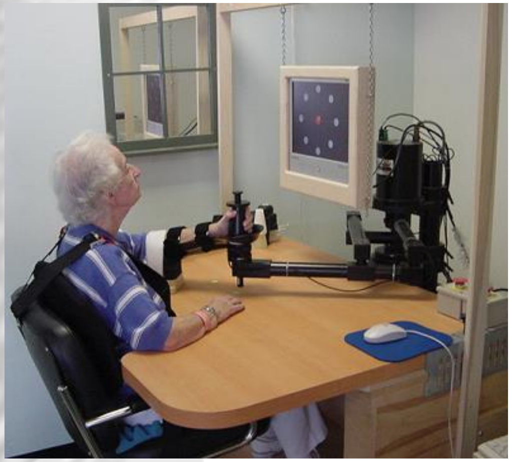
Adaptive integration of psychophysiological variables for robotic training

(Adaptivna integracija psihofiziololoških spremenljivk za robotsko urjenje)

Domen Novak, univ. dipl. inž. el.

Univerza v Ljubljani
Fakulteta za elektrotehniko

Rehabilitation robotics



MIT Manus, Boston

ARMin II, Zurich

Gentle/S, Ljubljana

BioRobotics, Washington

- <u>patient-cooperative robots</u>:

recognize and adapt to patient movement intentions and motor abilities

Biocooperative robotics

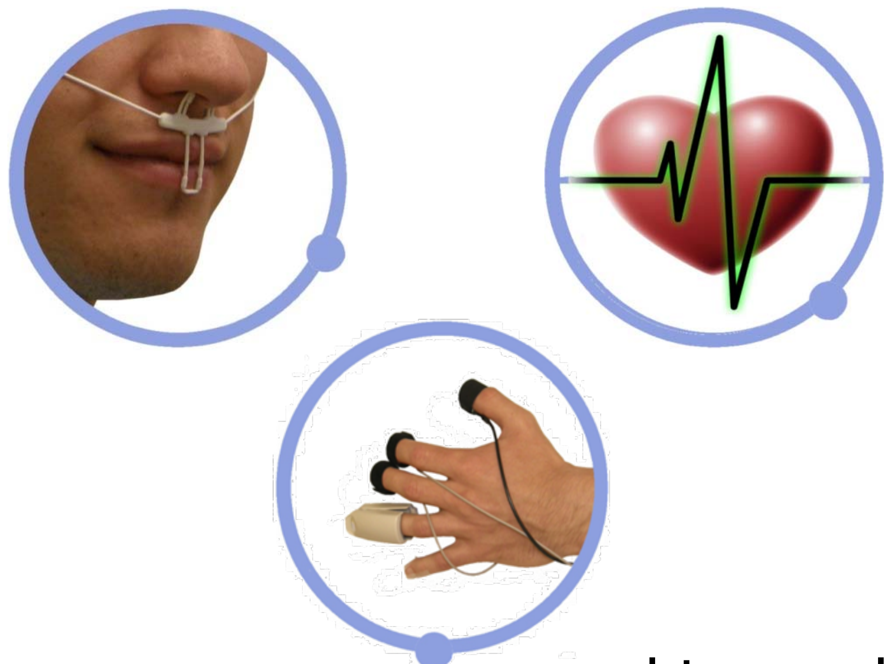
- robots that recognize psychological factors: stress, boredom...
- psychological factors (esp. motivation) very important for rehabilitation, but hard to measure
- possible solution:
  psychophysiological measurements

Psychophysiological measurements

- Measure how psychological stimuli affect physiological responses

respiration

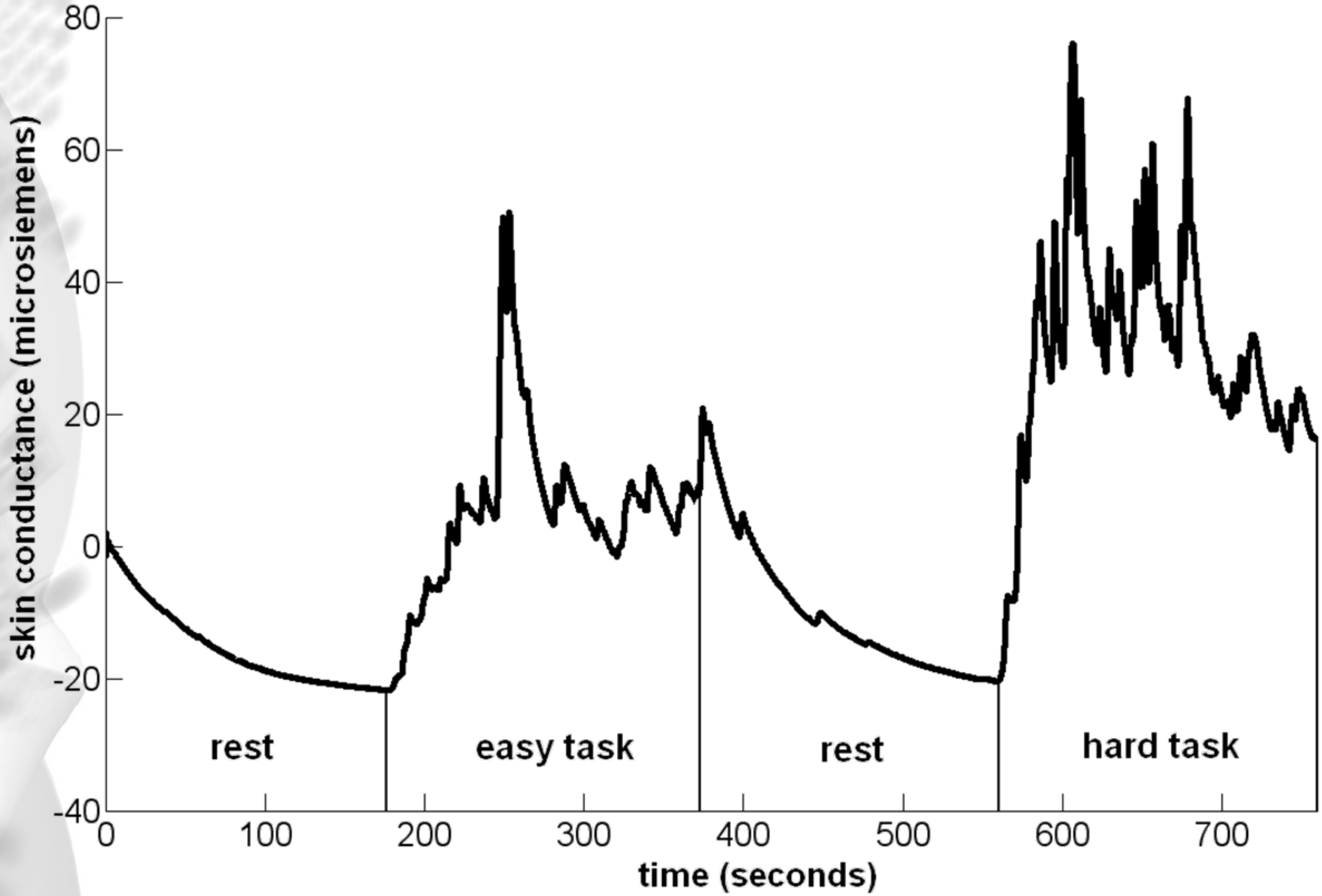
heart rate



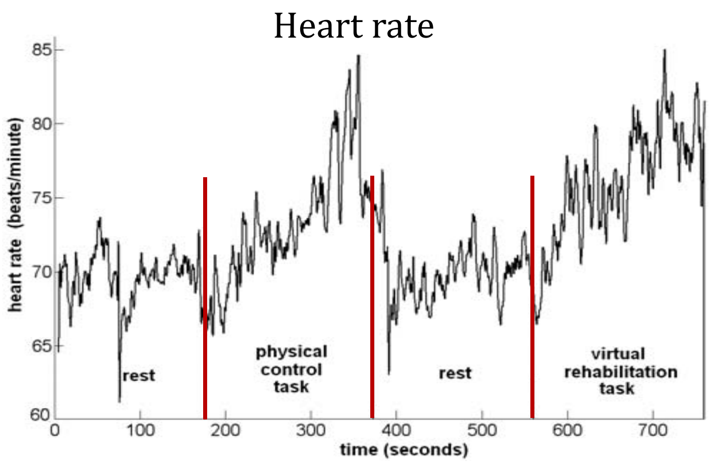
skin temperature

skin conductance

Example: skin conductance



Physiological feature extraction



Heart rate

mean HR

SDNN

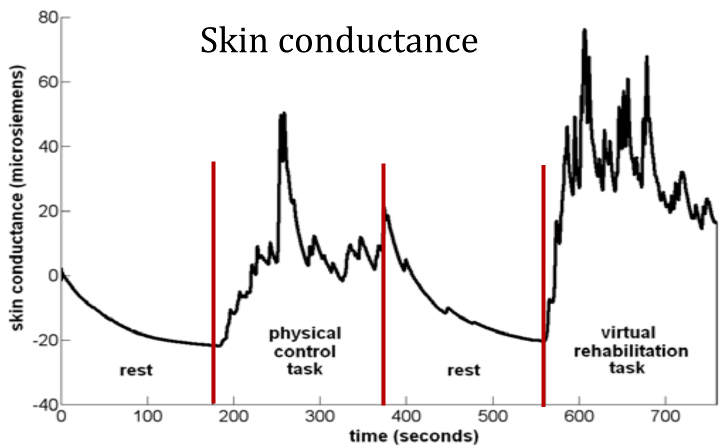
RMSSD

pNN50

LF/HF ratio

HF power (RSA)

LF power



Skin conductance

number of SCRs

mean SCR amplitude

final SCL (mS)

Well-established in literature!

