
HFES
Systems That Work for Humans
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HUMAN FACTORS AND ERGONOMICS SOCIETY
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All Human Versus Human-Robot Teaming: Measuring Neurophysiological Synchrony, Team Performance, and Trust during Search and Rescue

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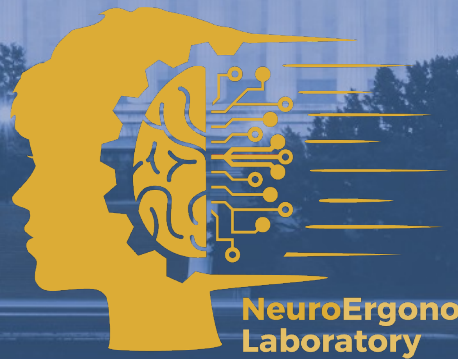

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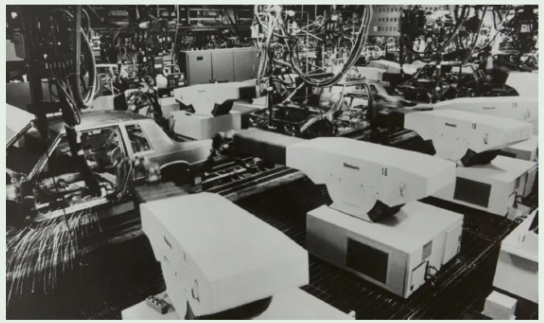
Human-Robot Teaming Evolution



- Separate workspace
- No human

- Separate workspace
- Shared part

- Same workspace
- Same part
- Single human

- Same workspace
- Same goal
- Multiple humans

Human Robot Teaming

Trust

Trust is critical in HRI

- Undertrust can lead to underutilization of the robot's capability
  - Failure of iRobot Packbots at Fukushima Daiichi [3]
- Overtrust can pose a critical safety problem
  - Victims followed the robot with poor performance [12]
- Trust in human-robot collaboration can impact system performance, acceptance, safety, and utilization [13]

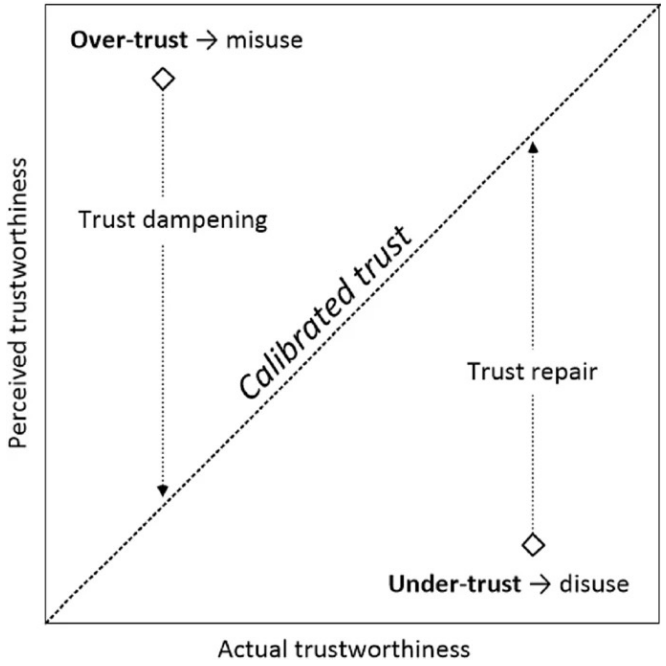


Image source:[15]

Multi-Human-Robot team (mHRT)

Definition

Human-Autonomy Team (HAT). "interdependence in activity and outcomes involving one or more humans and one or more autonomous agents, wherein each human and autonomous agent is recognized as a unique team member occupying a distinct role on the team, and in which the members strive to achieve a common goal as a collective" [1].

Why mHRT?

- **Robots**: sensor suite, carry payload Precise, Advanced sensors
  - Mapping and navigation
  - Mobile beacon (communication)
  - operate in hot zones, 70 firefighter causalities in 2021 [2]
- Reduce response and recovery time, first 48h are critical [3]
- "it takes two humans to operate one robot" in emergency response [3]

Image source: ANYbotics, KUKA

Current mHRT studies take a behavioral approach

Current literature

Effect of team composition on performance, mental models [20]

- Manipulations: HHH, HHA, HAA
- Virtual environment (emergency tasks) with three distinct roles
- # Agents ↑ performance ↑ trust in agent ↓ Perceived Team Cognition ↑

Assessing communication and trust in AI teammate [21]

- RPAS virtual, three distinct roles
- Degraded condition → anticipatory pushing of information & trust
  - HH ↑
  - HA ↓

Current evaluation methods

- Subjective analysis
- Surveys
- Communications
- Performance

Gaps

- Communication may not be reliable in unstructured environments
- Surveys may not align with behaviors [9, 23] and disrupt cognitive processes
- Need for more non-intrusive ways to capture team trust

The need for a Neuroergonomics approach

- Monitor changes over time continuously and un-obtrusively
- Mechanistic understanding of cognitive/affective processes [30], [31]
- Hyperscanning (study of concurrent brain imaging from two users) → uncovers interpersonal social interaction objectively [33]–[35]
  - Goal-oriented social interaction [9]
  - Alignment of oscillatory brain activity during social interaction, information exchange [10]

