The Next Generation of Brain-Computer Interfaces: Responding Implicitly to Users' Cognitive State

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CHANGE THE WORLD FROM HERE

The way we interact with computers hasn't changed very much.

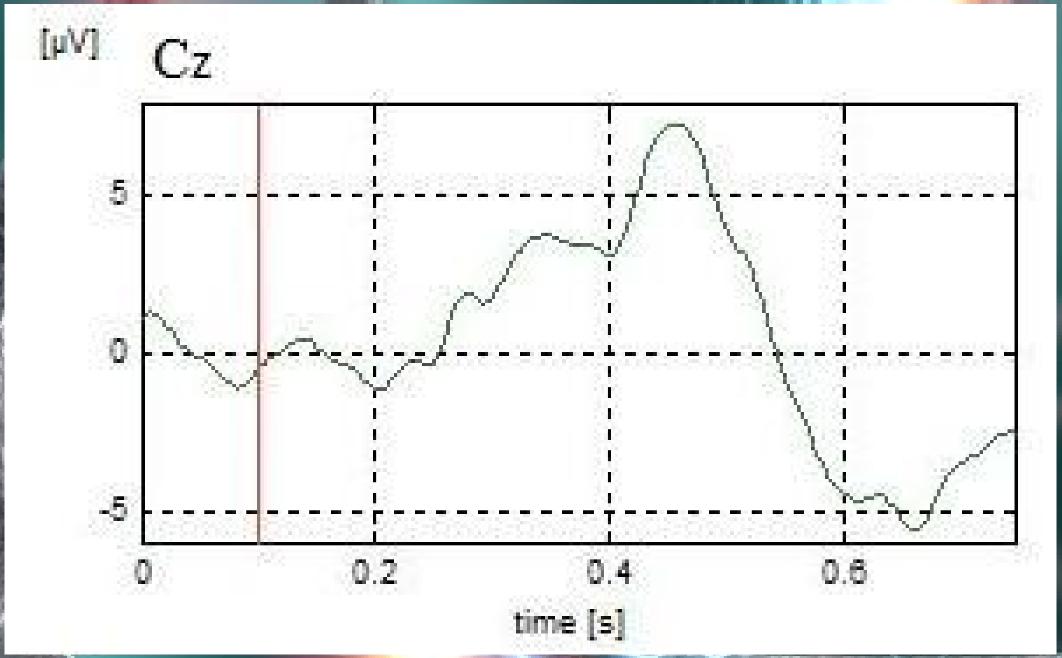

foursquare
Chegg


ROY
MARGIN RELEASE
2 3 4 5 6
Q W E R T
A S D F G H J K L
SHIFT KEY
Z X C V B N M
SHIFT KEY

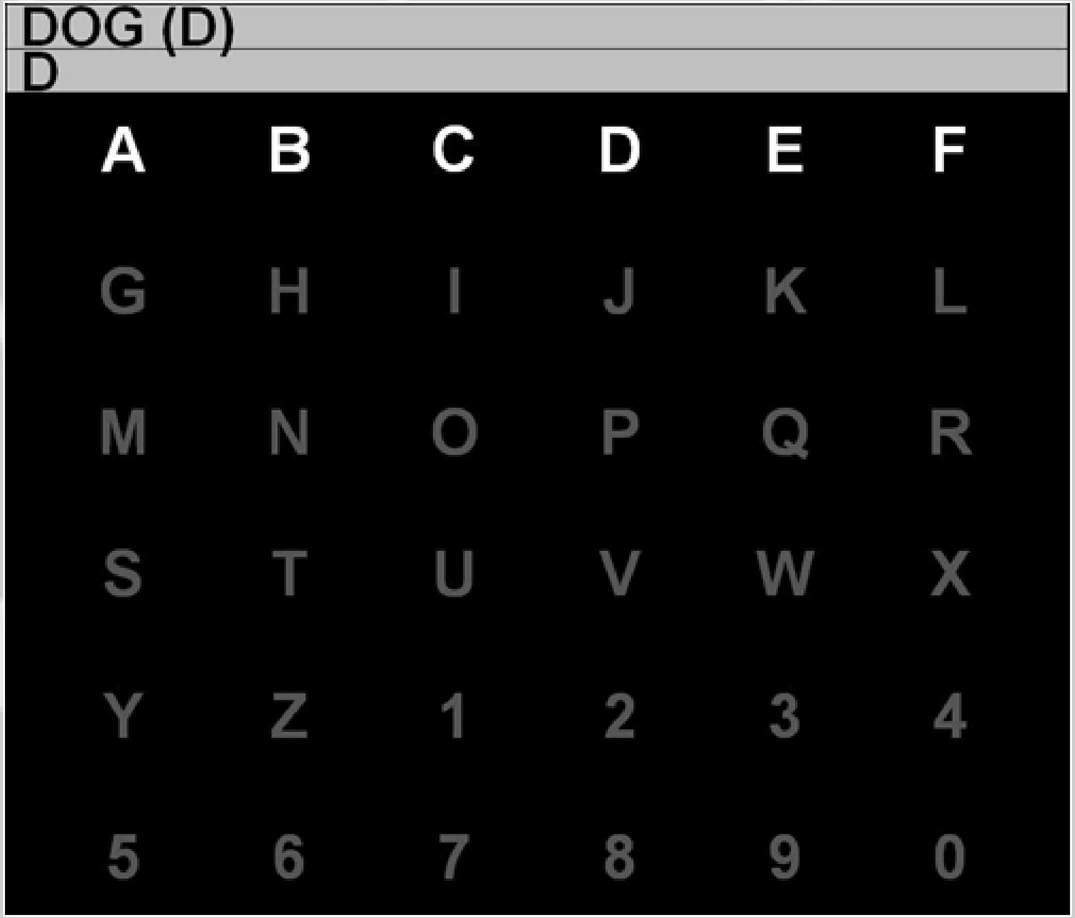
VISION


I'M GOING ON AN ADVENTURE!

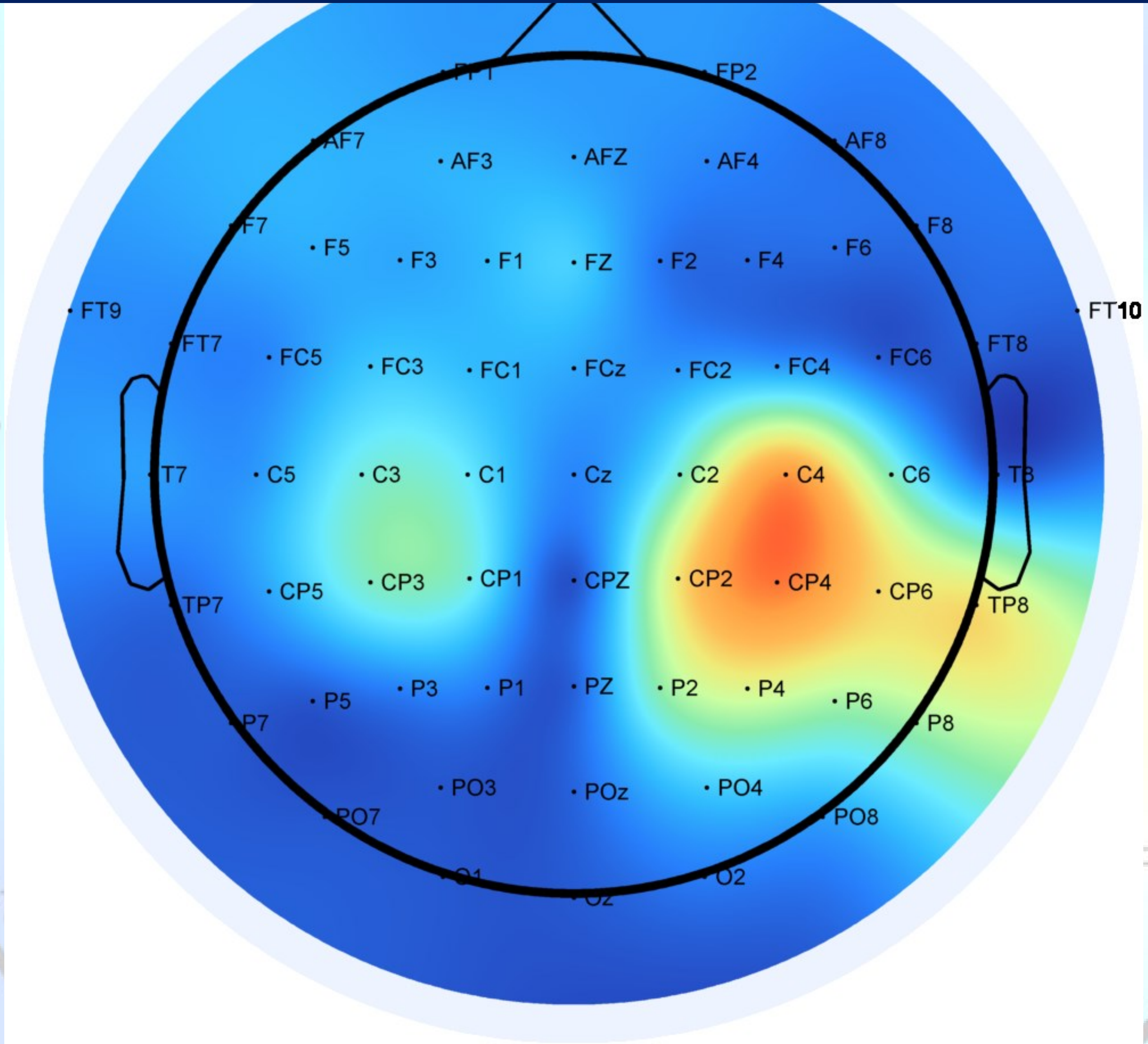
Traditional Brain-Computer Interfaces: P300 Signal



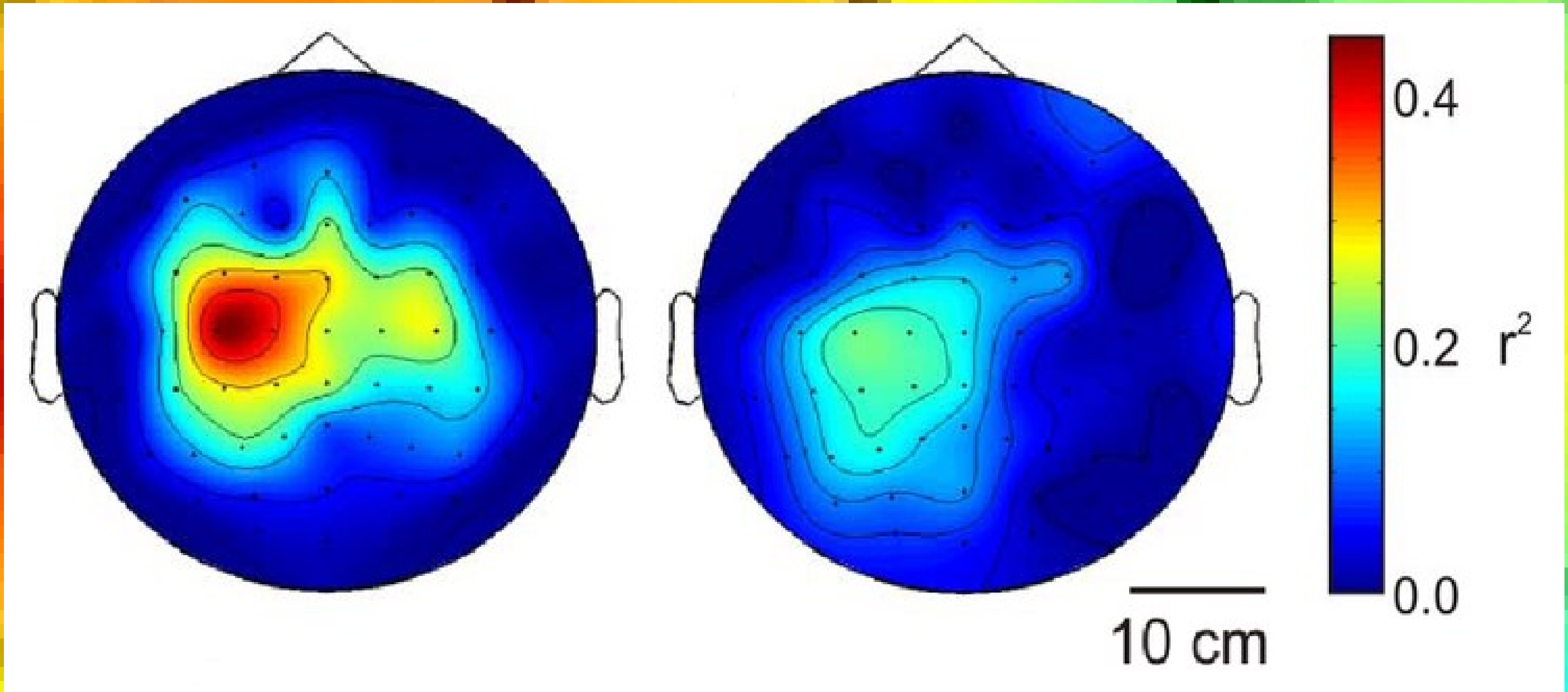
Traditional Brain-Computer Interfaces: P300 Signal



Traditional Brain-Computer Interfaces: Motor Imagery

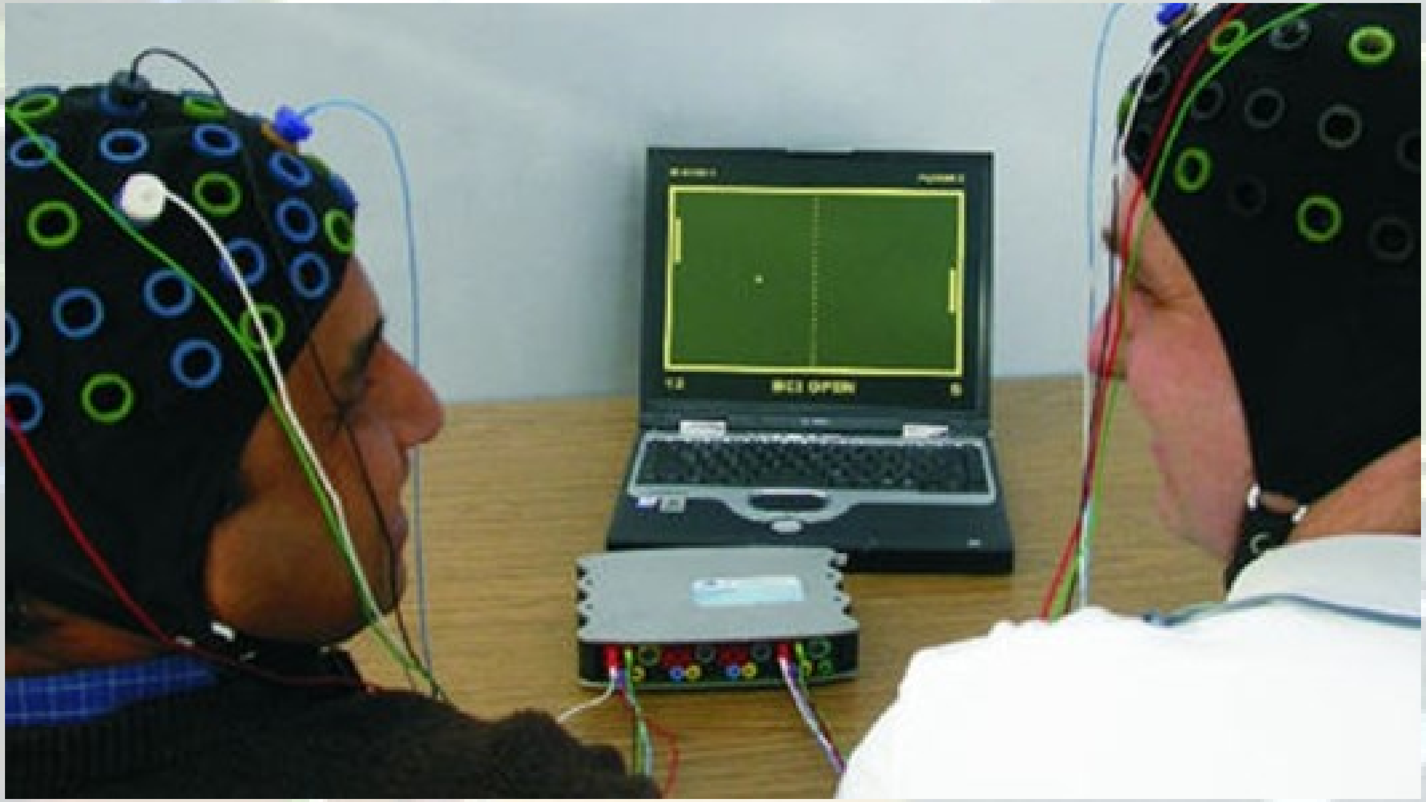


Traditional Brain-Computer Interfaces: Motor Imagery



Schalk et al. 2004

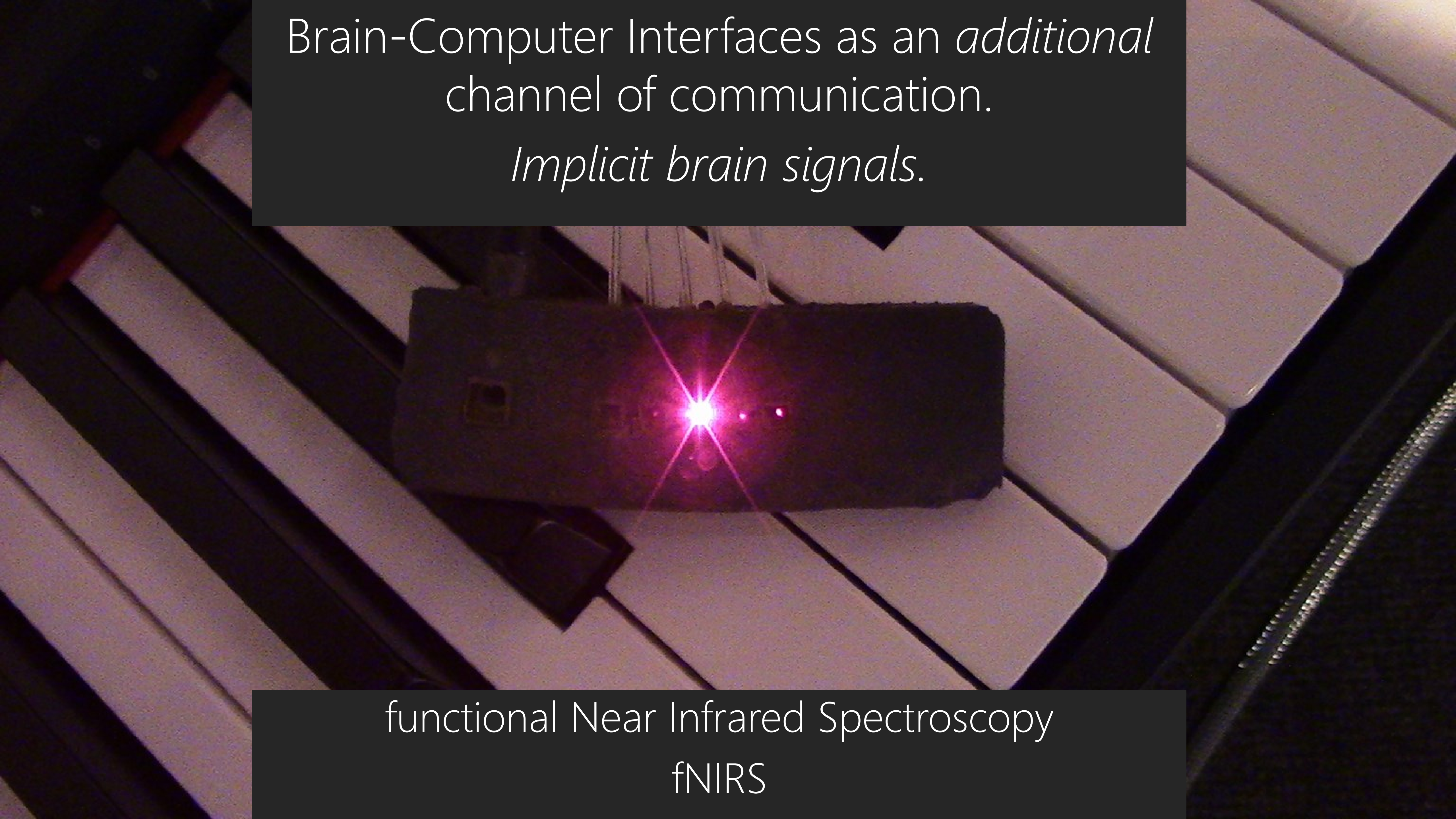
Traditional Brain-Computer Interfaces: Motor Imagery