State of the art prior to dissertation

- psychophysological measurements suggested for use in motor rehabilitation, but never implemented or analyzed

- sensor integration and interpretation a big challenge in general psychophysiology

Goal of doctoral dissertation

- integration of psychophysiological measurements with biomechanical and other measurements in a biocooperative feedback loop
- biocooperative feedback loop: adapt task difficulty so that patient always faces a moderate challenge that motivates and does not cause stress

Dissertation structure

- Analysis of rehabilitation-specific factors
  - Effects of physical activity
  - Effects of stroke
- Sensor integration and biocooperative control
  - Controlled laboratory setting
  - Clinical rehabilitation task

Dissertation structure

- Analysis of rehabilitation-specific factors
  - Effects of physical activity
  - Effects of stroke
- Sensor integration and biocooperative control
  - Controlled laboratory setting
  - Clinical rehabilitation task

Effects of physical activity

typical psychophysiological task

rehabilitation
(video courtesy ETH Zurich)

Effects of physical activity

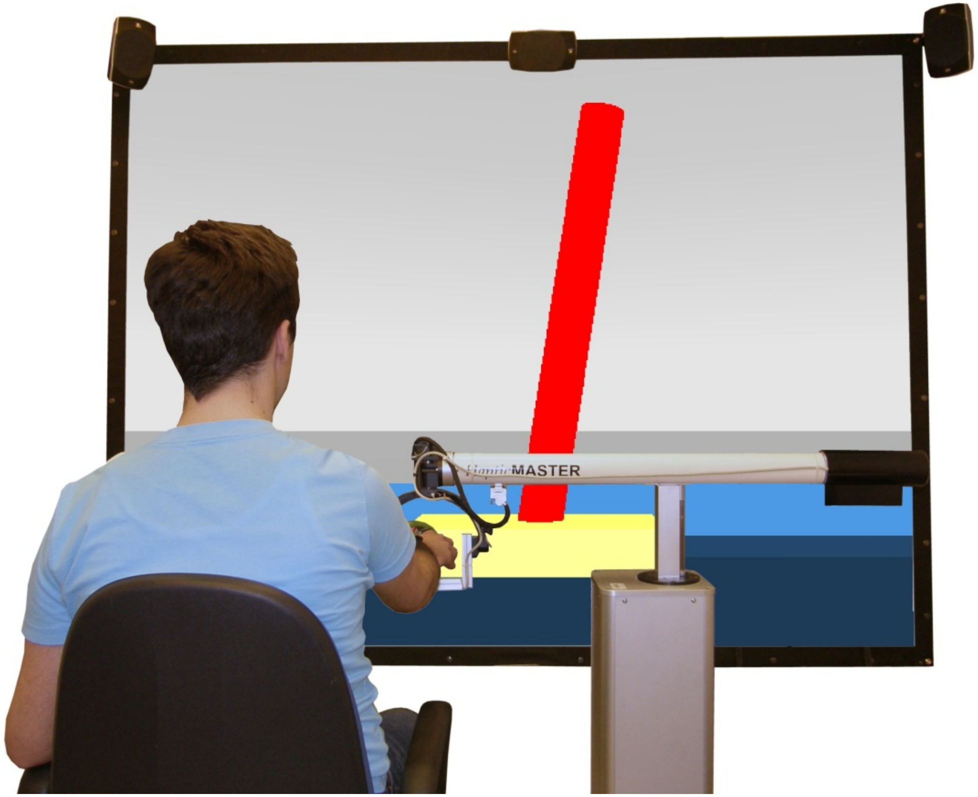
- Hypothesis: In haptic human–robot interaction, physiological responses are affected by both cognitive and physical workload.
  - The physiological effects of physical and cognitive workload are additive.
  - Both types of workload contribute significantly to physiological responses.

Effects of physical activity

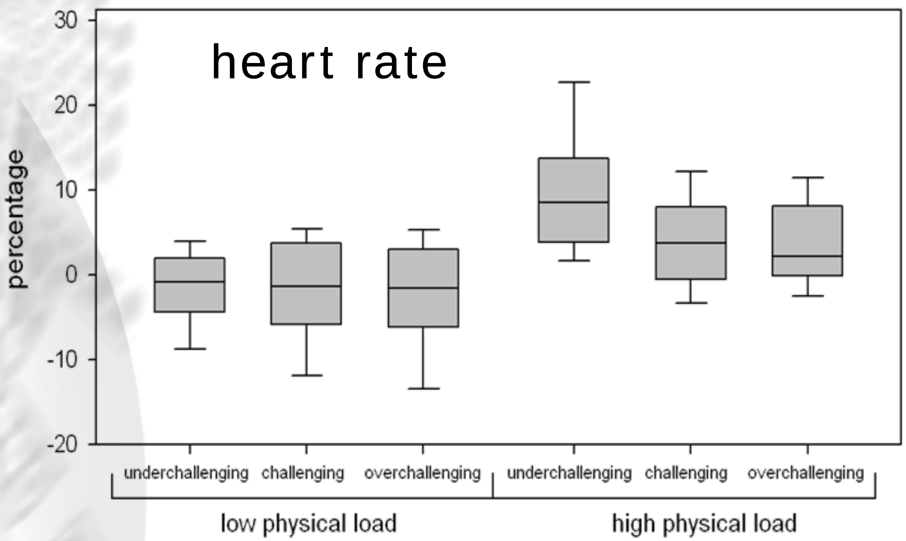
- task with physical and cognitive elements

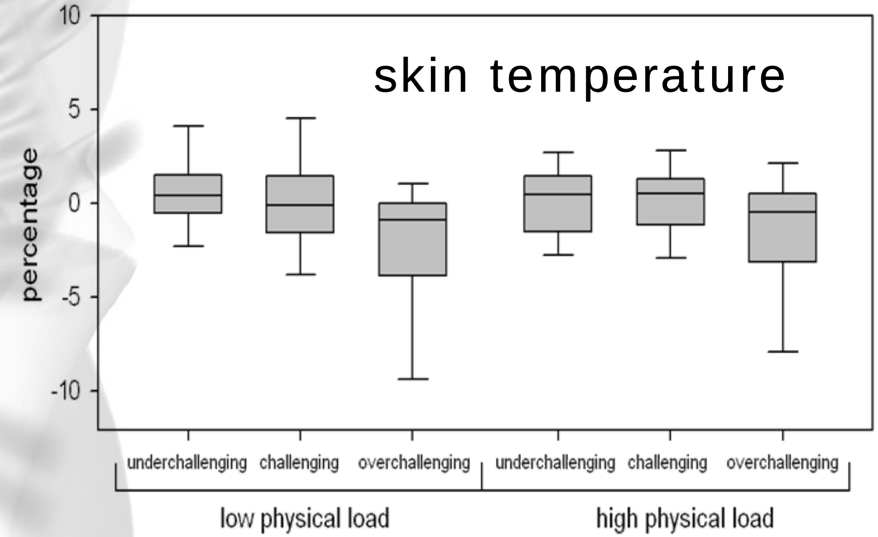
- 2 physical levels
- 3 cognitive levels
- 2 rest periods