↑ Inter-brain synchrony ↓

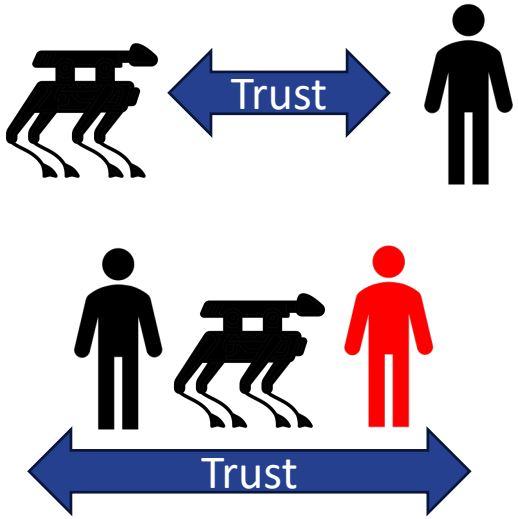
Limited studies examining neural synchrony in mHRTs

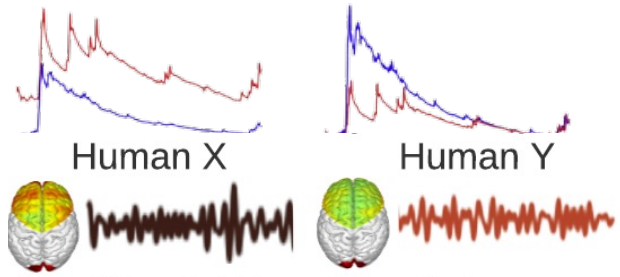
Objectives

Document
individual and team trust in all-human teams and human-robot teams

Compare
performance across the two team settings

Explore
neurophysiological synchrony among human-human dyads in all-human teams and mHRTs

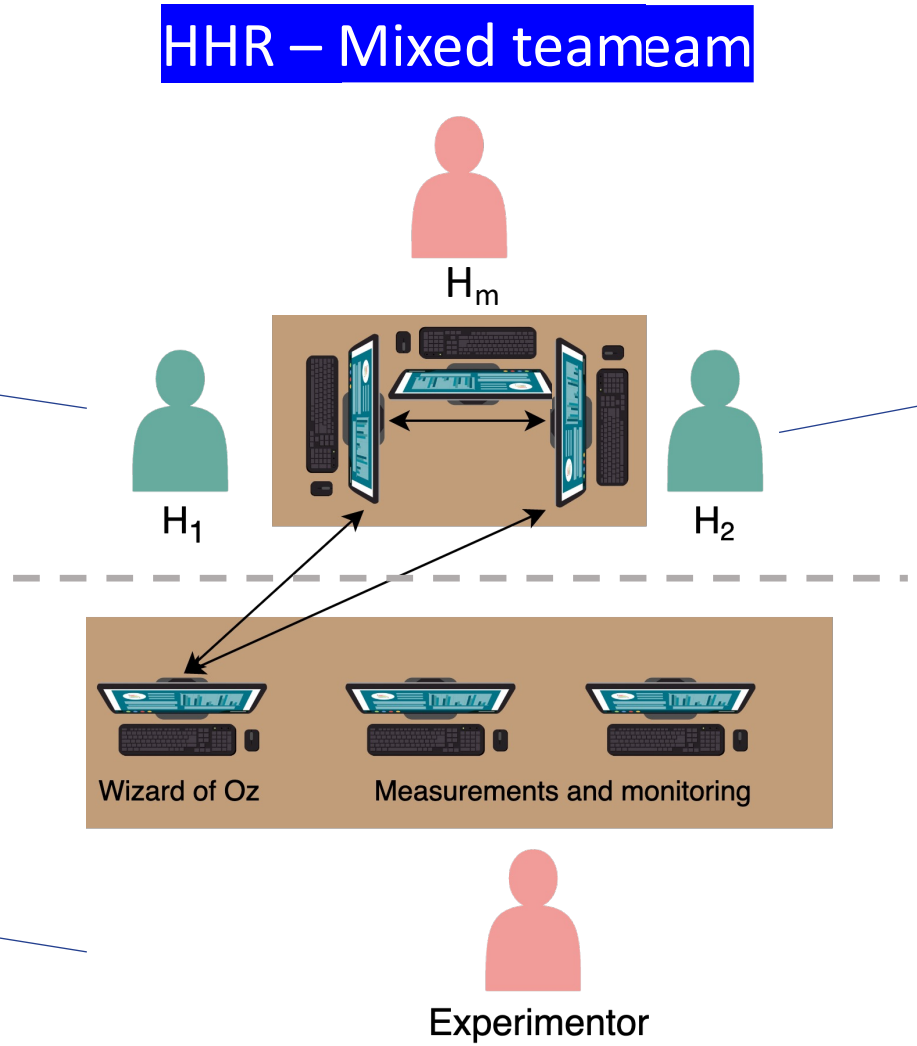




Team configurations

Mission Specialist
cooperated with team members to lead team, made critical decisions, log victims

