Contribution to the Study of the Use of Brain-Computer Interfaces in Virtual and Augmented Reality

Jonathan Mercier-Ganady

PhD Defense – October 12, 2015

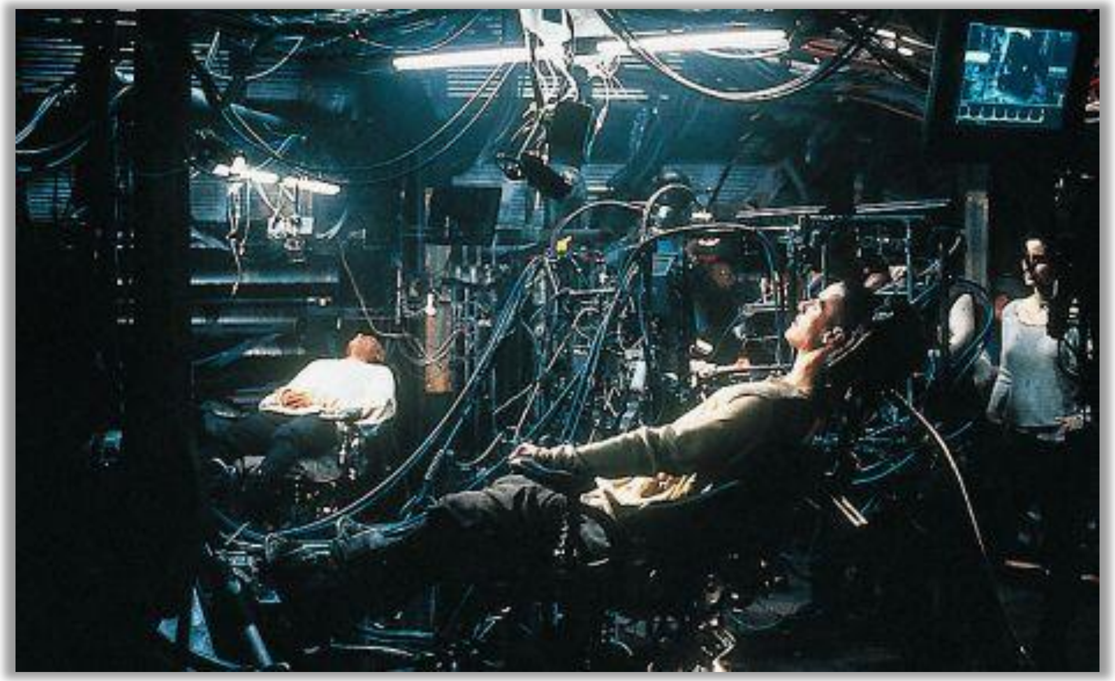
INVENTEURS DU MONDE NUMÉRIQUE
UMR IRISA
INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES RENNES
Région BRETAGNE
AGENCE NATIONALE DE LA RECHERCHE ANR

Advisors: Anatole Lécuyer and Maud Marchal

Introduction

- Interaction with virtual worlds using our brain?
- "Connecting" our brain with a virtual world?
  - Matrix (1999)
  - Source Code (2011)

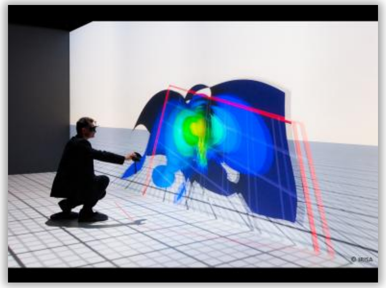
"Source Code". Summit Entertainment, 2011



"TheMatrix", Warner Bros, 1999

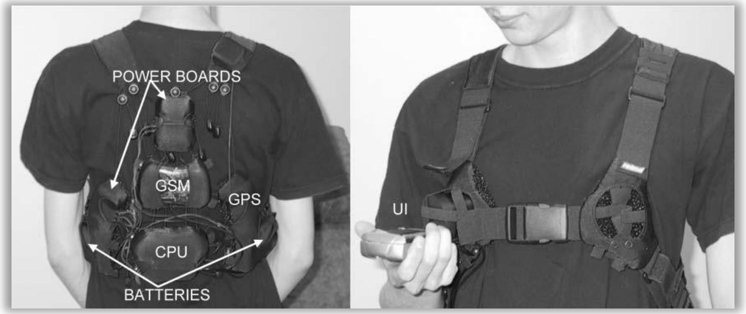
Introduction

- Definitions:
  - Brain-computer interface (BCI): system that "establishes a direct communication channel from the brain to an output device" [Blankertz et al., 2007]
  - Virtual reality (VR): "a real or simulated environment in which a perceiver experiences telepresence" [Steuer, 1992]
  - Augmented reality (AR): a reality "in which 3D virtual objects are integrated into a 3D real environment in real time" [Azuma et al., 1997]
- Objective: how can a brain-computer interface be used in combination with virtual/augmented reality?



The Homo Textilus project

- ANR "Homo Textilus" project (2012–2015): study next generations of smart clothes
  - Partners: Inria, Tomorrowland, Lutin, Lip6, GEMTEX, RCP Design Global
  - Smart clothes: "ordinary clothing, augmented with electrical or non-electrical components and intelligent fabrics" [Rantanen et al., 2000]
  - Applications: entertainment, medicine…
- Our objective within this project: integration of a brain-computer interface with smart clothes in VR/AR



Supporting structure for smart clothing
[Rantanen et al., 2002]

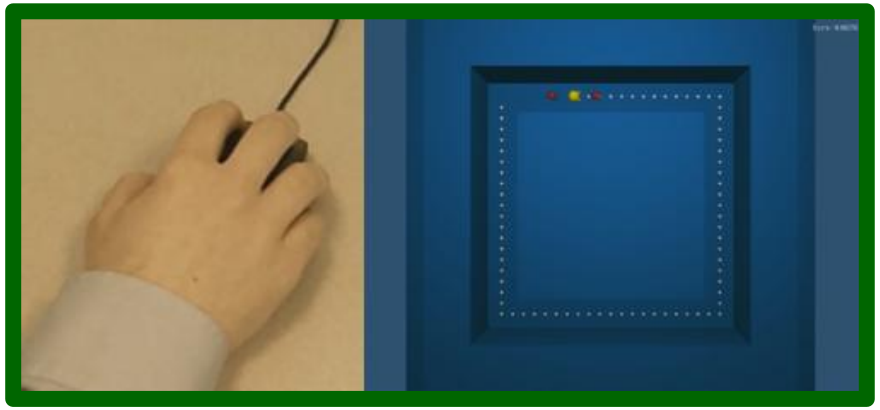
Fashion show,
Hussein Chalayan, 2007

Challenges

1. Studying compatibility between BCI and VR/AR systems:
   - Hardware/Software: are two systems compatible? (e.g. muscular noise)
   - Usage: identifying new usages of BCIs in VR/AR
2. Learning of brain-computer interfaces in virtual environments
   - Improving control of a BCI in a virtual environment?
3. Designing novel usages of BCIs combined with virtual/augmented reality for smart clothes
   - What novel uses can be found, especially in the context of smart clothes?

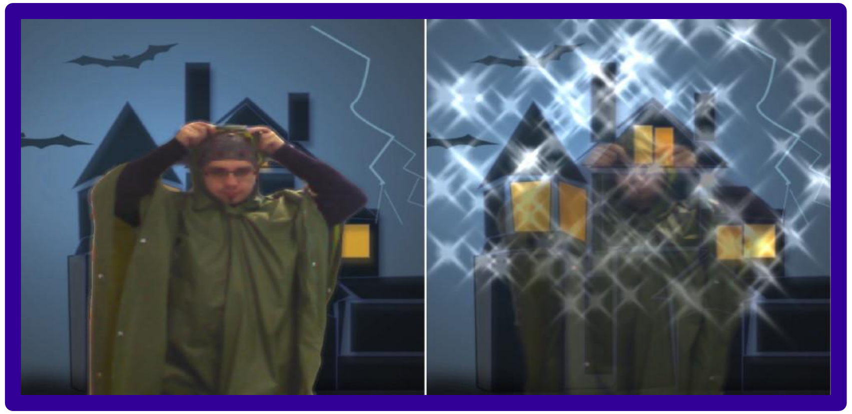
Contributions

1) Compatibility study between a brain-computer interface and another input device
2) Real-time brain activity visualization techniques using virtual or augmented reality
3) Novel smart clothes based on brain-computer interfaces and augmented reality



(1)

(2)



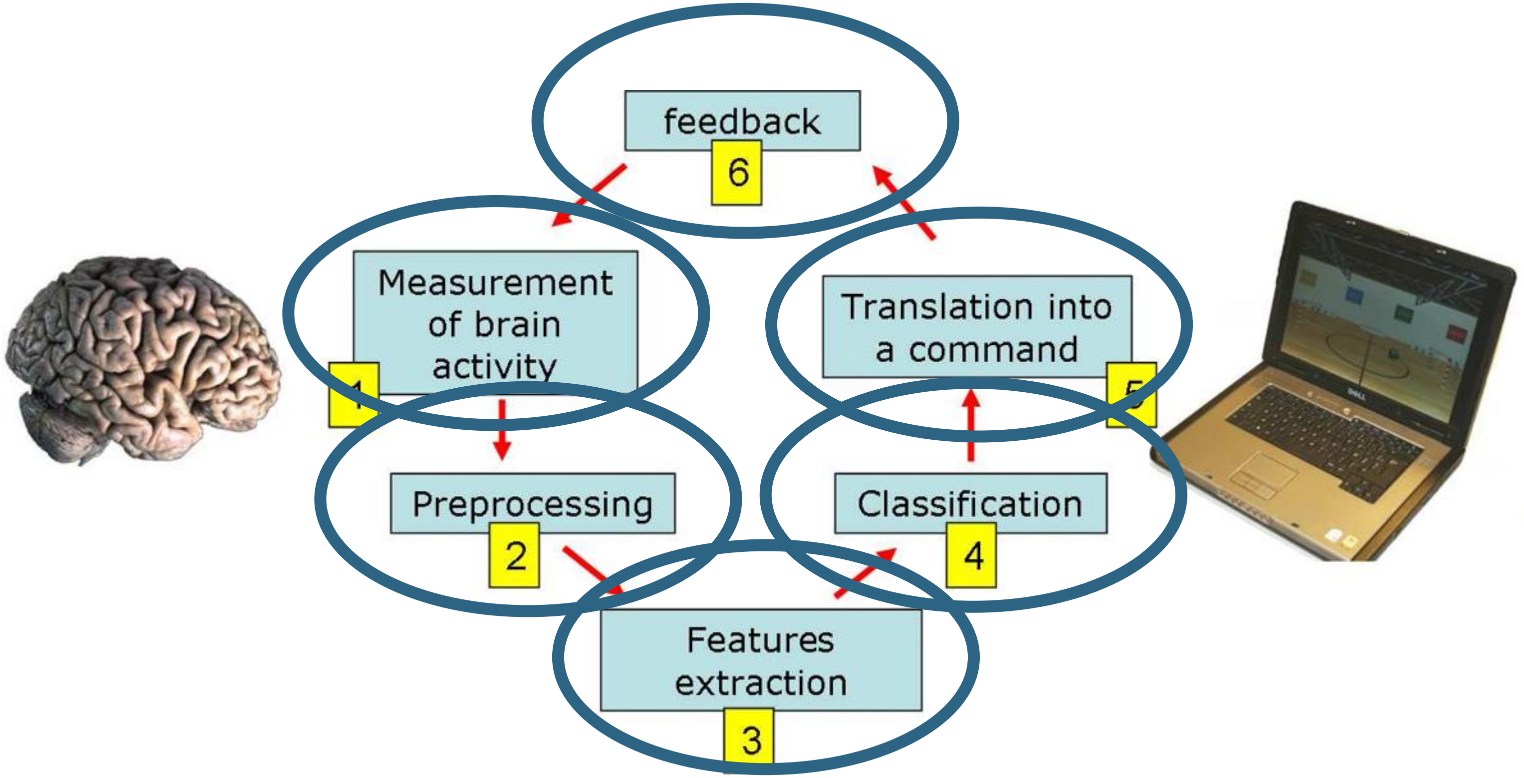
(3)

