Harnessing the Web for Population-Scale Physiological Sensing:

A Case Study of Sleep and Performance

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* Research performed at Microsoft Research

Human Cognitive Performance

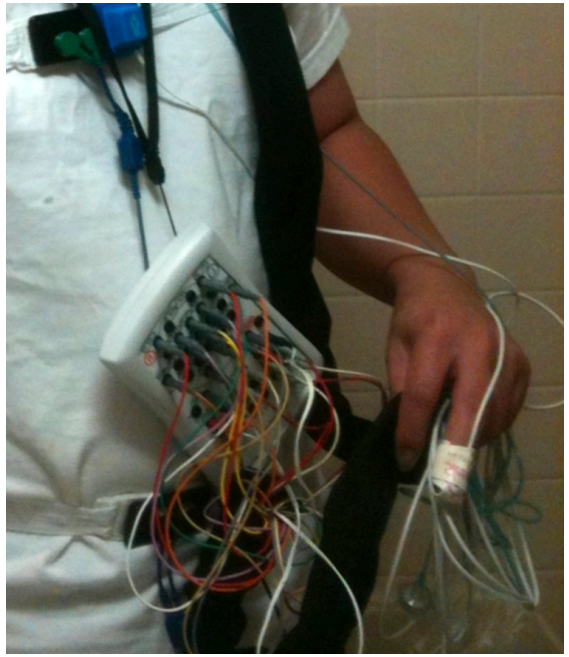
- Ability to perform mental actions and processes including attention, memory, reasoning, decision making, planning, etc.

- High cognitive performance important for:
  - Productivity [Colten & Altevogt, 2006]
  - Learning outcomes [Kelley et al., 2015]
  - Accident risk [Dinges, 1995]

- Laboratory setting: Performance varies throughout day [Van Dongen & Dinges, 2000] and is decreased after sleep loss [Dinges, 1995]

Existing Research

- Laboratory setting:
  - Induce sleep deprivation
  - Regular, intrusive, artificial performance tasks
  - Missing real-world influences incl. motivation, mood, illness, behavioral compensation (e.g., caffeine), and complex sleep patterns



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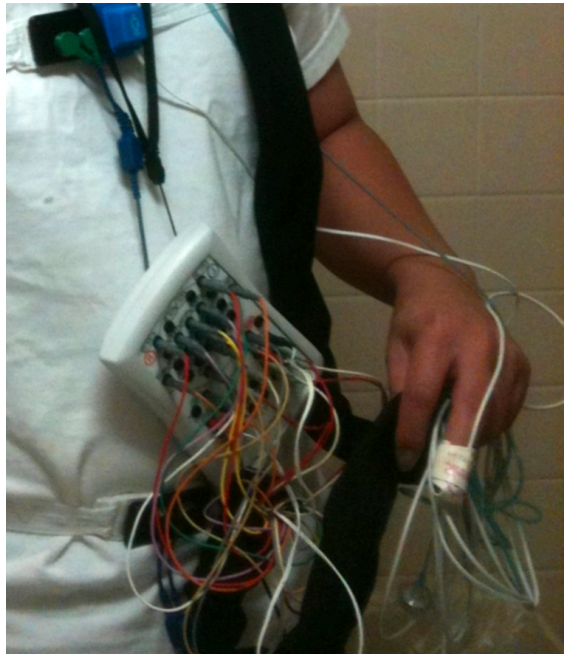

Lack of scalable methods to characterize real-world cognitive performance & sleep

[Roenneberg, 2013]

Open Research Questions

1. How does cognitive performance vary in the real world?
2. How do real-world sleep patterns impact performance?

Challenges

- Real-world more complex than laboratory
  → Need much larger dataset

- But existing methods don't scale!
- Need cognitive performance measurements
  - Annoying: Regular, intrusive, artificial performance tests
  - Should use performance on real tasks
- Need sleep measurements
  - Can't observe in lab or control as before
  - Can't trust subjective reports

- How can research progress outside the laboratory?

Our Key Insight

Use existing interactions with technology as a sensor into real-world cognitive performance.

Harnessing Search Engine Interactions

- Search engines are used repeatedly every day, awake or sleepy, by billions of people
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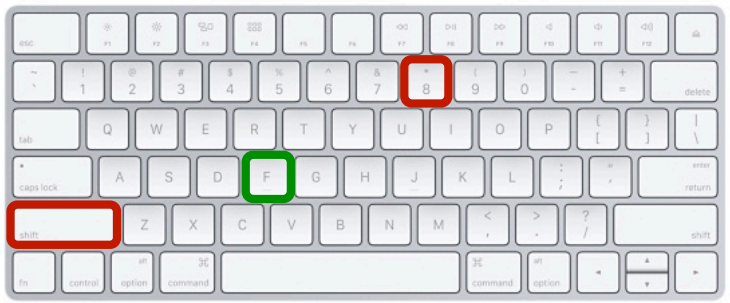