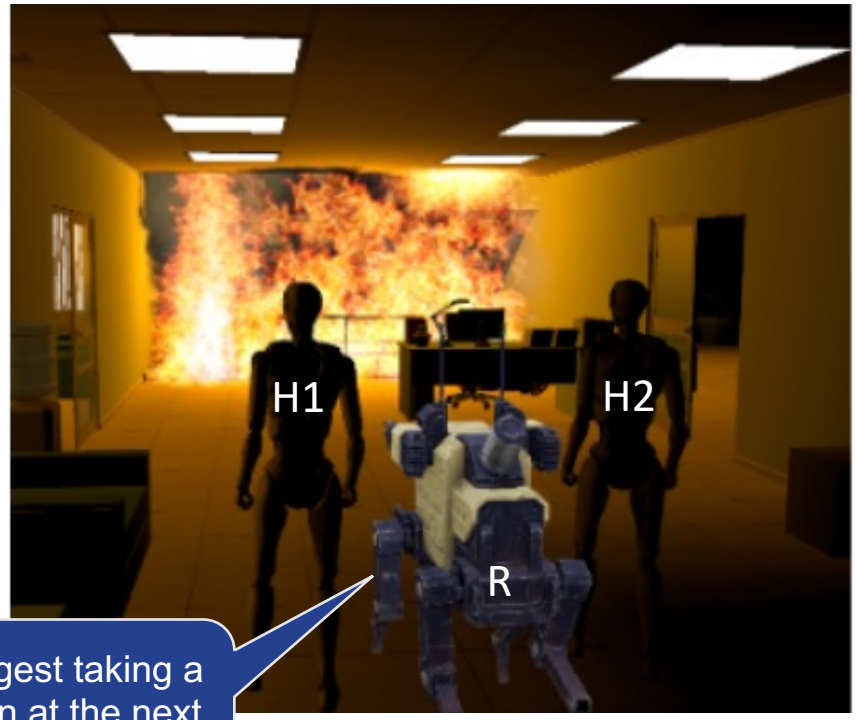
Navigator
Guided team by suggesting directions to locate victims based on thermal maps



Safety Officer
Monitored NOx levels of low, medium, high to ensure team safety

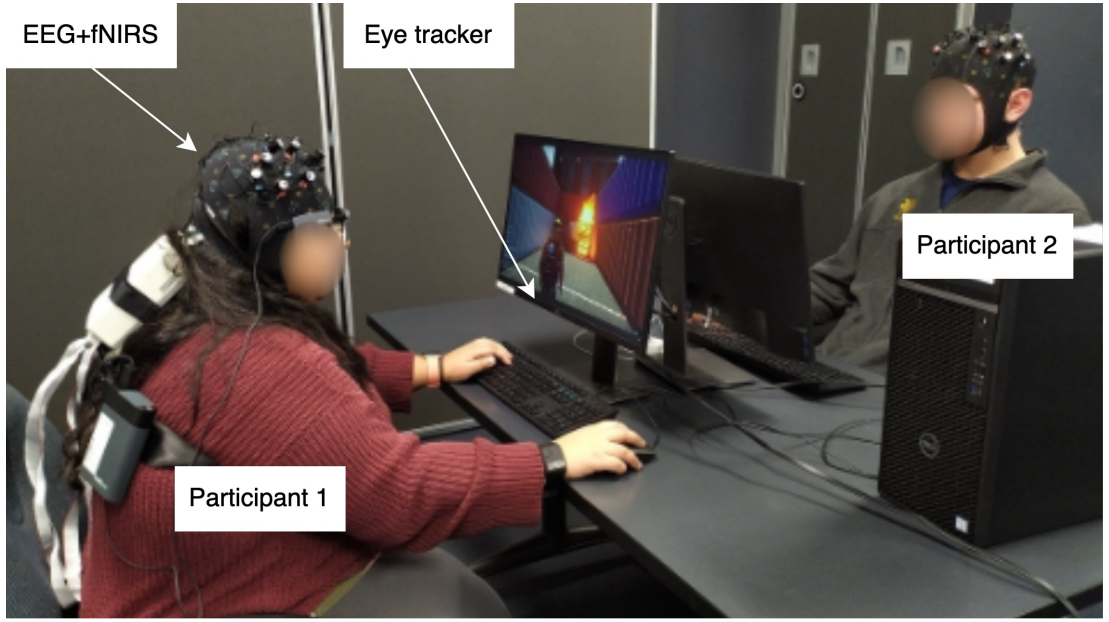
Test-bed and scenario developed with emergency response SMEs