Outline

1) **Related work**
2) Contribution 1: compatibility study between a brain-computer interface and another input device
3) Contribution 2: real-time brain activity visualization techniques using virtual or augmented reality
4) Contribution 3: designing novel usages of BCIs combined with virtual/augmented reality for smart clothes
5) Conclusion

Brain-Computer Interface

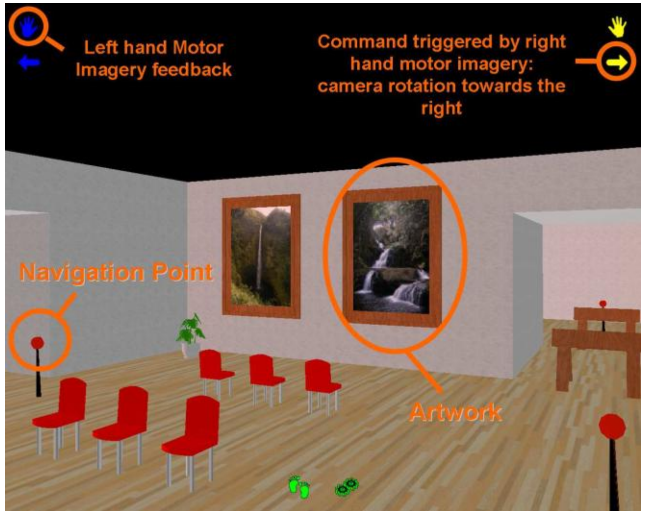
- BCI Loop [Lotte, 2008]
  1. Measurement
  2. Preprocessing
  3. Features extraction
  4. Classification
  5. Translation into a command
  6. Feedback



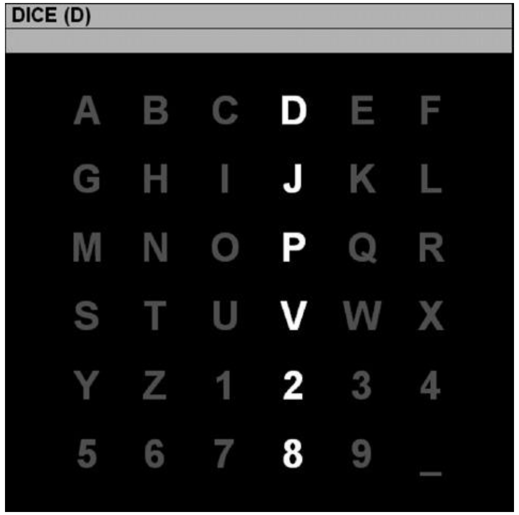
[Lotte, 2008]

Common BCI paradigms

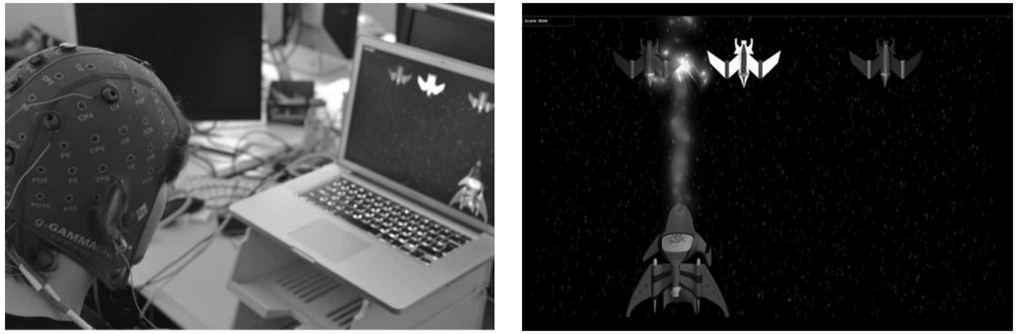
- Motor imagery: imagination of movements
  [Pfurtscheller and Neuper, 2001] [Lotte et al., 2010]
- P300: evoked potentials, rare and expected events
  [Donchin et al., 2000] [Krusienski et al., 2008]
- SSVEP: flickering visual targets
  [Müller-Putz et al., 2005] [Lee et al., 2010]
  [Legény et al., 2013]



[Lotte et al., 2010]



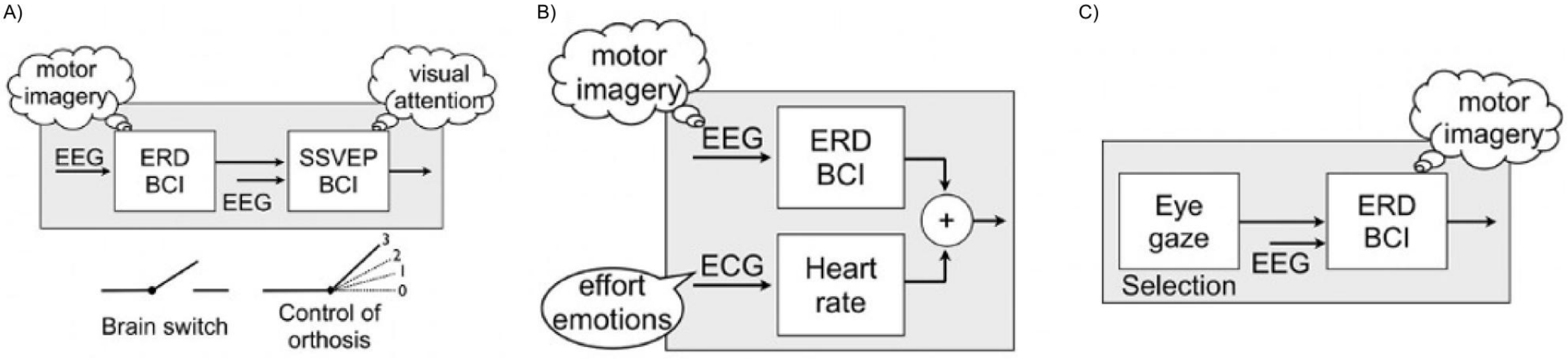
[Krusienski et al., 2008]



[Legény et al., 2013]

Hybrid BCI

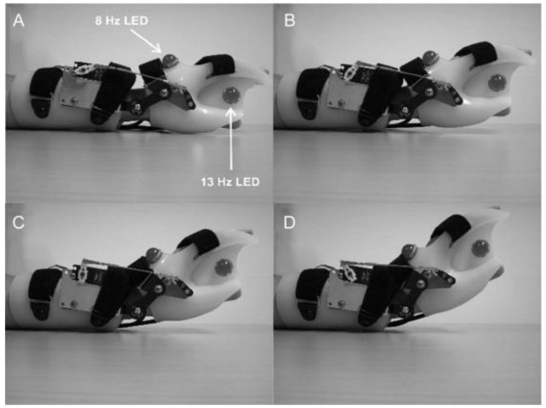
- Hybrid BCI: “a hybrid brain-computer interface (BCI) is composed of two BCIs, or at least one BCI and another system” [Pfurtscheller et al., 2010]



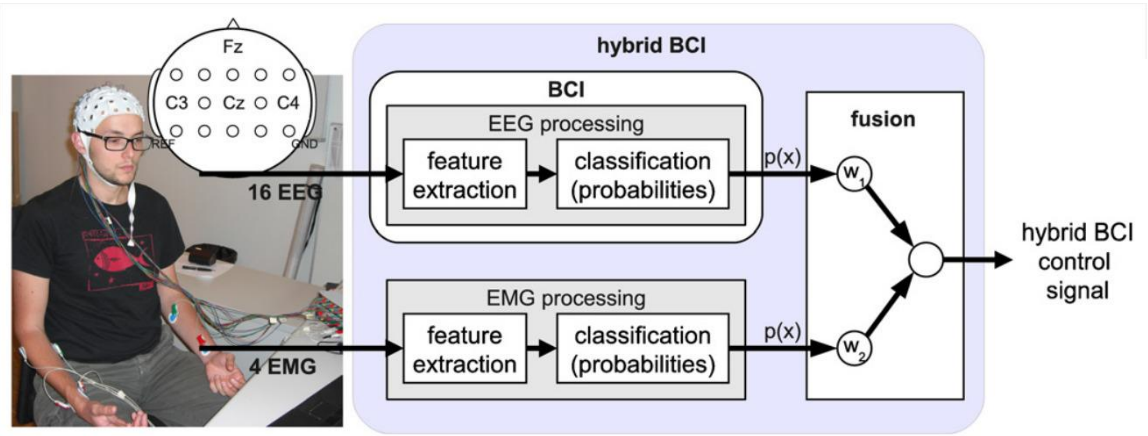
[Pfurtscheller, 2010]

Hybrid BCI

- Two types:
  - Pure (BCI only): [Riechmann et al., 2011] [Pfurtscheller et al., 2010] [Xu et al., 2013]
  - Mixed (BCI + other device): [Leeb et al., 2011] [Yong et al., 2011] [Shahid et al., 2011] [Postelnicu and Talaba, 2013]