Measuring Sleep

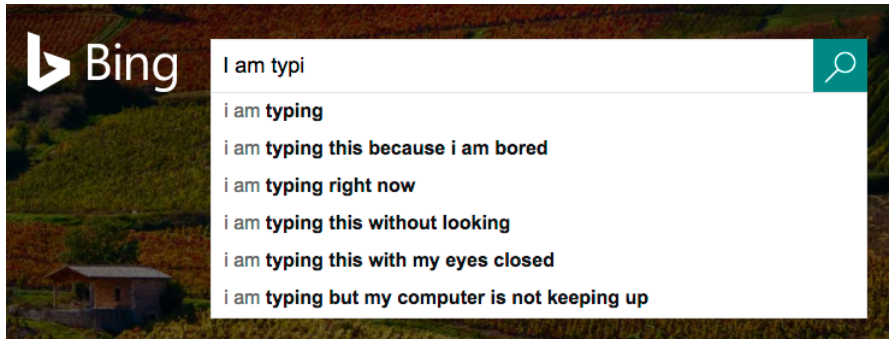
- Use wearable device
  - Many search engine users already own device
  - Objective measures of time in bed by clicking *"Start"* & *"I'm awake"* (plus accelerometer-based algorithm)

Real-World Sleep & Performance at Scale

- Our insights enable study of real-world performance & sleep at scale
- 400x larger study than ever before

Dataset

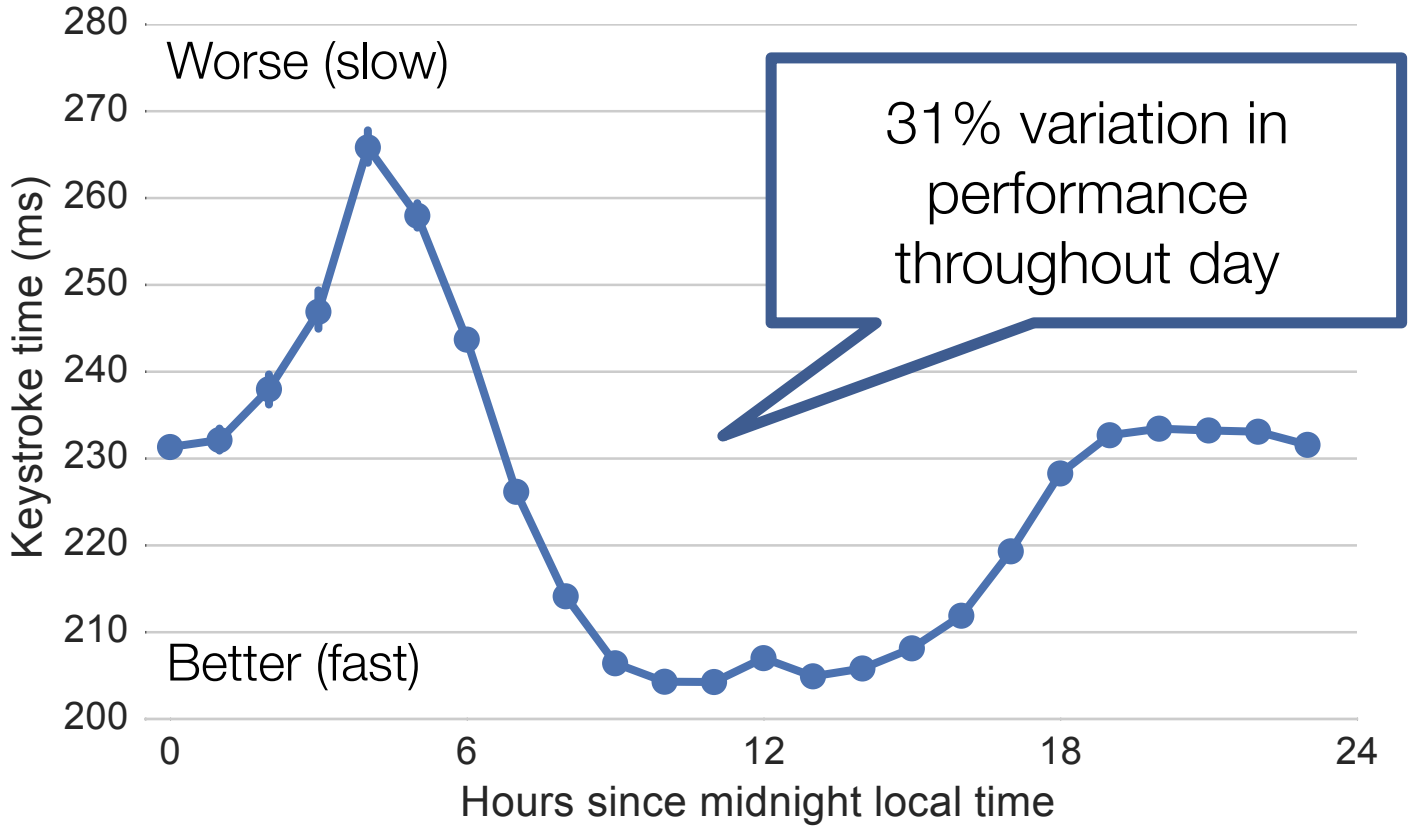
- Cohort: 32k users over 18 months
  - US representative age, BMI, sleep; mostly male (93%)
  - (Opt-in to link Bing searches & Band data)
- Performance: 75M interaction tasks
  - Keystroke time (and click time)
  - Bing search engine



- Sleep: 3M nights of sleep
  - Microsoft Band

How does cognitive performance vary in the real-world?