Task



Wizard-of-Oz

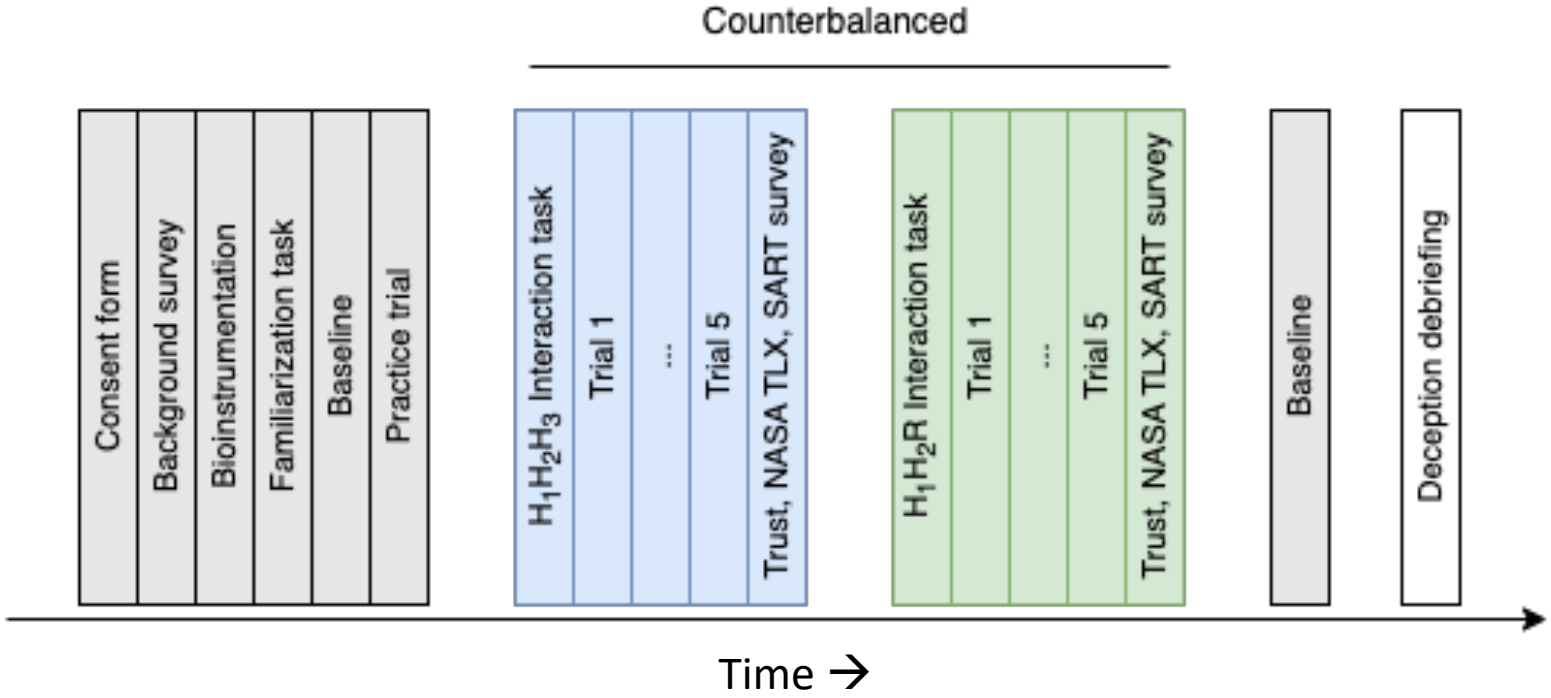
Task: Locate and mark victims in a burning building in set time



Robot suggests directions using pre-recorded AI-generated voice commands

Protocol

- Sixteen participants → 8 teams
  - 4 M-M dyads
  - 3 M-F dyads
  - 1 F-F dyads
  - mean age = 23.38 ± 4.41 y
  - time spent on video games: 4.73 ± 5.55 h/week
- 3 min per trial
- Statistical analysis using Linear Mixed Models (LMM)



Measurements at glance

Individual metrics

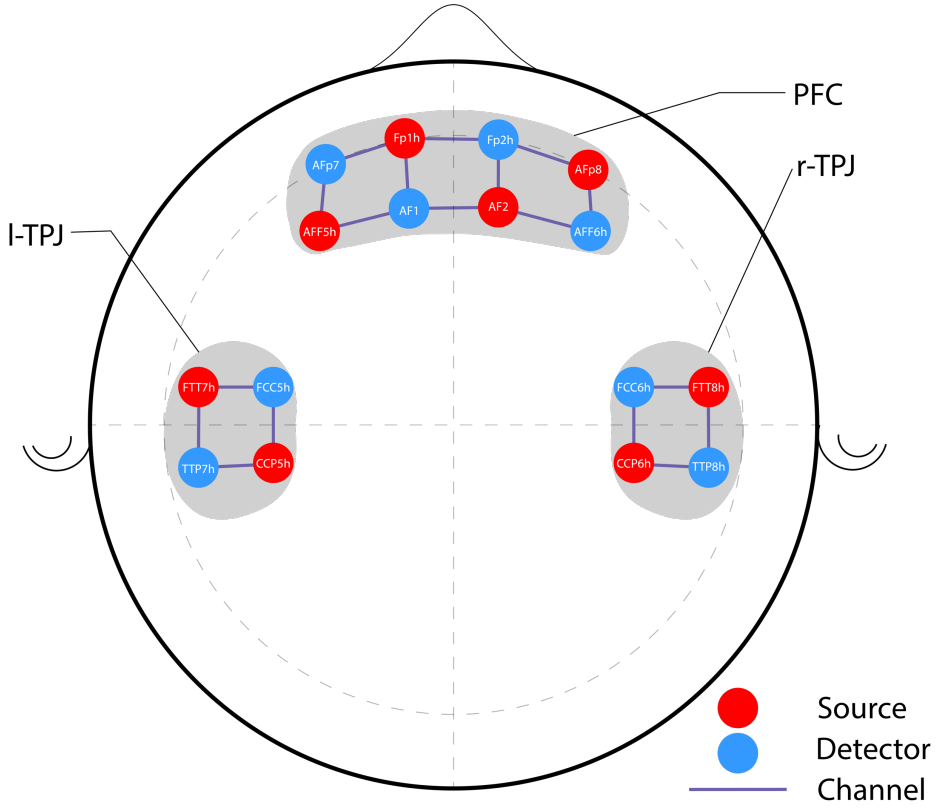
- Perception
  - Trust
  - Situation awareness [13]
  - Fatigue
- HRV features
  - Heart rate
  - SDNN