- 30 subjects



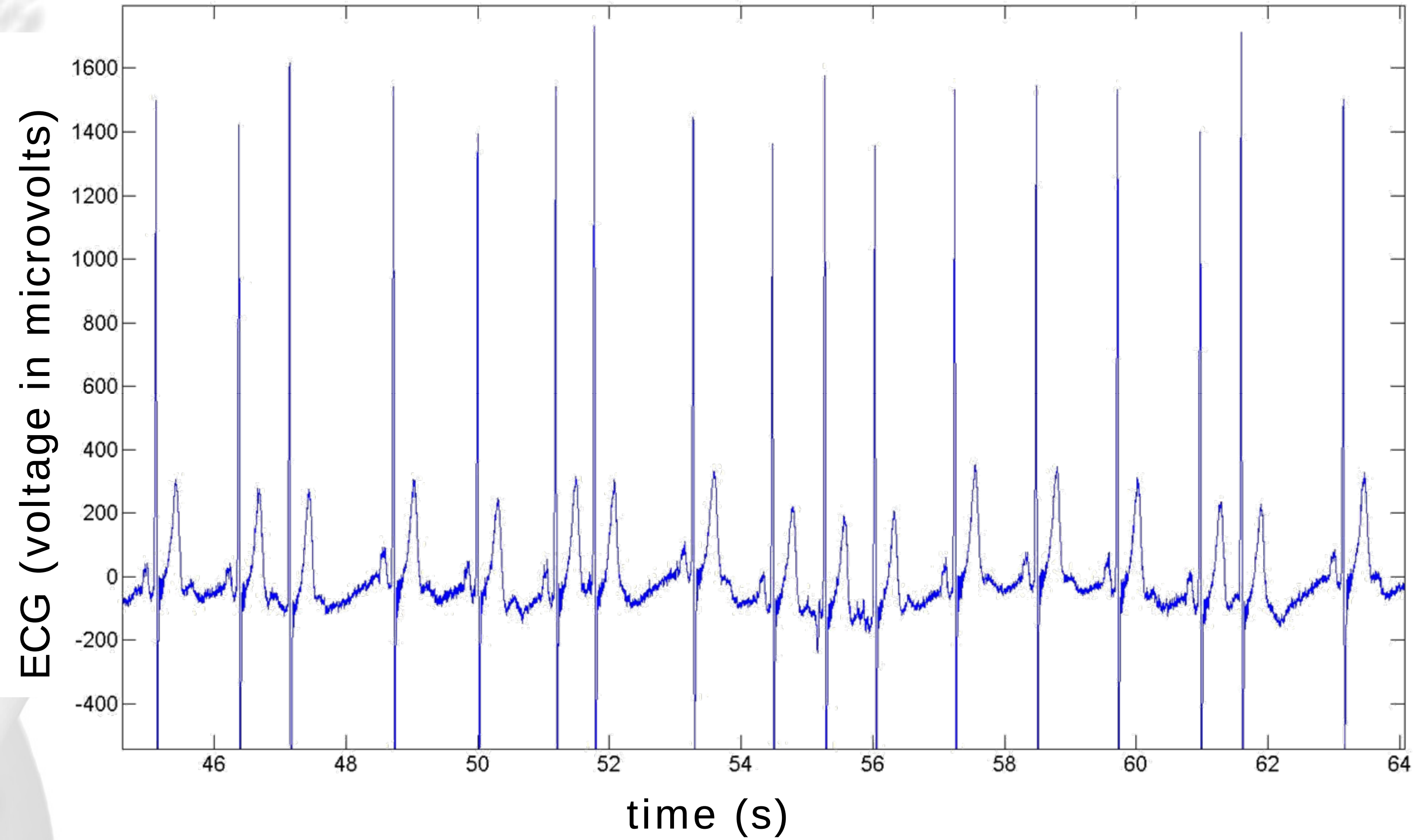
Results





- **heart rate**: physical activity
- **skin conductance**: both cognitive and physical activity
- **respiration**: cognitive activity
- **skin temperature**: cognitive activity

Analysis of effects of stroke



Analysis of effects of stroke

- Hypothesis: Stroke patients have weakened or even absent psychophysiological responses compared to control subjects.
  - When performing a purely cognitive task, stroke patients nonetheless exhibit significant responses.
  - When performing a rehabilitation task, stroke patients nonetheless exhibit significant responses.

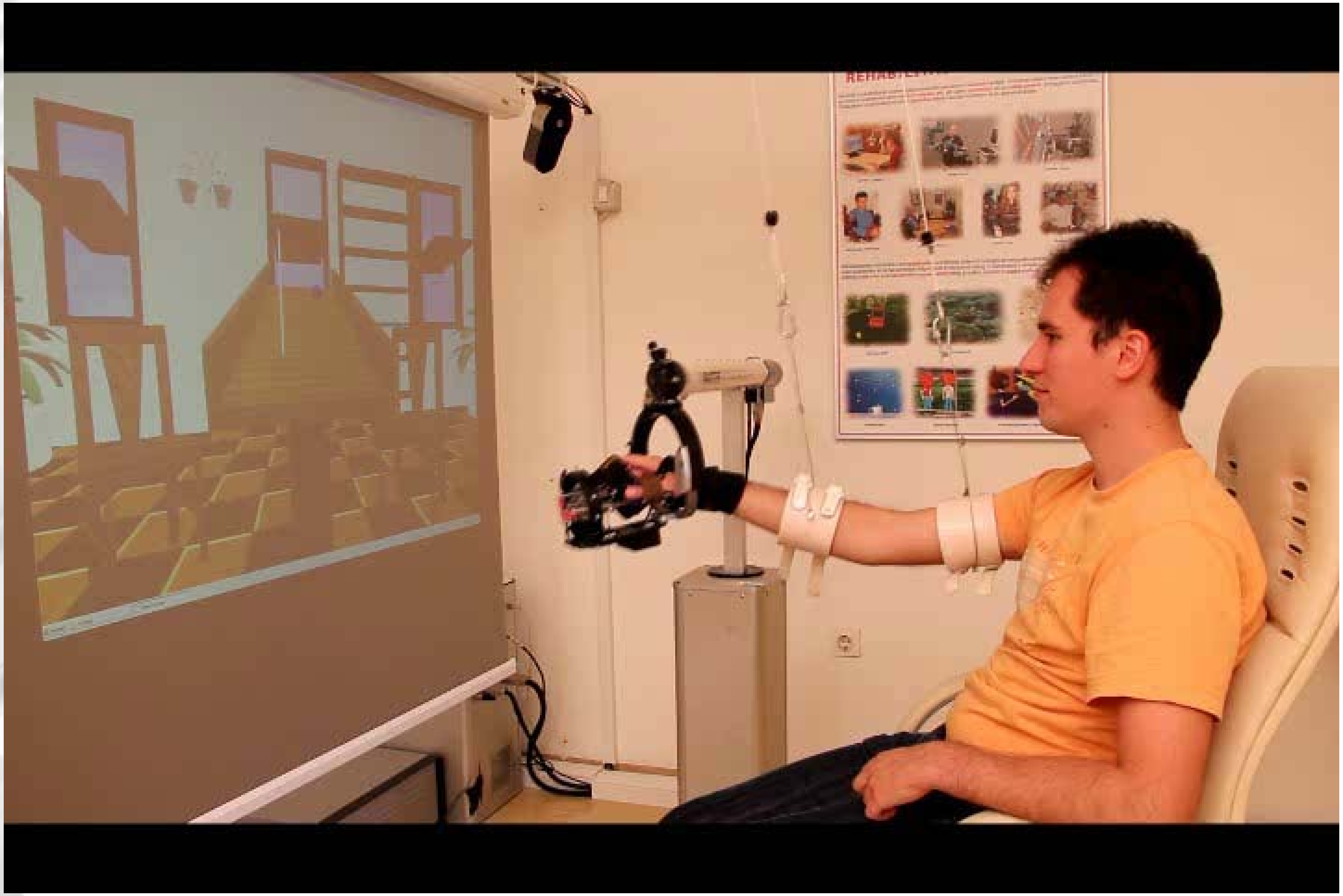
Analysis of effects of stroke

- task suitable for rehabilitation
- physical control task (left-right movement)
- cognitive control task (Stroop task)