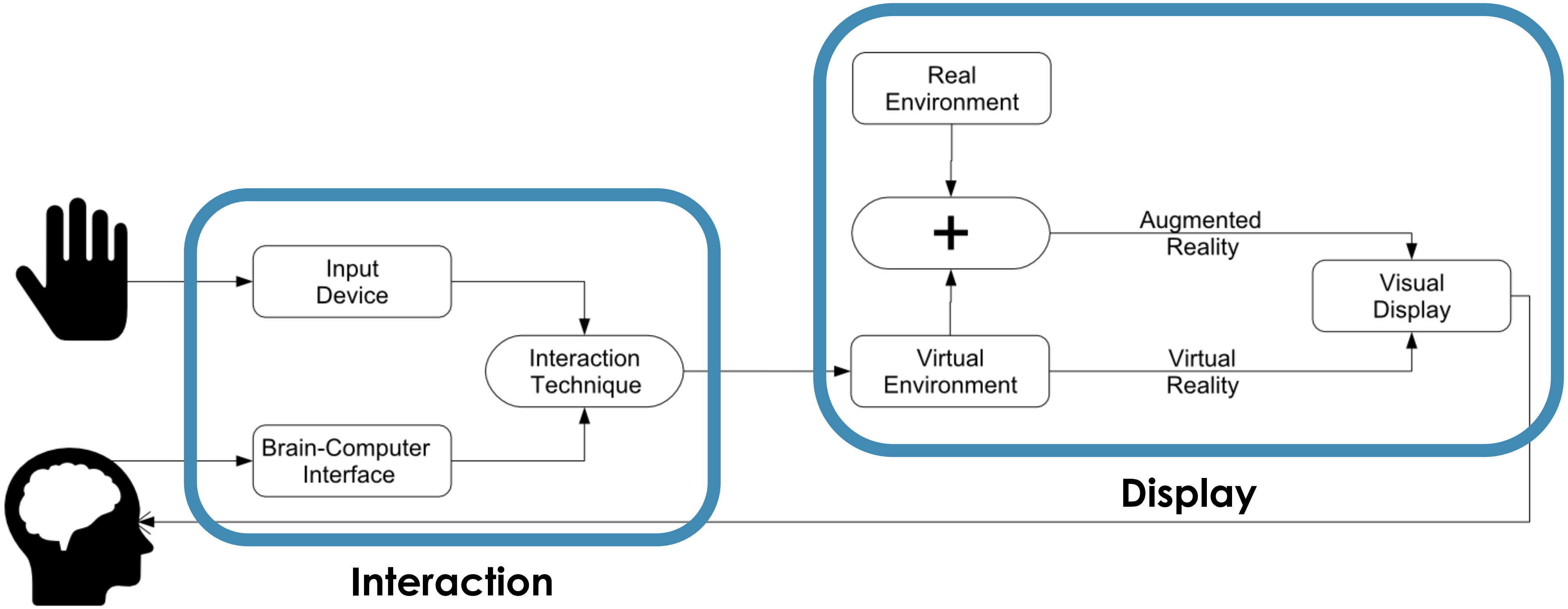


[Pfurtscheller, 2010]



[Leeb et al., 2011]

Hybrid BCI and VR/AR

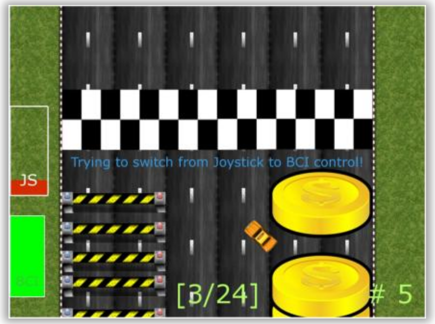


Interaction technique: “fusion of input and output, consisting of all software and hardware elements, that provides a way for the user to accomplish a task” [Tucker, 2004].

BCIs and motor activity

- Previous examples of combined use
  - BCI/mouse: « AlphaWow »: [Nijholt et al., 2009]
  - BCI/joystick: [Kreilinger et al., 2012]
- Previous studies on the influence of motor activity on BCI performance:
  - 1) Locomotion: [Lotte et al., 2009]
  - 2) Speech: [Gürkök et al., 2010]
- Result: BCI compatible with locomotion and speech
- Limitation: no BCI performance study when manipulating a device and very few studies in VR/AR

[Nijholt et al. 2009]



[Kreilinger et al. 2012]

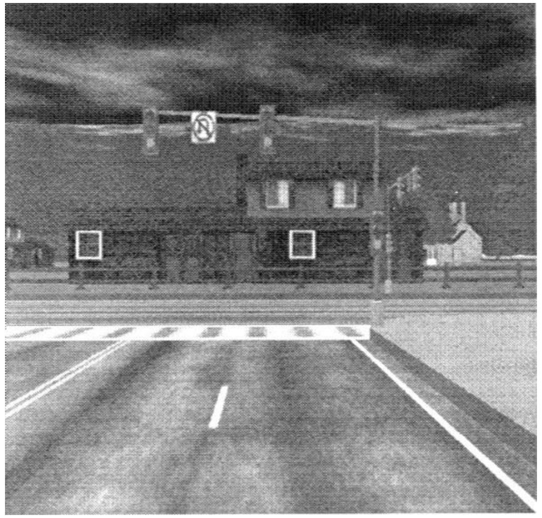
[Lotte et al. 2009]

BCIs and virtual reality

- 2-way connection:
  - VR as a testbed for BCI systems and studies

    [Bayliss and Ballard, 2000]
  - BCI as a novel input for VR systems

    [Edlinger et al., 2011]



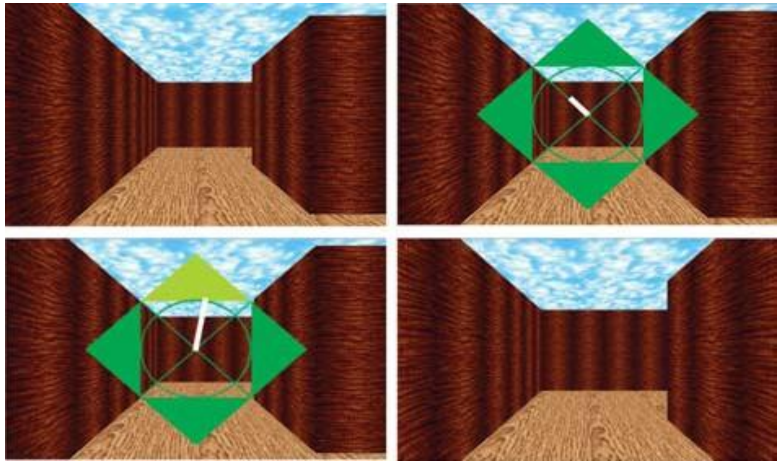
[Bayliss and Ballard, 2000]

[Edlinger et al., 2011]

[Edlinger et al., 2011]

BCIs and virtual reality

- Categorization depending brain activity pattern [Lotte et al., 2013a]
  - Motor imagery [Ron-Angevin et al., 2009] [Velasco-Álvarez et al., 2010] [Lotte et al., 2010]
  - SSVEP [Lalor et al., 2005] [Legény et al., 2011]
  - P300 [Donnerer and Steed, 2010]
- Note: suitability of BCI paradigms depending on VR tasks



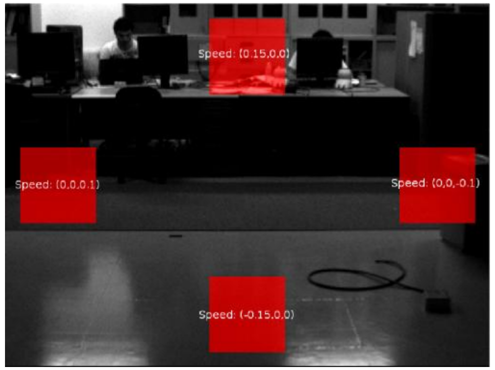
[Ron-Angevin et al., 2009]

[Lalor et al., 2005]

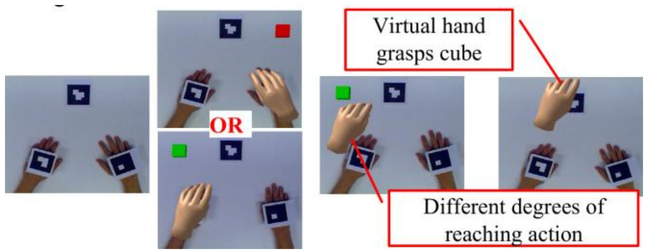
[Donnerer and Steed, 2010]

BCIs and augmented reality

- Combining BCI and AR:
  - Incorporate BCIs “into daily life” by designing a “wearable BCI” [Navarro, 2004]
- Other main categories depending on task:
  1) Manipulation of real objects [Lampe et al., 2014] [Gergondet et al., 2011] [Escolano et al.,2009] [Escolano et al.,2012]
  2) Manipulation of virtual objects [Chin et al., 2010] [Faller et al., 2010] [Buttfield et al., 2006]
  3) Visualization and analysis of brain activity [Frey et al., 2014] [Acar et al., 2014]



[Gergondet et al., 2011]



[Chin et al., 2010]

[Frey et al., 2014]

BCIs and augmented reality: synthesis

- Most frequent task: manipulate robots or robotic arms
- BCI device: almost all EEG-based BCI
- BCI paradigm: P300 and SSVEP
- 3D task: selection
- AR device: mostly computer screen
- Note: new objectives / combinations, smart clothes