Diurnal Performance Variation



- Performance far from constant (31% variation)
- Slowest during typical sleep times (circadian rhythm)

Error bars (all figures): 95% confidence interval

Robustness of Results

Findings are robust. Not explained by…

- Effects of individual users / Population differences
  - Observe true within-person variation
- Type of query
  - Control for click entropy to capture query intent (navigational vs. informational)
  - Similar results for specific queries like “facebook”
- Learning effects
  - Few queries repeat; show no signs of learning effects
- Weekend vs. weekday effects
- Network latency dynamics

How can we model real-world performance variation?

Modeling Challenges

- Three biological processes
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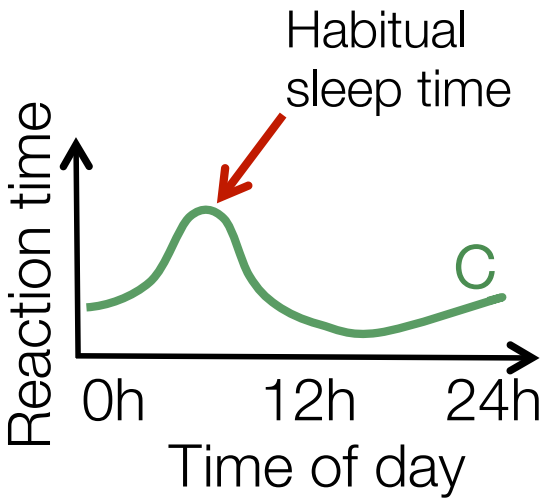
  1. Circadian rhythm (C): time-dependent, behavior-independent, near 24h oscillations



Modeling Challenges

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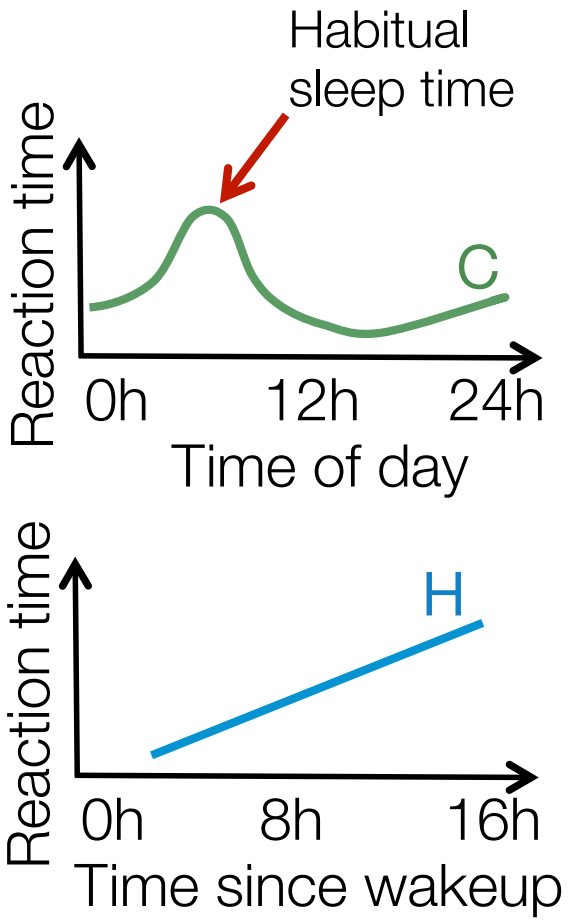
  2. Homeostatic sleep drive (H): the longer awake, the more tired you become



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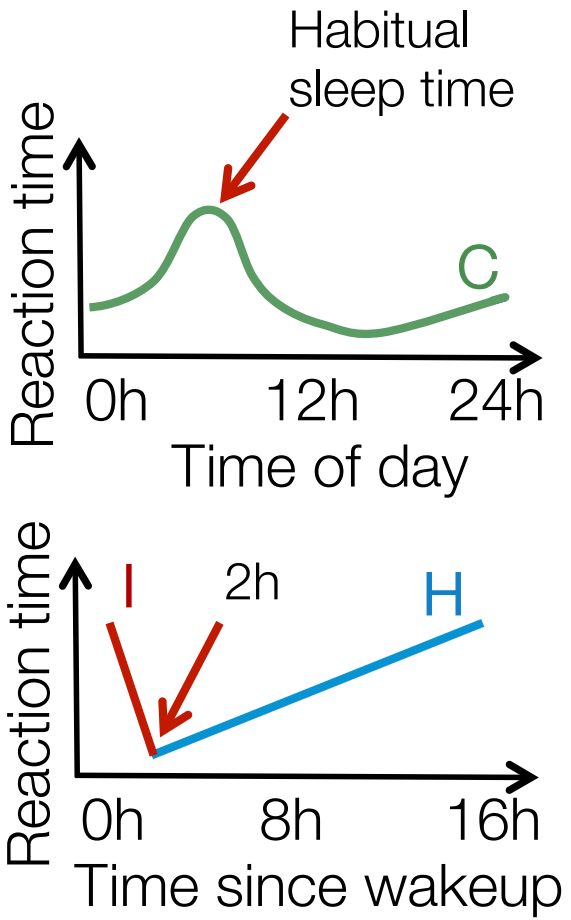