Joint team metrics

- Perception
  - Team trust [14]
- Inter-Brain Synchrony (IBS) [10]
- HRV synchrony [15]
  - Recurrence Rate (RR)
  - Determinism (DET)
- Performance

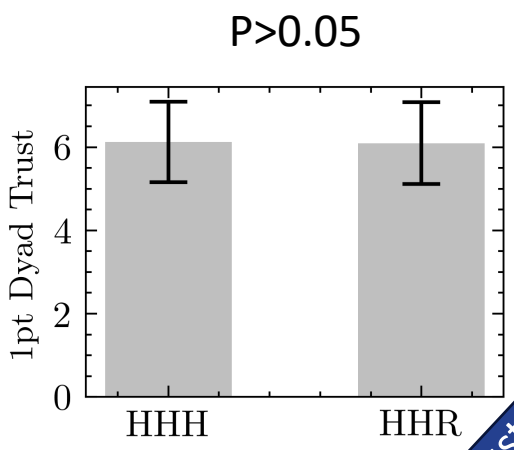
Neurophysiological synchrony

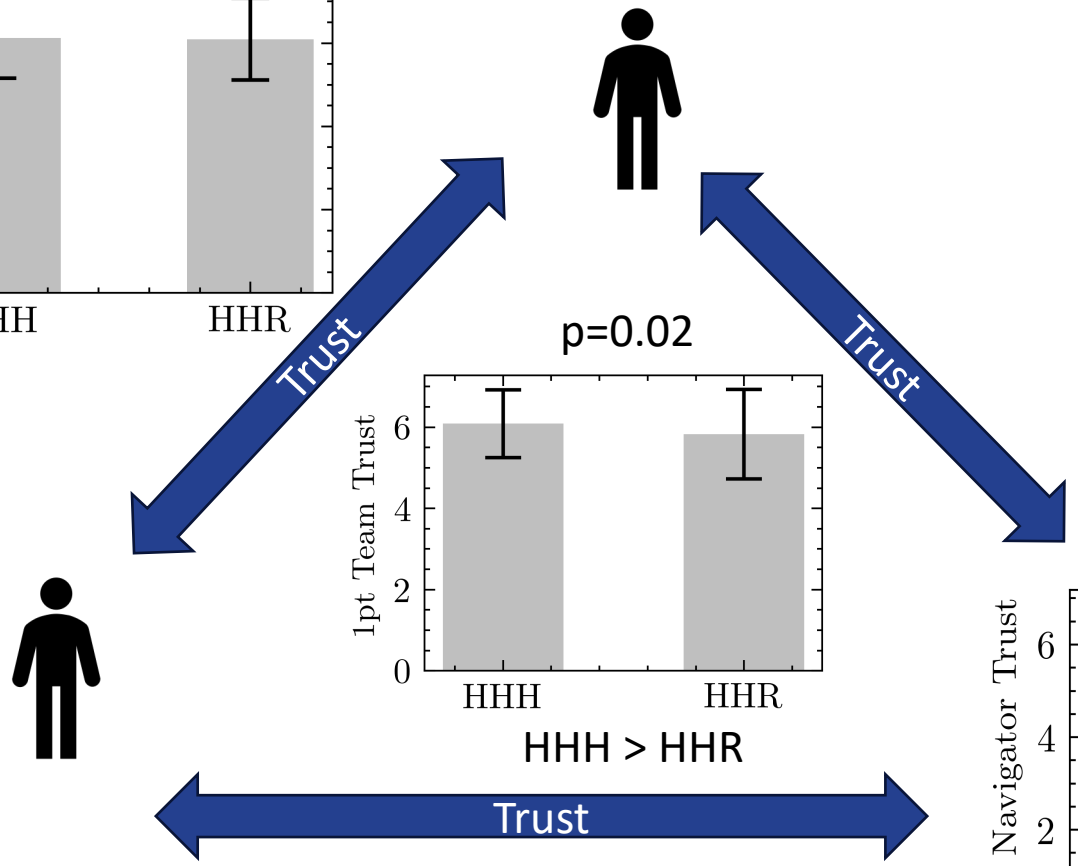
- correlated with an enhanced ability to complete cooperative tasks [16]
- can reflect shared attention, joint cognition [17]

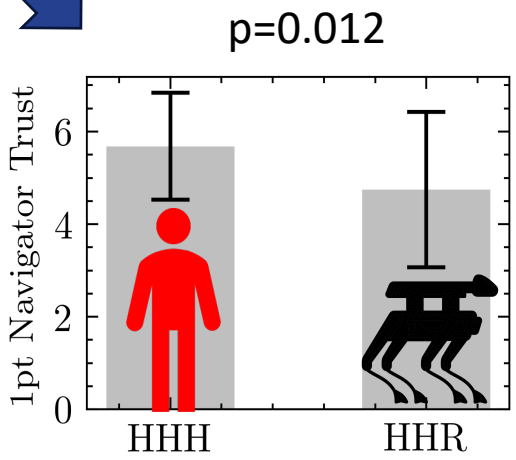


Prefrontal cortex (PFC)
Left temporoparietal junction (l-TPJ)
Right temporoparietal junction (r-TPJ)