- 23 stroke patients
- 23 controls

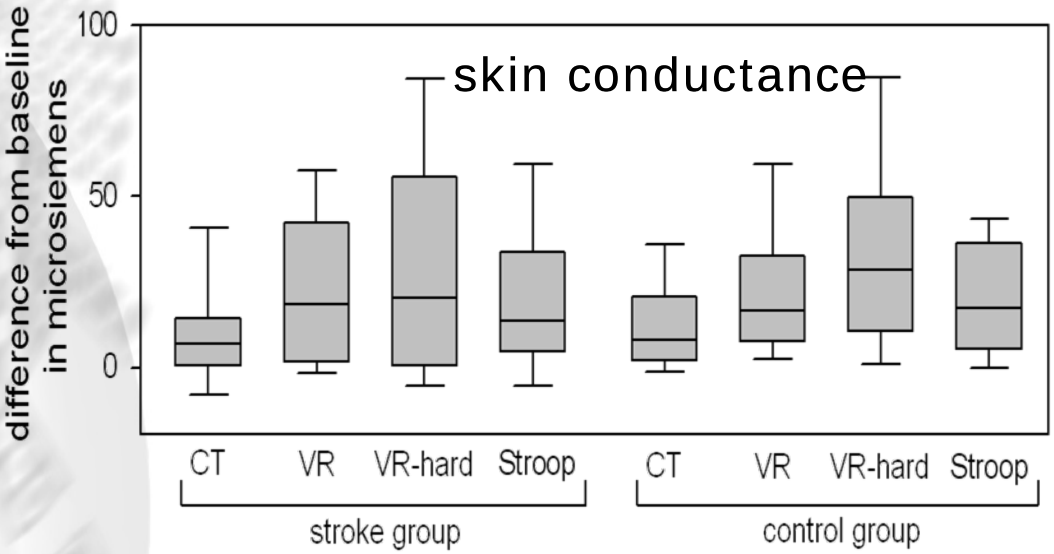
RED
BLUE
GREEN

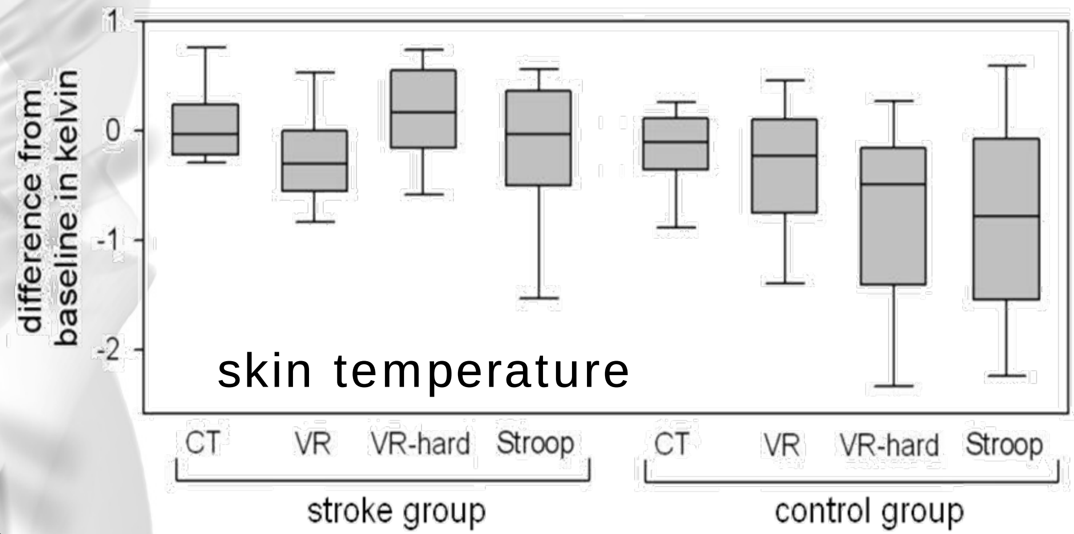
Rehabilitation task



2 difficulty levels!

Results





Skin conductance:
- few differences between controls and patients
- large differences between tasks
- well-correlated with self-reported arousal

Skin temperature, heart rate:
- responses much more evident in controls

Respiration:
- no useful information

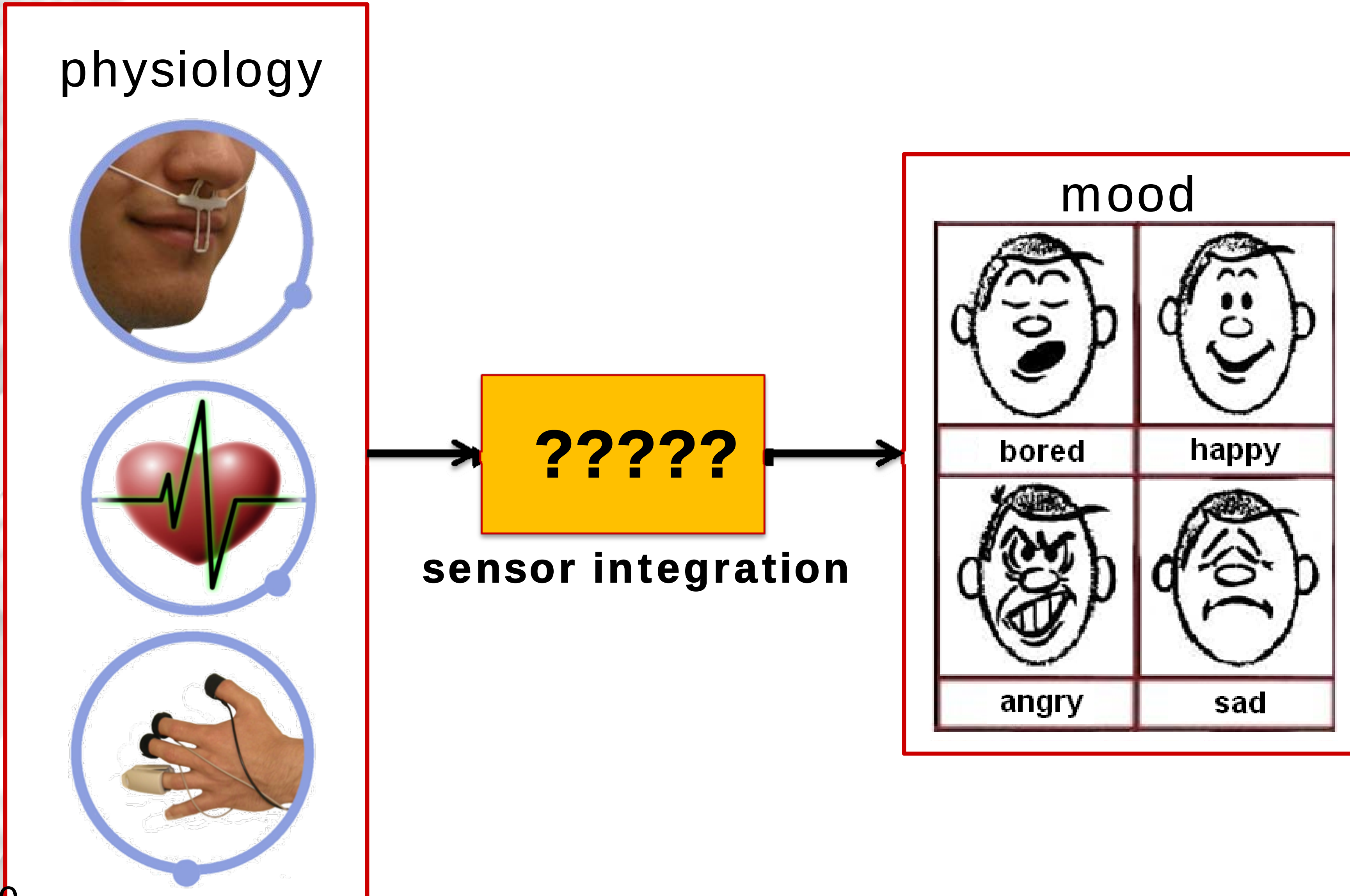
Conclusions – statistical analysis

- respiration and skin temperature less affected by physical activity, but more by stroke
- skin conductance less affected by stroke, but more by physical activity
- decision made to nonetheless proceed with sensor integration

