep loss in all operations
  - Early mornings
  - Short layover periods
  - Night flying
  - Circadian desynchronization
- Some duty-related changes in ratings of fatigue and mood
- Changes in dietary habits and appetite
- More physical symptoms reported during duty periods

# NASA Aviation Studies

- Augmented long-haul operations (survey)
- Corporate/business/executive (survey)
- Regional carriers (survey)
- Planned in-flight rest
- Simulator studies
  - Alertness breaks
  - ULR

Image: NASA Spinoff, 2006

# NASA Aviation Activities

- Principle and guidelines for duty/rest scheduling
- Education and training
  - Workshops
  - Publications
- Fatigue and Performance Modeling Workshop
- NTSB accident investigation

# NASA Aviation Studies: Current Methods

jove Journal of Visualized Experiments www.jove.com

Video Article

## Collecting Sleep, Circadian, Fatigue, and Performance Data in Complex Operational Environments

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URL: https://www.jove.com/video/59851
DOI: doi:10.3791/59851

Keywords: Behavior, Issue 150, fatigue, sleep, circadian phase, alertness, psychomotor vigilance task, NASA-PVT

Date Published: 8/8/2019

Citation: Arsintescu, L., Kato, K.H., Hilditch, C.J., Gregory, K.B., Flynn-Evans, E. Collecting Sleep, Circadian, Fatigue, and Performance Data in Complex Operational Environments. *J. Vis. Exp.* (150), e59851, doi:10.3791/59851 (2019).

**Abstract**

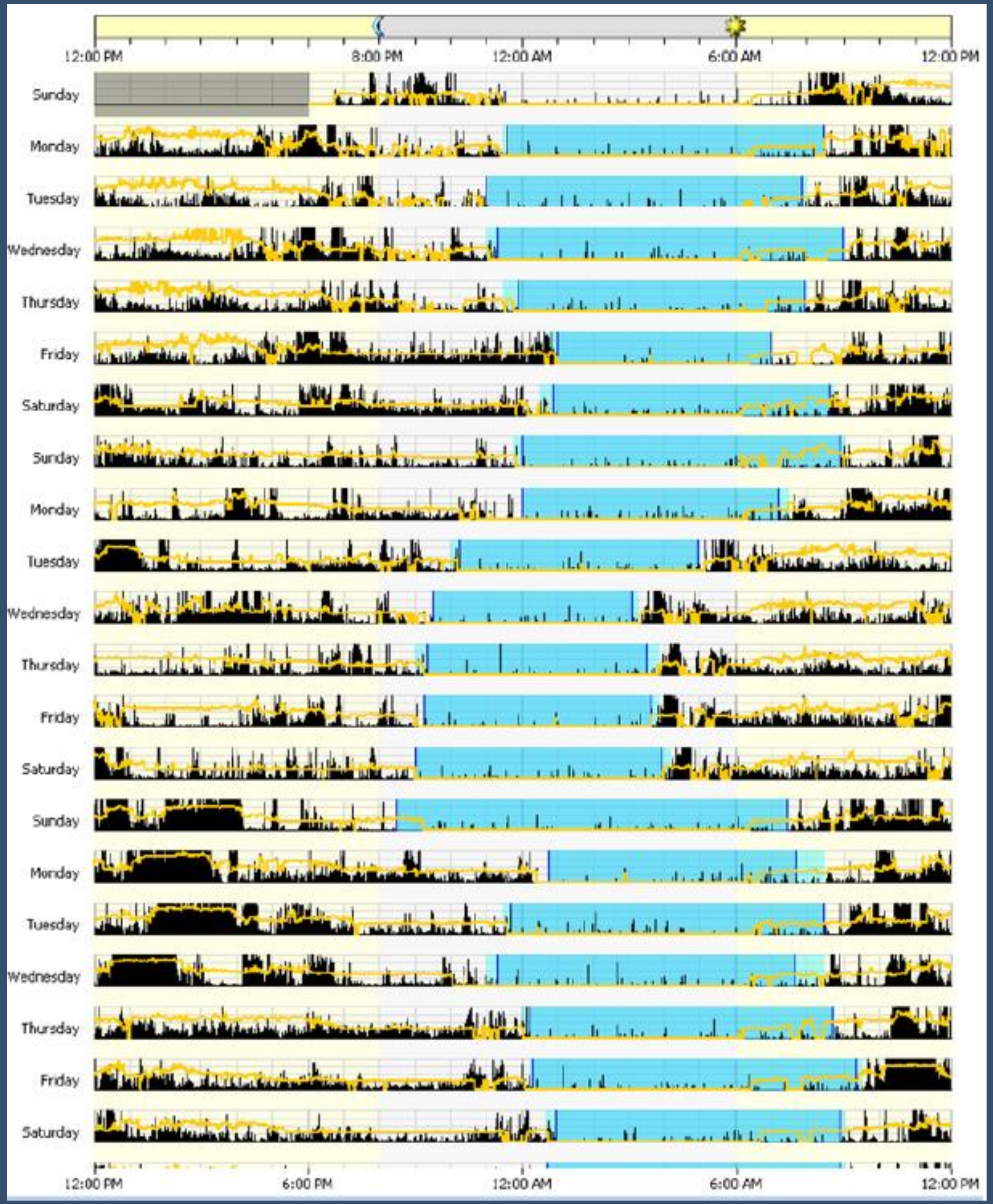
Sleep loss and circadian misalignment contribute to a meaningful proportion of operational accidents and incidents. Countermeasures and work scheduling designs aimed at mitigating fatigue are typically evaluated in controlled laboratory environments, but the effectiveness of translating such strategies to operational environments can be challenging to assess. This manuscript summarizes an approach for collecting sleep, circadian, fatigue, and performance data in a complex operational environment. We studied 44 airline pilots over 34 days while they flew a fixed schedule, which included a baseline data collection with 5 days of mid-morning flights, four early flights, four high-workload mid-day flights, and four late flights that landed after midnight. Each work block was separated by 3–4 days of rest. To assess sleep, participants wore a wrist-worn research-validated activity monitor continuously and completed daily sleep diaries. To assess the circadian phase, pilots were asked to collect all urine produced in four or eight hourly bins during the 24 h after each duty block for the assessment of 6-sulfatoxymelatonin (aMT6s), which is a biomarker of the circadian rhythm. To assess subjective fatigue and objective performance, participants were provided with a touch-screen device used to complete the Samn-Perelli Fatigue Scale and Psychomotor Vigilance Task (PVT) during and after each flight, and at waketime, mid-day, and bedtime. Using these methods, it was found that sleep duration was reduced during early starts and late finishes relative to baseline. Circadian phase shifted according to duty schedule, but there was a wide range in the aMT6s peak between individuals on each schedule. PVT performance was worse on the early, high-workload, and late schedules relative to baseline. Overall, the combination of these methods was practical and effective for assessing the influence of sleep loss and circadian phase on fatigue and performance in a complex operational environment.

**Video Link**

The video component of this article can be found at https://www.jove.com/video/59851/