Results: Subjective Measures

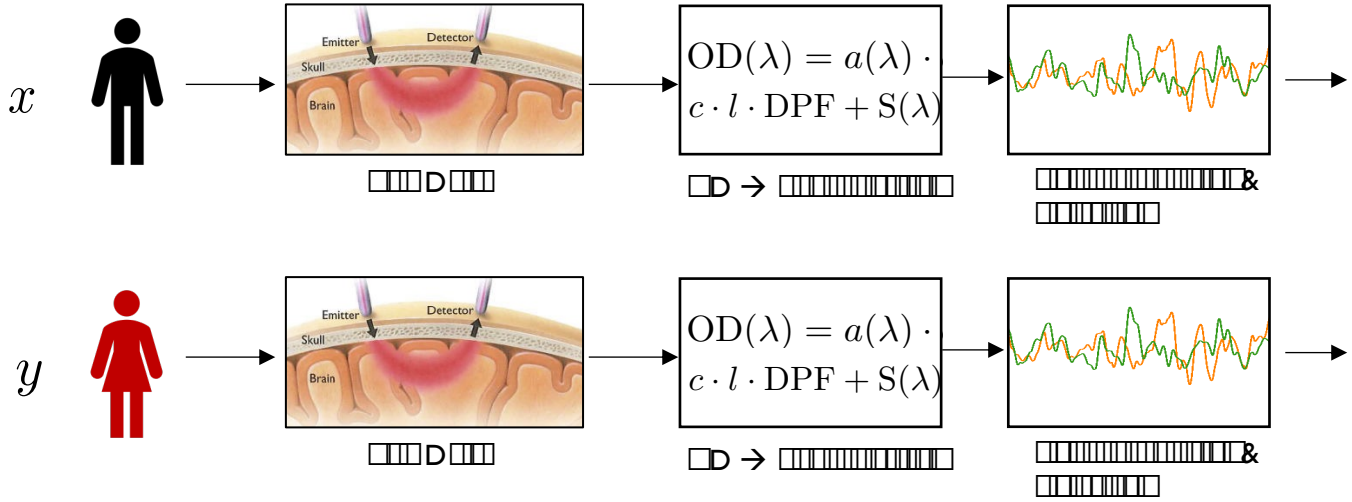






- Trust between dyads remained intact [8]
- Human navigator is trusted
- Team trust was higher in HHH
- Higher fatigue (p = 0.025) in HHH
  - Robot use mitigated fatigue
- Comparable situation awareness, perceived workload, mental effort (all p's>0.05)

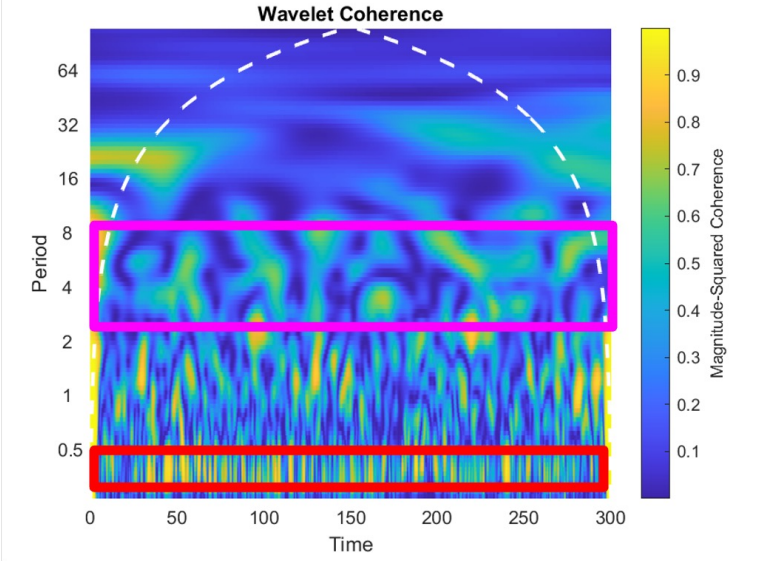
Computing Neural synchrony



$$\mathrm{OD}(\lambda) = a(\lambda) \cdot c \cdot l \cdot \mathrm{DPF} + \mathrm{S}(\lambda)$$

For each region in {PFC, r-TPJ, l-TPJ} compute WTC

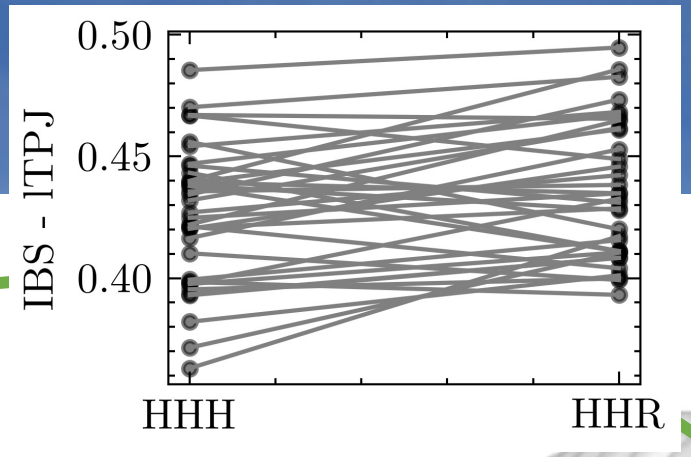
$$\hat{C}_n^2 = \frac{\left|\left\langle W_n^{xy}(s).s^{-1}\right\rangle\right|^2}{\left\langle W_n^{xx}(s).s^{-1}\right\rangle\left\langle W_n^{yy}(s).s^{-1}\right\rangle}$$