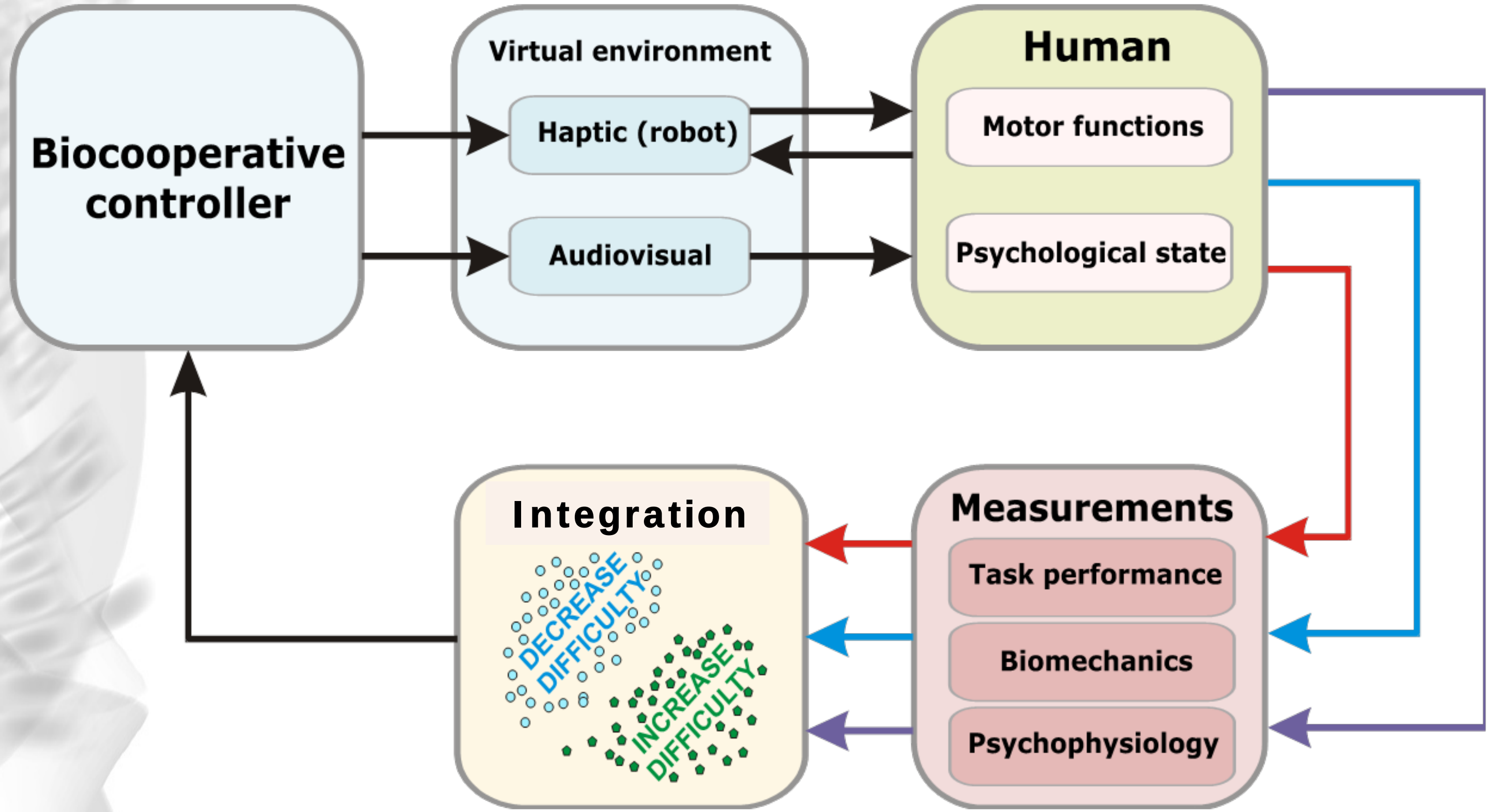
Dissertation structure

- Analysis of rehabilitation-specific factors
  - Effects of physical activity
  - Effects of stroke
- Sensor integration and biocooperative control
  - Controlled laboratory setting
  - Clinical rehabilitation task

Sensor integration



Biocooperative feedback loop

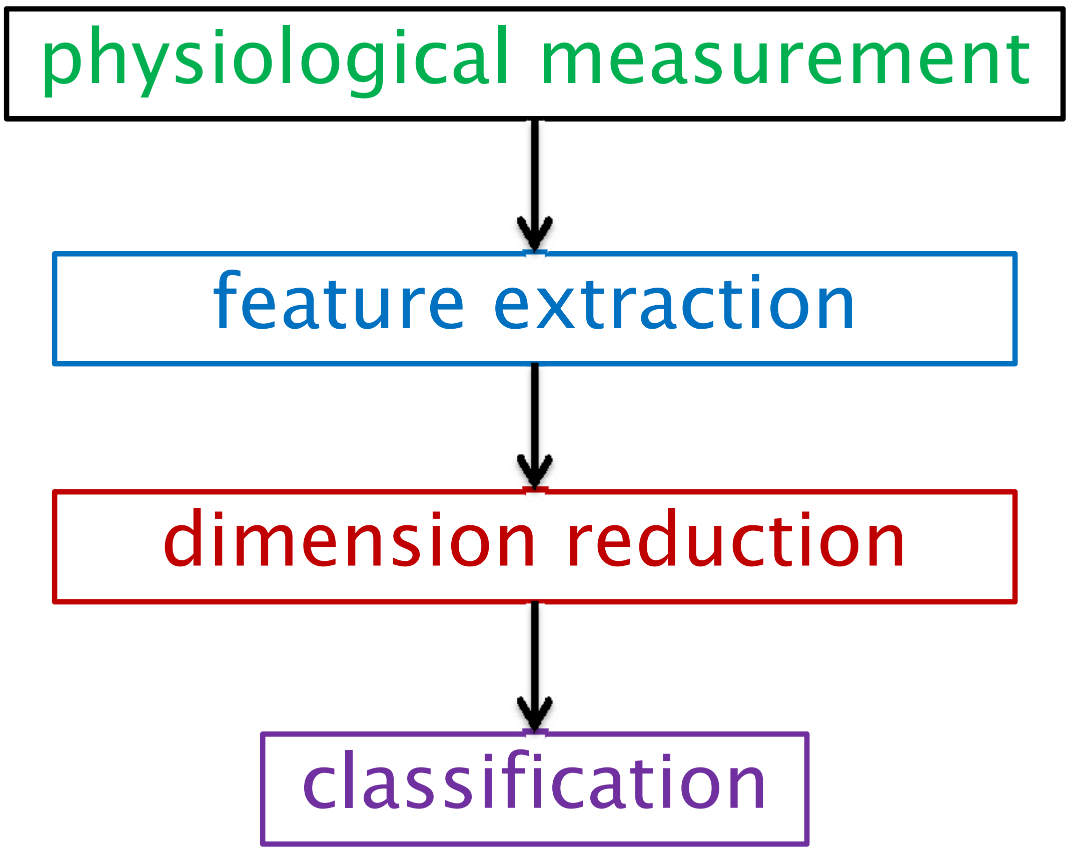


Our biocooperative feedback loop

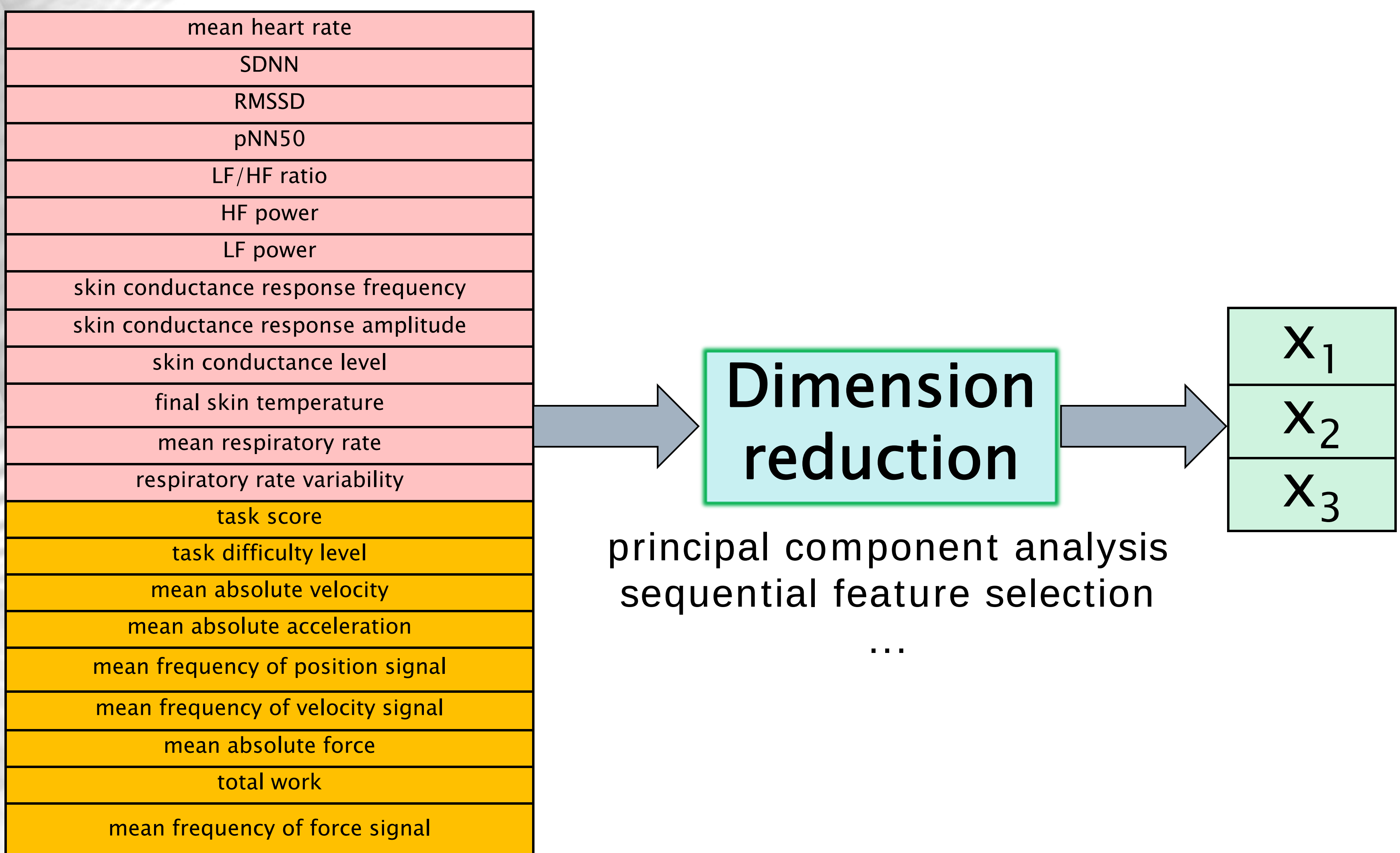
- state of the art in applied psychophysiology:
  - classify 2 or 3 levels of workload
  - predefined action for each possible level (e.g. increase difficulty)

- our implementation:
  - classify task as too easy or too hard
  - too easy → increase difficulty
  - too hard → decrease difficulty