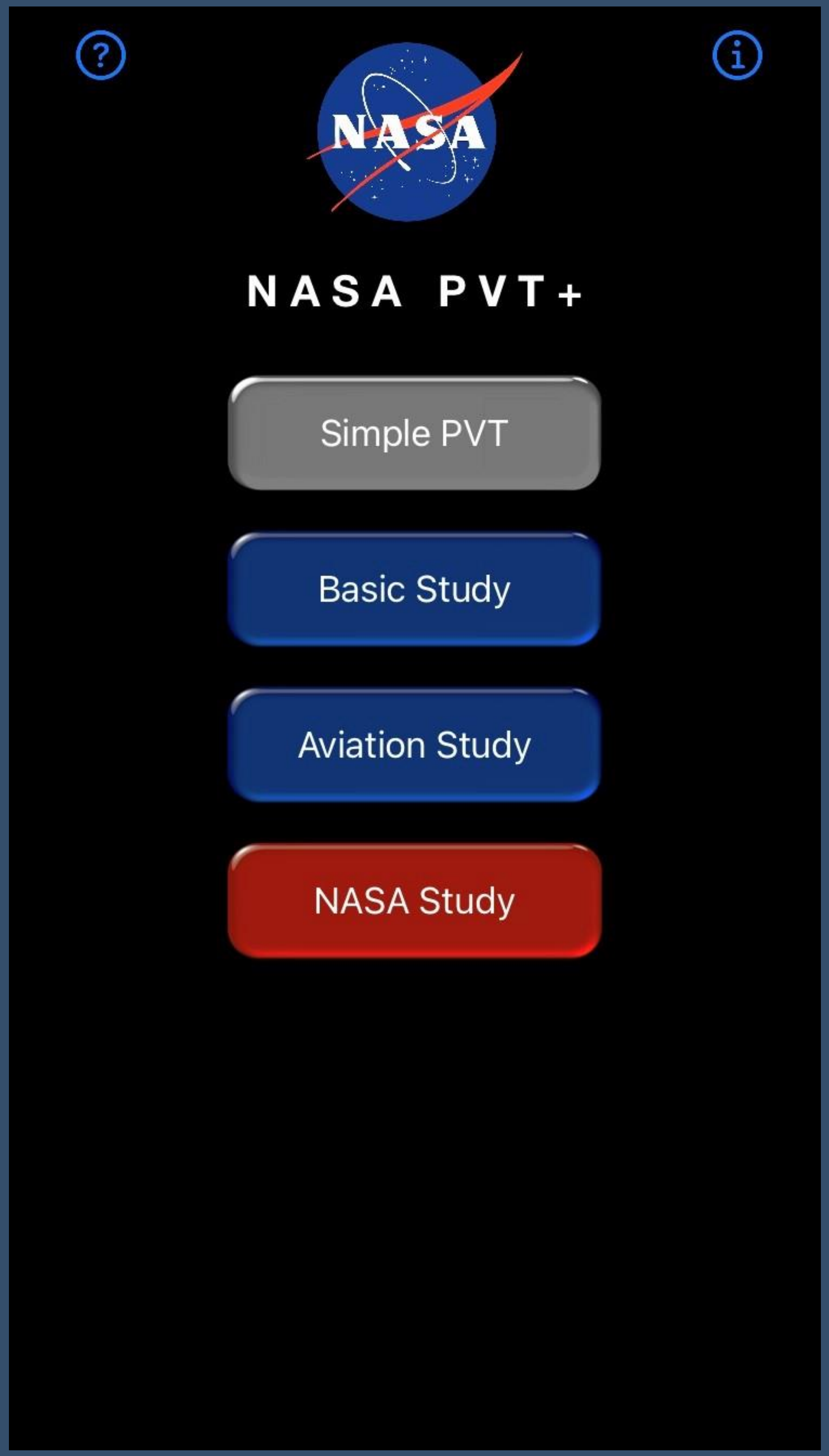
Image: Arsintescu, et al, JOVE, 2019

# NASA Aviation Studies: Current Methods

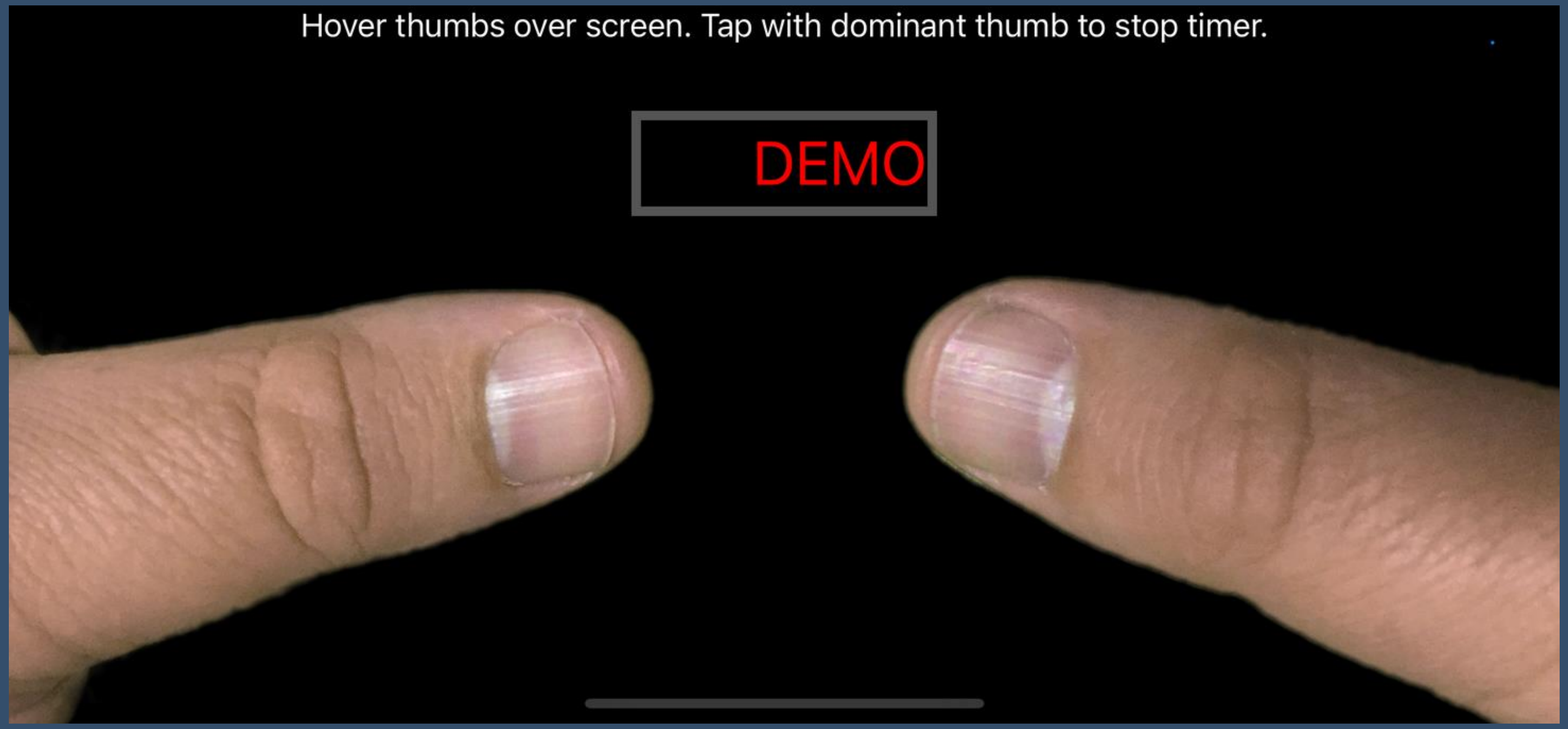

Images: Arsintescu, et al, JOVE, 2019

# NASA Aviation Studies: Current Methods




Images: Apple; personal

# NASA Aviation Studies: Current Methods

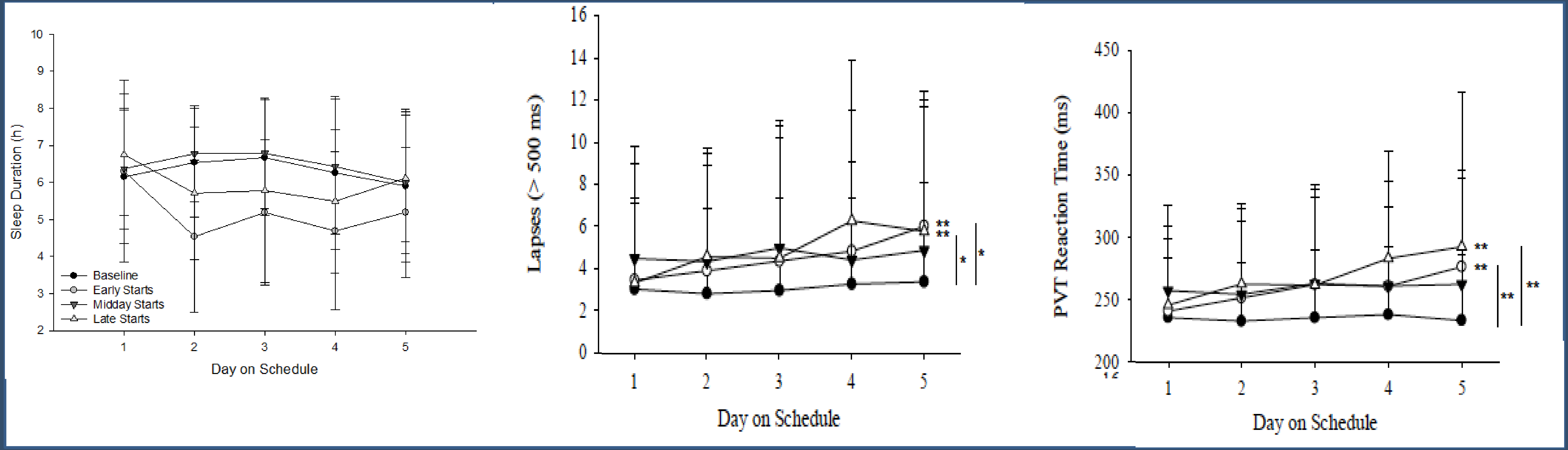




Images: Arsintescu, et al, JOVE, 2019

# Sleep and Circadian Rhythms in Aviation

- "Daytime" schedules sometimes encroach on the night
- Study of 44 pilots found worse performance during a sequence of early starts compared to mid-morning or mid-day starts (Flynn-Evans *et al*. 2018)




Images: Flynn-Evans, et al, Sleep Health, 2018

# Sleep and Circadian Rhythms in Aviation

- Study of 95 short-haul pilots collected data pre- & post-FDP, and at TOD (Arsintescu *et al*. 2021)
- Early starts and late finishes reduce alertness and performance
  - Pilots reported higher fatigue and experienced worse performance following late finishes
  - Sleep was shorter preceding early start duties