Traditional Brain-Computer Interfaces

Designed for severely disabled people.

Too slow and too inaccurate for the general population.


Brain-Computer Interfaces as an *additional* channel of communication.
Implicit brain signals.
functional Near Infrared Spectroscopy
fNIRS

Why brain-computer interfaces?

An *additional* channel of information.

An objective measure into the user's cognitive state.

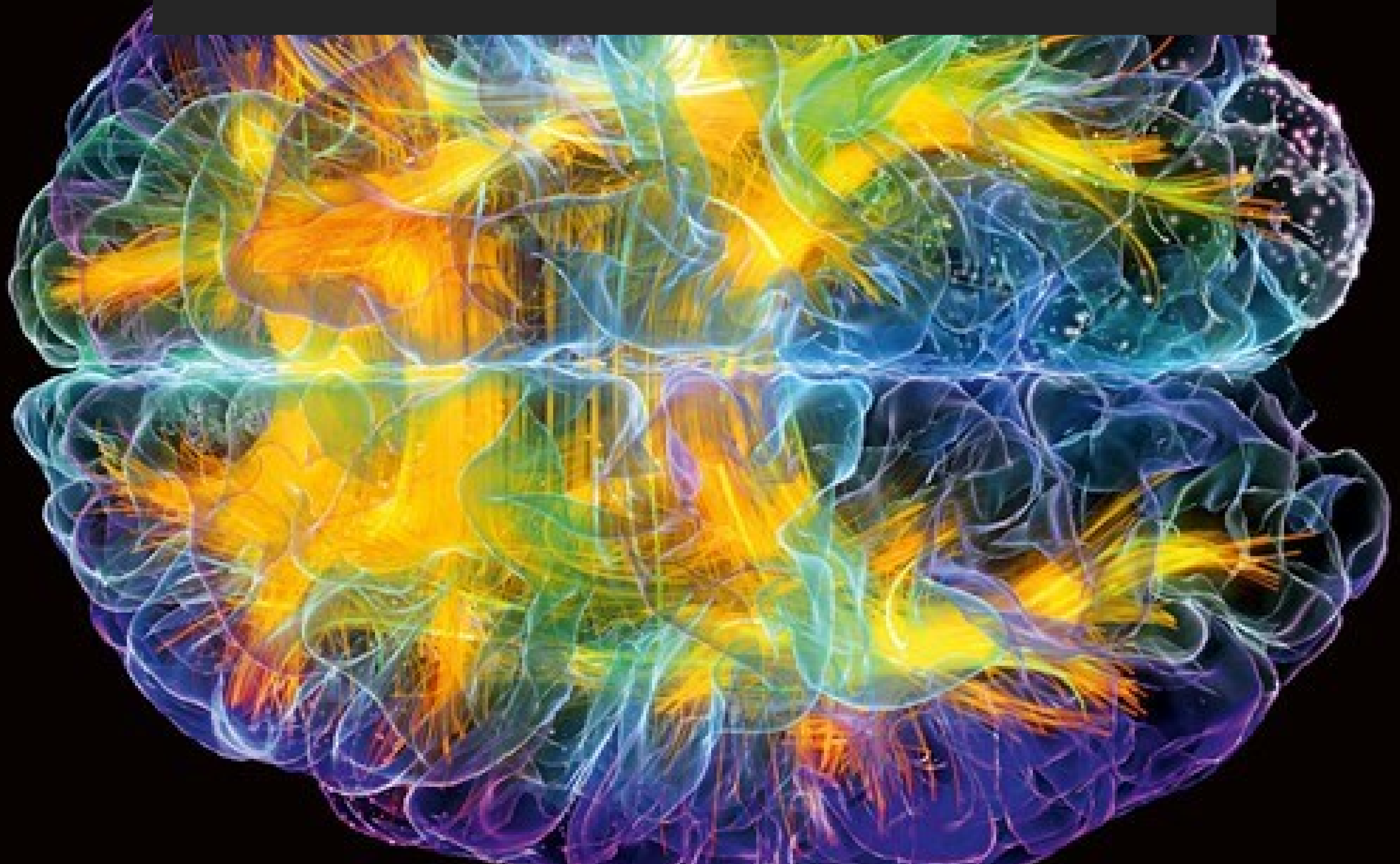
A continuous flow of information in real-time.
(Questionnaires are discrete points in time and prone to bias).

Carried out in the background – no additional effort from user.

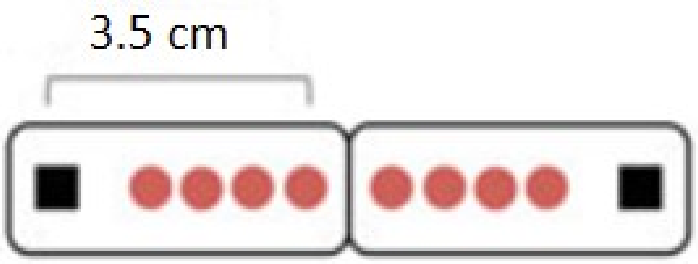
fNIRS System

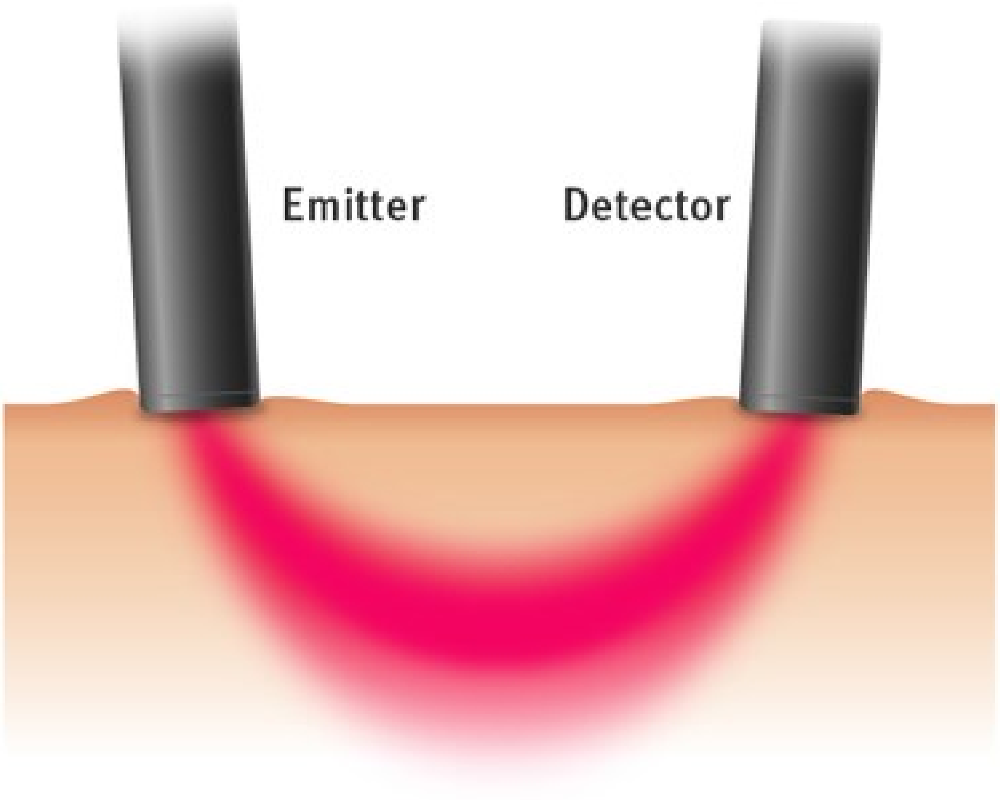
The System

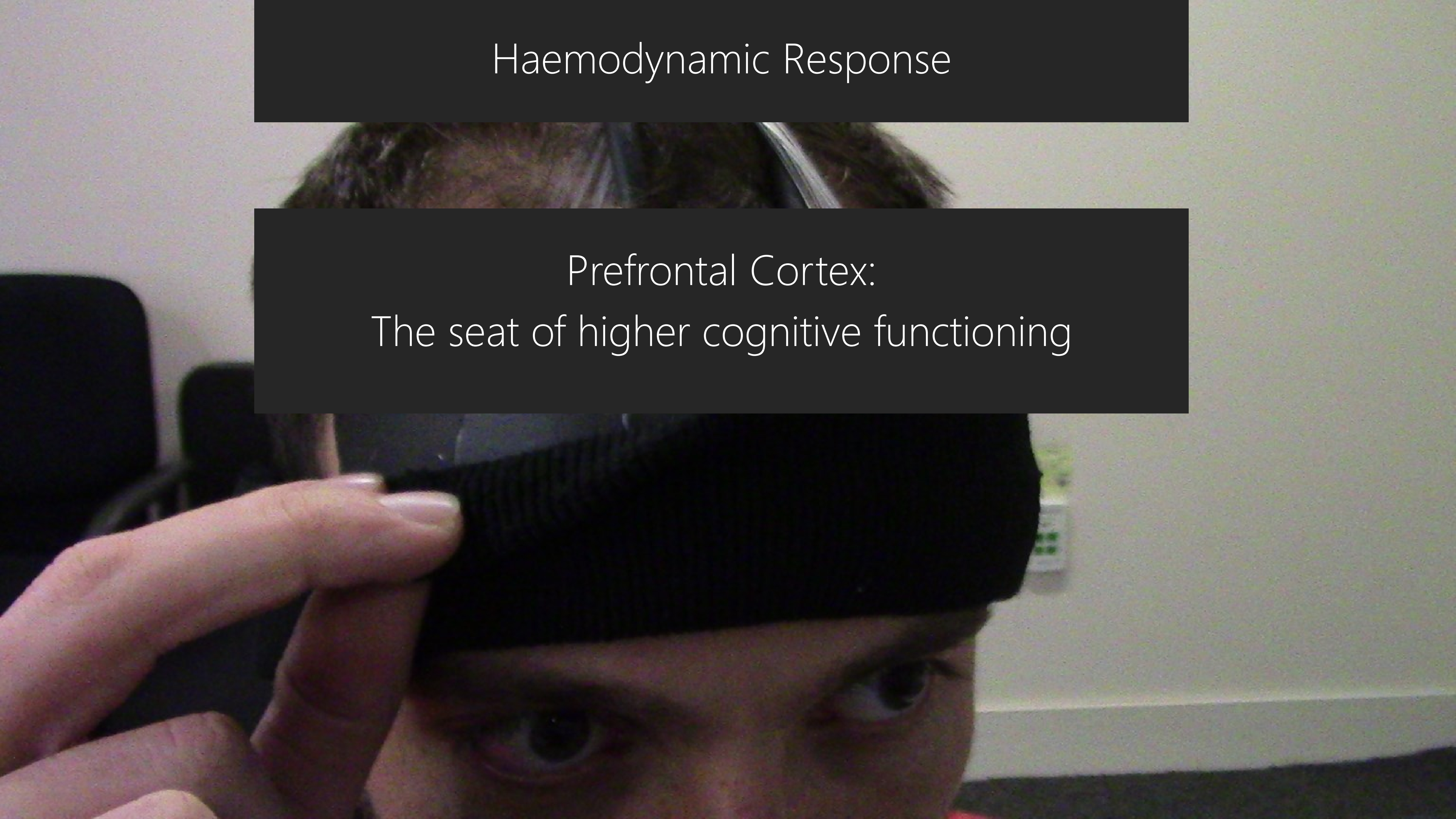
Haemodynamic Response

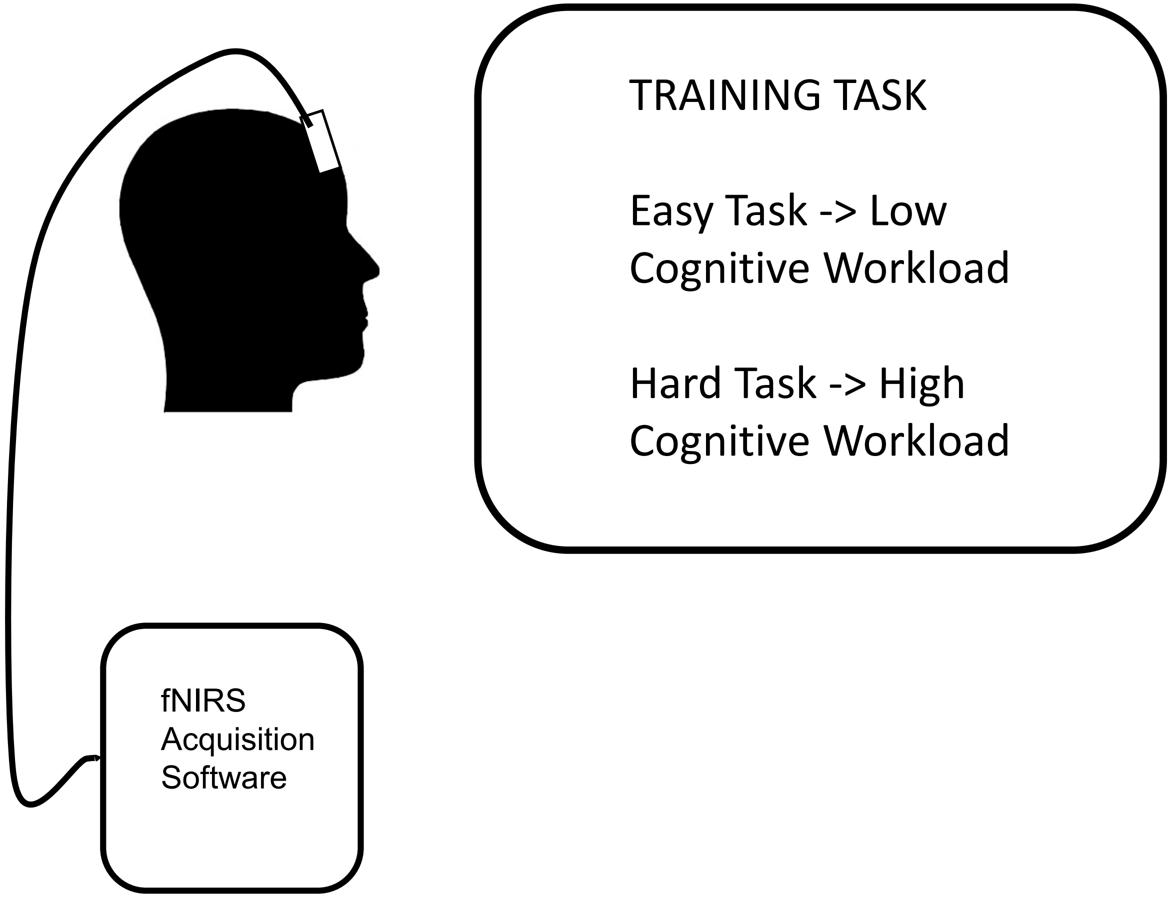


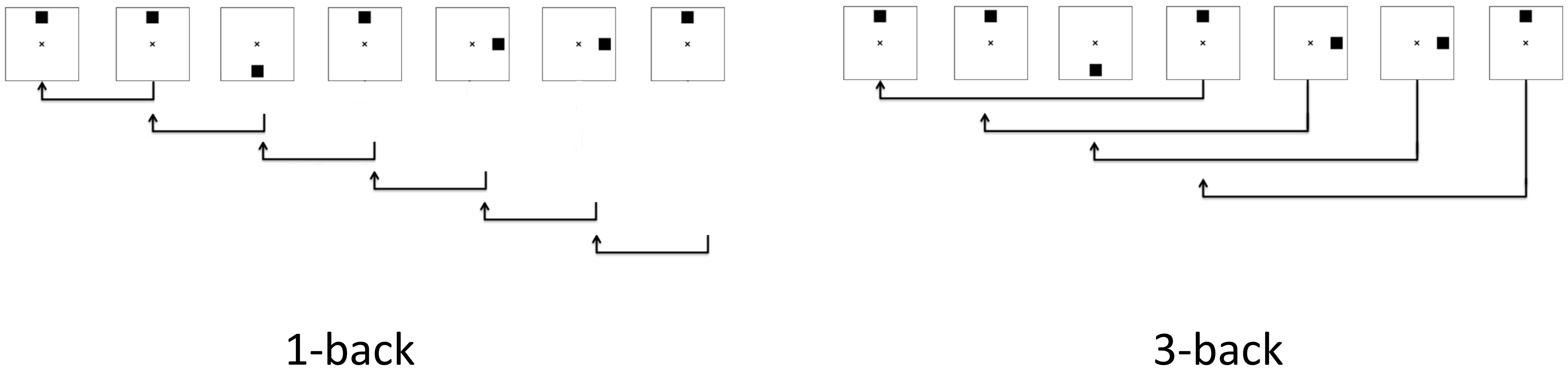
functional Near Infrared Spectroscopy
fNIRS