Sensor integration

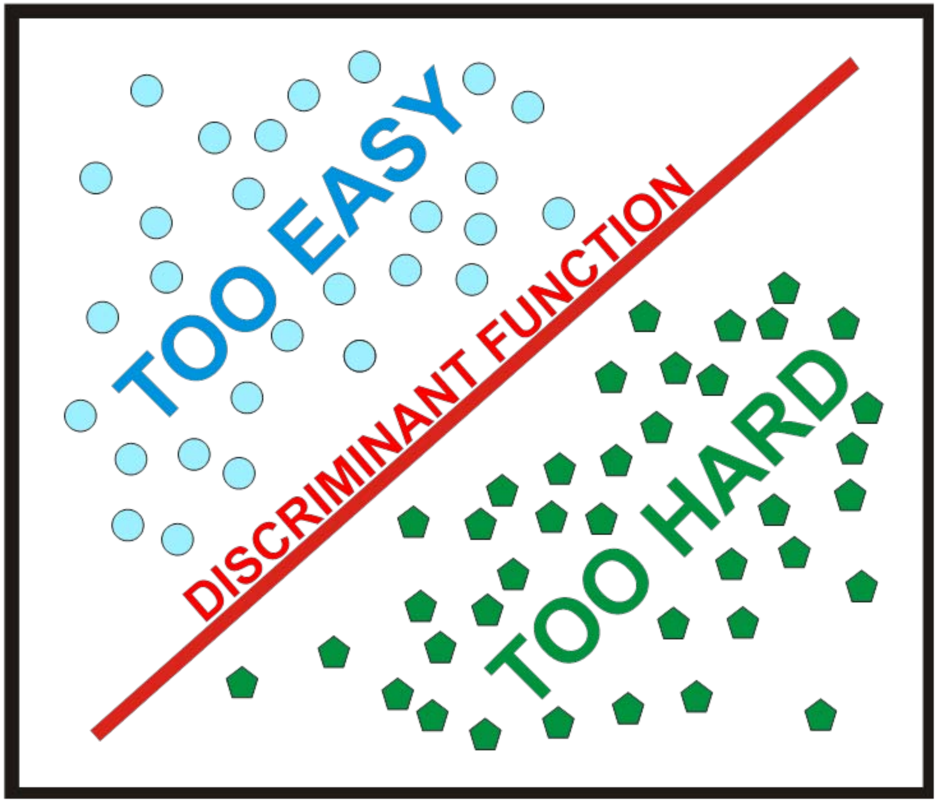


Dimension reduction



Classification

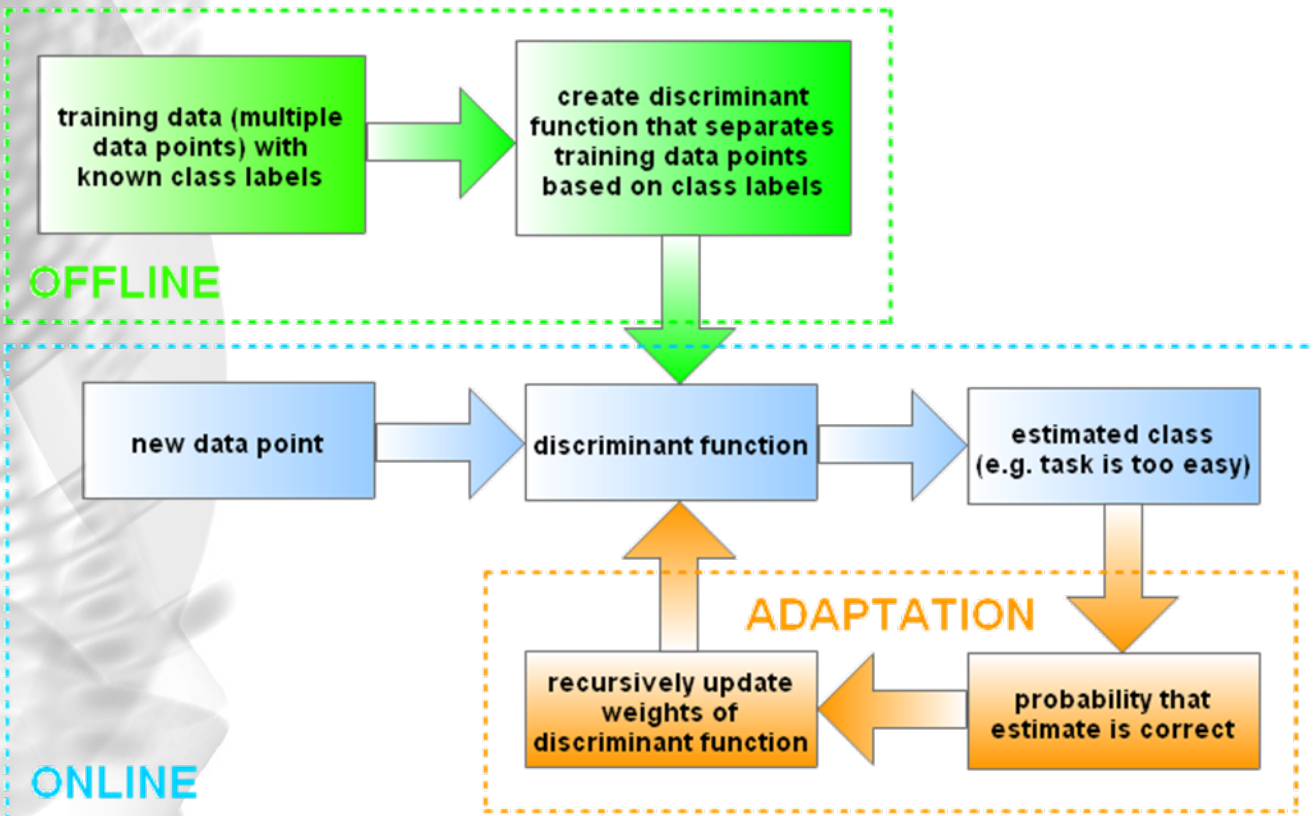
- statistics and machine learning
- methods:
  - discriminant analysis
  - naive Bayes
  - nearest-neighbors
  - support vector machine
  - classification tree



Adaptive classification

- large <u>**intersubject differences**</u> in physiology
- <u>require an adaptive method</u> of sensor integration that adapts to the current user during the task
- <u>does not yet exist in psychophysiology!</u>

Adaptive discriminant analysis



Linear discriminant analysis

$$D(\boldsymbol{x}) = b + \boldsymbol{w}^{\mathrm{T}} \cdot \boldsymbol{x}$$

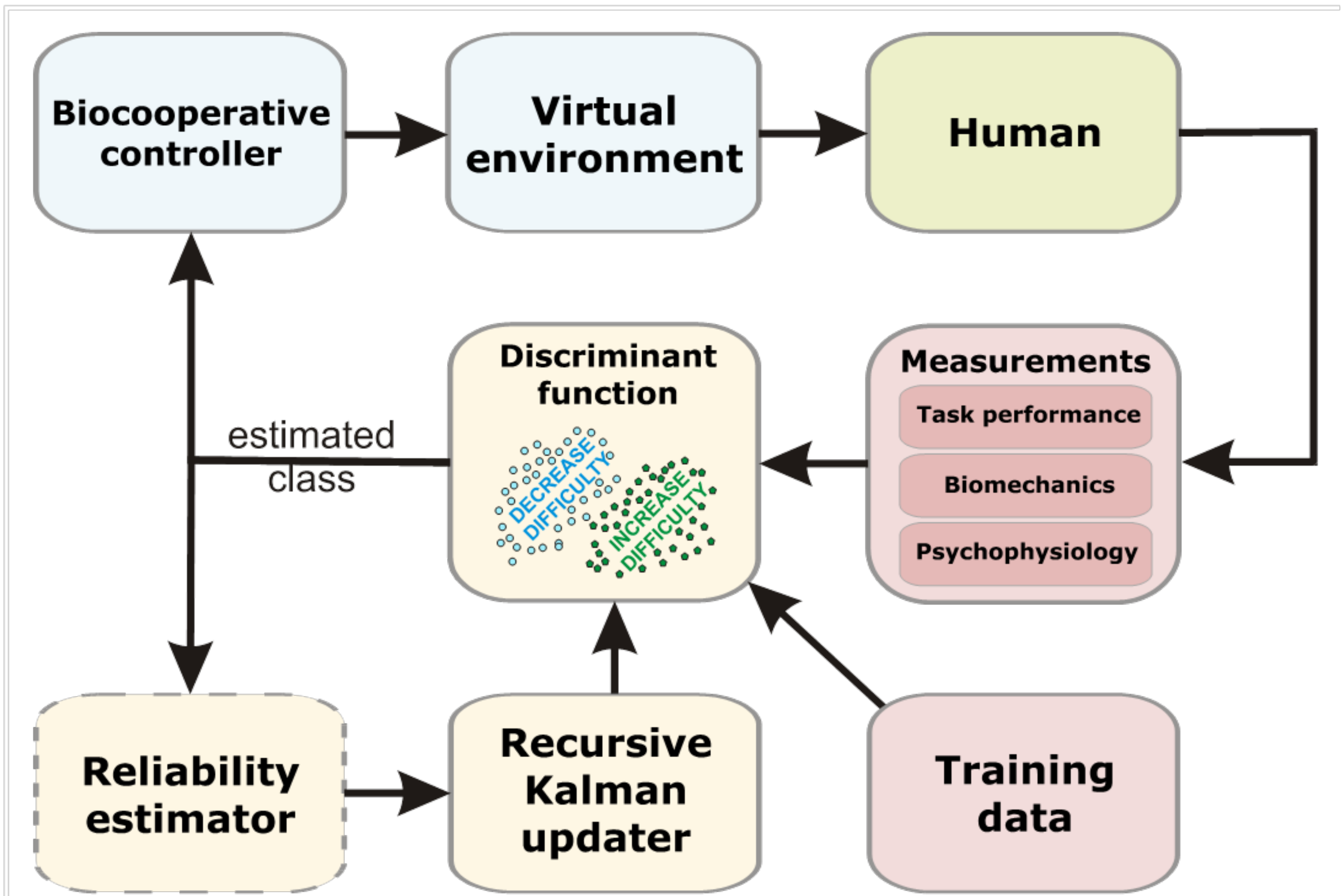
$$b = -\boldsymbol{w}^{\mathrm{T}} \cdot \frac{1}{2} \cdot (\boldsymbol{\mu}_1 + \boldsymbol{\mu}_2)$$

$$\boldsymbol{w} = (\Sigma_1 + \Sigma_2)^{-1} \cdot (\boldsymbol{\mu}_2 - \boldsymbol{\mu}_1)$$