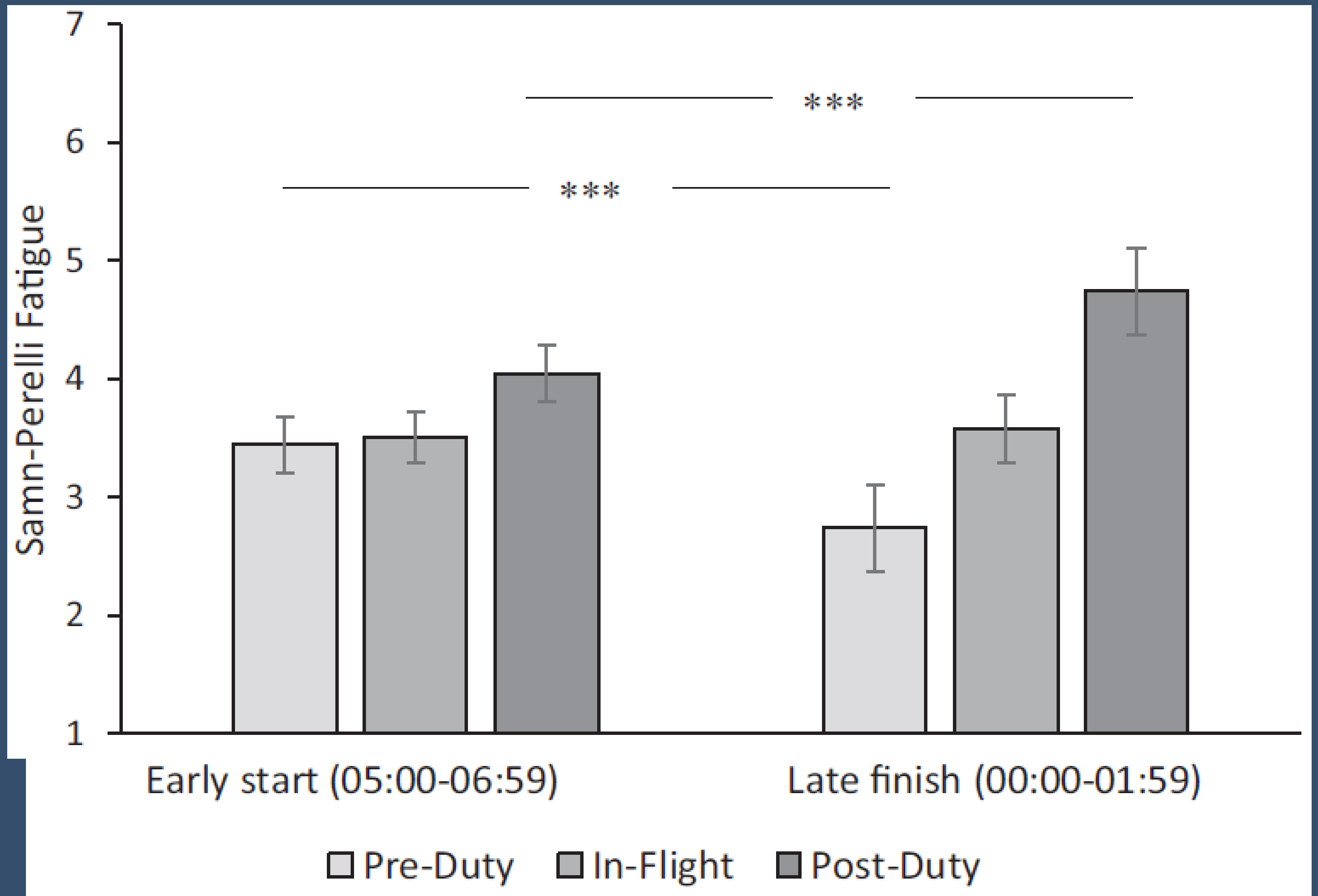



**TABLE 2** Sleep characteristics prior to duty by duty start time

| Start of duty | Waketime (hh:mm) | Bedtime (hh:mm) | Sleep duration (h) |
|---|---|---|---|
| 05:00–06:59 (early) | 04:19 (01:14) | 21:15 (02:01) | 6.90 (1.30) |
| 07:00–10:59 (mid-morning) | 06:30 (01:22) | 22:29 (01:27) | 7.54 (1.57) |
| 13:00–16:59 (afternoon) | 09:16 (01:19) | 01:05 (01:21) | 8.39 (1.47) |
| 17:00–20:59 (evening) | 09:27 (01:37) | 02:09 (01:31) | 8.26 (1.73) |

Sleep characteristics are reported as mean (standard deviation).
Abbreviation: hh:mm, hours and minutes.

Images: Arsintescu, et al, JSR, 2021

# Light as a Countermeasure

- Circadian response to light follows a phase response curve (PRC)
  - Light in biological morning = phase advance
  - Light in biological evening = phase delay
- Flight crew often begin work before sunrise
- Laboratory protocols not feasible for real world implementation
  - Commercial light devices have been developed for at home use