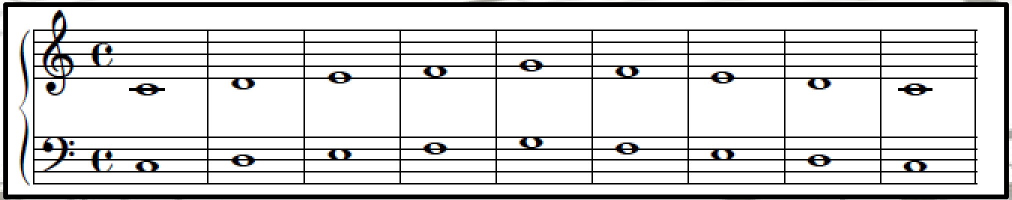



Haemodynamic Response
Prefrontal Cortex:
The seat of higher cognitive functioning


TRAINING TASK
Easy Task -> Low Cognitive Workload
Hard Task -> High Cognitive Workload
fNIRS Acquisition Software


1-back
3-back

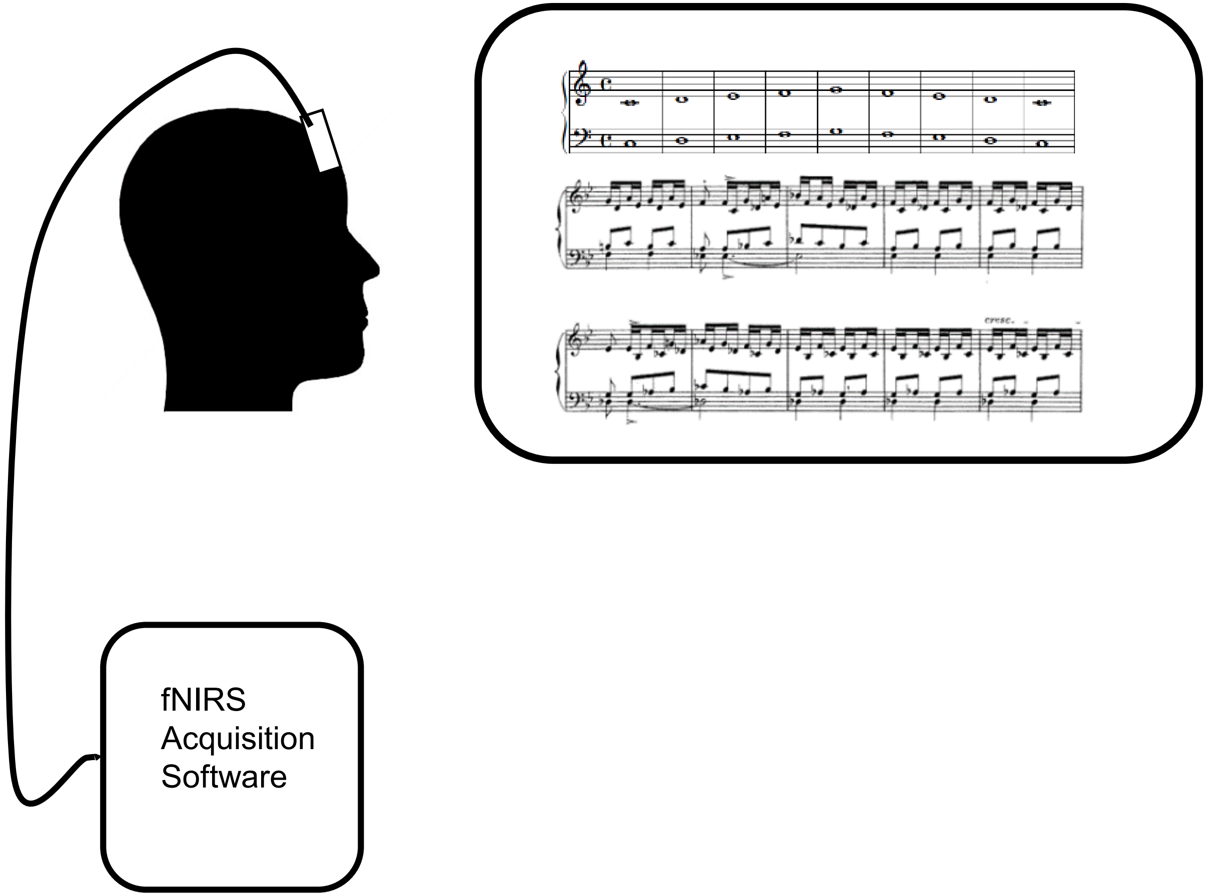
Training Task

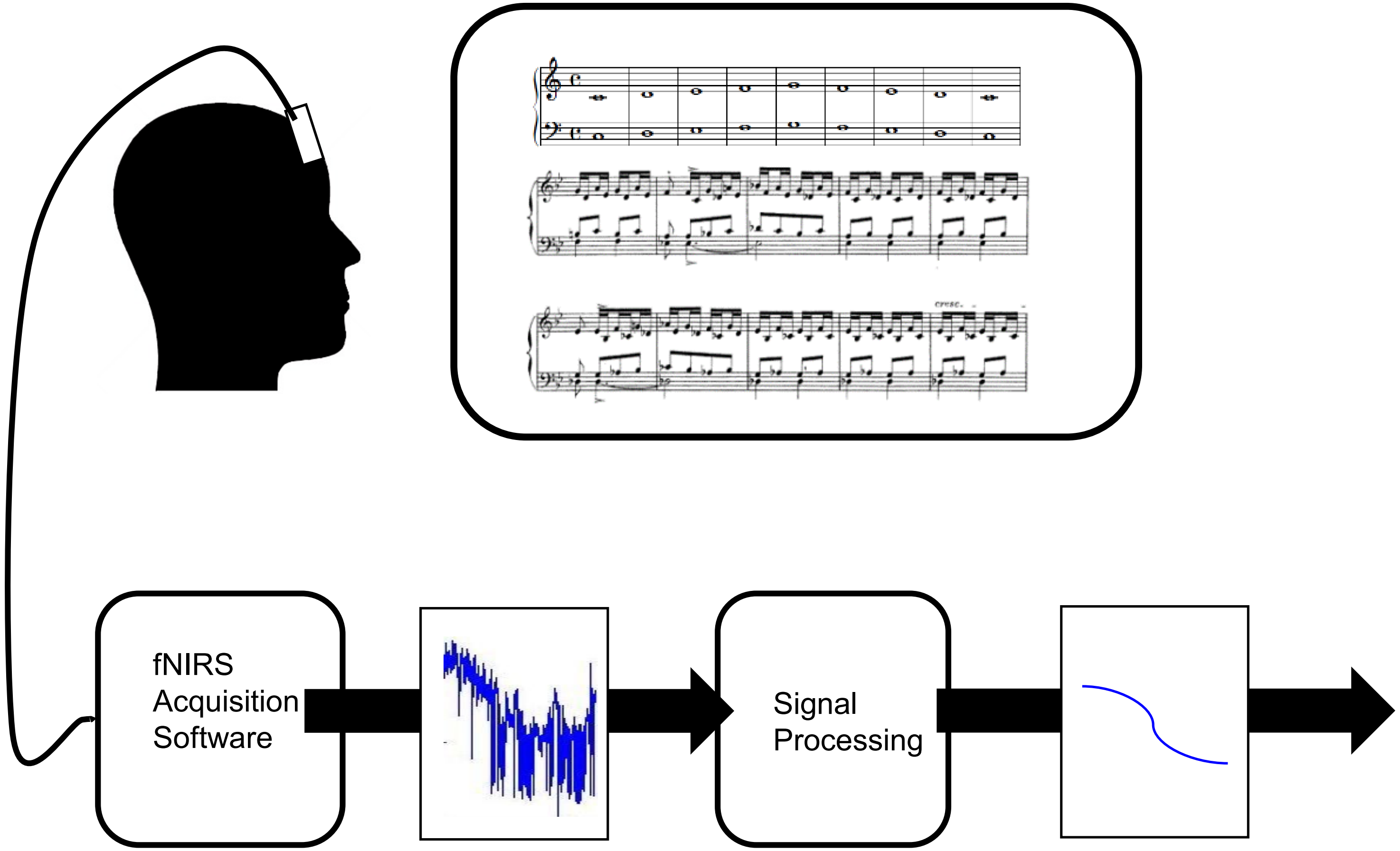


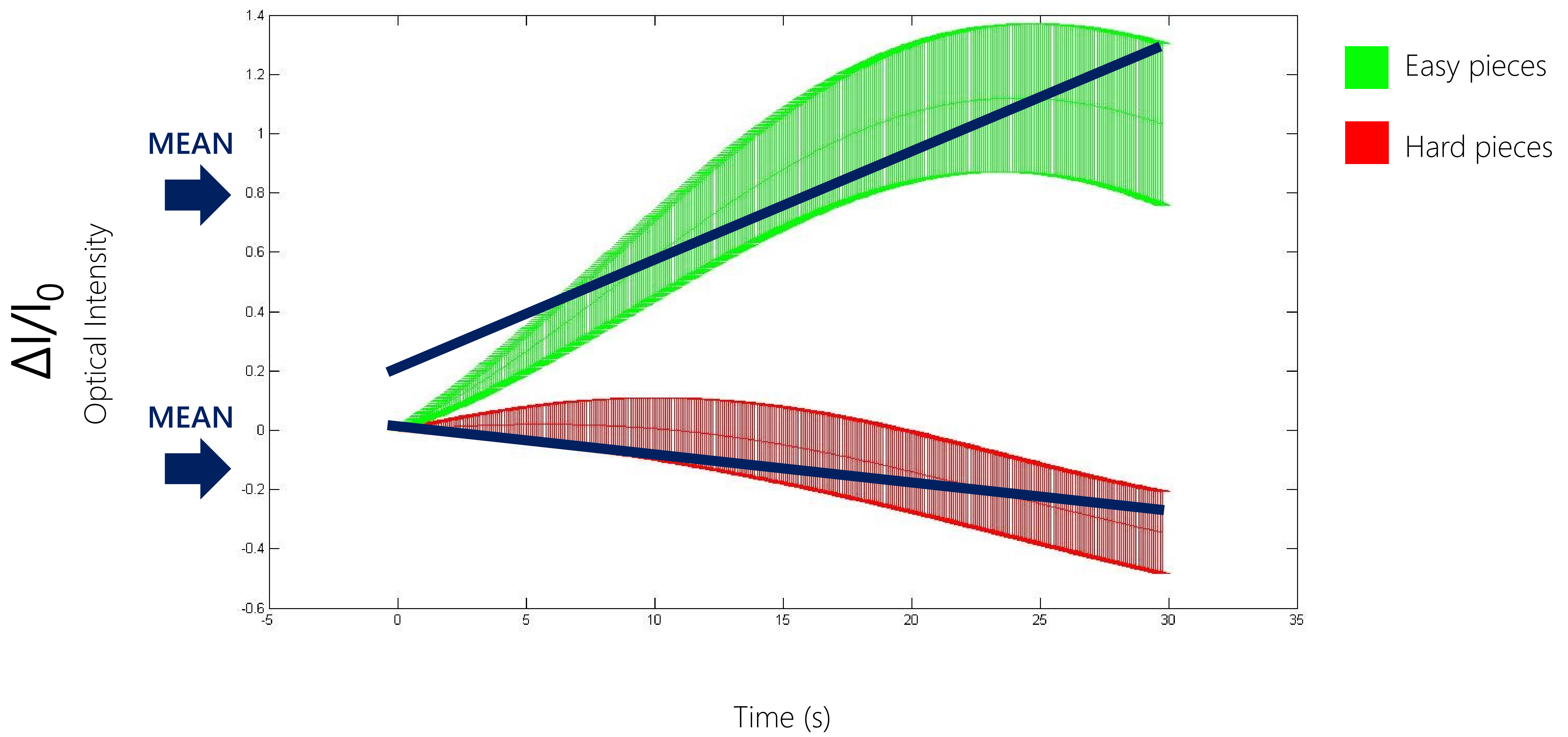
15 easy pieces

vs.