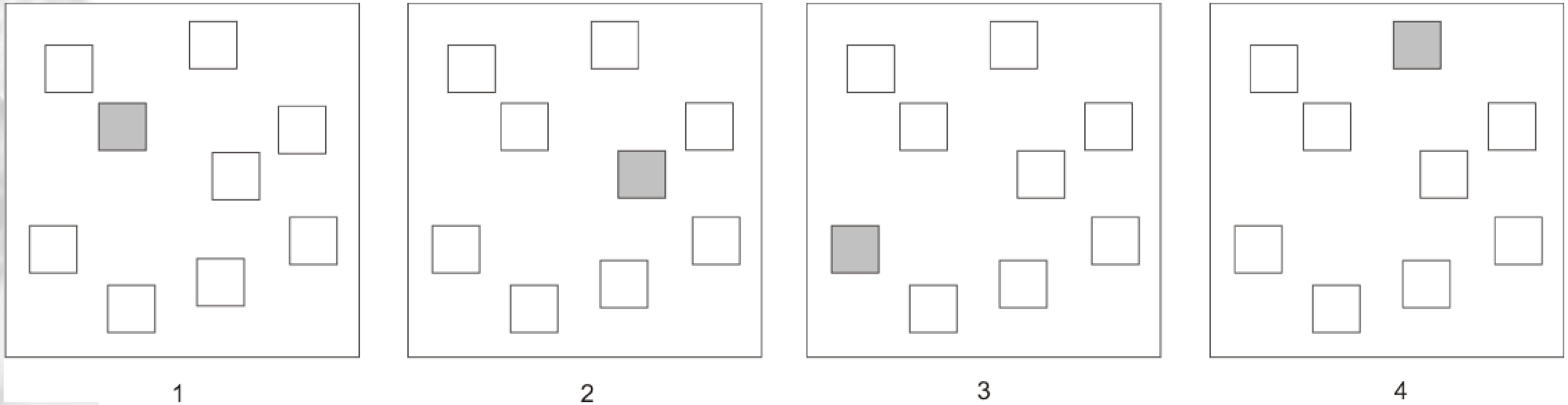
Kalman adaptive Linear discriminant analysis

$$\begin{aligned}
\boldsymbol{H}_k &= [1, \boldsymbol{x}_k^{\mathrm{T}}] \\
e_k &= y_k - \boldsymbol{H}_k \cdot \widehat{\boldsymbol{w}}_{k-1} \\
v_k &= 1 - UC \\
Q_k &= \boldsymbol{H}_k \cdot \boldsymbol{A}_{k-1} \cdot \boldsymbol{H}_k^{\mathrm{T}} + v_k \\
\boldsymbol{k}_k &= \frac{\boldsymbol{A}_{k-1} \cdot \boldsymbol{H}_k^{\mathrm{T}}}{Q_k} \\
\widehat{\boldsymbol{w}}_k &= \widehat{\boldsymbol{w}}_{k-1} + \boldsymbol{k}_k \cdot e_k \\
\widetilde{\boldsymbol{A}}_k &= \boldsymbol{A}_{k-1} - \boldsymbol{k}_k \cdot \boldsymbol{H}_k \cdot \boldsymbol{A}_{k-1} \\
\boldsymbol{A}_k &= \frac{\mathrm{trace}(\widetilde{\boldsymbol{A}}_k) \cdot UC}{p} + \widetilde{\boldsymbol{A}}_k
\end{aligned}$$

Adaptive biocooperative feedback

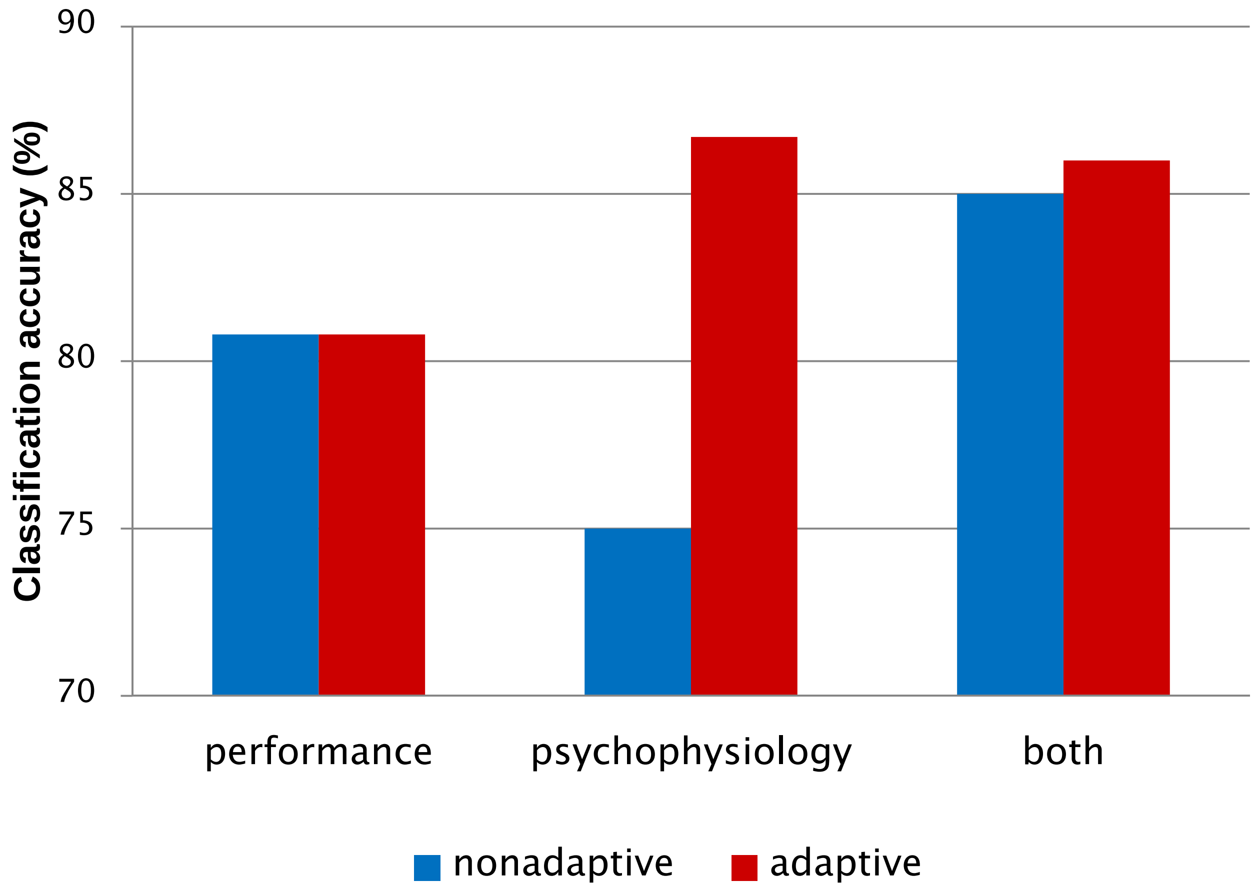


Implementation: laboratory task



- 8 difficulty levels
- 20 subjects
- each subject increases or decreases difficulty 6 times
- measurements: task performance and psychophysiology