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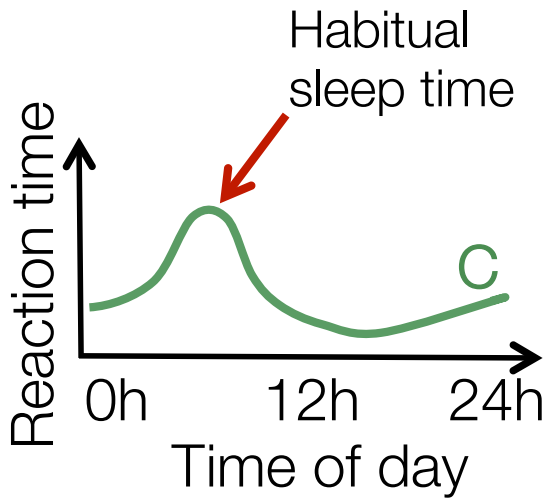

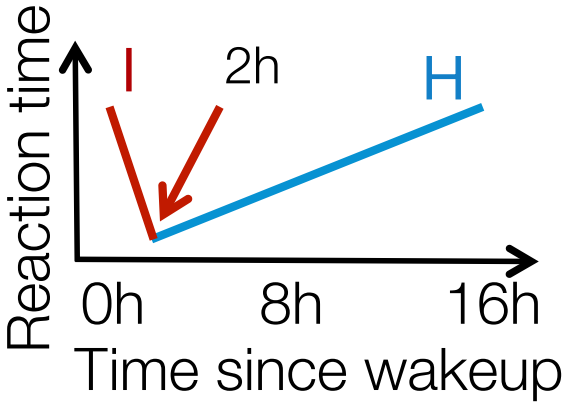

- Hard to disentangle effects
  - Many factors, highly correlated
  - Lab: Forced desynchrony protocol
  - Our method: Variation across millions of real-world interactions (web search)

Statistical Model

- Generalized Additive Model
  - Intercept
  - Keystroke (control for key pressed: “A”, “a”, “@”, …)
  - Time of day (circadian rhythm)
  - Time since wakeup (homeostatic sleep drive & sleep inertia)

$$y_i = \alpha + f^k(x_i^k) + f^t(x_i^t) + f^w(x_i^w) + \epsilon_i$$

Keystroke time

Residual

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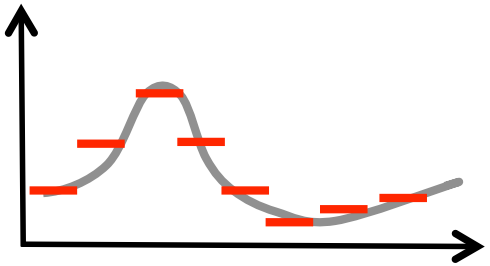
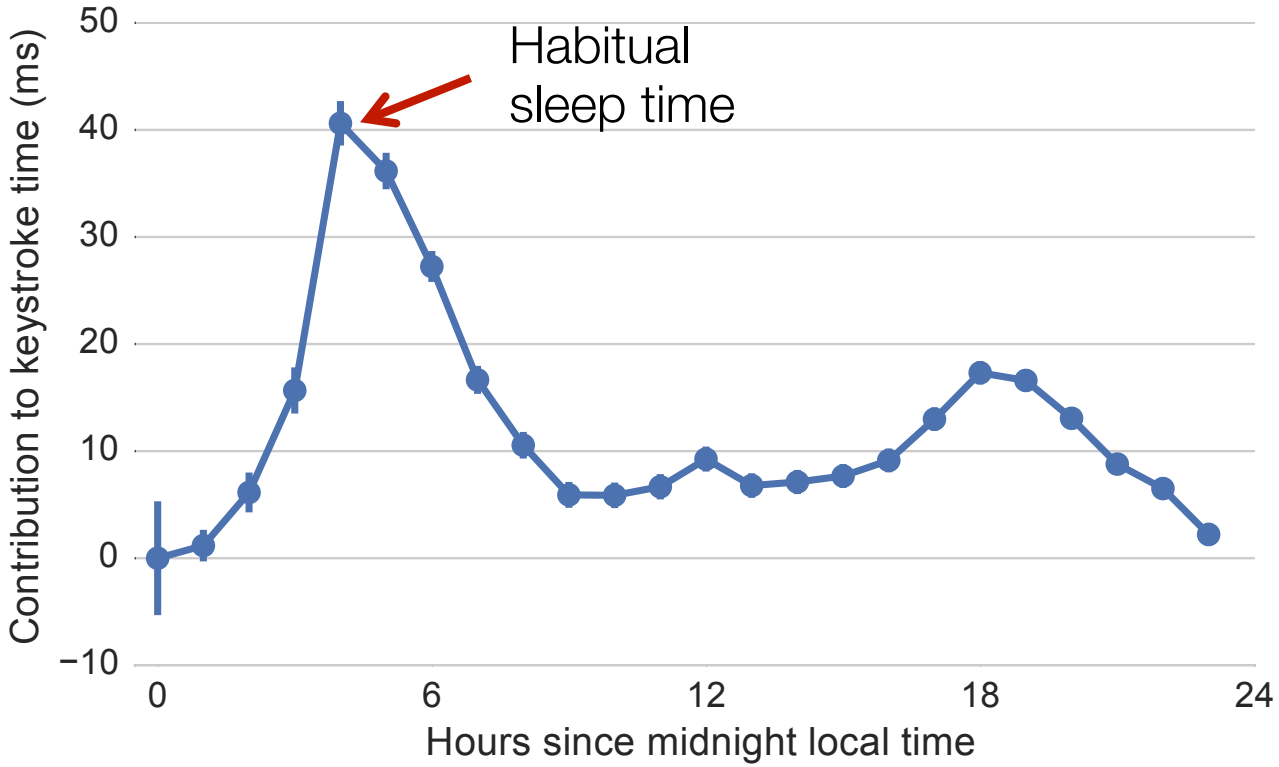
Residual