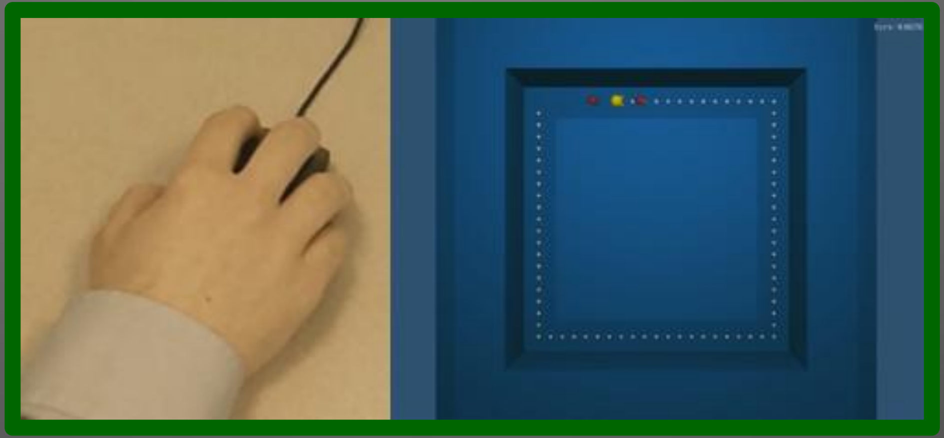
System	Objective	BCI device	BCI paradigm	3D task	AR device
[Escolano et al., 2009]	Manip. a robot	EEG	P300	Select./Nav.	CS
[Lenhardt and Ritter, 2010]	Manip. a robotic arm	EEG	P300	Select./Manip.	HMD[1]
[Kansaku et al., 2010]	Manip. a robot	EEG	P300	Select.	CS
[Faller et al., 2010]	Avatar control in 3D env.	EEG	SSVEP	Select./Nav.	HMD
[Chin et al., 2010]	Manipulation virtual objects	EEG	MI	Manipulation	CS
[Kansaku, 2011]	Manip. a robot	EEG	P300	Select./Nav.	CS/HMD[1]
[Takano et al., 2011]	Home automation	EEG	P300	Select.	CS/HMD[1]
[Gergondet et al., 2011]	Manip. a robot	EEG	SSVEP	Select./Nav.	CS
[Escolano et al., 2012]	Manip. a robot	EEG	P300	Select./Nav.	CS
[Blum et al., 2012b]	X-ray device manipulation	EEG	SSVEP[2]	Control	CS/HMD[1]
[Martens et al., 2012]	"pick-and-place" task Manip. a robotic arm	EEG	P300/SSVEP	Manipulation	HMD
[Katyal et al., 2013]	Manip. a robotic arm	EEG/ECoG	SSVEP/MI/ME	Select./Manip.	CS
[McMullen et al., 2014]	Manip. a robotic arm	ECoG	ME	Select./Manip.	CS
[Lampe et al., 2014]	Manip. a robotic arm	EEG	MI/ME	Select./Manip.	CS
[Katyal et al., 2014]	Manip. a robotic arm	EEG/ECoG	SSVEP/MI/ME	Select./Manip.	CS
[Iturrate et al., 2014]	Virtual object selection	EEG	P300/evoked potentials	Select.	Transp. panel[1]
[Petit et al., 2014]	Manip. a robot	EEG	SSVEP	Select./Nav.	HMD
[Frey et al., 2014]	Visualize the brain activity	EEG	Brain activ. topology	None	Video-projector
[Acar et al., 2014]	Fear treatment	EEG	Freq. band meas.	None	Smartphone

Outline

1) Related work
2) **Contribution 1: compatibility study between a brain-computer interface and another input device**
3) Contribution 2: real-time brain activity visualization techniques using virtual or augmented reality
4) Contribution 3: designing novel usages of BCIs combined with virtual/augmented reality for smart clothes

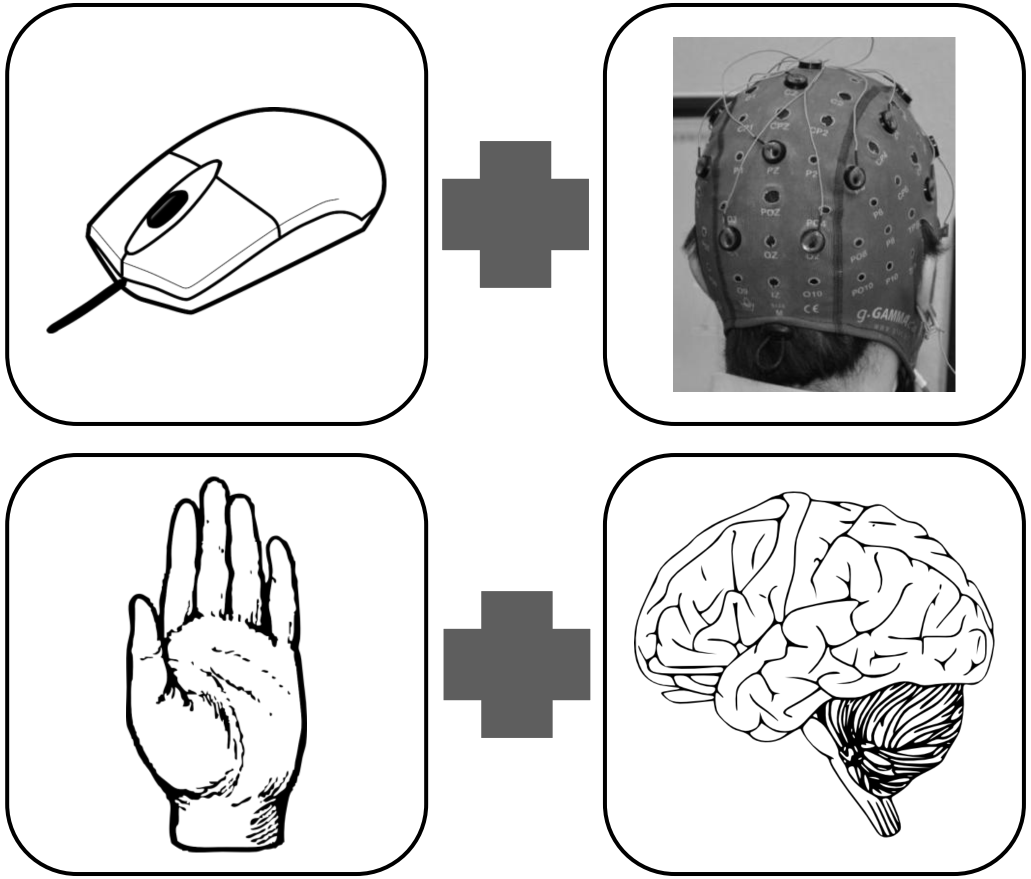
1) Conclusion

Compatibility study between a brain-computer interface and motor activity



Introduction

- Context: combined use of a BCI and another device
- Objective: influence of motor activity on BCI when manipulating a mouse
- Hypothesis: BCI performance should decrease with complexity of motor activity
- Method: user study using a virtual environment (video-game)



Brain-Computer Interface used

- Acquisition: electroencephalography (EEG)
- Signal-processing: regression-based algorithm [George et al., 2011]
    - Training: 2 sessions (relaxation vs. concentration)
    - On-line use of algorithm: automatic estimation of concentration level
- Extracted mental activities: “relaxation” vs. “concentration” mental states using a threshold

User study

- Test different levels of motor activity: from no motor activity to a highly demanding motor activity
- Test the influence on BCI performance
- Virtual environment: simplified Pac-Man video-game
- Task: eat pellets while avoiding ghosts

Experimental conditions

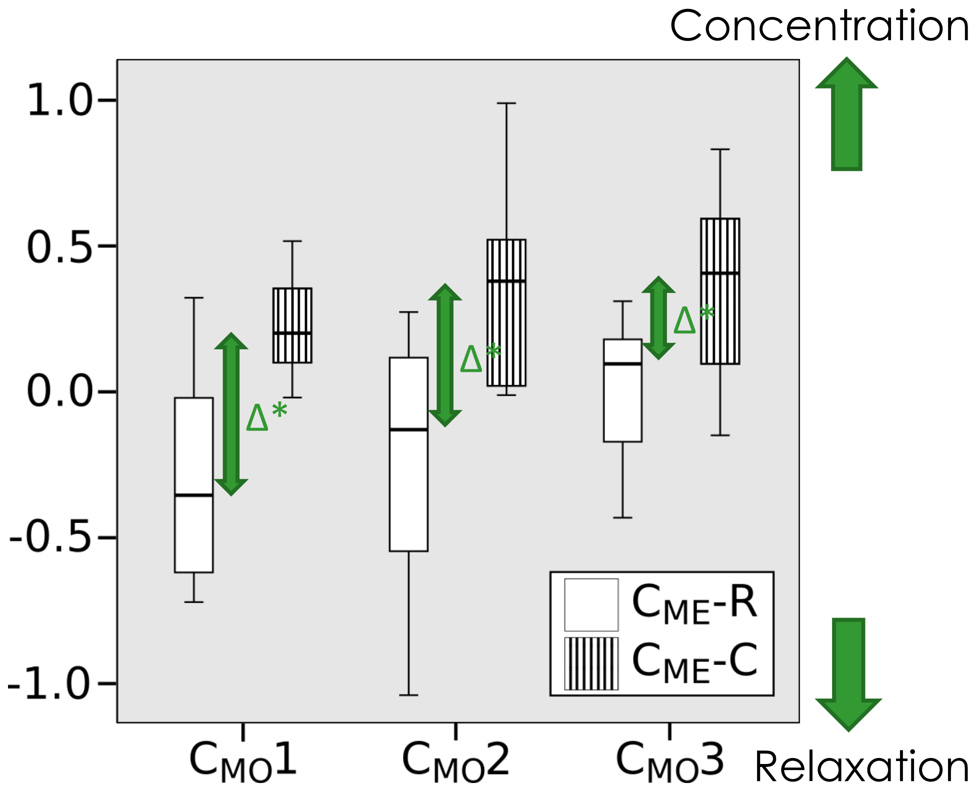
- 3 motor activity conditions:
  - $C_{MO}1$: no motor activity, no hand movement
  - $C_{MO}2$: semi-automatic motor activity, circular hand movement
  - $C_{MO}3$: highly demanding motor activity: adaptive movement

Experimental conditions

- Training: 1 min (relaxation 30 sec, concentration 30 sec, no motor activity)
- 12 trials => 3 motor act. * 2 mental act. * 2 repetitions
- Total duration: 18 min
- Participants: 7 males / 1 female, age: 21-28 (mean 24)

Regression results

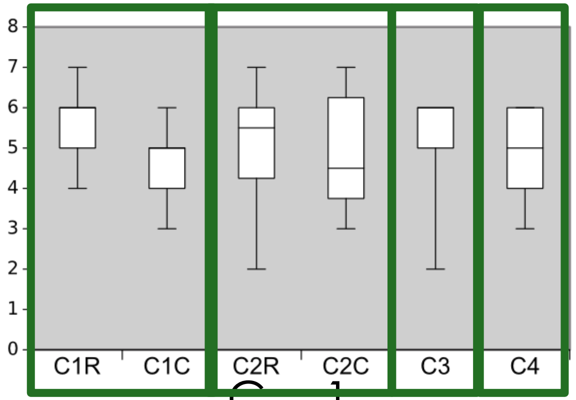
- Statistical analysis:
  mixed between-within subjects ANOVA
- Significant difference between relaxation and concentration for the different motor activities
  - $C_{MO}1(t(7) = -3,65, p = 0,008)$
  - $C_{MO}2(t(7) = -4,07, p = 0,005)$
  - $C_{MO}3(t(7) = -3,02, p = 0,019)$