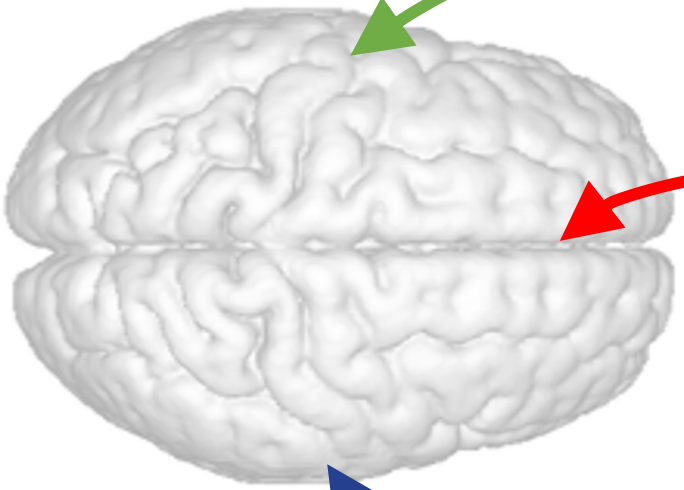
IBS = mean of Band of interest, heart rate

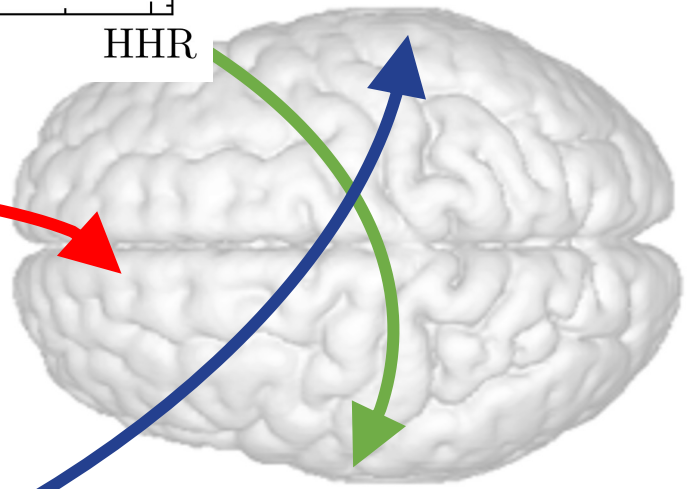
Wavelet Transform Coherence (WTC)

Neural Synchrony

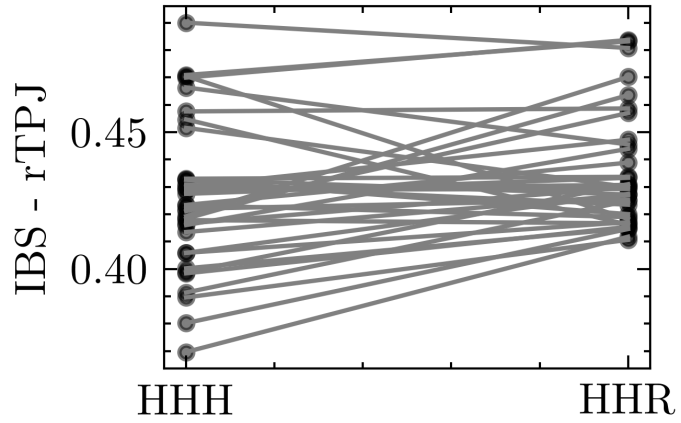


H1





H2



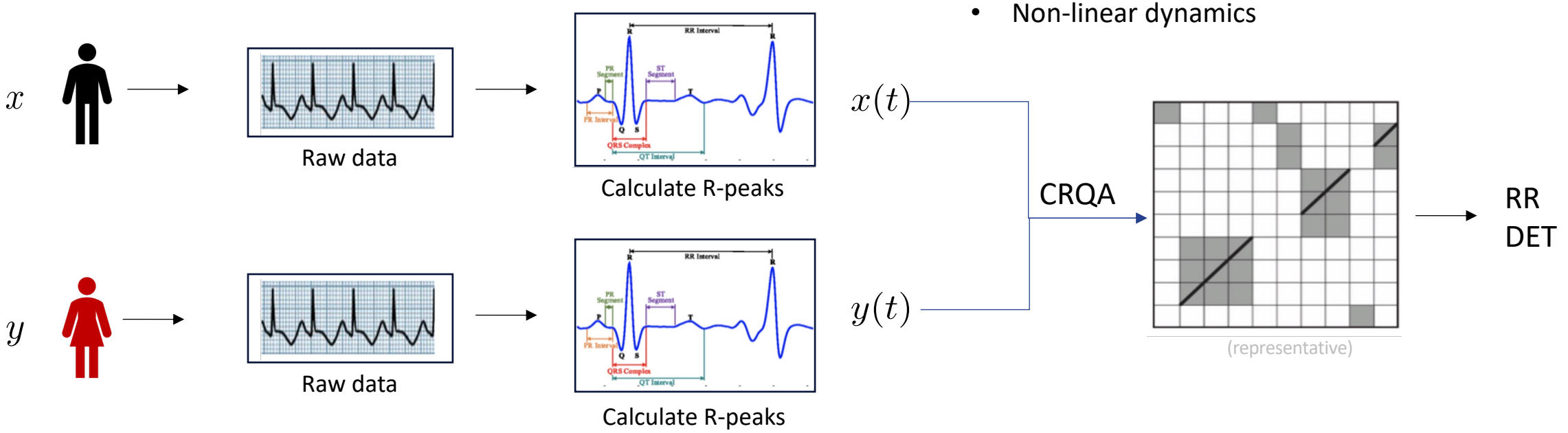
- **PFC**: HHR~HHH (p>0.05)
- **l-TPJ**: HHR>HHH (p = 0.004)
- **r-TPJ**: HHR>HHH (p = 0.012)