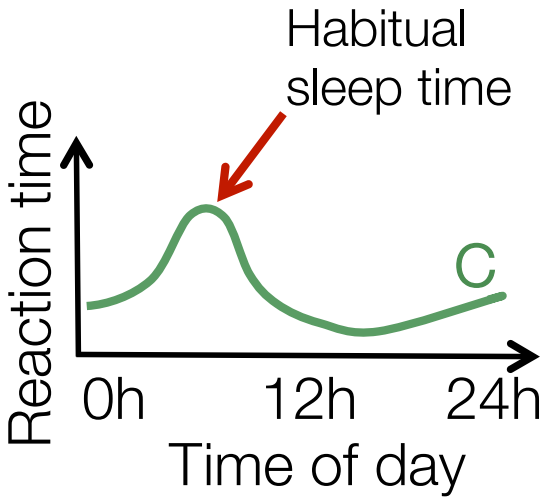
- Parameter learning
  - Fine-grained discretization functions (non-parametric)
  - Least squares optimization



Model Estimates: Time of Day

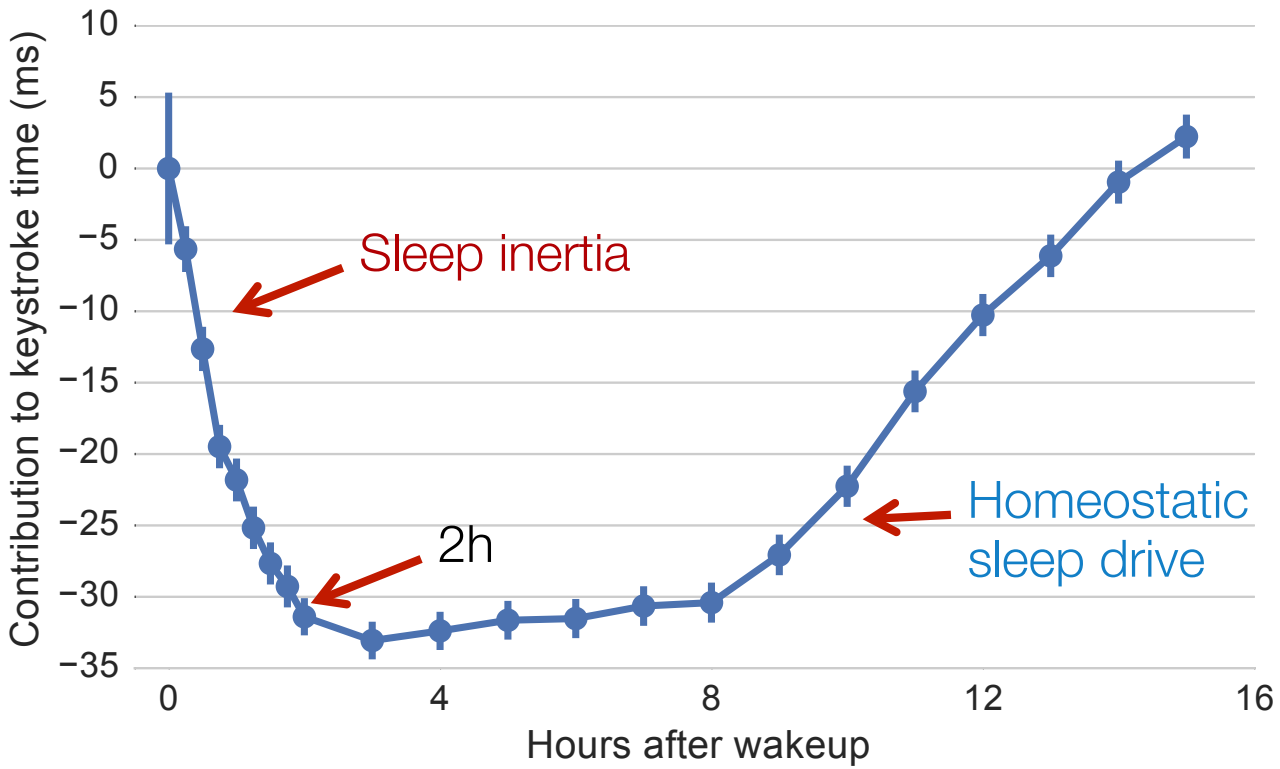


$f^t(x_i^t)$

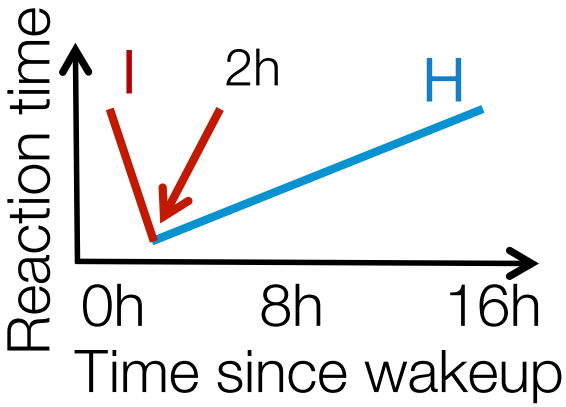


- Model identifies underlying circadian rhythm
- Consistent with lab-based studies