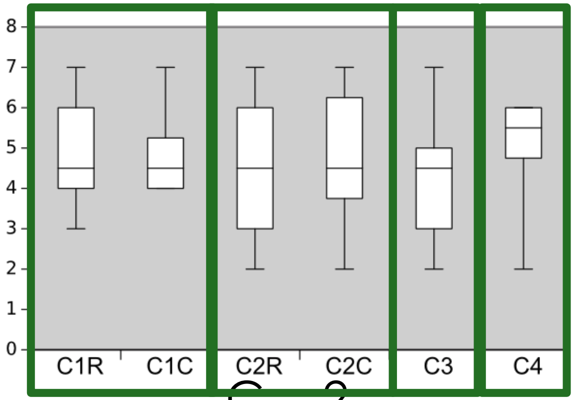
Δ*: significant result

Questionnaire results

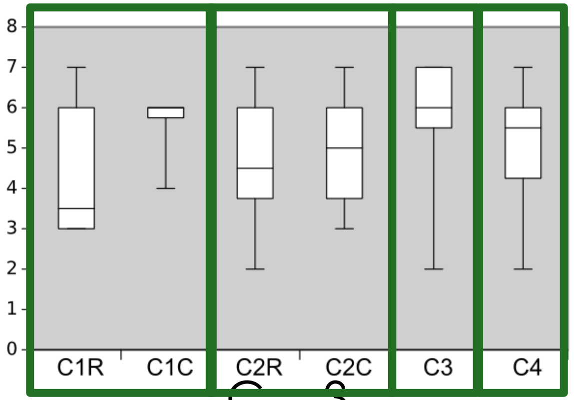
- Criteria:
  - Ability to generate mental activity (C1R, C1C)
  - Ability of the system to detect mental activity (C2R, C2C)
  - Appreciation of game conditions (C3)
  - Fatigue (C4)



$C_{MO}1$



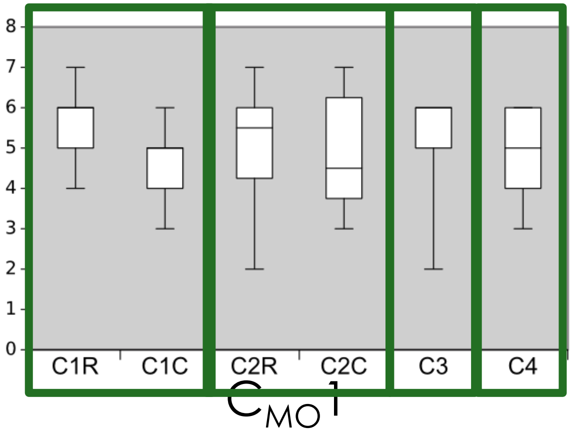
$C_{MO}2$

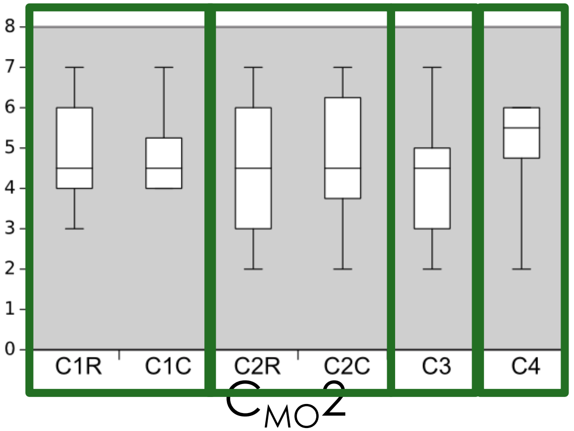


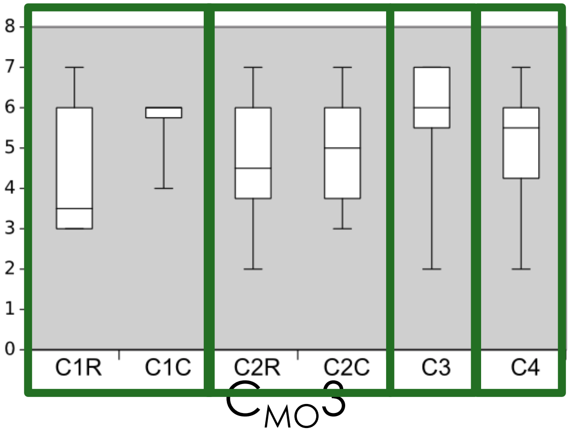
$C_{MO}3$

Questionnaire results

- Mental activity generation: no impact from motor activity detected by the participants (Friedman test: no significant difference between conditions)
- Mental activity: correctly detected
- Participants enjoyed the conditions of interaction, not too tiring

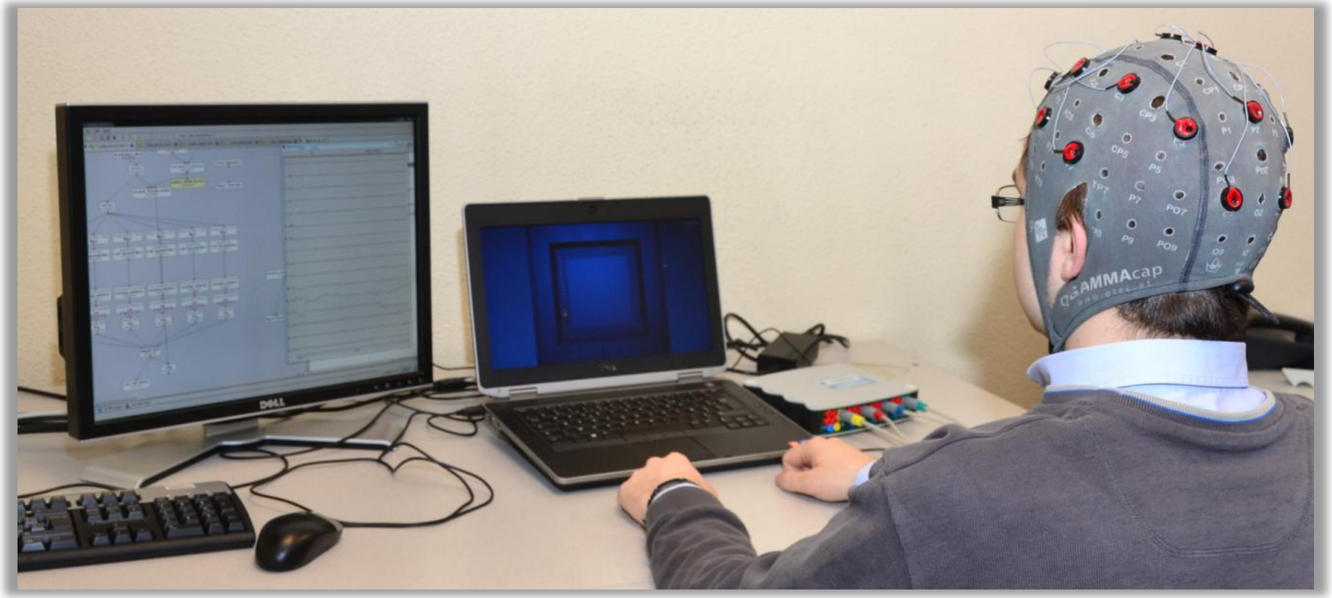






Summary

- Objective: study the influence of manipulating an input device such as a standard computer mouse on the performance of a BCI system
- Experimental study: video-game
- Result: users could control a simple BCI, even when running a highly demanding motor activity



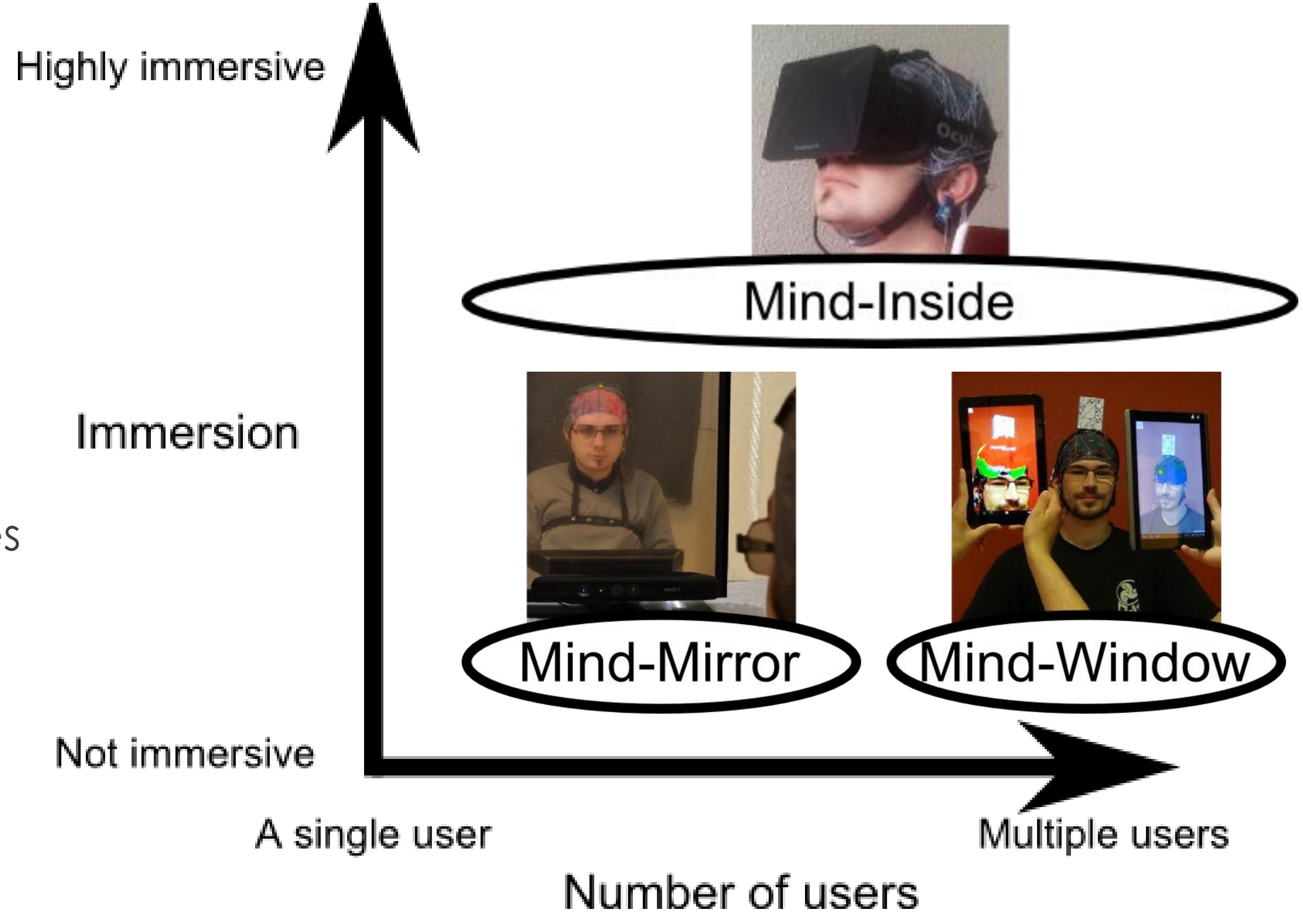
Outline

1) Related work
2) Contribution 1: compatibility study between a brain-computer interface and another input device
3) **Contribution 2: real-time brain activity visualization techniques using virtual or augmented reality**
4) Contribution 3: designing novel usages of BCIs combined with virtual/augmented reality for smart clothes
5) Conclusion