# Light Study: Protocol

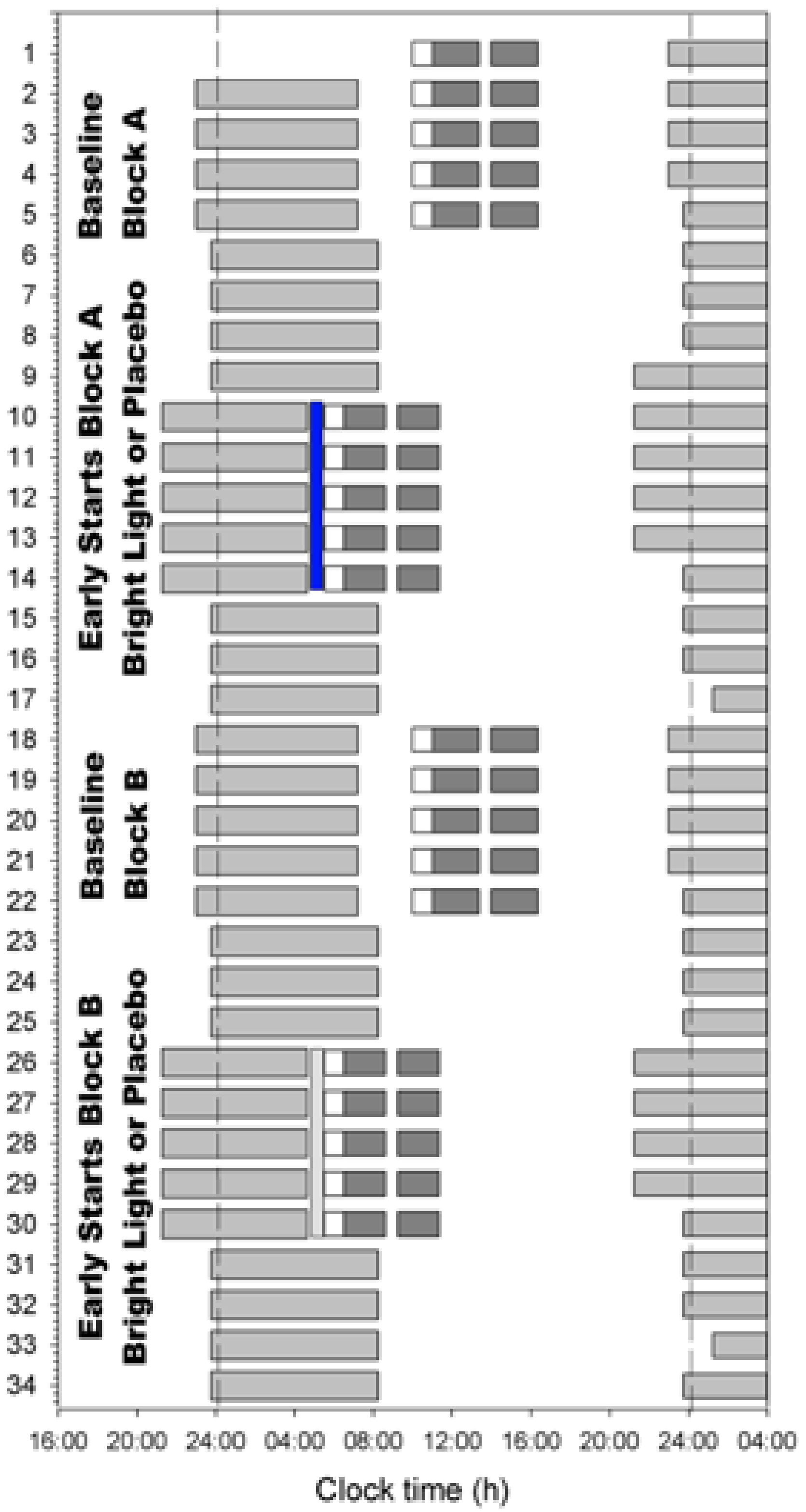
**n = 34 short-haul pilots**

- Daily assessments for 34 days
  - October-December
- Randomized cross-over trial
  - Luminette glasses (468 nm, 1500 lux)
  - Clear placebo glasses
  - 25 m before early starts
- Return to domicile daily

**Outcomes**

- Sleep: continuous actigraphy, daily sleep logs
- Performance: PVT
- Self-report fatigue: KSS
- Fatigue countermeasures

Glasses at home before early starts

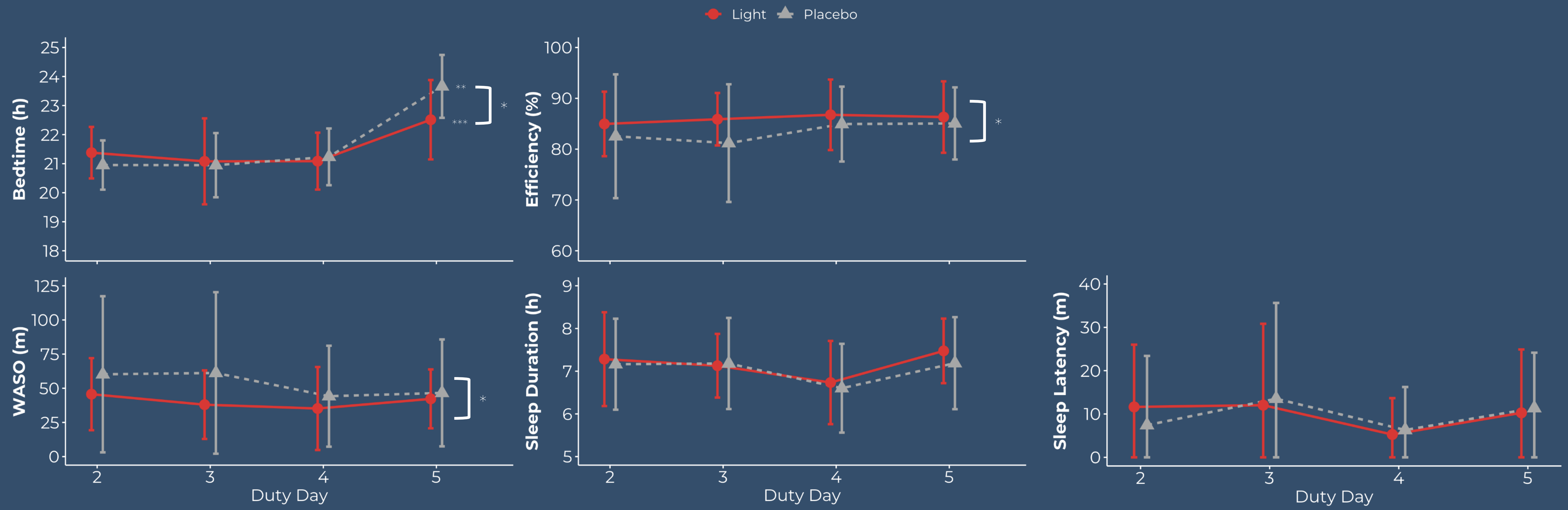


# Light Study: Flight Characteristics

| | n (duty days) | Flight 1 Start Time (h, sd) | Number of legs (sd) | Flight Duration (h; sd) |
|---|---|---|---|---|
| Placebo | 152 | 0656 (0059) | 2.28 (0.66) | 2:04 (0:39) |
| Light | 143 | 0712 (0106) | 2.27 (0.66) | 2:07 (0:39) |
| Baseline (P) | 143 | 1355 (0213) | 2.65 (0.96) | 2:02 (0:38) |
| Baseline (L) | 149 | 1347 (0212) | 2.65 (0.93) | 2:00 (0:32) |