Model: Time After Wakeup



$$f^w(x_i^w)$$



- Model identifies underlying homeostatic sleep drive and sleep inertia consistent with lab-based studies (validation)
- New insights: It was impossible to measure real-world cognitive performance at scale. Now we can!

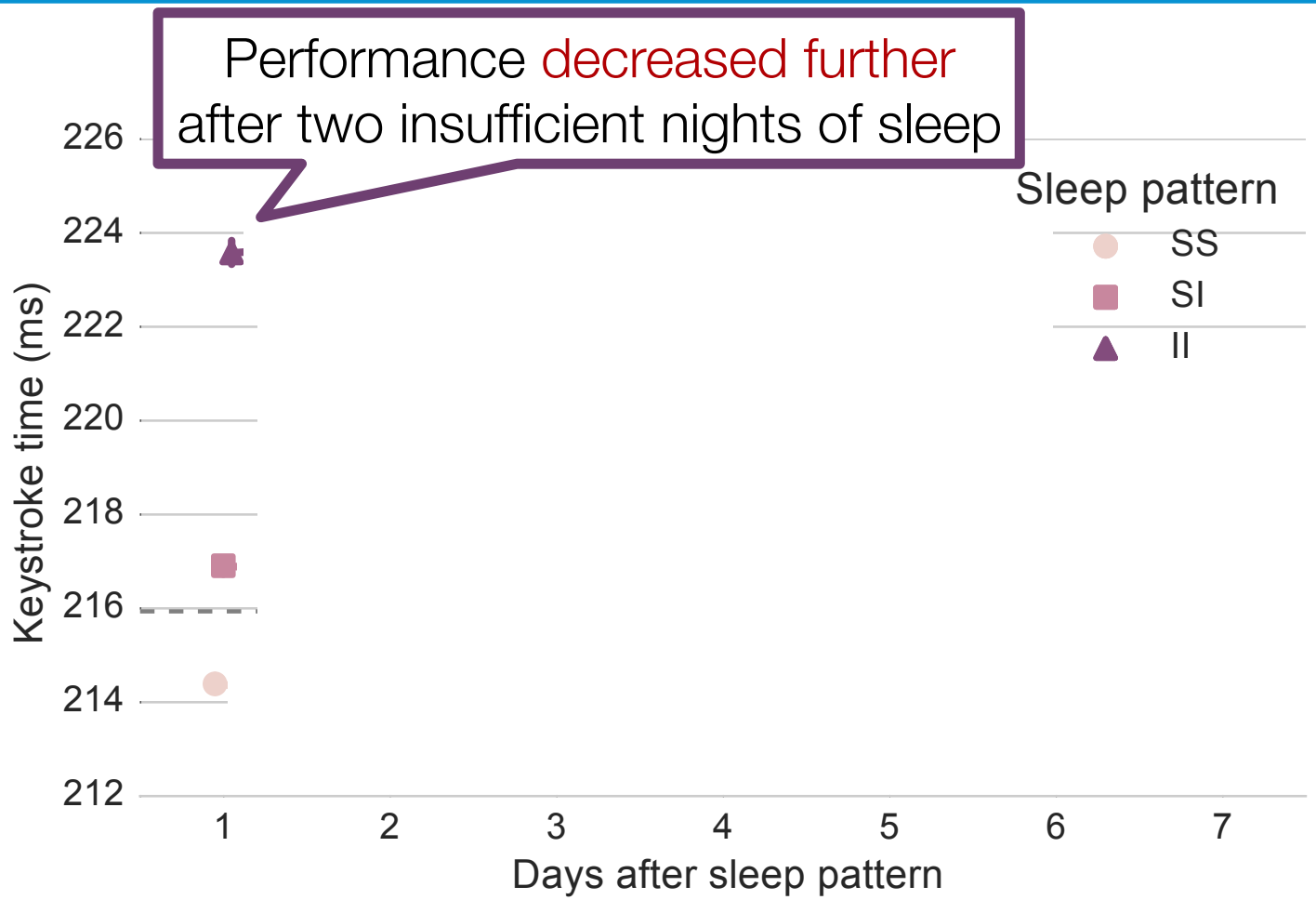
How do real-world sleep patterns impact performance?