Real-time brain activity visualization using virtual or augmented reality

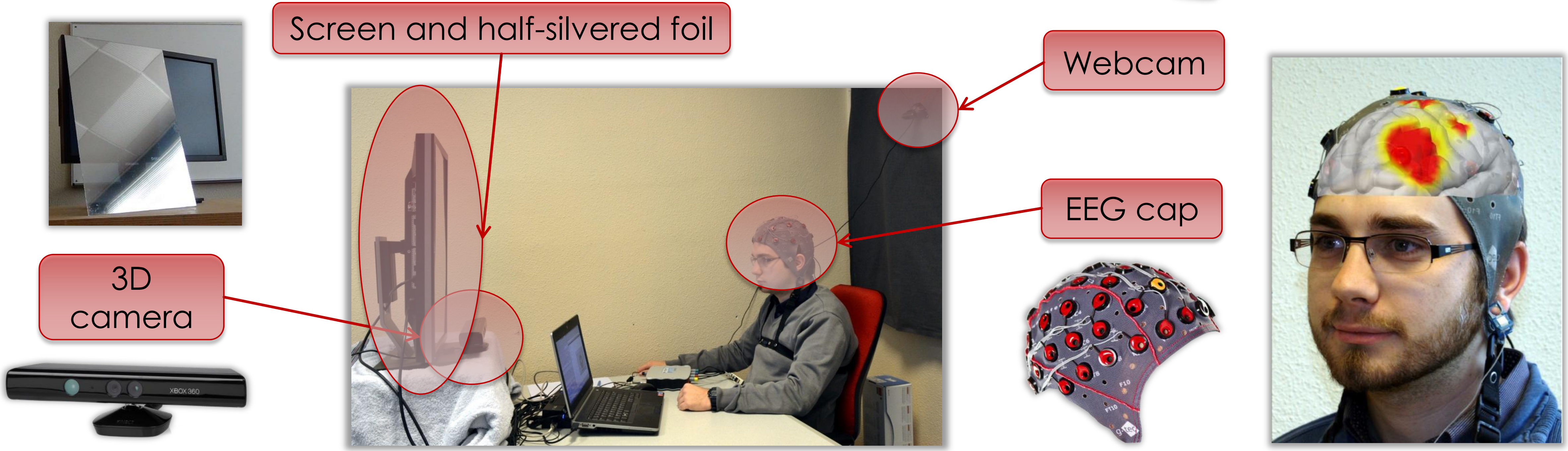
Approach

- Objective: brain activity visualization using VR/AR
- Applications:
  - Entertainment: novel user experience
  - Education: visualize/learn brain areas topography
- 3 systems with different objectives
  1) Mind-Mirror
  2) Mind-Window
  3) Mind-Inside



The Mind-Mirror

- Objective: online display of brain activity in situ as in a mirror
- Main components:



Features

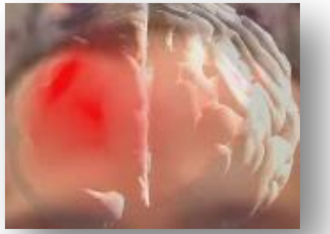
- Half-silvered foil visualization
- Rear-view using a webcam

Features

- Classification mode: concentration state (concentrate/relax)

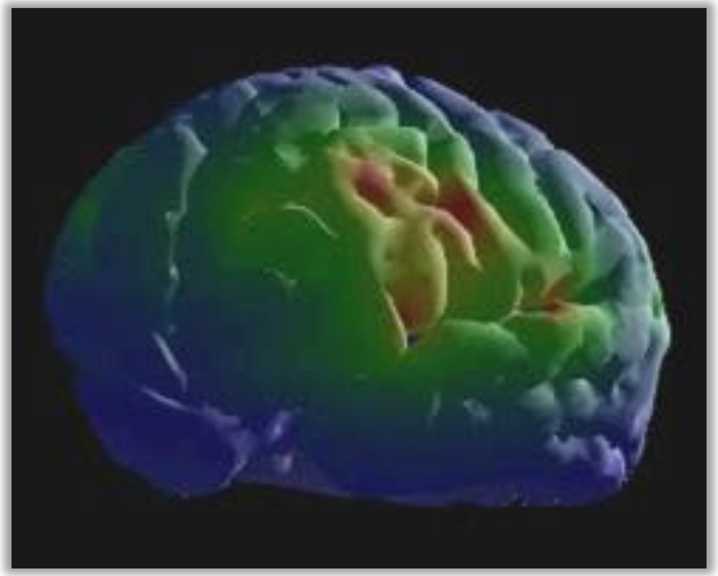
- Classifier detection:
  - **Relaxation**

  - **Concentration**

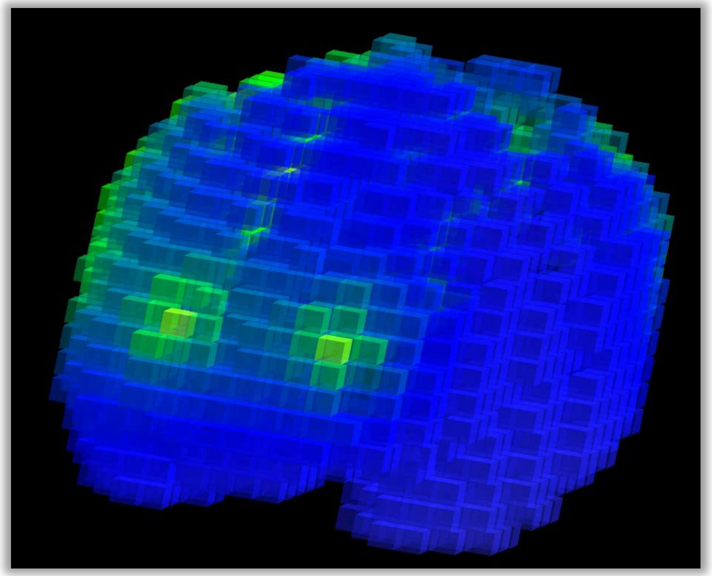


- Spatial information: brain topography

Visualization technique: topography

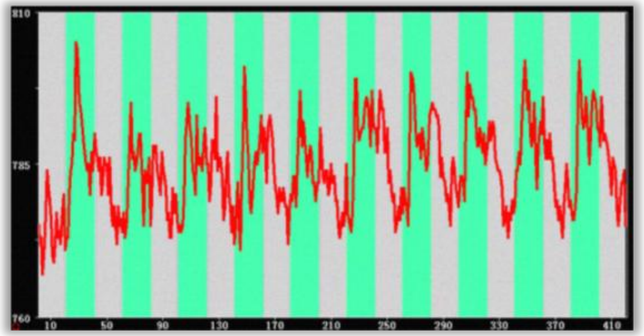


Visualization technique: voxels

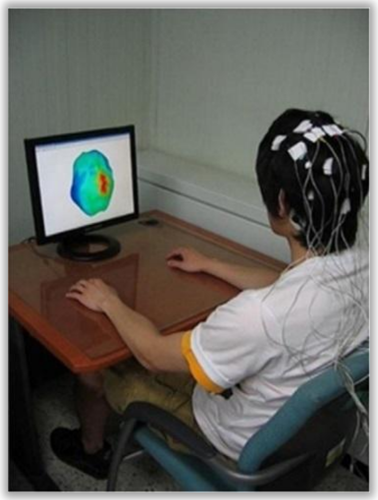


User study in neurofeedback context

- Context: neurofeedback, learn to concentrate/relax
- Neurofeedback: progressively learning to control a brain pattern while continuously observing a real-time feedback about this pattern [Demos, 2005].
  - Pathologies: attention deficit, depression, stroke, etc.
- Neurofeedback and brain visualization:
  - Simple 2D graphics Graph/Gauge [Li, 2010]
  - 2D brain image [Hwang, 2009]
- VR now used for neurofeedback [Cho et al., 2004]



[Li, 2010]

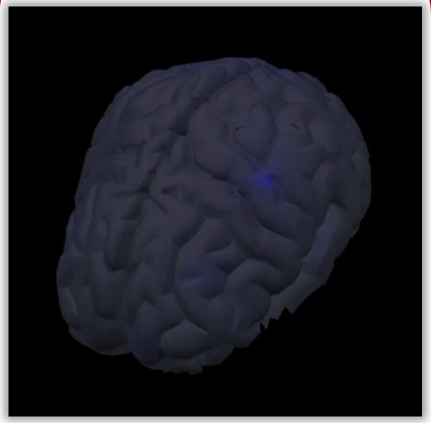


[Hwang, 2009]