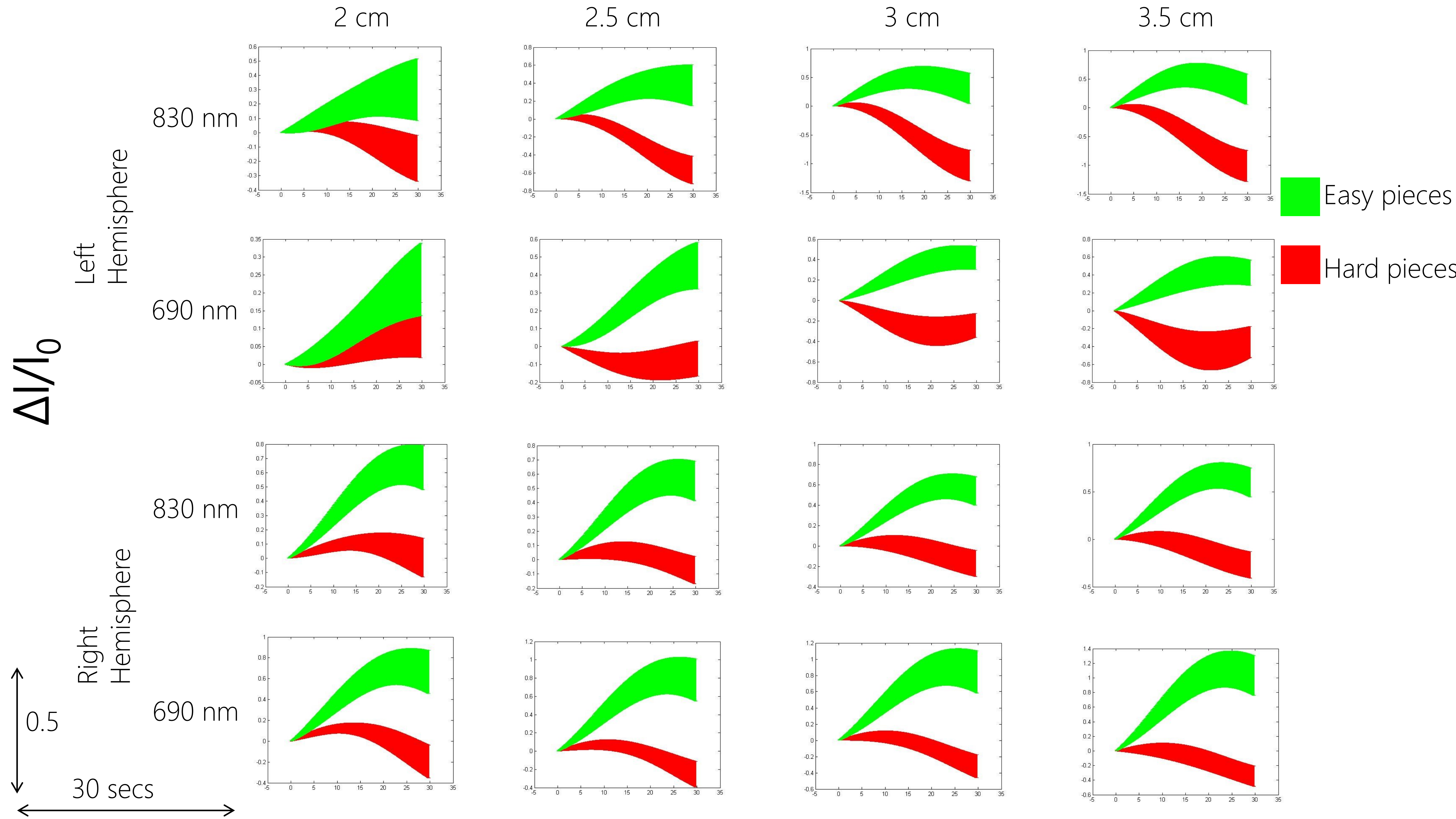
15 hard pieces


fNIRS
Acquisition
Software

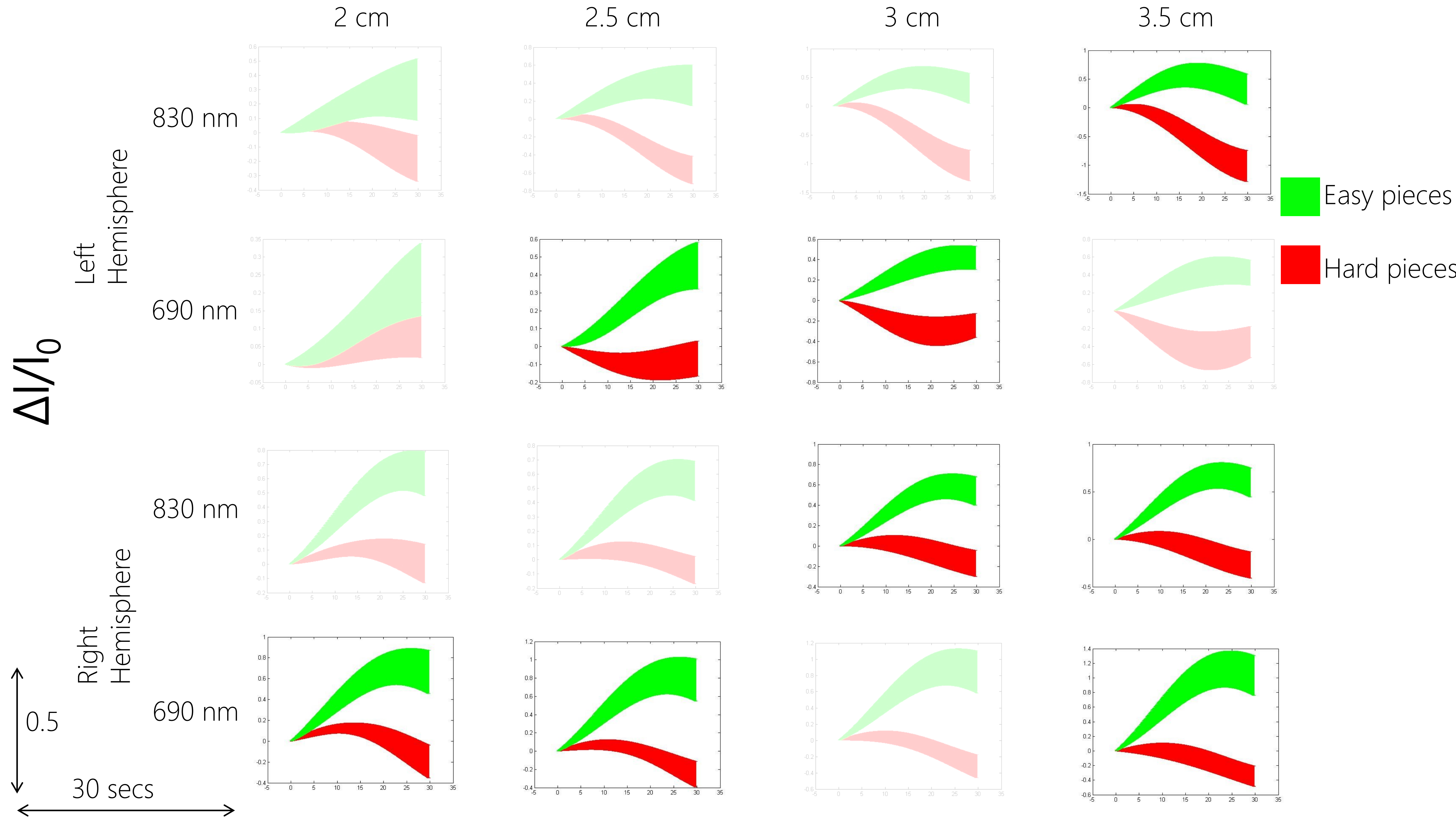

fNIRS
Acquisition
Software
Signal
Processing



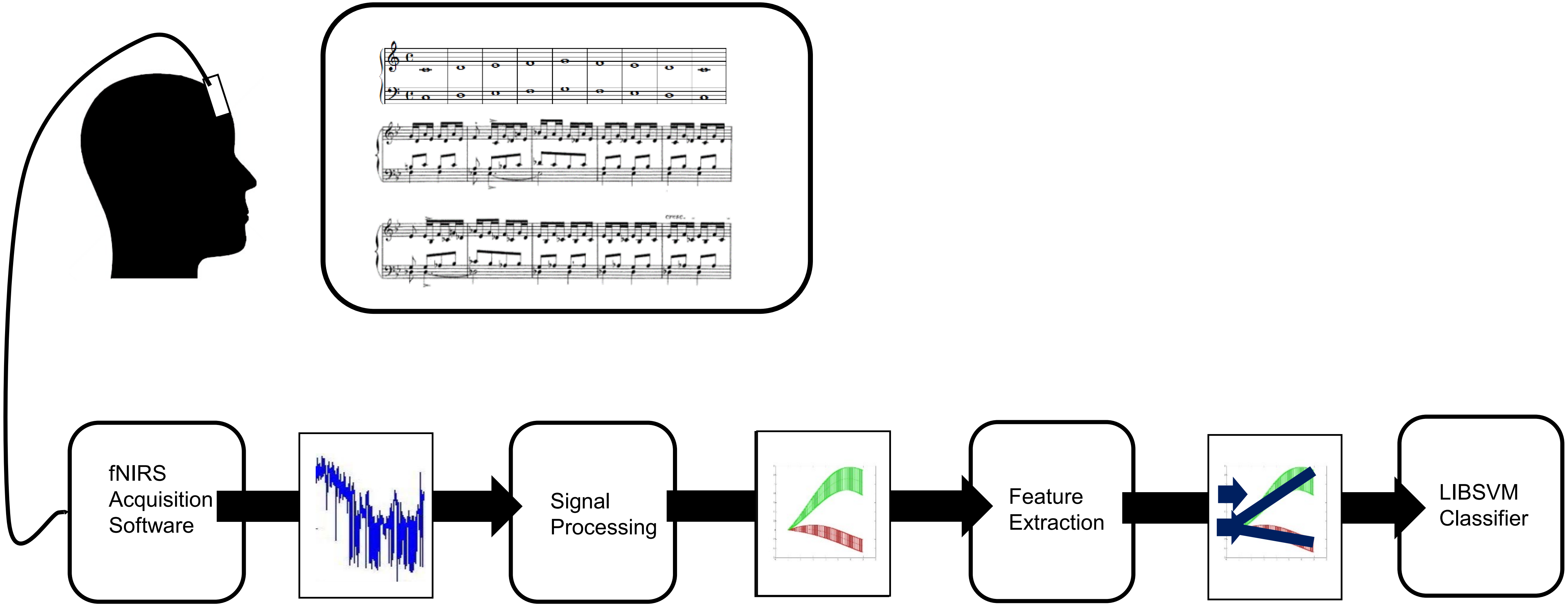
Easy pieces
Hard pieces
MEAN
MEAN
ΔI/I0
Optical Intensity
Time (s)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-5
0
5
10
15
20
25
30
35

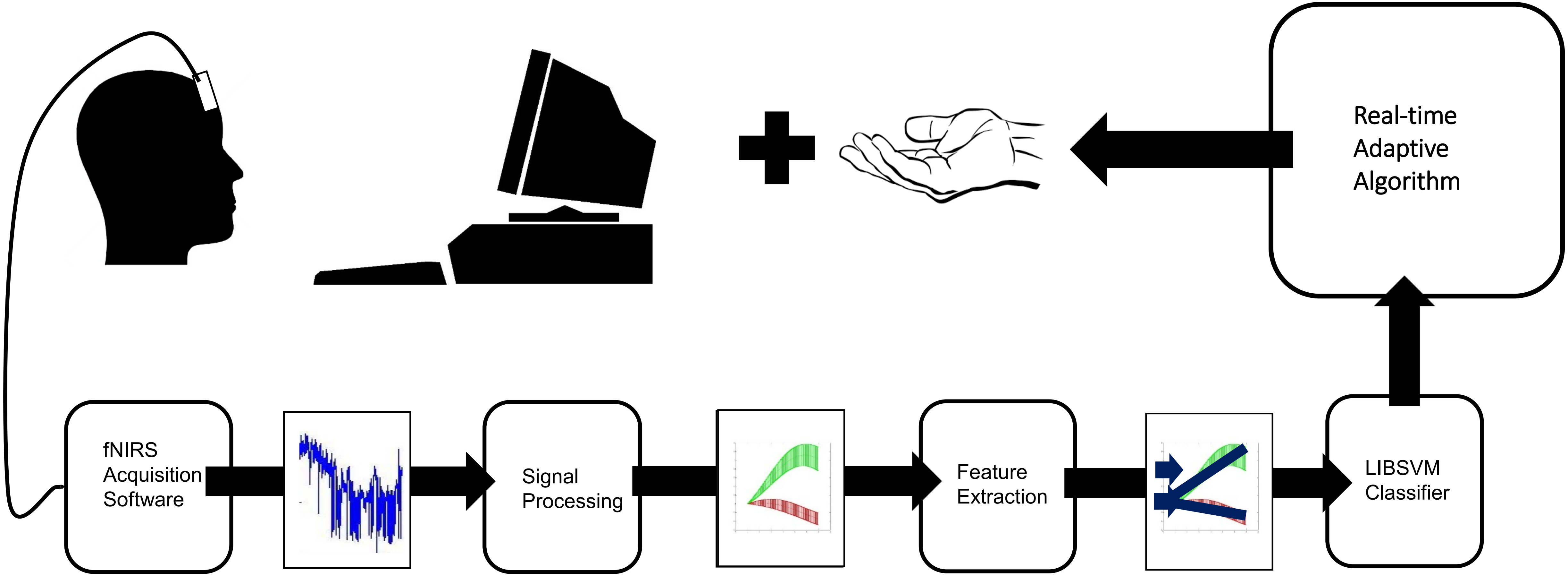


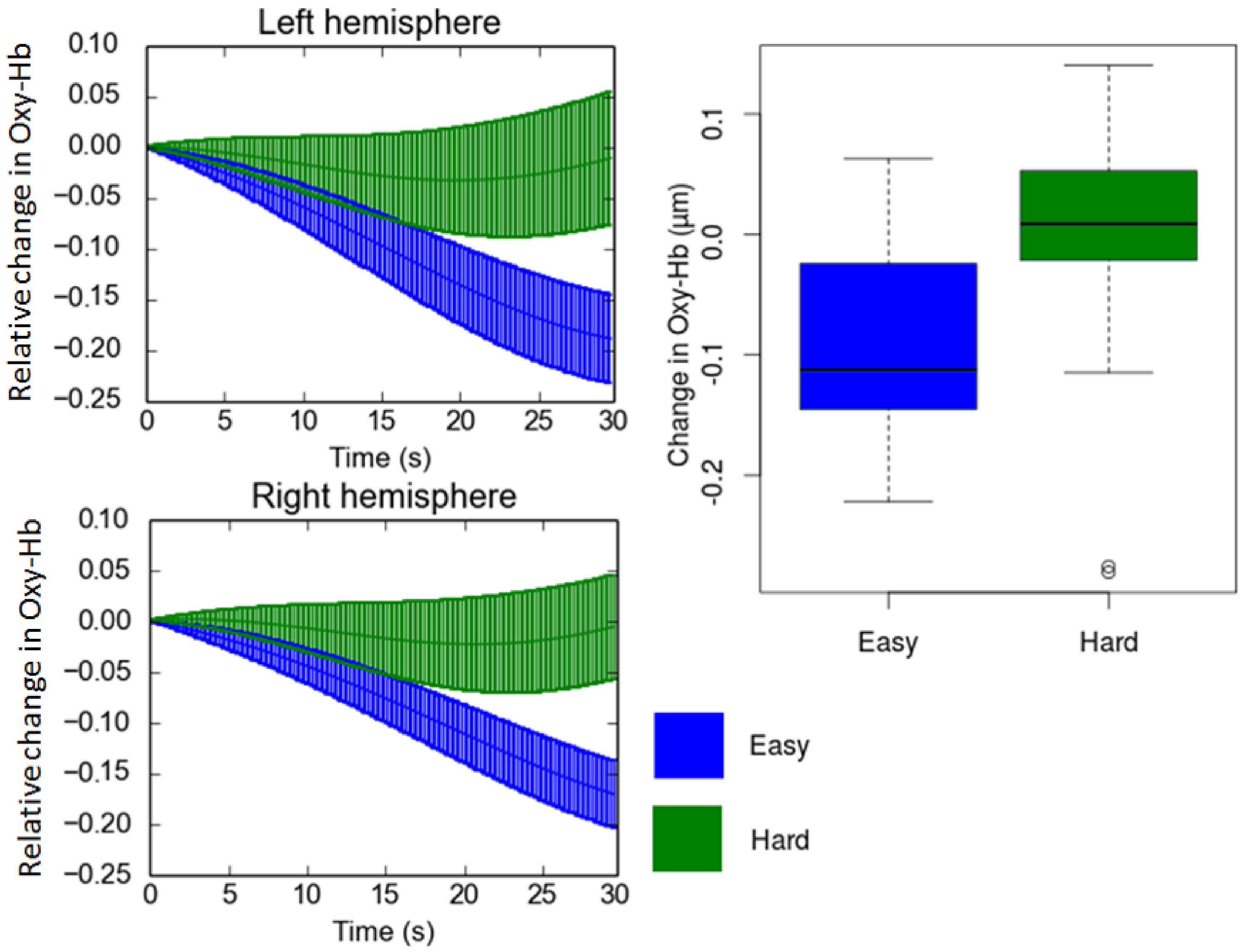
2 cm
2.5 cm
3 cm
3.5 cm
830 nm
690 nm
830 nm
690 nm
Left Hemisphere
Right Hemisphere
ΔI/I0
Easy pieces
Hard pieces
0.5
30 secs



2 cm
2.5 cm
3 cm
3.5 cm
830 nm
690 nm
830 nm
690 nm
Left Hemisphere
Right Hemisphere
ΔI/I0
0.5
30 secs
Easy pieces
Hard pieces


fNIRS Acquisition Software
Signal Processing
Feature Extraction
LIBSVM Classifier


Real-time
Adaptive
Algorithm
fNIRS
Acquisition
Software
Signal
Processing
Feature
Extraction
LIBSVM
Classifier



Left hemisphere
Relative change in Oxy-Hb
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
0
5
10
15
20
25
30
Time (s)
Right hemisphere
Relative change in Oxy-Hb
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
0
5
10
15
20
25
30
Time (s)
Change in Oxy-Hb (μm)
0.1
0.0
-0.1
-0.2
Easy
Hard
Easy
Hard

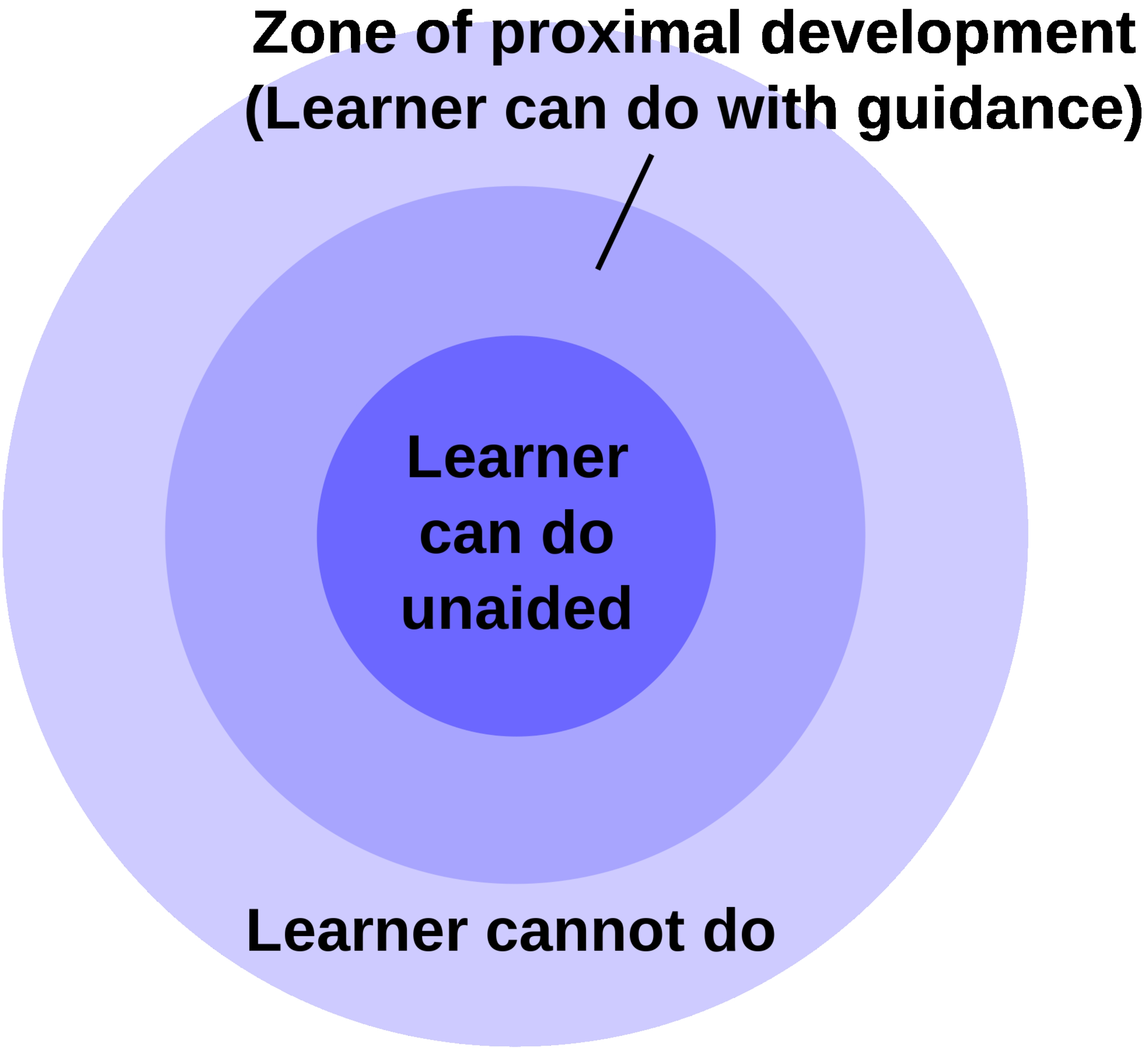
BACh: Brain Automated Chorales

Adaptive brain-computer interface that dynamically increases the levels of difficulty in a musical learning task.

Learn Piano with BACh: An Adaptive Learning Interface that Adjusts Task Difficulty Based on Brain State

Yuksel, B.F., Oleson, K.B., Harrison, L., Peck, E.M., Afergan, D., Chang, R., and Jacob, R.J.K.