# Light Study: Sleep Outcomes

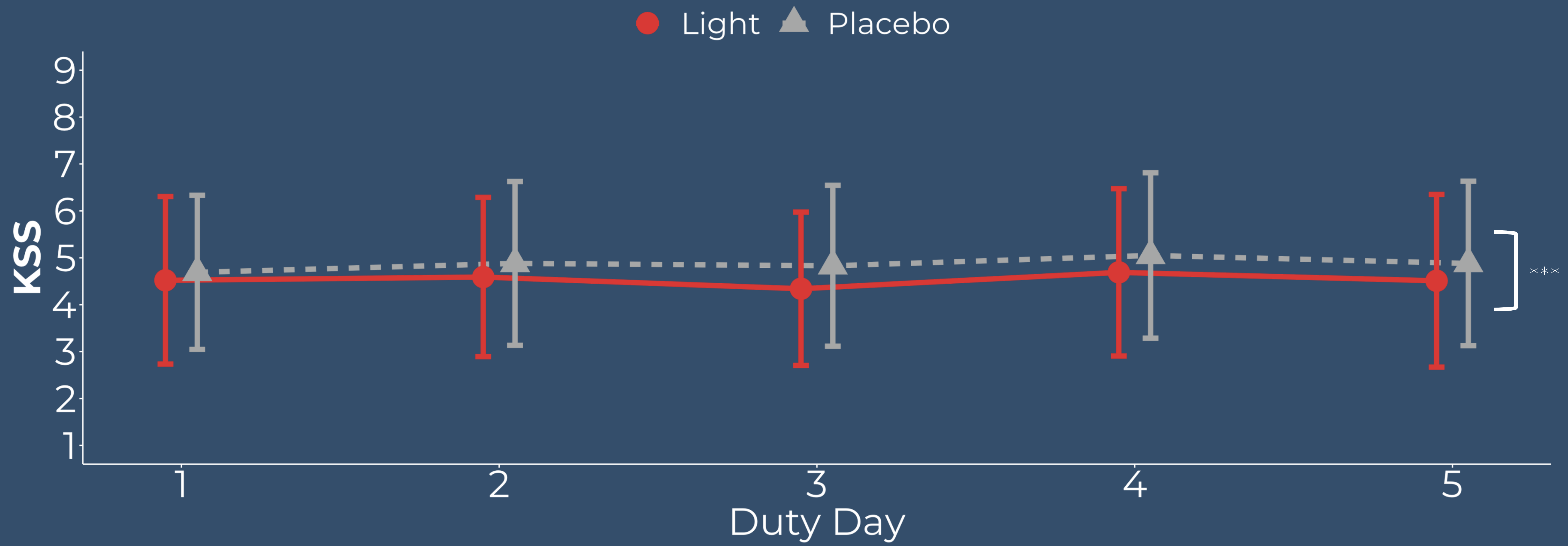
*Improvements in WASO and efficiency*




Actigraphy

# Light Study: Sleepiness

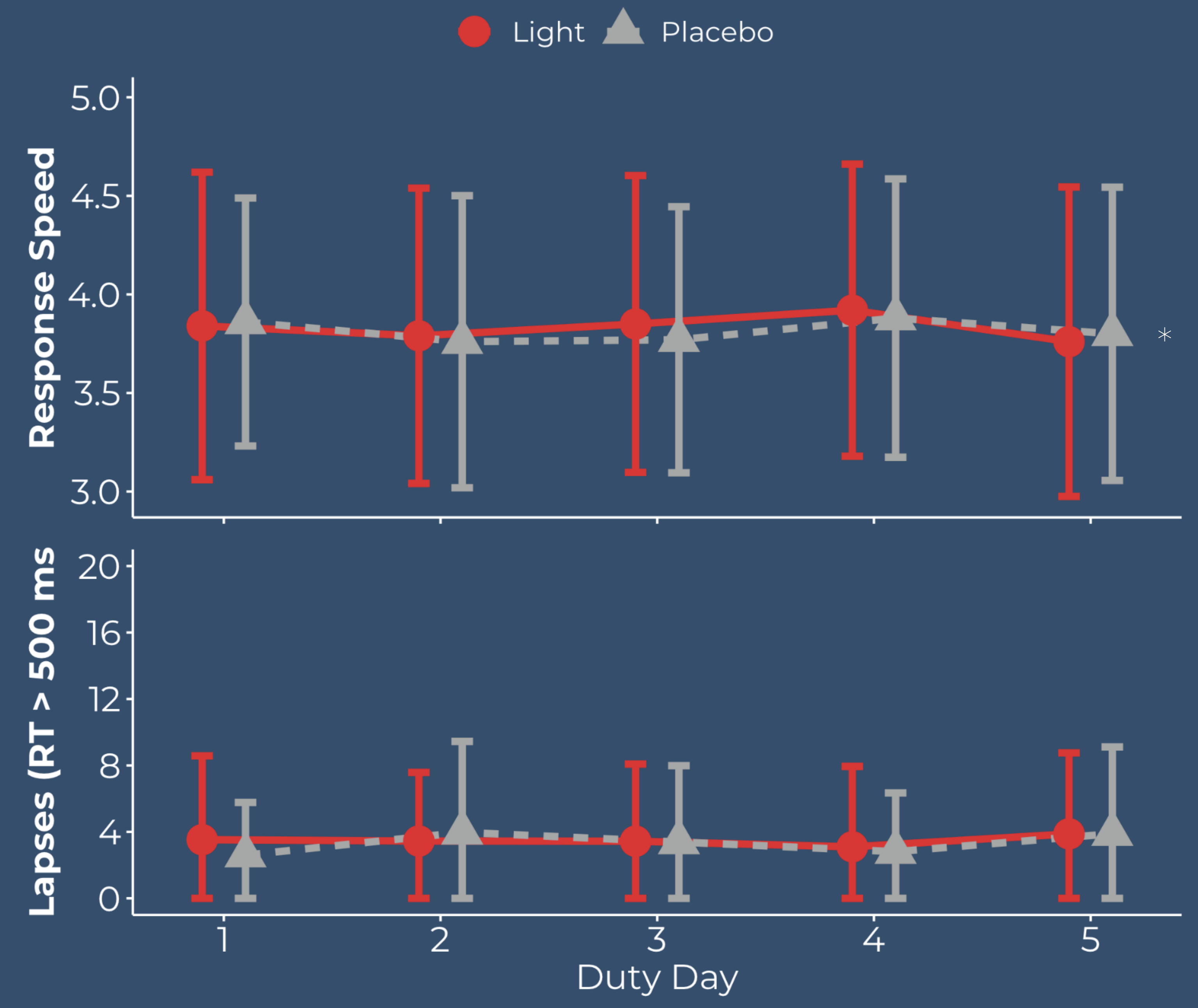
*Light reduced sleepiness*



# Light Study: Performance outcomes

*No difference between conditions*

| | Mean RT (SD) | Lapses (SD) | Response speed (SD) |
|---|---|---|---|
| Placebo | 318 (111) | 3.3 (4.5) | 3.8 (0.7) |
| Light | 319 (117) | 3.5 (4.7) | 3.8 (0.8) |
| Baseline | 299 (153) | 2.9 (5.7) | 4.0 (0.8) |
| Baseline | 310 (175) | 2.6 (4.5) | 4.0 (0.7) |



# Light Study: Findings

- Strong compliance (93% of days)
  - Placebo 25 min (+/- 7.6)
  - Luminette 25 min (+/- 5.7)
- Small improvements in sleep, WASO and ratings of sleepiness
- Further evaluation of melatonin needed to assess phase shifts
- Limitations
  - Light may not have been bright enough
  - Evening light may have been too bright

# Survey Study: In-Flight Rest Periods

- US-based augmented long-haul flight ops (Gregory *et al*. AMHP 2021)
  - Self-reported in-flight sleep duration and ratings of sleep quality
  - Samn-Perelli and KSS ratings @ TOD, before and after rest break
- 500 pilots responded/787 flights
- Noninferiority testing: 2$^{nd}$ vs 3$^{rd}$ rest break
  - FAR 117.17.c.1 specifies that landing pilot must have 2 consecutive hr of in-flight rest during 2$^{nd}$ half of flight

# Survey Study: Findings

- Most rest facilities either FAR Class 1 or 2
- All breaks of equivalent duration (~2.3 hr)
- First break used primarily by relief pilots
- Most sleep reported during break 2 = 1.55 hr (N.S.)
- Break 2 noninferior to break 3
  - Better sleep quality, fewer disturbances
  - Lower Samn-Perelli and KSS ratings @ TOD

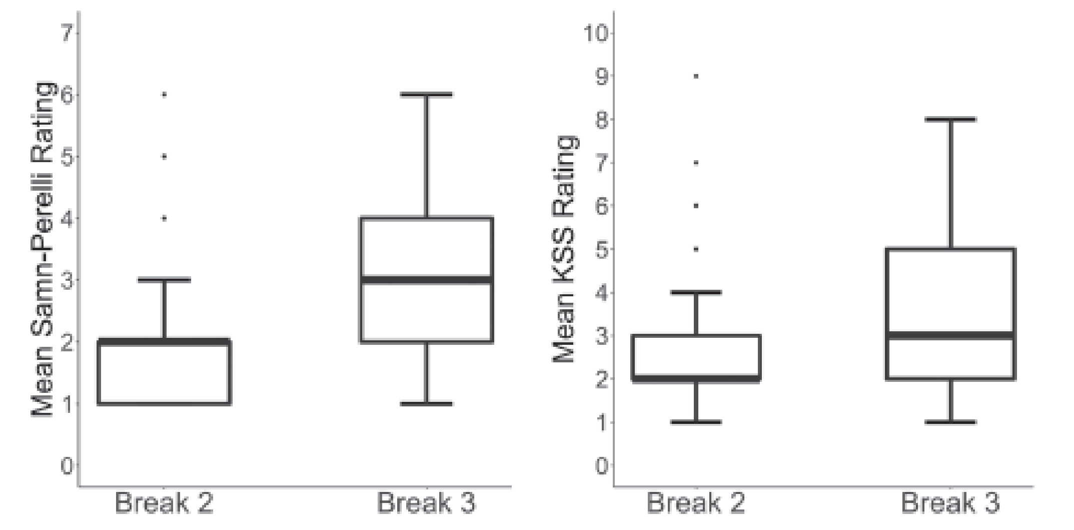



**Fig. 1.** Samn-Perelli (left) and Karolinska Sleepiness Scale (KSS; right) ratings at top of descent from landing crew pilots by rest break taken. The lower and