Results of classification



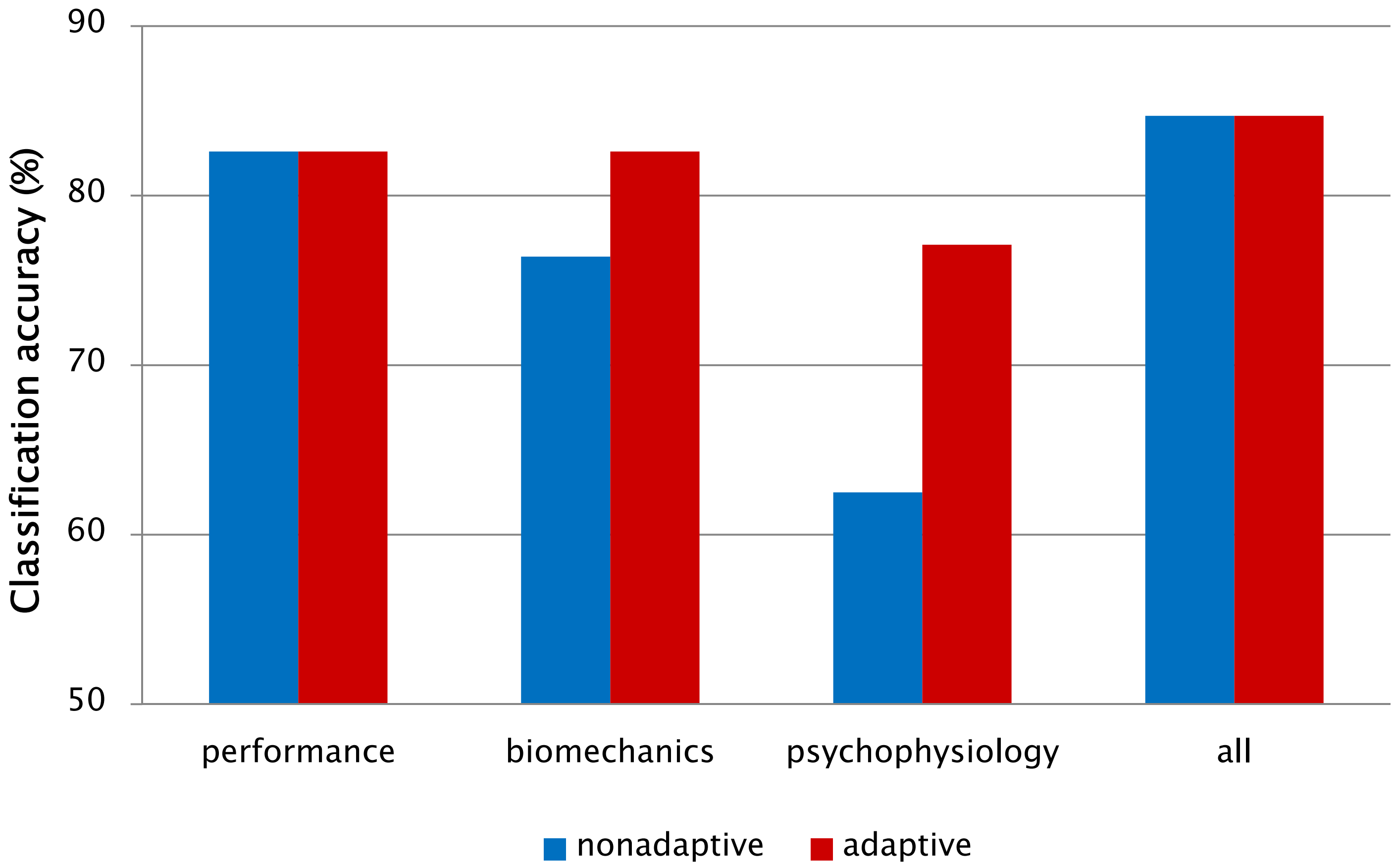
(leave-one-subject-out crossvalidation)

Implementation: rehabilitation task

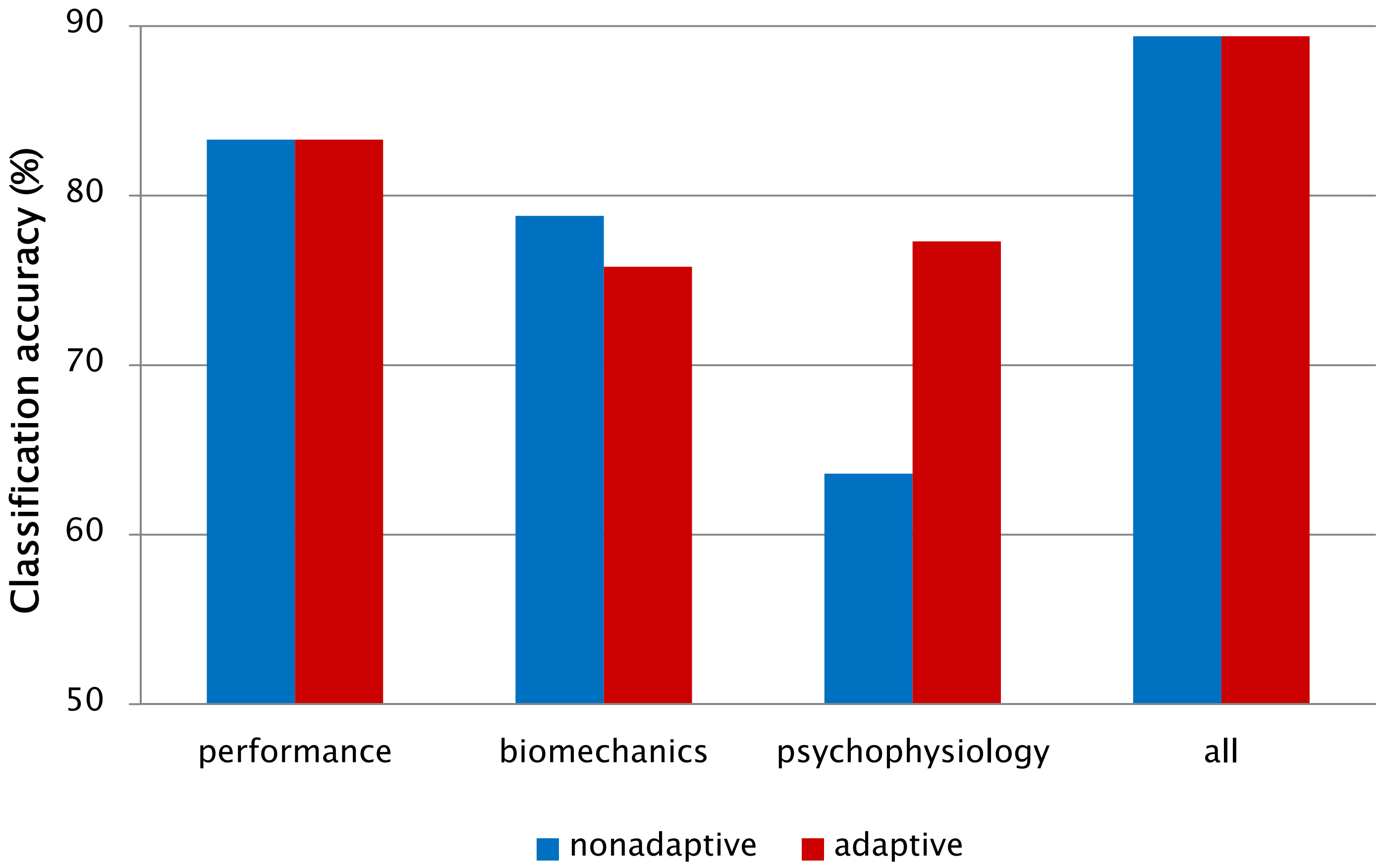
- ball–catching task as used previously
- 7 difficulty levels
- each subject changes difficulty 6 times

- two phases:
  - open–loop
    - 24 controls
    - 11 patients
  - closed–loop
    - 10 controls
    - 6 patients

Open–loop results: controls



Open-loop results: patients



Closed-loop validation

- nonadaptive linear discriminant analysis with performance and psychophysiology
- tested online in a fully closed loop

- controls: accuracy of **88.3%**
- patients: accuracy of **88.9%**

Conclusions of sensor integration

- online closed loop successfully implemented
- psychophysiological measurements not ideal as a primary source of information
- adaptive method can improve accuracy

- can provide supplementary information
- useful when task performance measures not available (many rehabilitation tasks)
- potentially very useful for other HCI fields

Original scientific contributions

- Analysis of healthy subjects' psychophysiological responses to a combination of psychological and physical activity in haptic human-robot interaction
- Analysis of psychophysiological differences between healthy subjects and hemiparetic patients in clinical rehabilitation scenarios
- Psychophysiological sensor fusion for task suitability assessment in rehabilitation robotics using different methods
- An adaptive method that can adapt to intersubject differences in psychophysiological responses
- A biocooperative controller that can adapt the parameters of a rehabilitation task based on adaptive fusion of psychophysiological, biomechanical and other sensors

Acknowledgments

The MIMICS team

- Matjaž Mihelj (almighty advisor)
- Jaka Ziherl (VR, haptics)
- Andrej Olenšek (VR)
- Maja Milavec (psychologist)
- Nika Goljar (URI–Soča)
- Metka Javh (URI–Soča)
- Marko Munih (almightier boss)

and all the rest...

Thank you for your attention!

"Science is like sex; it may give some practical results, but that's not why we do it."