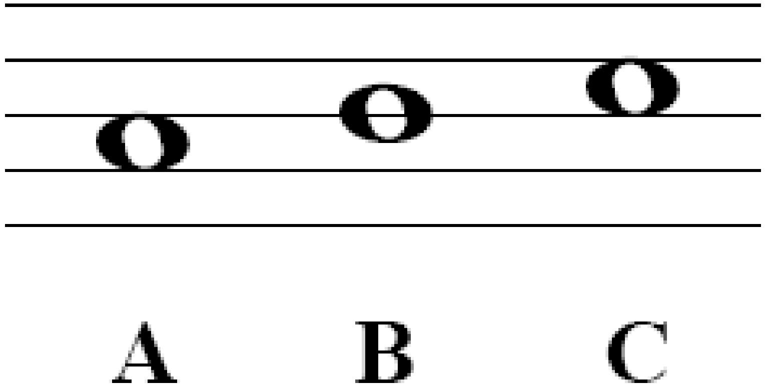
Proc. CHI 2016



Vygotsky, 1978

Finite Cognitive Workload

Schemata – Units of Learning



Their honour precarious, their liberty provisional, lasting only until the discovery of their crime; their position unstable, like that of the poet who one day was feasted at every table, applauded in every theatre in London, and on the next was driven from every lodging, unable to find a pillow upon which to lay his head, turning the mill like Samson and saying like him……

Why Learning?

One factor is repeatedly highlighted in CLT as the weak link in learning studies: *the measurement of cognitive workload*.

An adaptive learning system that could adjust task difficulty in real-time based on learner's cognitive workload could be a powerful learning tool.

Why Music?

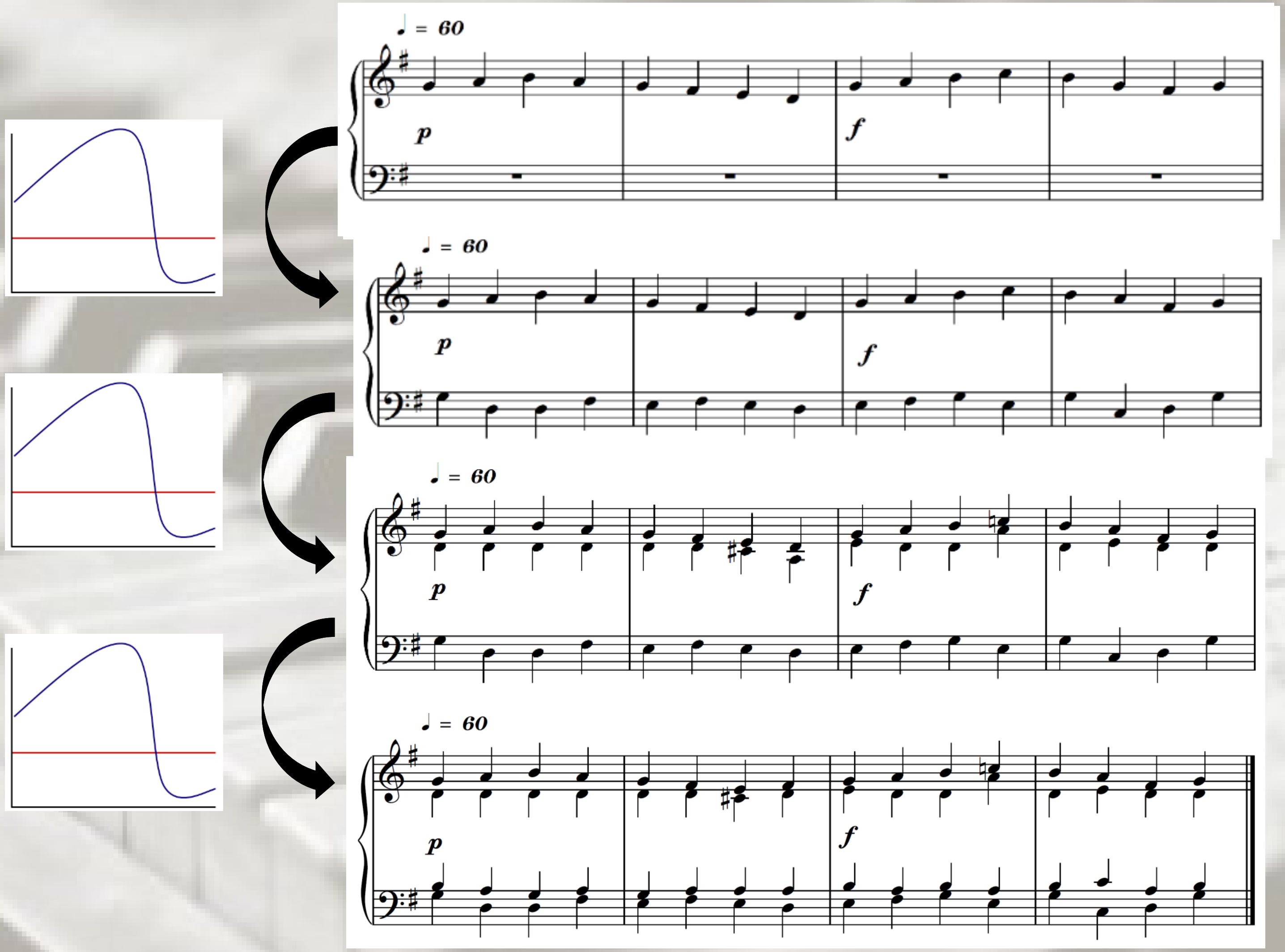
Musical task lends itself well to learning :

Learning

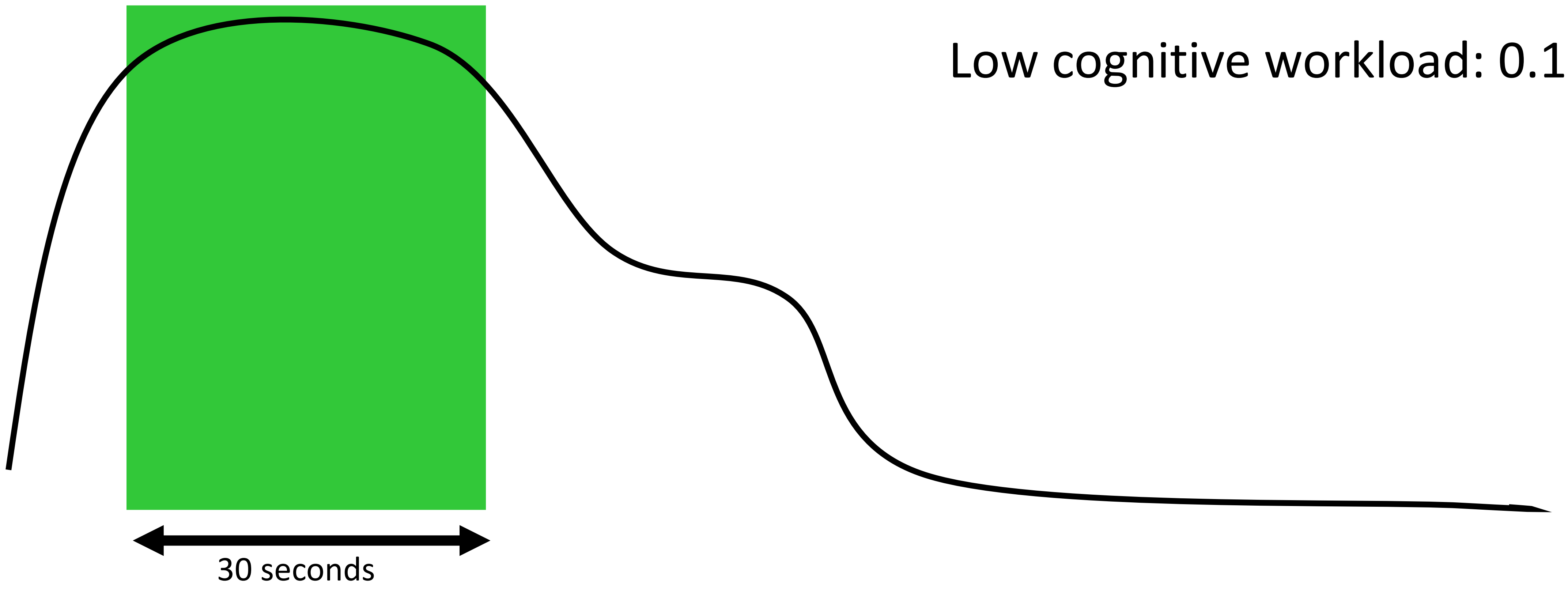
Task segmentation with increasing levels of difficulty to high element interactivity due to concurrency.

Straightforward evaluation in terms of accuracy and speed when compared to a control condition.

Difficulty level increases when learners' cognitive workload *falls below a threshold,* indicating they can handle more information.

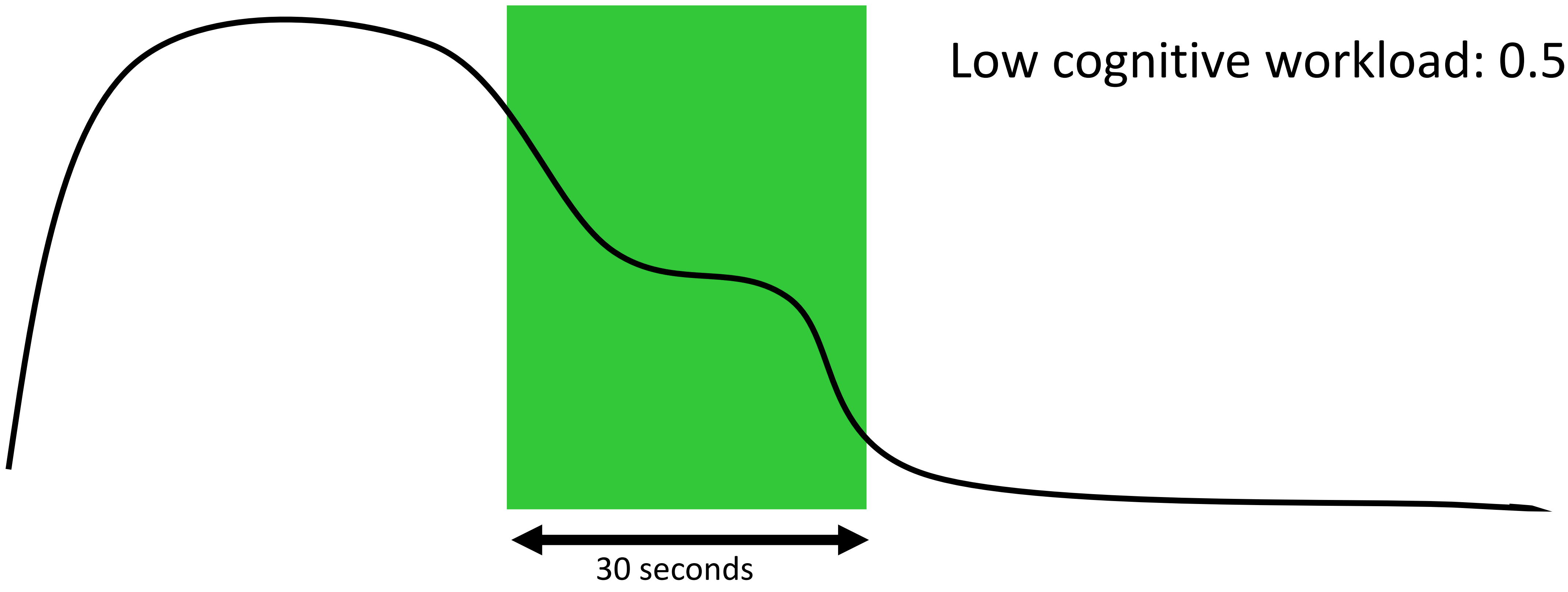


BACh's algorithm



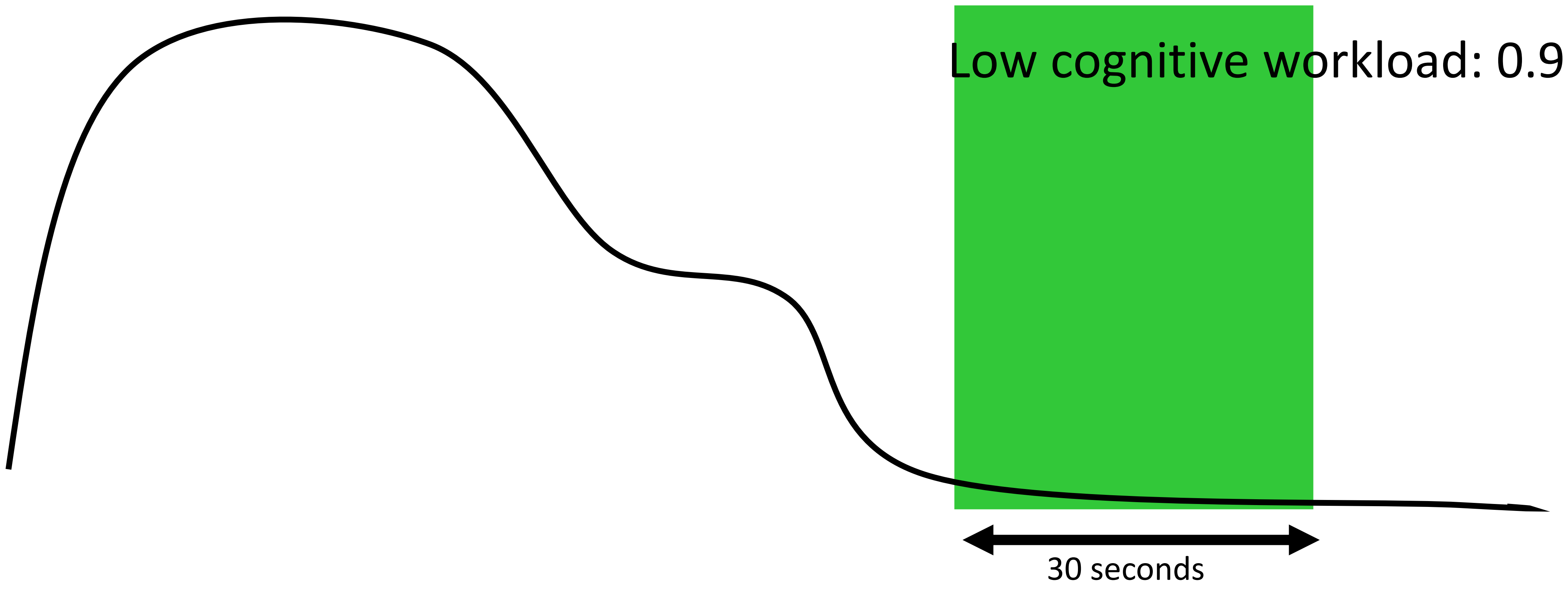
Low cognitive workload: 0.1

BACh's algorithm



Low cognitive workload: 0.5

BACh’s algorithm

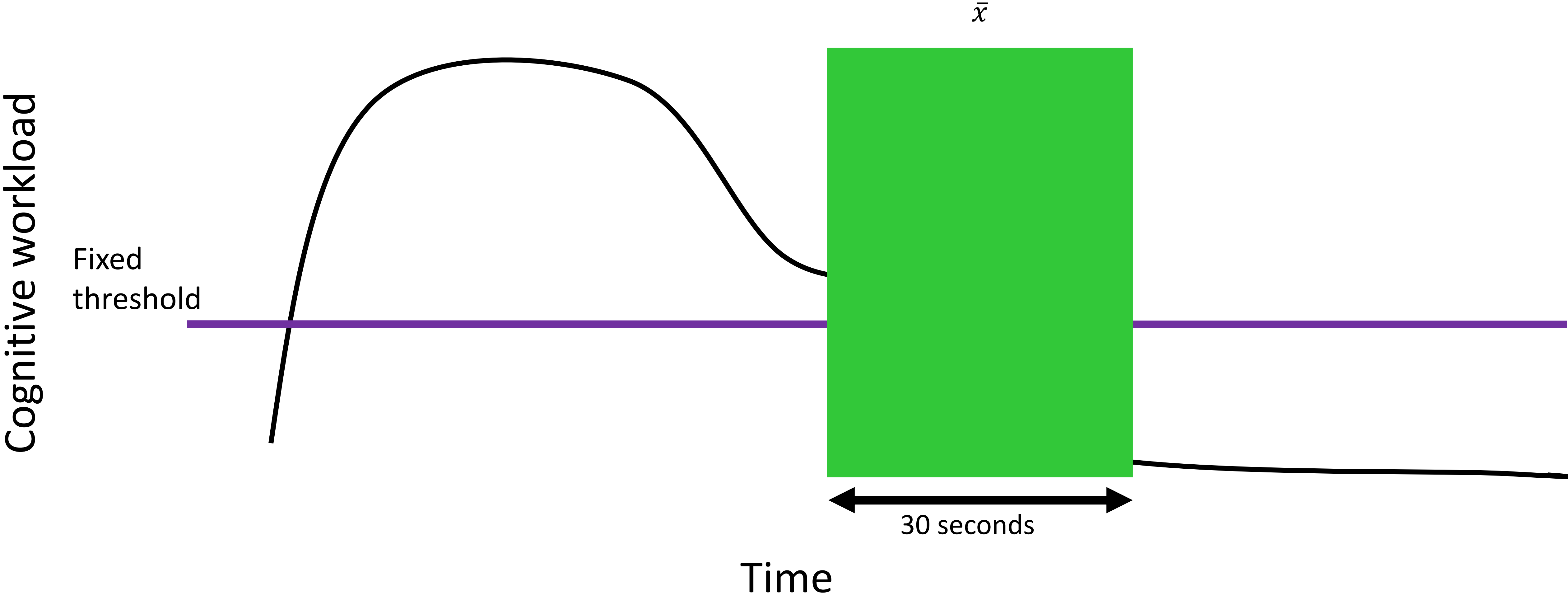


BACh's algorithm

BACh analyzed last 30 seconds of real-time fNIRS data using a sliding window to calculate a prediction of high or low cognitive workload with a confidence value.

A fixed threshold confidence value was *initially* attempted to adjust learning task difficulty.