Image: Gregory, et al, AMHP, 2021

# Survey Study: Findings

- Both rest breaks 2 and 3 significantly reduced Samn-Perelli and KSS ratings following break compared to before break
- Pilots reported most sleep during breaks that started during HBT morning

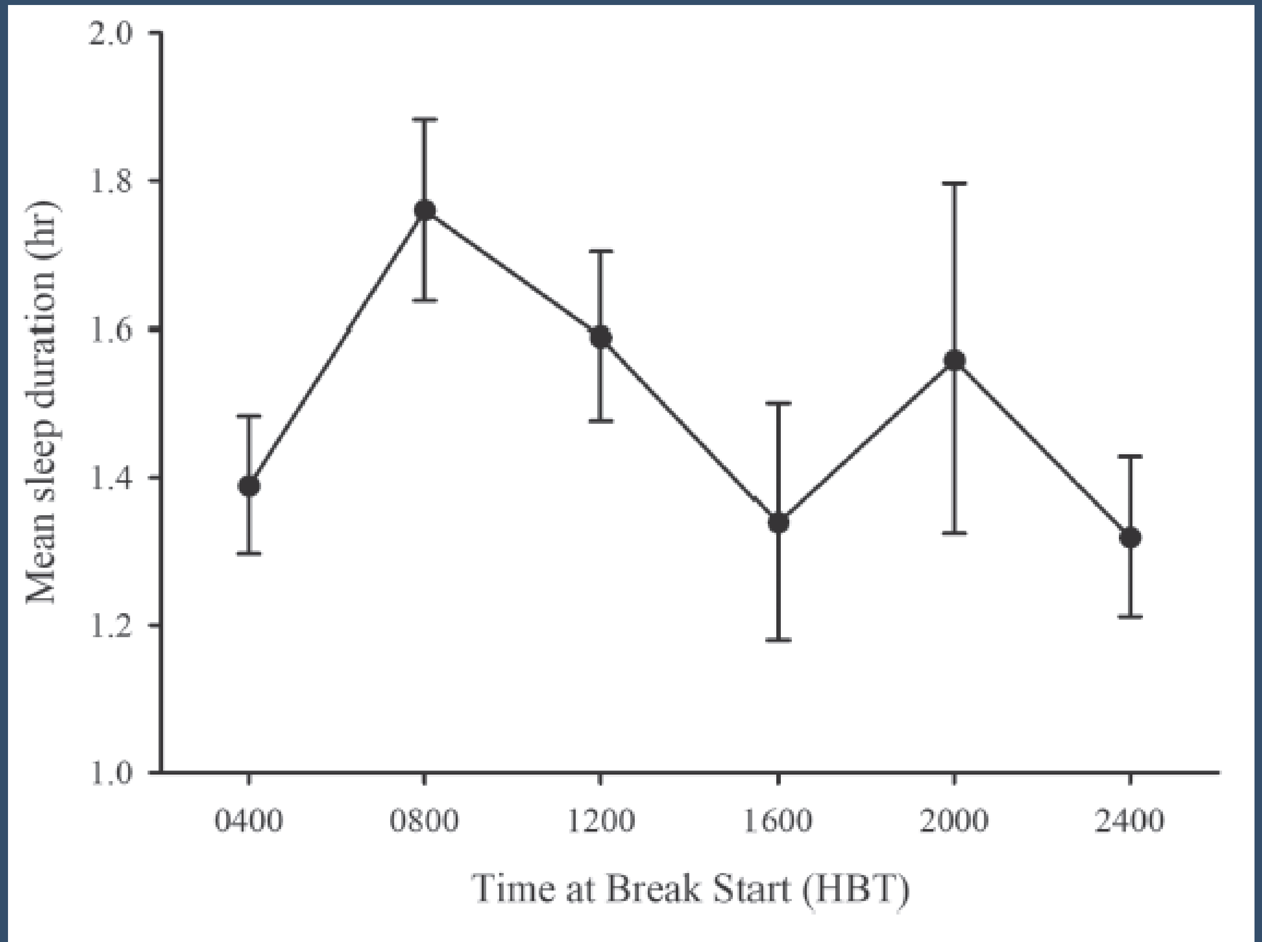


**Fig. 4.** Mean sleep duration based on the break start time across time of day

Image: Gregory, et al, AMHP, 2021

# Focus Group Study: Short-haul

- 14 CFR Part 117: Flightcrew Member Duty and Rest Requirements
  - Introduced 2012, implemented 2014
- Introduced max flight duty periods based on # flights, FDP start timing
  - Min rest = 10 hr
- Shared responsibility tween pilots and management
- Evidence suggests short-haul flying contributes to fatigue risk
- Only anecdotal data about fatigue under 14 CFR Part 117

# Focus Group Study: Short-haul

- CAMI-NASA project to provide data on impact of short-haul ops on pilot sleep, sleepiness, performance and workload
- Develop scope of proposed S-H study
- Interview US commercial S-H pilots to identify fatigue factors
- Systematic, qualitative approach to capture pilot experiences

# Focus Group Study: Methods

- Pilots recruited via email
- Focus groups held online
- Anonymous participation
  - Letter code, no cameras
- Transcription and note-taking
- Standardized script and questions
- Each participant responded to each question in random order

# Focus Group Study: Short-haul

ICAO definition:

Fatigue is defined as a physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crew member's alertness and ability to safely operate an aircraft or perform safety-related duties.

# Focus Group Study: Methods

Q1. Are there any types of short-haul operations that you think lead to elevated fatigue?

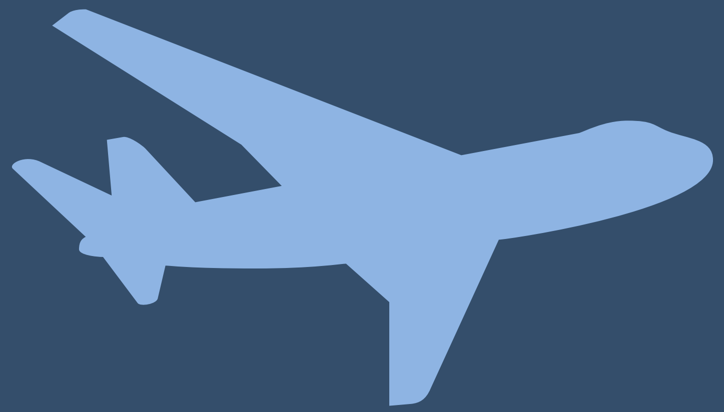
Q2. Are there any type(s) of short-haul operations that you think are not fatiguing?

Q3. What type(s) of short-haul operations do you think are the most important for us to study?