Sleep Loss over *Multiple* Nights

1. Can we observe an additive effect of multiple nights with little sleep?
2. How long does it take to recover from sleep loss? (Given real-world sleep patterns)

- Measure performance over 7 days after zero (SS), one (SI), or two (II) insufficient nights of sleep (less than 6h)

Recovering from Sleep Loss



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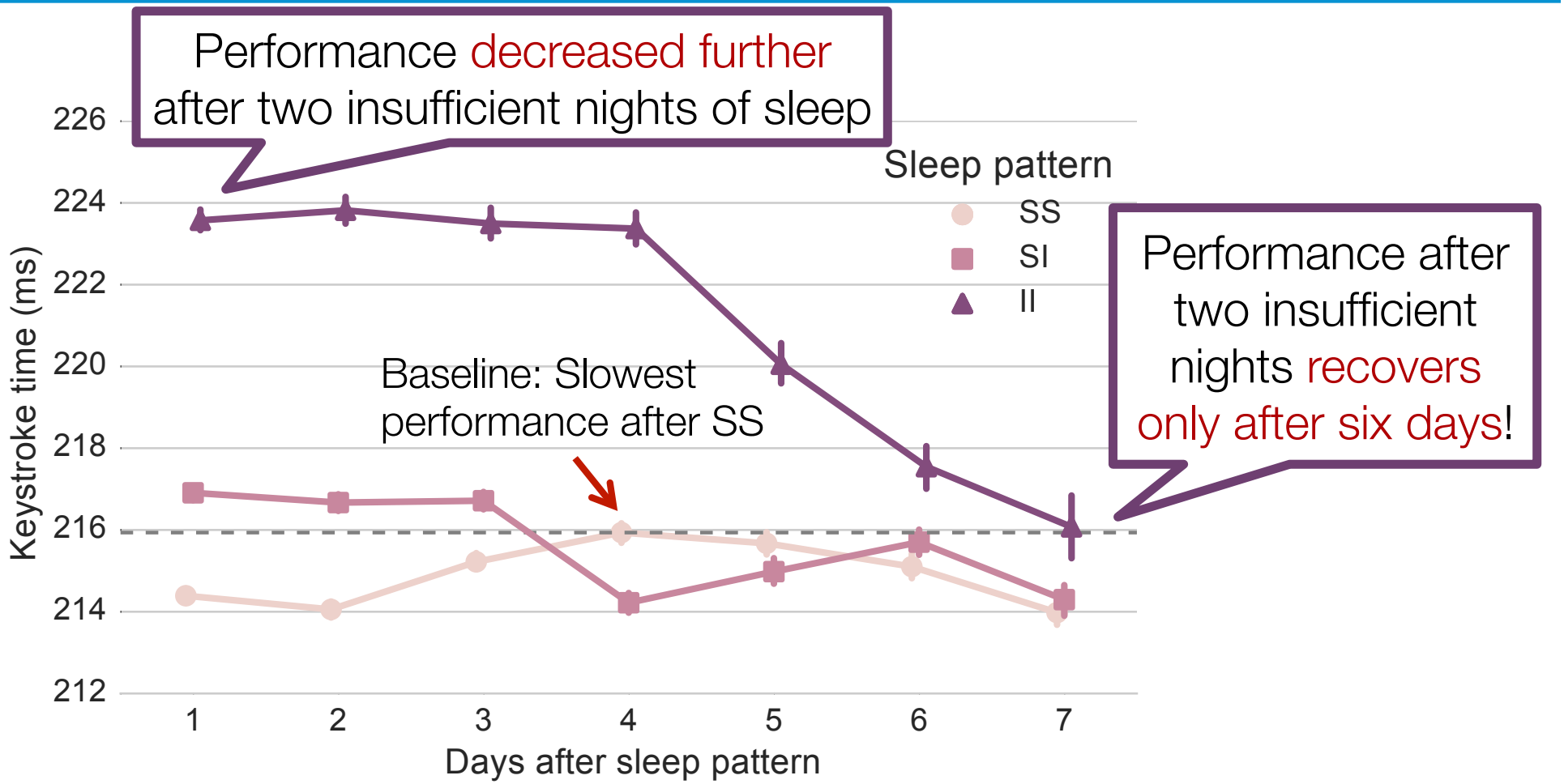
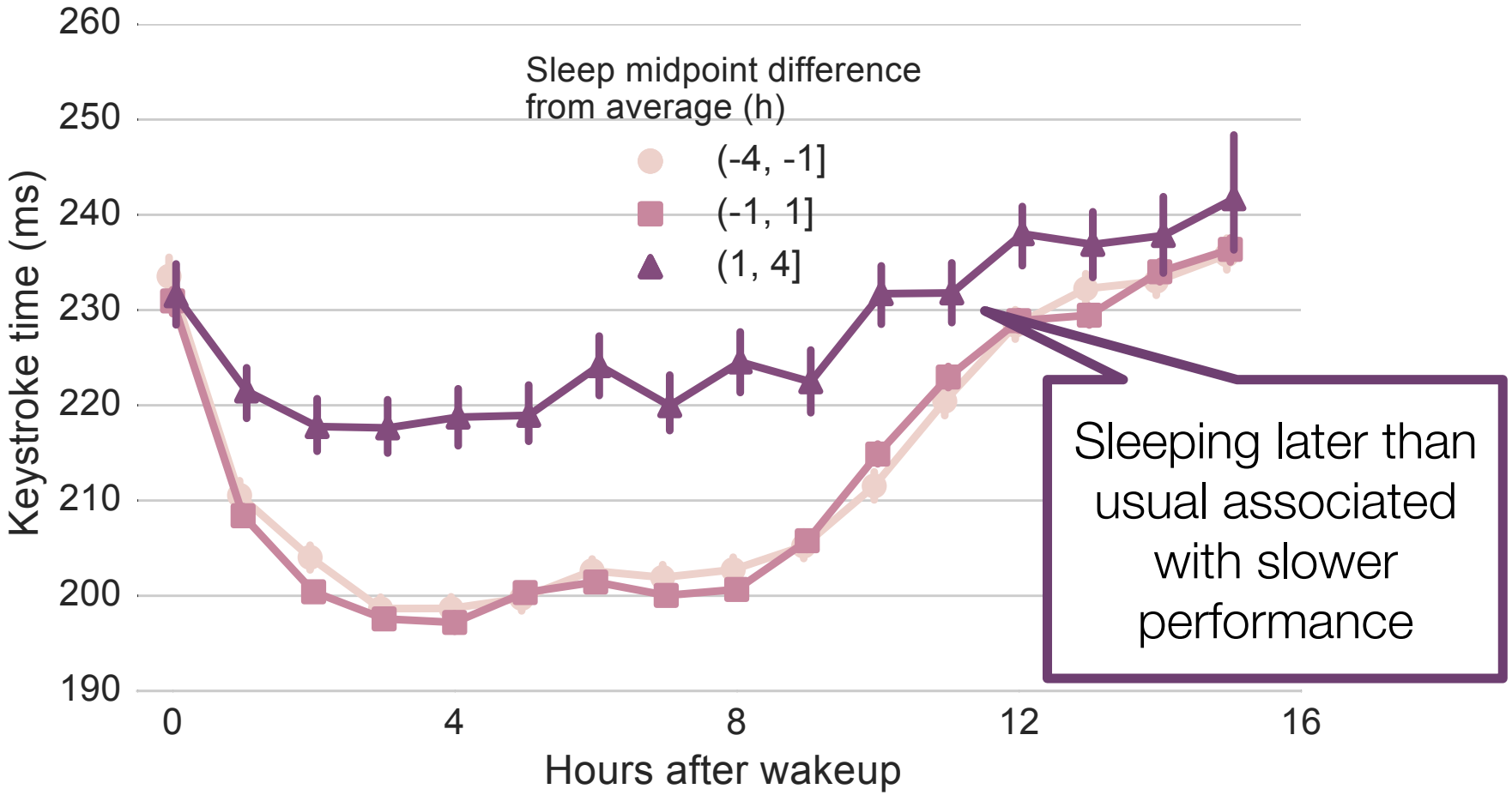


Performance by Sleep *Timing*



- We control for sleep duration (7-8h)

Our Contributions

- New method: Use existing technology interactions to study sleep and cognitive performance
  - Large-scale, real-world (outside of laboratory)
  - Continuous, non-intrusive measurements of realistic tasks
- New insights: Real-world performance is not constant but exhibits variation based on time of day and complex sleep patterns. We are the first to quantify these effects.

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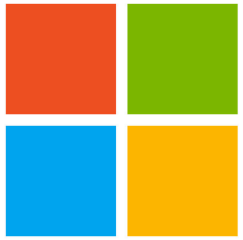
- Population-scale Physiological Sensing
  - Physiology: Branch of biology dealing with the functions and activities of living organisms and their parts
  - Learn about biological functions through user activity logs

Acknowledgments

- Research performed during internship at Microsoft Research



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Ask me anything!

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