BACh's algorithm

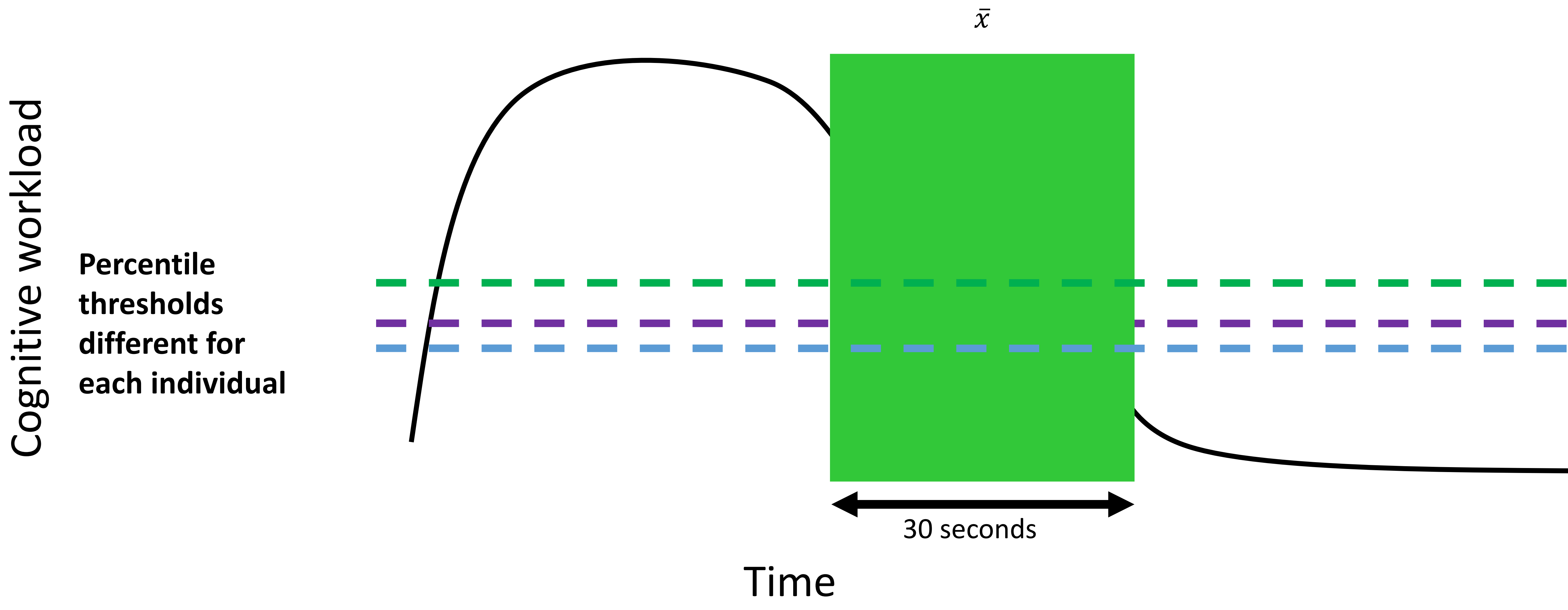


BACh's algorithm

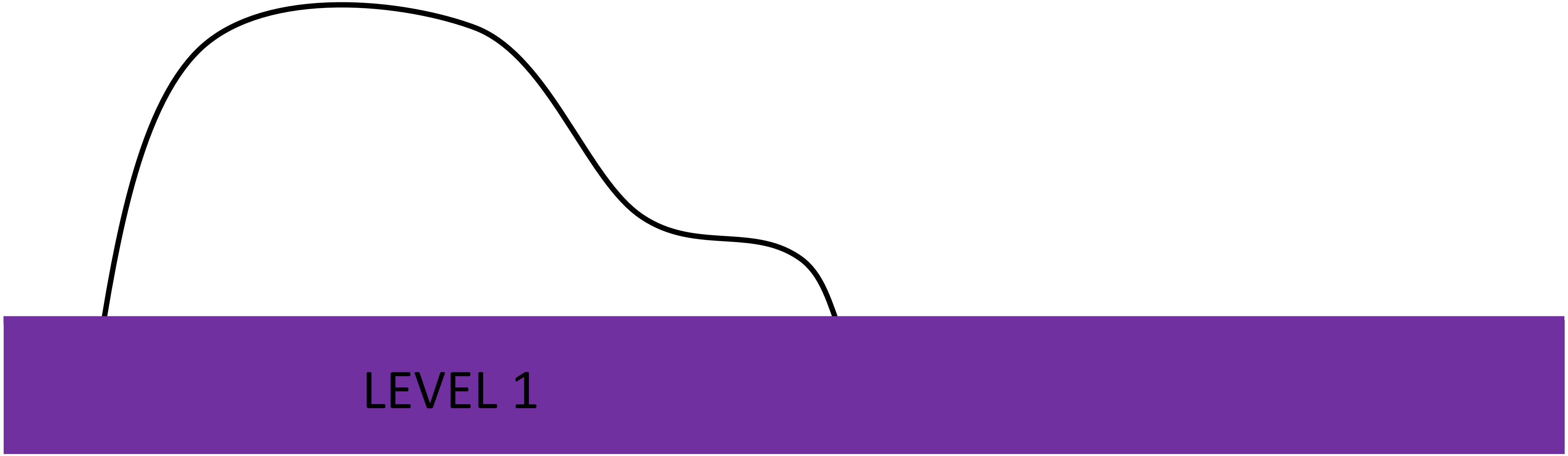
However, pilot studies showed that this was not sensitive enough by itself for the varying levels of difficulty.

BACh therefore used an algorithm that used *percentile automated thresholds* by first measuring range of confidence values for set of period of time during each level. *Percentiles were different for each level of difficulty.*

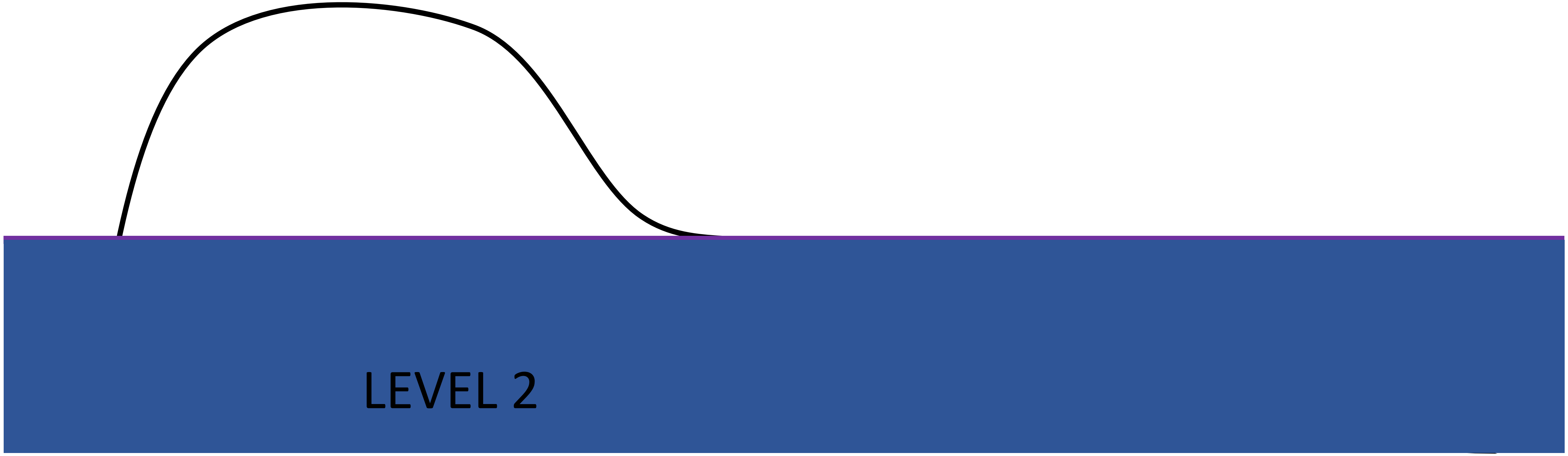
BACh's algorithm



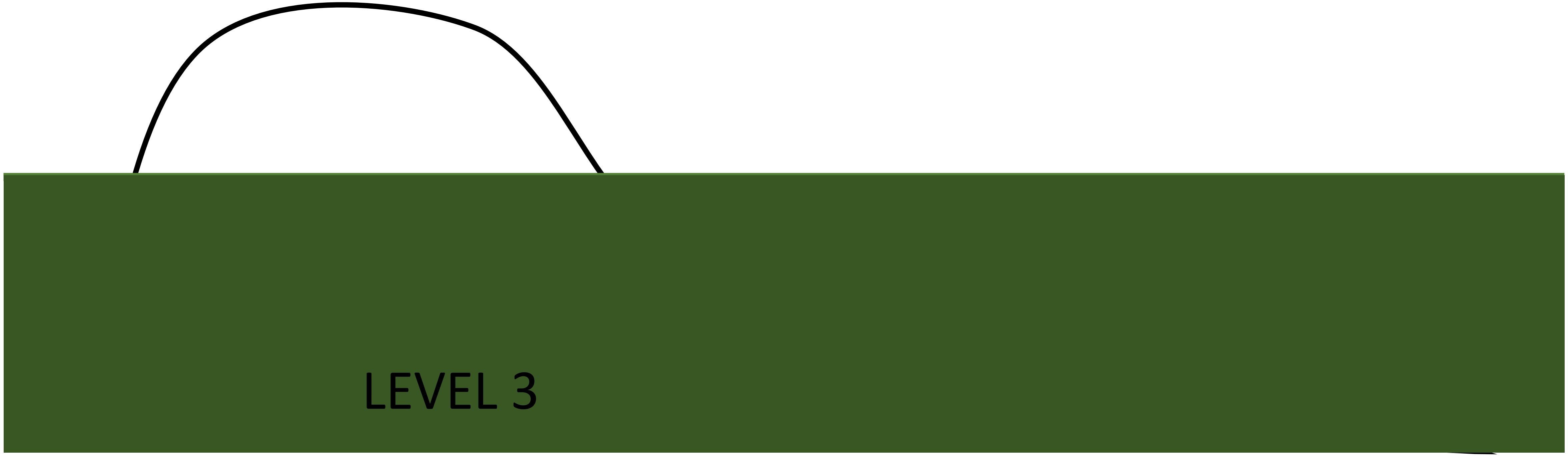
BACh’s algorithm



BACh's algorithm



BACh’s algorithm

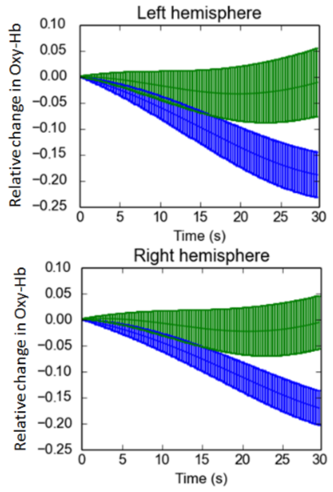


BACh’s algorithm

BACh

Training Task:
Easy vs Hard Pieces

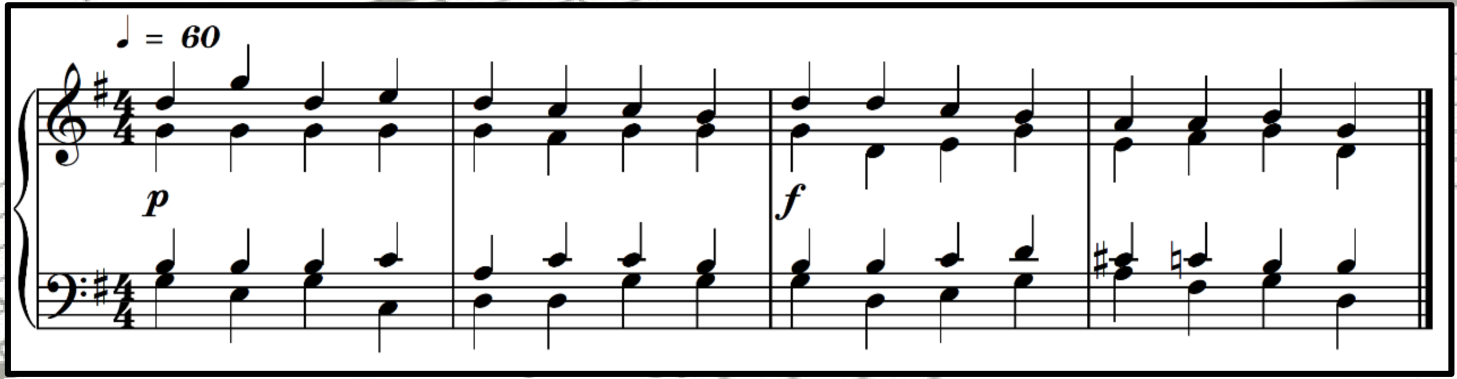
Modeling High and Low Cognitive Workload



Real-Time Task:
Adapting Difficulty Levels in Learning Task

Compared BACh to a control condition: Two Bach chorales with same difficulty.

BACh Condition



Normal Condition

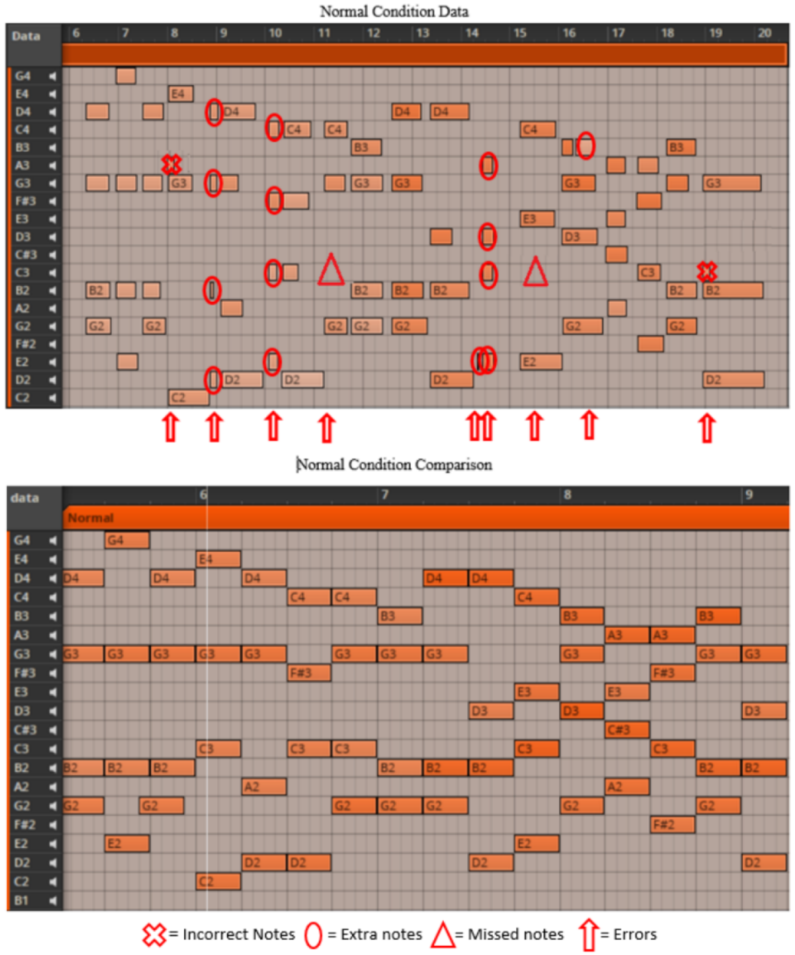
Evaluation of Dependent Variables

Correct notes	Account for precision
Incorrect notes	Account for precision
Extra notes	Correct repeat or incorrect extra note
Errors	Temporal group of incorrect or extra notes
Missed notes	Account for recall
Total time played	Overall speed
Gap between notes	Incomplete learning of involves variance
Beats per minute	Overall speed

Scripts to computationally compare some of MIDI data to groundtruth.

```
midi time list:  [7061, 8547, 9833, 11079, 13143,
13673, 16024, 16669, 18733, 20051, 22050, 23924, 26270,
26509, 28367, 30406, 31074, 32567, 34093, 35527, 37303,
37819]
midi note list:  [55, 67, 74, 59, 59, 67, 79, 52, 59,
67, 74, 55, 60, 67, 48, 76, 50, 67, 74, 59, 74, 57, 67,
50, 66, 72, 60, 52, 50, 66, 60, 72, 72, 67, 55, 60, 71,
67, 55, 59, 74, 67, 59, 55, 74, 62, 59, 50, 52, 62, 69,
52, 60, 72, 64, 60, 52, 71, 67, 62, 55, 71, 61, 69, 64,
57, 66, 60, 54, 69, 55, 67, 71, 59, 60, 67, 59, 50, 62]
number of beats played:  22
total time:  33279
note gap: 1512.6818181818182
average tempo:  39.665  BPM
note gap range:  -838.3181818181818  to  1273.
6818181818182  ms
average note variance:  45.83264462809923  ms
number of each note played:  Counter({67: 12, 59: 9,
60: 8, 55: 7, 74: 6, 50: 5, 52: 5, 71: 4, 72: 4, 62: 4,
66: 3, 69: 3, 64: 2, 57: 2, 76: 1, 79: 1, 48: 1, 54: 1,
61: 1})
total notes played:  79
```

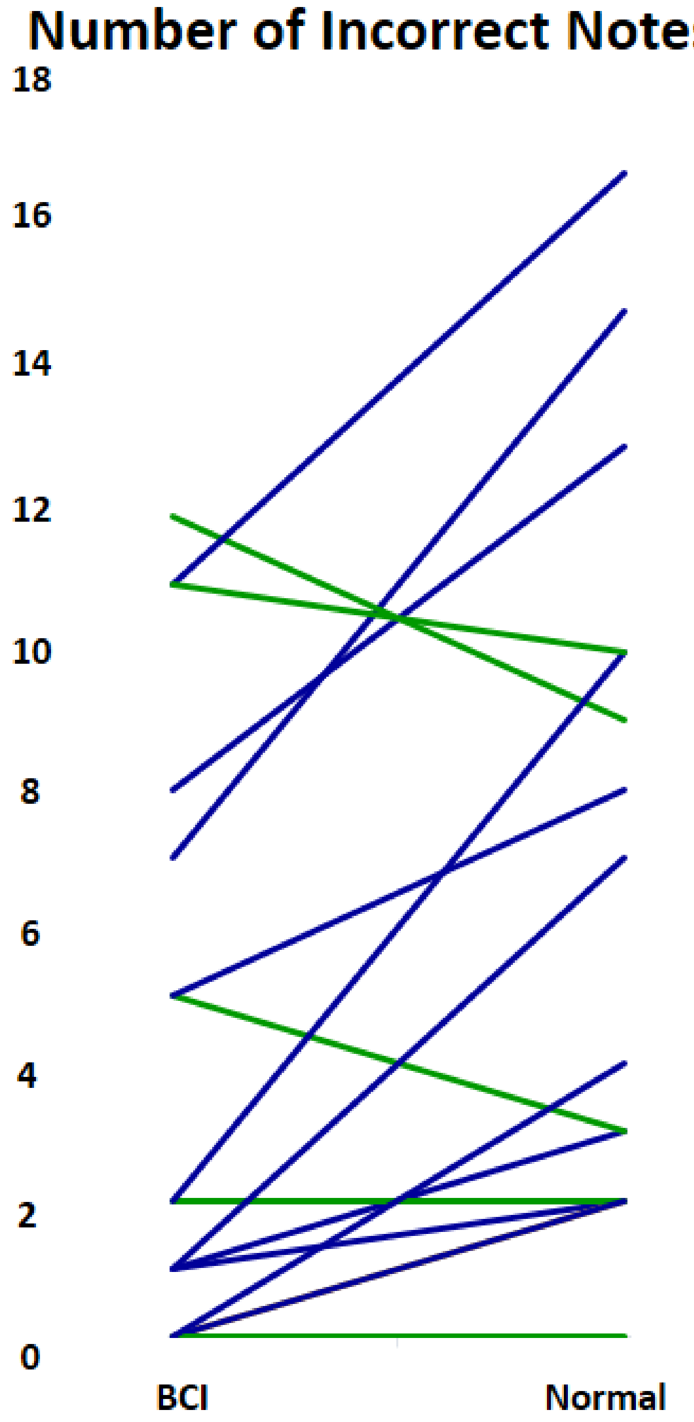
Other dependent variables compared by hand as score following is an open research problem.