# Focus Group Study: Analytic Methods

- Cleaned transcripts
- Identified recurring ideas
- Developed code book
- Coded transcripts
- Reviewed and finalized codes
- Code frequencies counted
- Grouped codes into themes
- Themes ranked by frequency

# Focus Group Study: Results



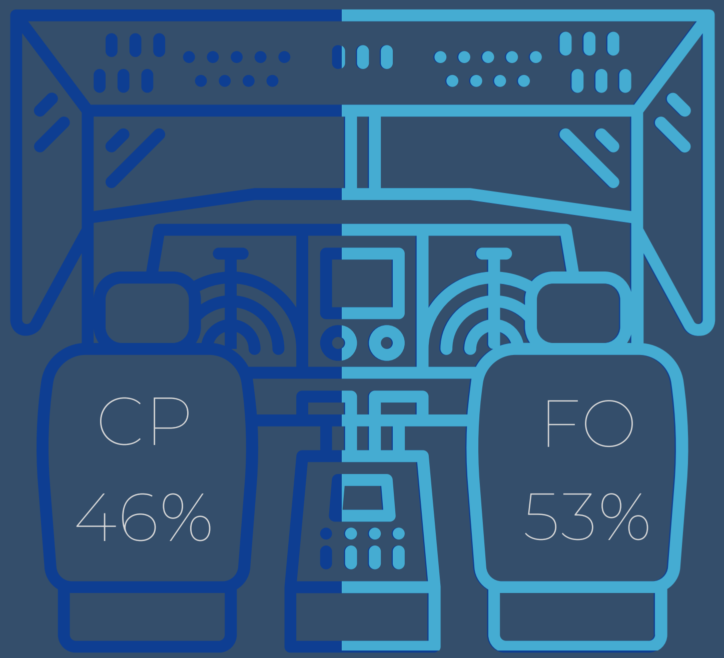
4 airlines

14 focus groups

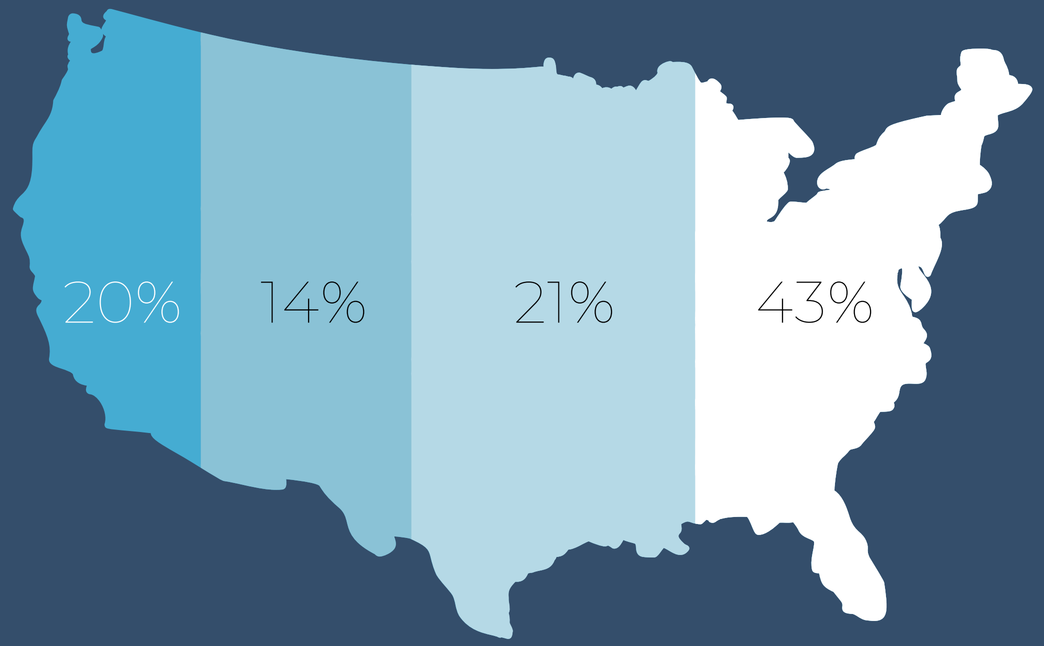
90 pilots

# Focus Group Study: Results

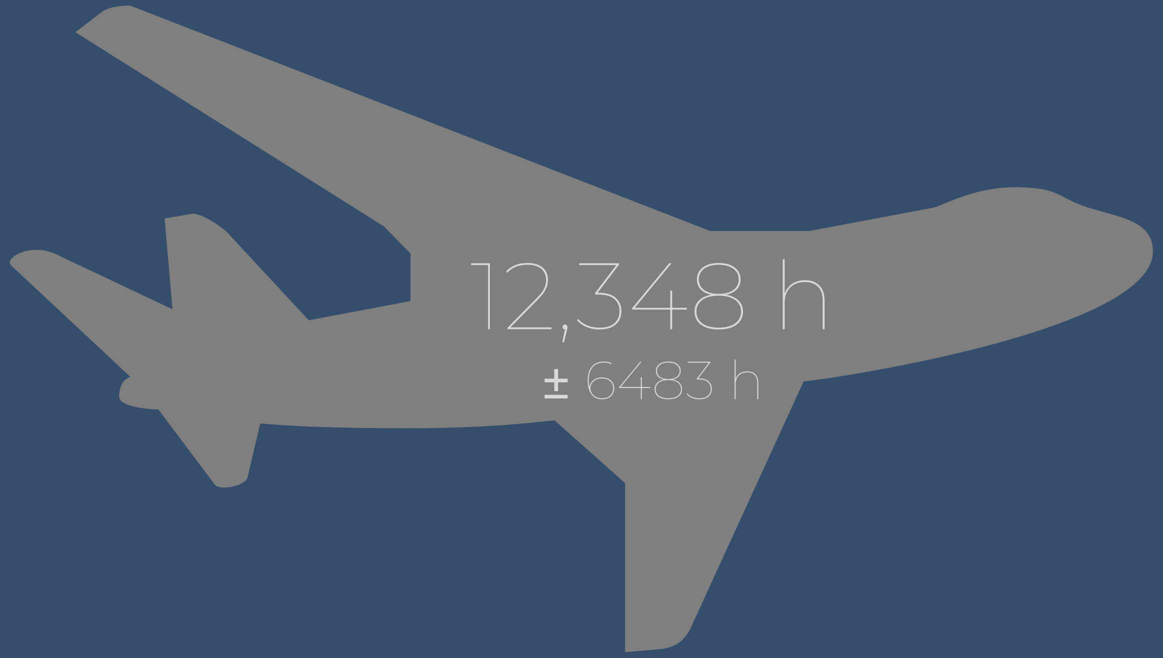
Seat position



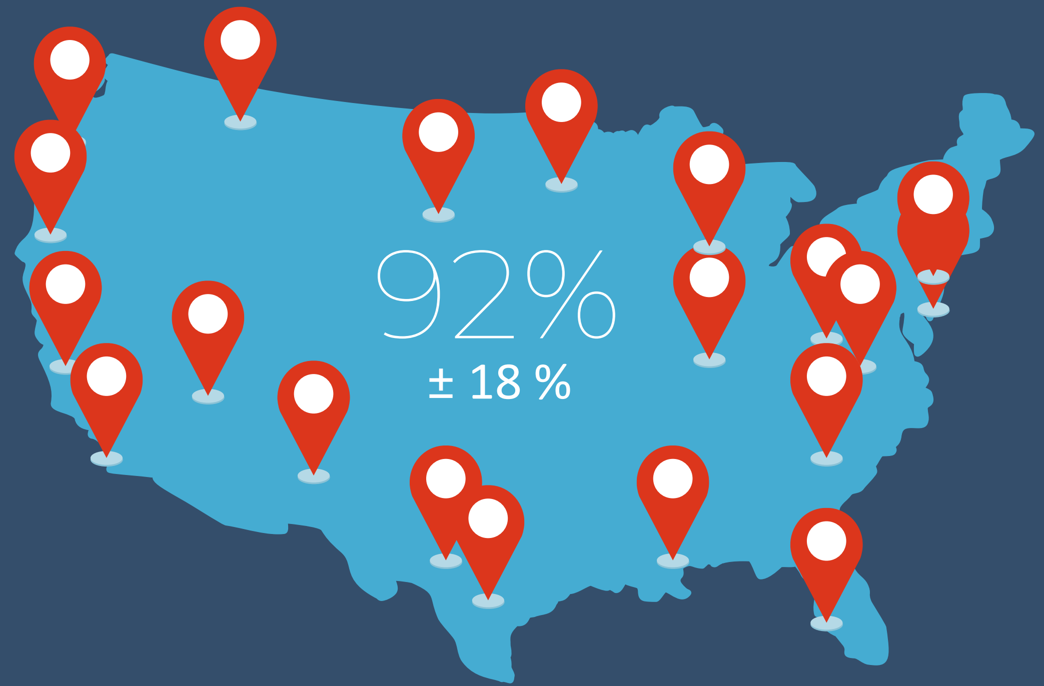

Base
time zone




Lifetime
flying hours




Short-haul
flying



# Focus Group Study: Results

# Focus Group Study: Results

- 5 broad fatigue categories identified
  - Circadian disruption
  - Workload/hassle factors
  - Rest opportunity
  - Schedule changes
  - Long sits