User study description

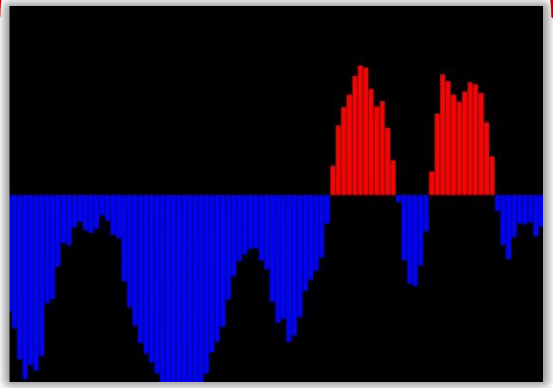
- Objective: compare the Mind-Mirror as an alternative to classical neurofeedback display systems (2D gauge)
- Population: 12 participants (aged from 21 to 30, mean 25, SD 2.8)
- Apparatus: EEG cap, subject specific model
- Task: concentrate or relax alternatively for 25 seconds each (12 repetitions)
- Conditions: Mind-Mirror, 2D gauge
- Criteria: neurofeedback performance (classification accuracy), subjective questionnaire

Mind-Mirror



(+): spatial info (topography)

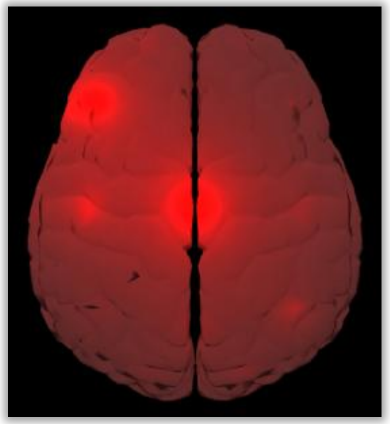
2D gauge

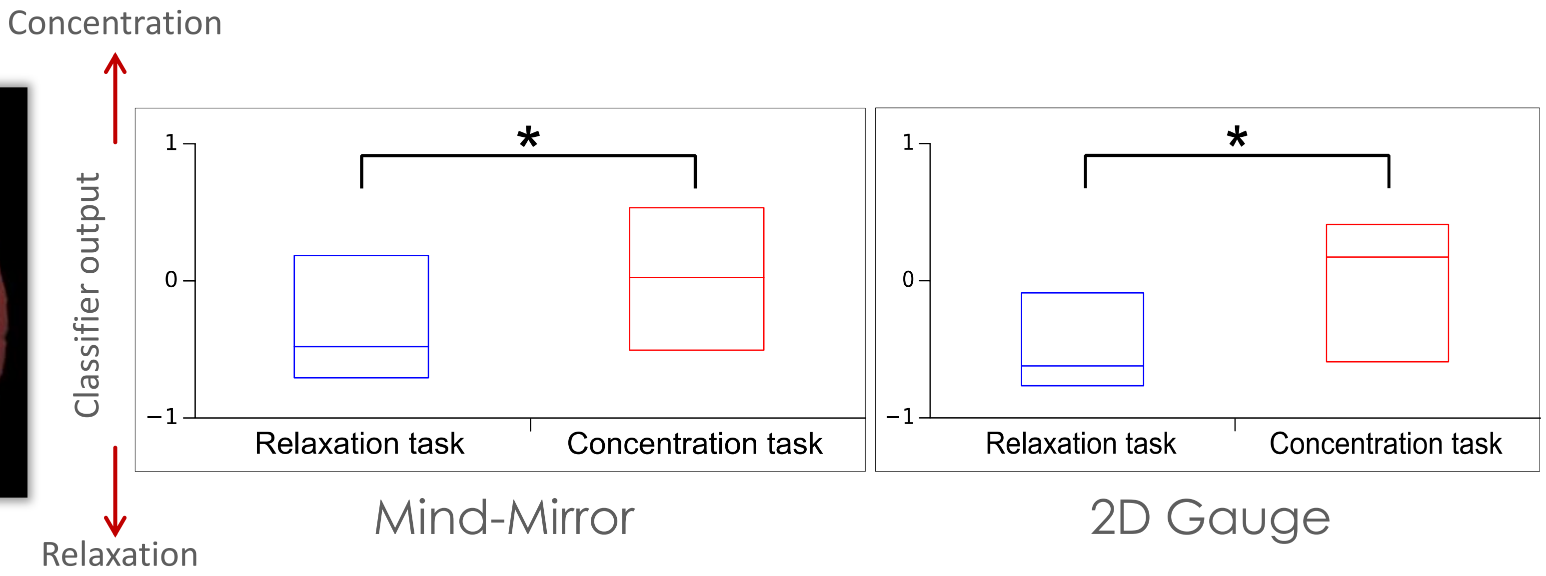


(+): temporal info (evolution)

Results (1/2)

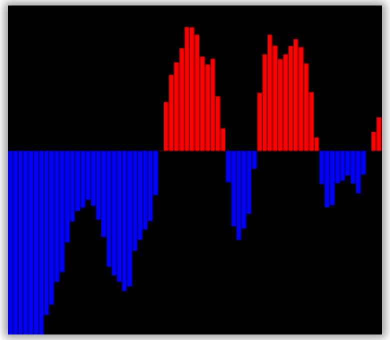
1. The system was able to detect the two different mental states (concentrate/relax) with the Mind-Mirror (significant difference)
2. No significant difference between Mind-Mirror and 2D gauge





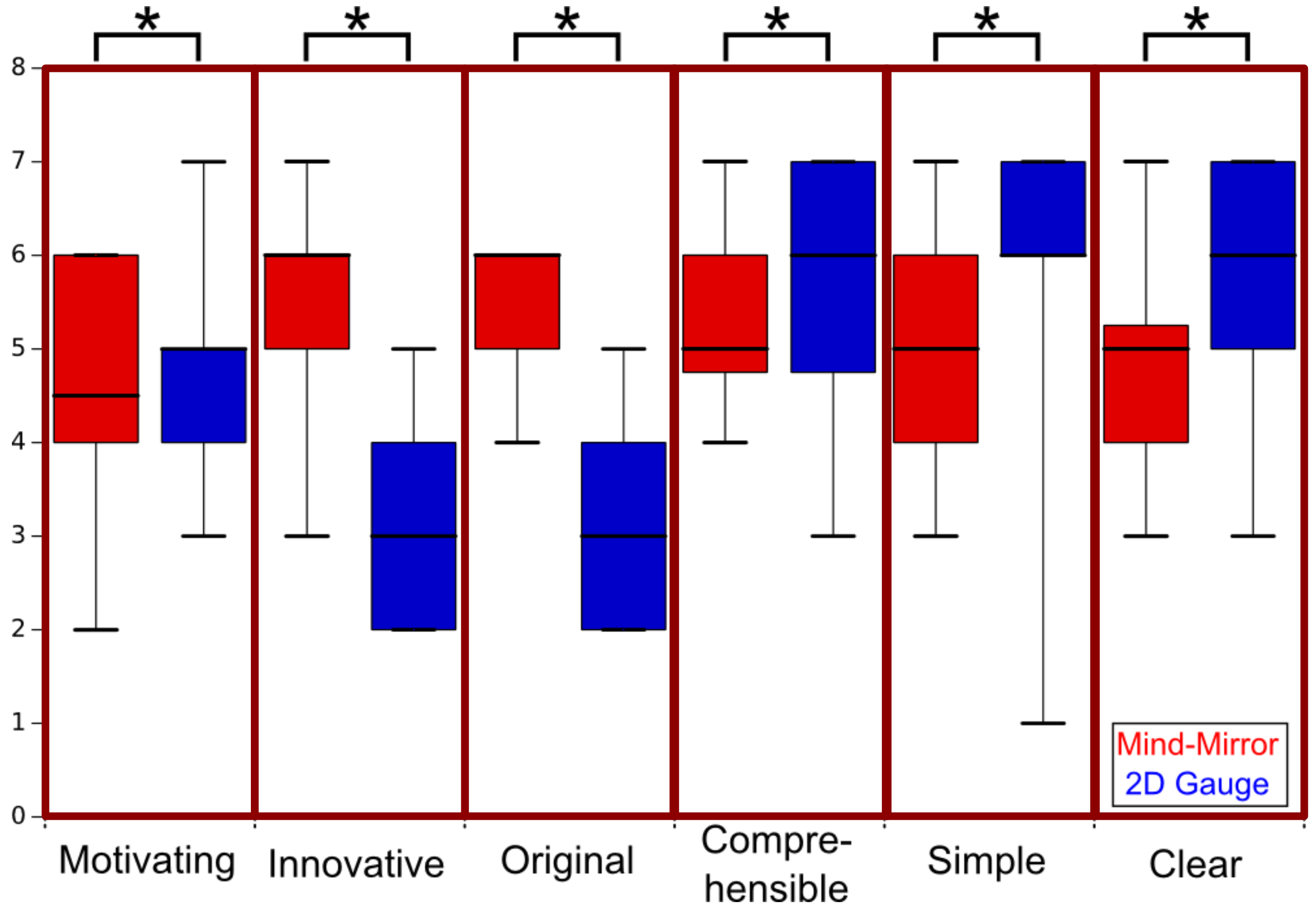
Mind-Mirror

2D Gauge



Results (2/2)

- Questionnaire:
  - Mind-Mirror pros:
    - Motivating
    - Innovative
    - Original
  - Gauge pros:
    - Comprehensible
    - Simple
    - Clear