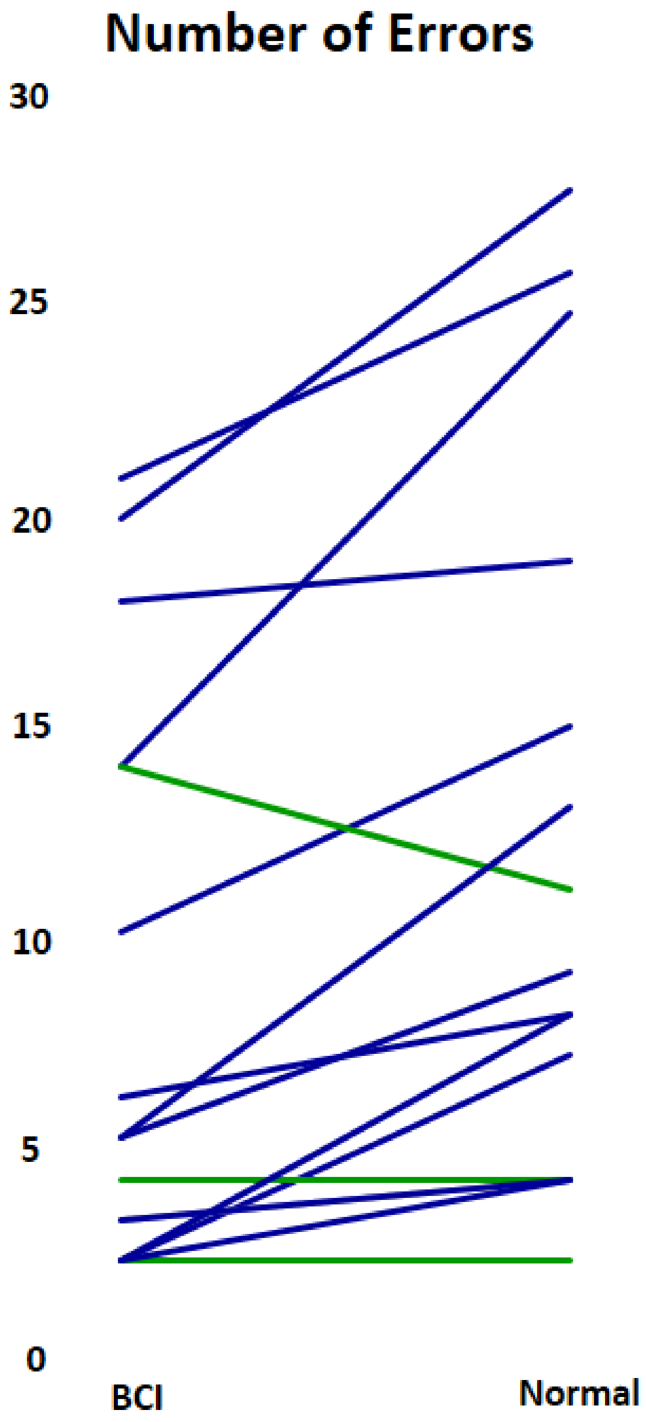


Results of Wilcoxon Signed-rank test (significant results highlighted in bold)

Dependent Variable	Z	*p*	effect size
Number of correct notes	-1.9689	**0.05202**	0.304
Number of incorrect notes	2.4401	**0.0153**	0.377
Number of missed notes	2.3151	**0.01911**	0.357
Number of errors	3.0351	**0.003793**	0.468
Number of extra notes	0.8796	0.3633	–
Total time played	2.5337	**0.009186**	0.391
Mean gap between notes	2.482	**0.01099**	0.383
Average BPM	-2.719	**0.00525**	0.419

Increased Accuracy





Number of Incorrect Notes

p =.02

Number of Errors

p =.0004

Upward sloping lines indicate better performance in BCI condition.

Increased Speed

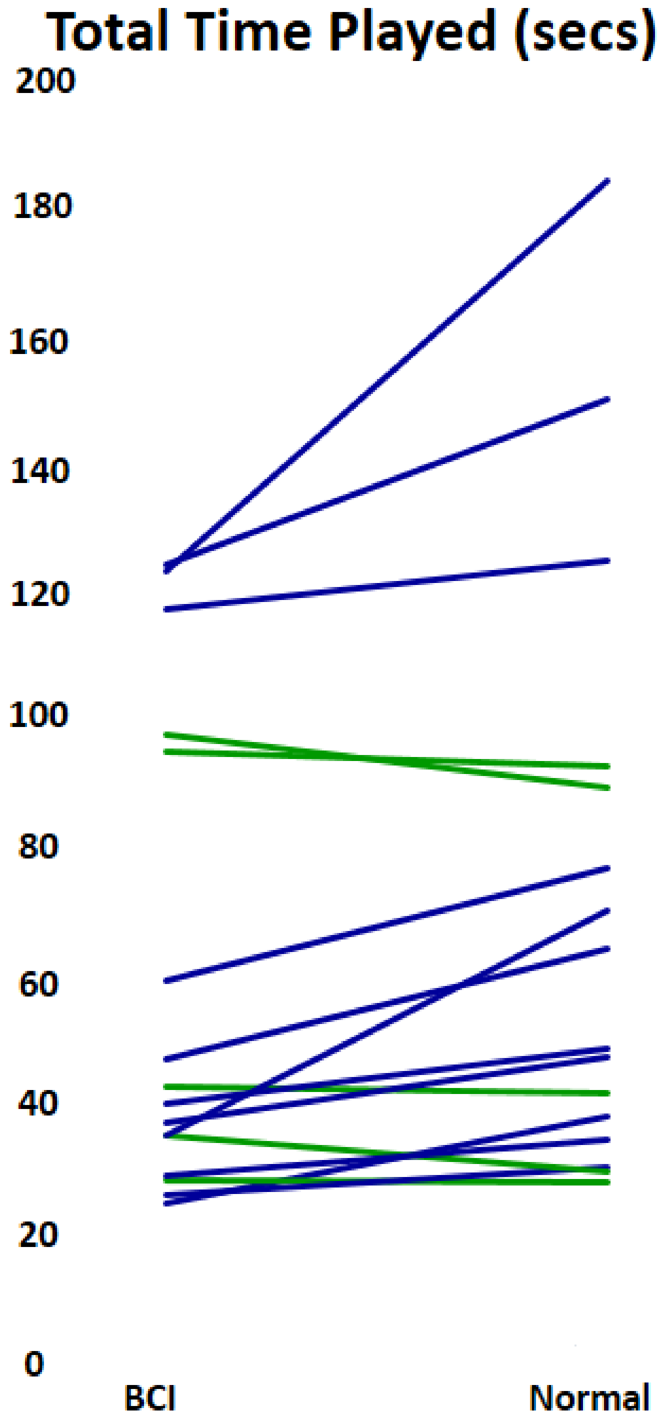
Mean Gap Between Notes

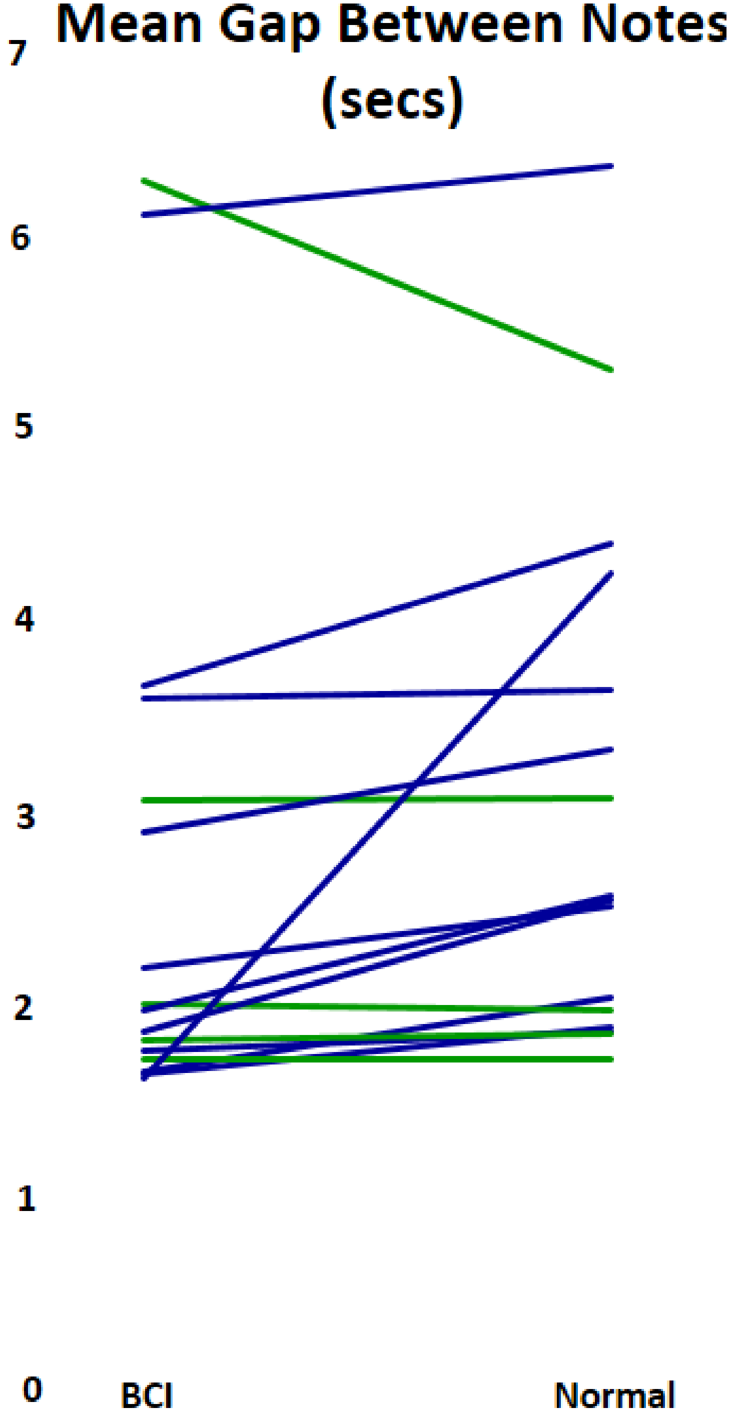
$p = .01$

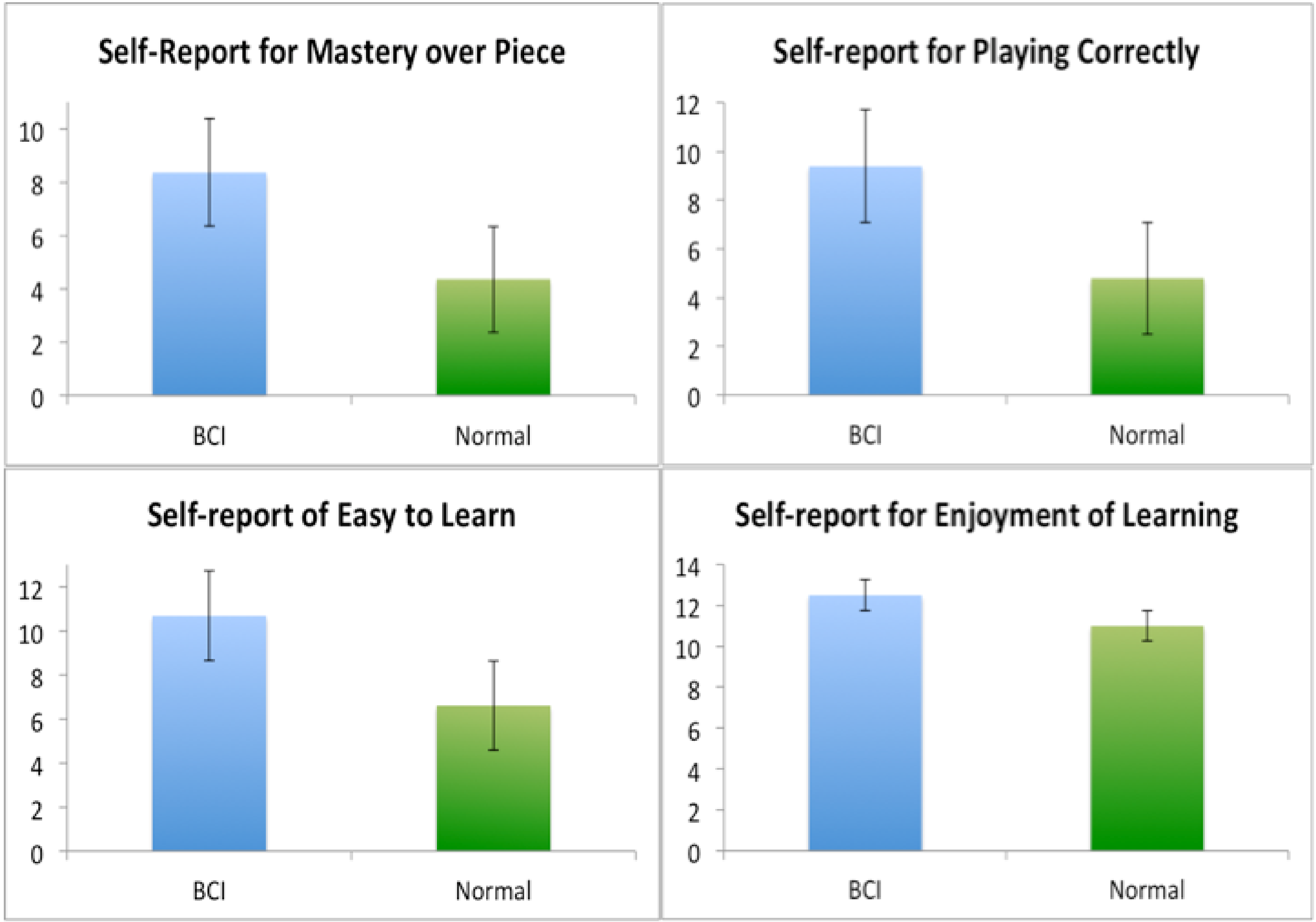
Total Time Played

$p = .009$

Upward sloping lines indicate better performance in BCI condition.







Self-Report for Mastery over Piece
10
8
6
4
2
0
BCI
Normal
Self-report for Playing Correctly
12
10
8
6
4
2
0
BCI
Normal
Self-report of Easy to Learn
12
10
8
6
4
2
0
BCI
Normal
Self-report for Enjoyment of Learning
14
12
10
8
6
4
2
0
BCI
Normal

Timing of Changes:
Interview Data

"I thought it was good timings because by the time I learned, it gave me enough time to learn the individual lines, one by one."

"I thought they were good times for changes, all of them."

"Having a timing system can be jarring; you should only add new things when you know that the person has completed the existing part, but these timings were fine."