*"There's a, you know, 9:00 AM show and then a 2:00 PM show, and then a 5:00 AM show….your body doesn't know what it's doing."*

# Focus Group Study: Results

**Table 3**
Themes ranked by frequency of codes within each theme.

| Theme | Description | N | % |
|---|---|---|---|
| *Circadian switches* | Changing from early to late starts (or *vice versa*) | 171 | 10.5 |
| *Rest duration (layover)* | Inadequate rest opportunity between FDPs | 153 | 9.4 |
| *High workload/hassle factors* | Factors adding to workload | 151 | 9.3 |
| *Number of flights* | Multiple flights in an FDP | 121 | 7.4 |
| 14 CFR *Part 117 matters* | Matters related to flight/duty/rest regulations | 93 | 5.7 |
| *Long sits* | Long wait time between flights within an FDP | 85 | 5.2 |
| *Red-eyes* | Overnight flights | 83 | 5.1 |
| *Unpredictability* | Last minute schedule changes | 79 | 4.9 |
| *Aircraft & crew swaps* | Changing aircraft or crewmembers within an FDP | 73 | 4.5 |
| *Rest timing* | Inappropriate timing of rest opportunities | 73 | 4.5 |
| *Out-of-hours work* | Any duty period outside of "9am-5pm" | 68 | 4.2 |
| *Early duties* | Early duty start times | 64 | 3.9 |
| *Short turn time* | Lack of time between flights within an FDP | 53 | 3.3 |
| *Length of duty* | Long duty hours | 46 | 2.8 |
| *Rest quality* | Quality of rest environment (e.g., hotel) | 45 | 2.8 |
| *Schedule design* | Design of trip and monthly schedule | 38 | 2.3 |
| *Trip length* | Multiple consecutive FDPs | 37 | 2.3 |
| *Late duties* | Late duty finish times | 25 | 1.5 |
| *Fatigue call issues* | Issues related to reporting fatigue | 24 | 1.5 |
| *Length of flights* | Short flights | 20 | 1.2 |
| *Rest - circadian disruption* | Rest opportunities during long (24–30h) layovers | 20 | 1.2 |
| *Deadheading* | Positioning flight with pilot as a passenger | 14 | 0.9 |
| **Total** | | **1625**[a] | |

Image: Hilditch, et al, Transport Policy, 2023

# Focus Group Study: Next steps

- Defining scope of field study
  - <u>Circadian disruption</u>
  - High workload
  - Rest opportunity
  - Schedule changes
  - Long sits

# Short-Haul Field Study: Methods

### Overnight FDPs

An FDP in which the pilot is operating one or more flights through the WOCL (0200-0559h) relative to the pilot's home-base time or clock time.

OR

### Circadian Switching

At least one FDP that starts between 0000-0659h relative to home-base time, followed by at least one FDP that ends between 0000-0659h, or *vice versa*, within the same trip (e.g., an FDP that begins at 0500h and the next FDP ends at 0100h, or *vice versa*).

AND

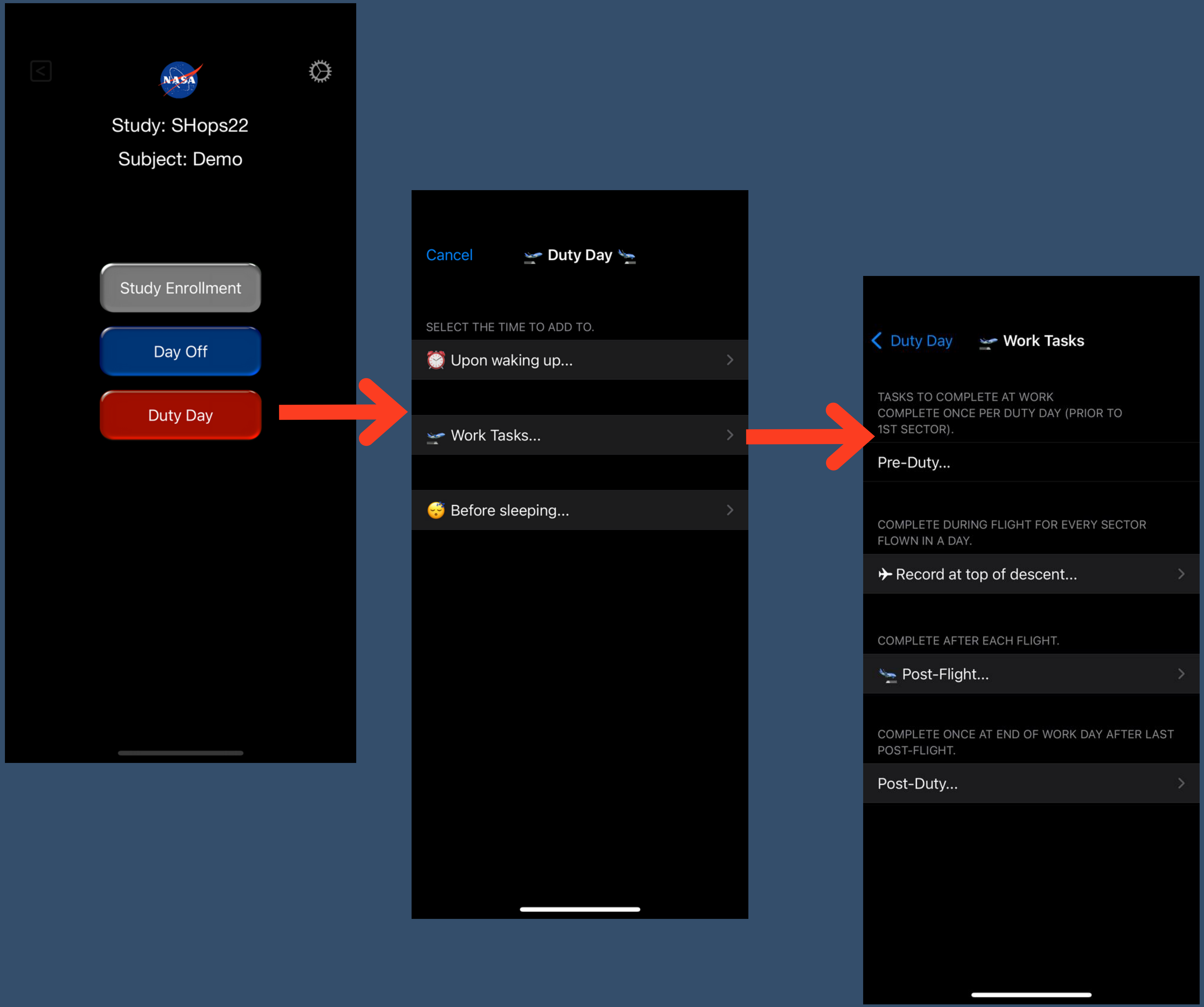
### Trip without Circadian Disruption

This trip must not contain any duties that are scheduled to begin or end between 0000h and 0659h, relative to home-base time.

# Focus Group Study: Methods

- Condition/airline breakdown
  - 18 per condition
    - Overnight or circadian switching
    - Within-subject design
  - 36 total per airline
    - 15 additional participants to account for attrition
    - Max per airline = 51
  - Max total study = 204

# Short-Haul Field Study: Methods




Images: Arsintescu, et al, JOVE, 2019; personal

# Focus Group Study: PVT+ App

- Baseline questionnaires
- Sleep logs
- Self-report scales
- Fatigue countermeasures
- *Hassle factors*
- *Workload ratings*
- *Rest opportunity*
- *Turn times*
- *Schedule changes*
- Psychomotor vigilance task (PVT)

# Short-Haul Study: Status

- Recruitment and data collection underway
- Using multifaceted approach (advertisements, emails, video, etc)
- Positive feedback on study procedures
    - Few issues w/ data collection/compliance
    - App working well
    - No issues w/ actigraphy
- Regular meetings w/ collaborators and study stakeholders

# NASA Aviation Studies: Future Directions

- Lighting interventions
  - Assess “light diet”, provide education/control over evening light
- Automation
- Controlled rest
- Effectiveness of modeling tools
- Implementation of FRMS

# NASA Ames Fatigue Countermeasure Laboratory

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