Neural Synchrony

- Inter-brain-synchrony higher in temporoparietal junction of brain
  - brain regions implicated in social cognition and teamwork [11]
  - team actively engaged in joint cognition, working together to achieve a common goal
    - shared mental representations of the tasks leading to the high efficiency of information exchange [12]
- IBS higher in HHR compared to HHH
  - more joint complex cognition to work with robot [9]
- IBS in PFC comparable across conditions

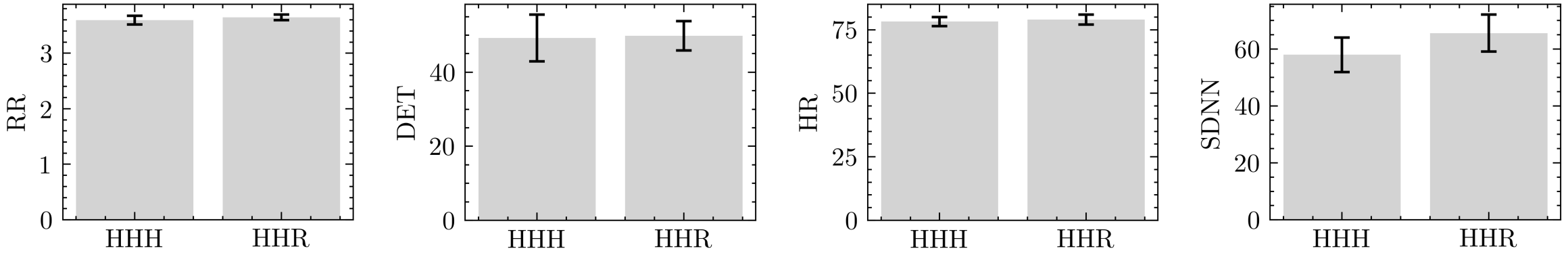
Computing HRV Synchrony

Cross Recurrence Quantification Analysis (CRQA)
- Captures recurring patterns of the dynamical system
- Non-linear dynamics



HRV synchrony
- correlated with an enhanced ability to complete cooperative tasks [16]
- can reflect shared attention [17]
- emotions such as appreciation or compassion are associated with a more coherent rhythm [18]

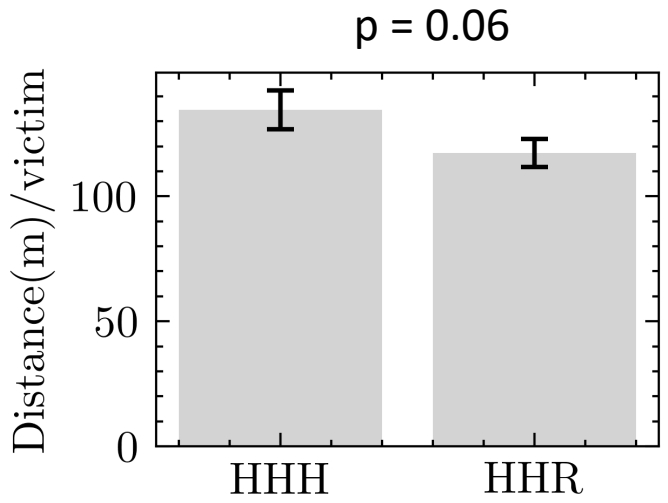
Results: Heart Rate Variability



Fatigue ↑ SDNN ↓

- Human team members exhibited comparable physiological responses (HRV)
  - Further investigation with more data is needed to test the sensitivity
- Although not significant, perceived higher fatigue in all human teams is indicated by lowering of SDNN

Results: Performance



Teams performed more efficiently in the HHR condition compared to the HHH condition [20]

Key Takeaways

A. mHRT performed better in assigned tasks than the all-human team, and helped mitigate fatigue

B. Team trust and trust in navigator was **higher in all-human team compared to mHRT,** while the trust between the human dyads remained comparable

C. Human **dyads in mHRT** exhibited **greater neural synchrony** (r-TPJ, l-TPJ) indicating greater cooperative behavior, indicative of higher performance

Limitations and future directions

- Simulated environments
- Participants (size, demographics)
- Need to balance gender distributions in dyads
- Analyze communication data, and in-depth analysis of performance data

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