Timing of Changes:

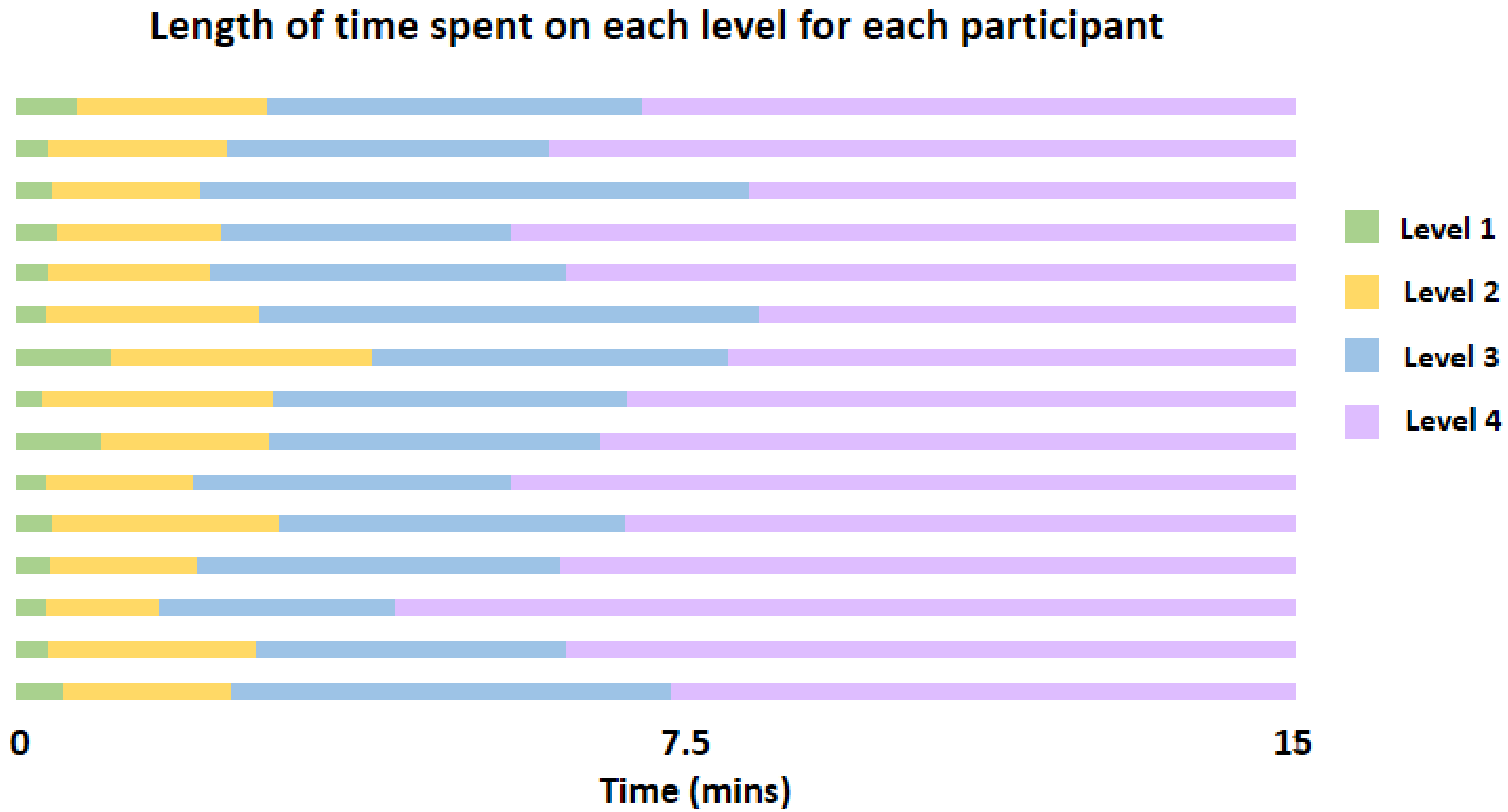
Interview Data

"I wasn't sure if you were controlling it or not because when it was added it was a pretty appropriate time for me to add on a part…

I wasn't sure if it was timed or if you were like 'oh, she's done with this part, so add on the second part.'"

Timing of Changes:

Variance in Individual Differences of Level Changes



Modeling and Adapting to Cognitive Workload

What about high cognitive workload?

- Mapping physiological signals to psychological states.

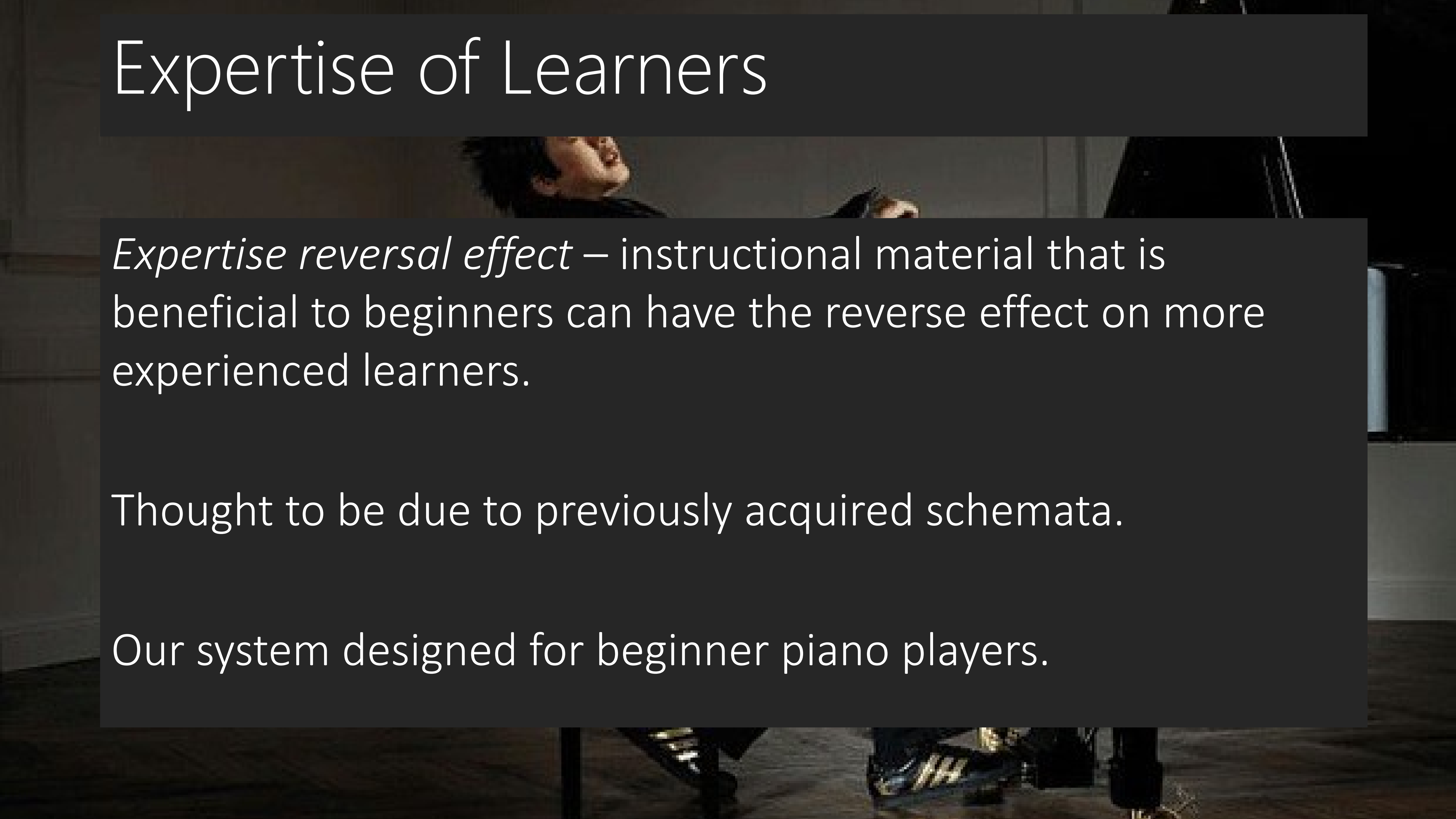
Open research problem whether high cognitive workload is ‘good’ or ‘bad’.

Solution may lie in measuring emotion in conjunction with cognitive workload.

Responding to Learners Individually

Moving away from fixed percentage thresholds, early studies showed early on this wouldn't work.

Came to algorithm that would assess learner cognitive workload using both the learner's brain data from training task *and percentile from current level of difficulty.*



Expertise of Learners

Expertise reversal effect – instructional material that is beneficial to beginners can have the reverse effect on more experienced learners.

Thought to be due to previously acquired schemata.

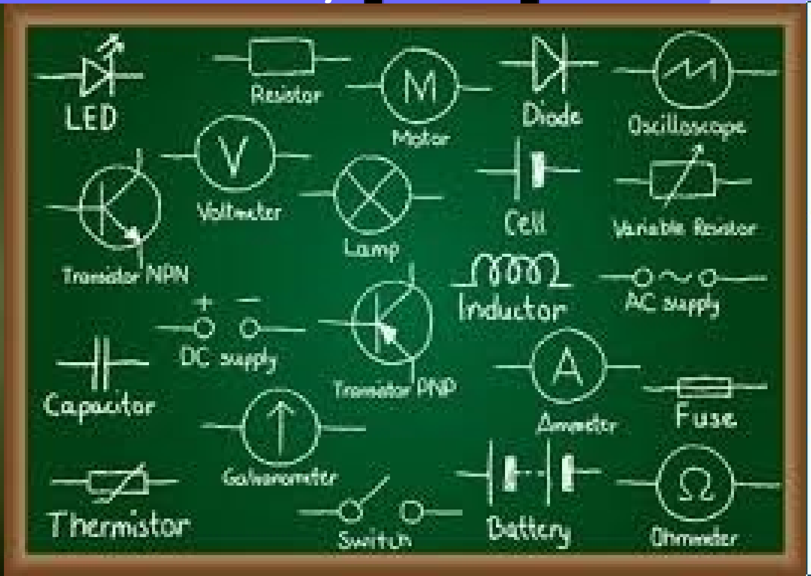
Our system designed for beginner piano players.

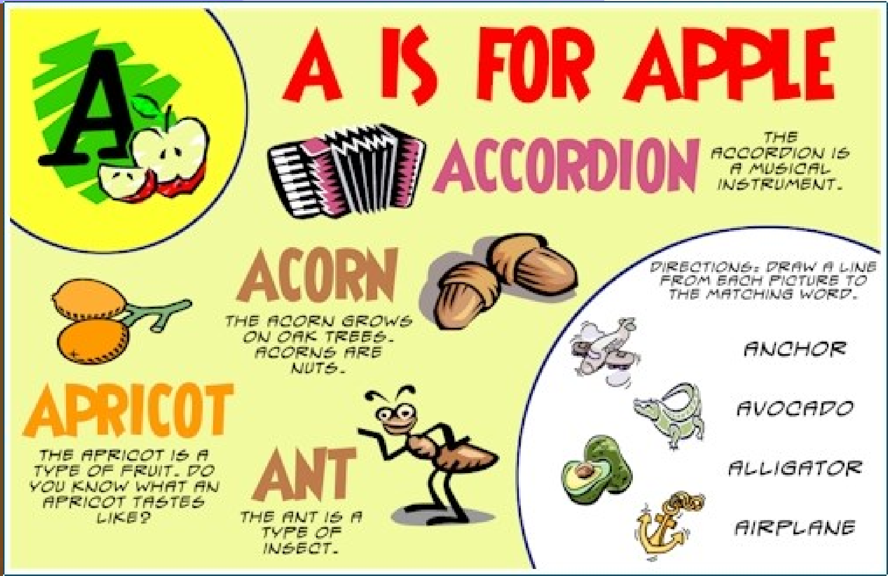
Generalizability to other fields

Underlying principle behind BACh is very simple:

Increase learning task difficulty as cognitive workload falls below a certain threshold using brain sensing.

This can be investigated in any field where tasks can be broken down into increasing difficulty levels.

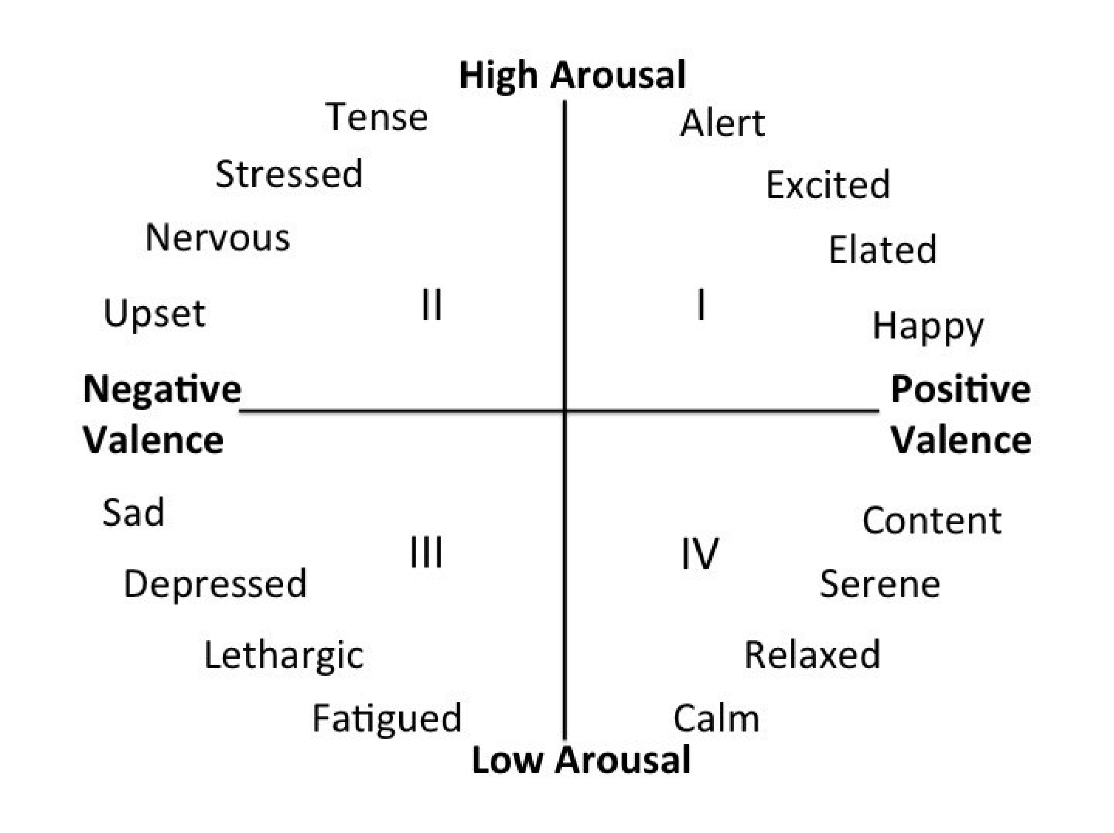




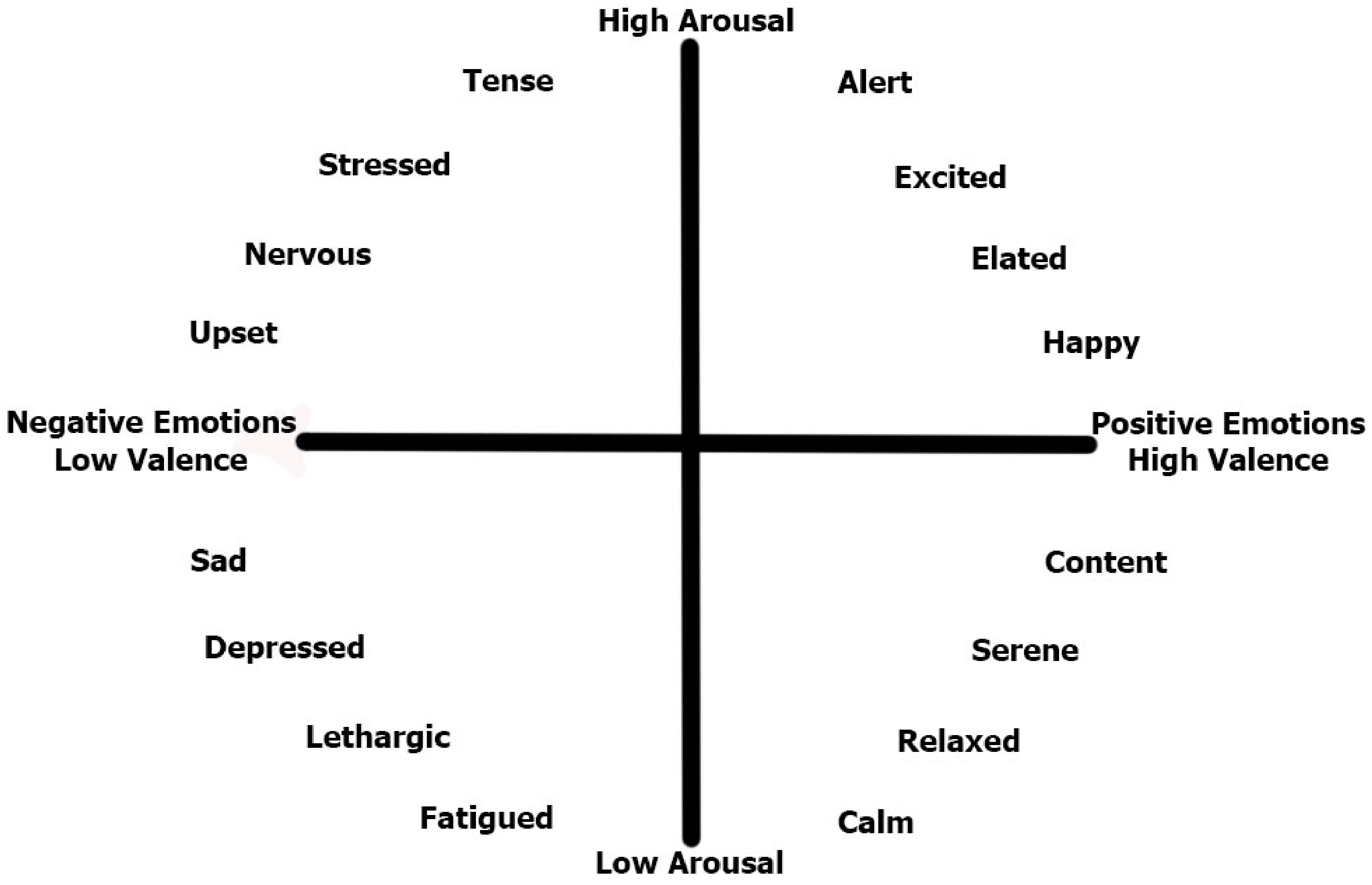
Future Work

- Emotion and learning are very closely tied together, with frustration often preceding giving up.

- A learning tool that detects both cognitive workload and affective state could be very powerful indeed.



Cognitive *and* Affective State In Conjunction




empatica
High Arousal
Tense
Alert
Stressed
Excited
Nervous
Elated
Upset
Happy
Negative Emotions
Low Valence
Positive Emotions
High Valence
Sad
Content
Depressed
Serene
Lethargic
Relaxed
Calm
Low Arousal
ENGAGEMENT
AFFDEX FACIAL CODING TRACKS
EXPRESSIONS AND
INTERPRETATION
CONFUSION
affectiva
HD