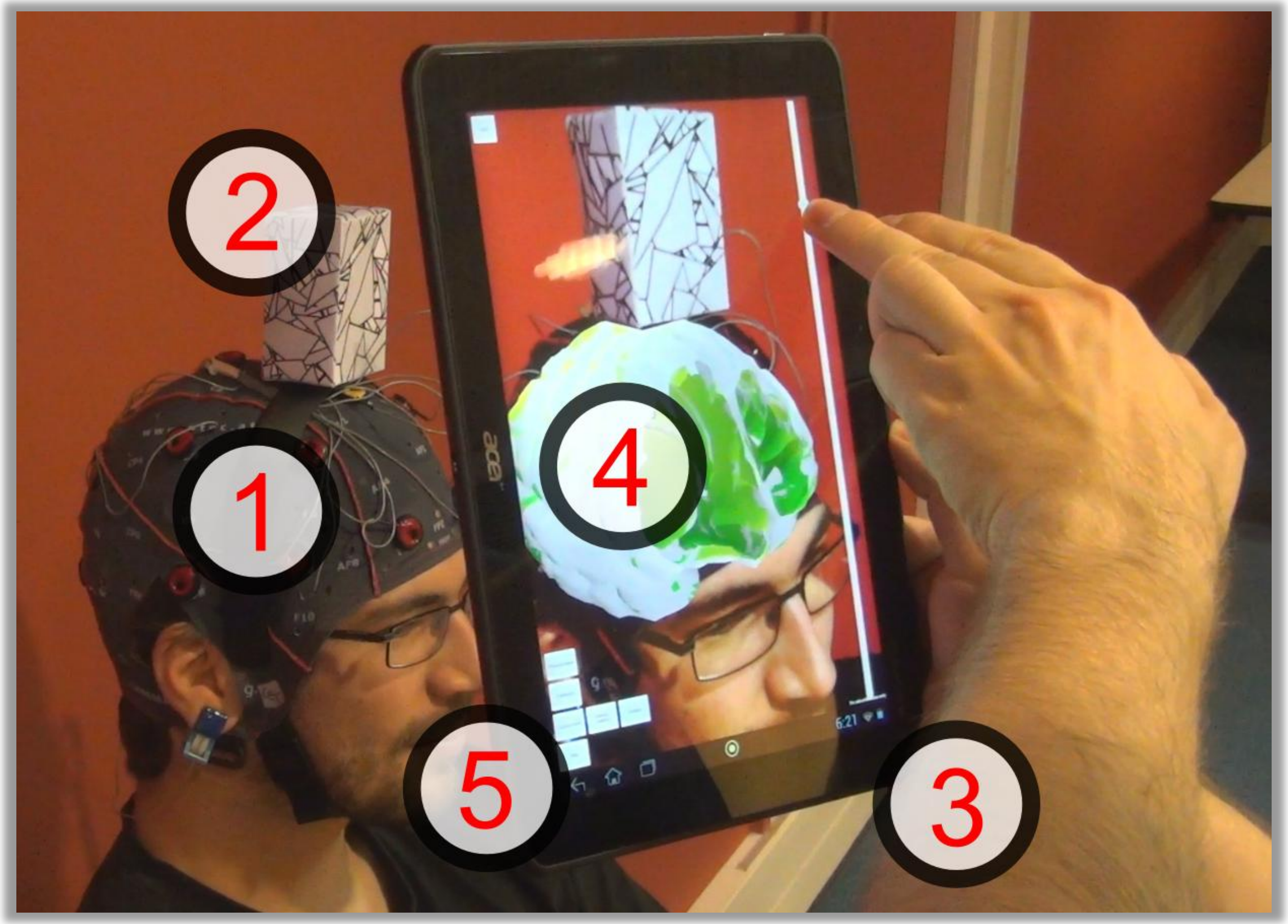


Discussion

- Participants have particularly appreciated its innovation and originality
- Some participants noticed a “slight lack of readability”
- Mind-Mirror: spatial information / 2D Gauge: temporal information
  - Future work: adding previous brain states
- Conclusion: the Mind-Mirror is a novel tool for mirror-based brain activity visualization

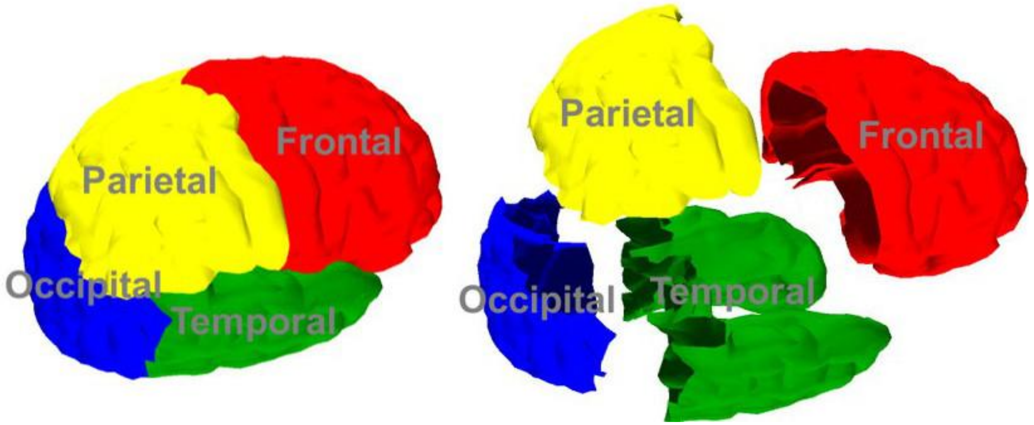
Mind-Window

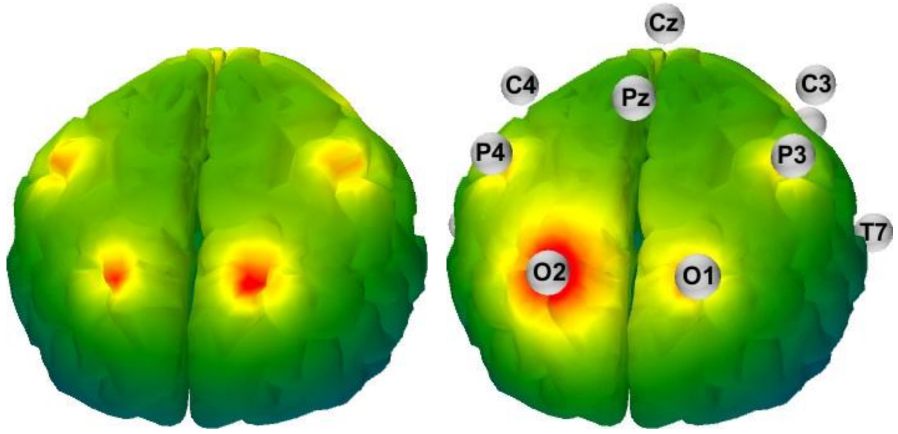
- Objective: real-time brain activity visualization for multiple users
- Approach:
  - AR
  - Tablet PCs
- Main components:
  1) EEG headset
  2) 3D marker
  3) Tablet PC
  4) Virtual brain
  5) User interface

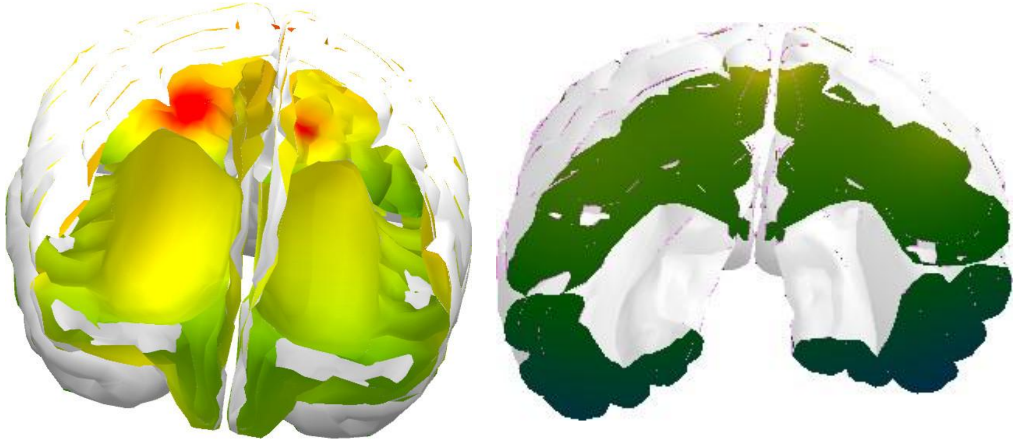


Visualization tools

- Topography + electrode names
- Cutting plane
- Brain areas







Mind-Window (video)

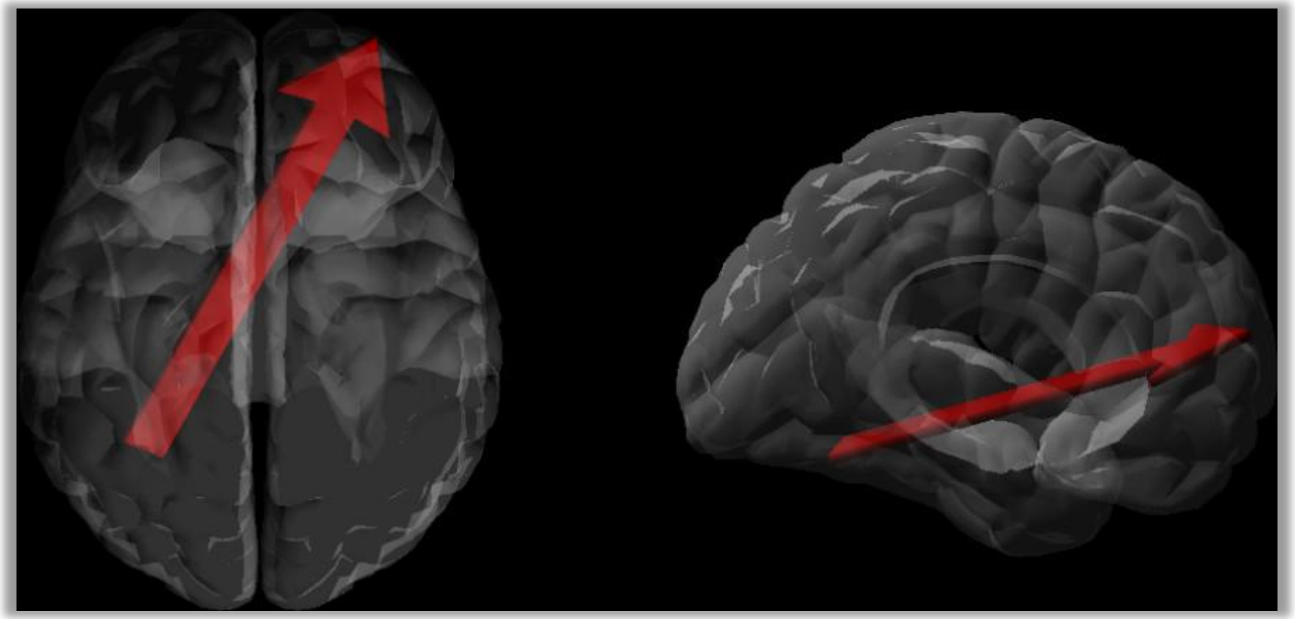
Conclusion: mobile tool for multi-user real-time brain activity visualization

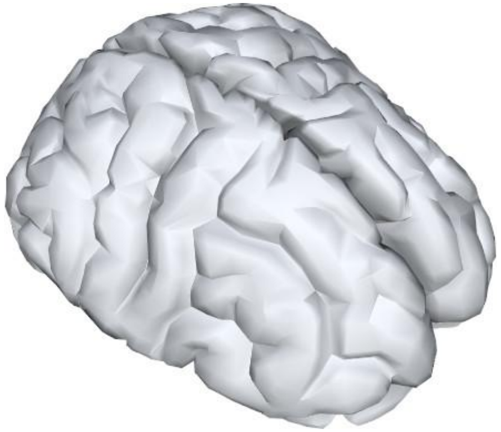
The Mind-Inside

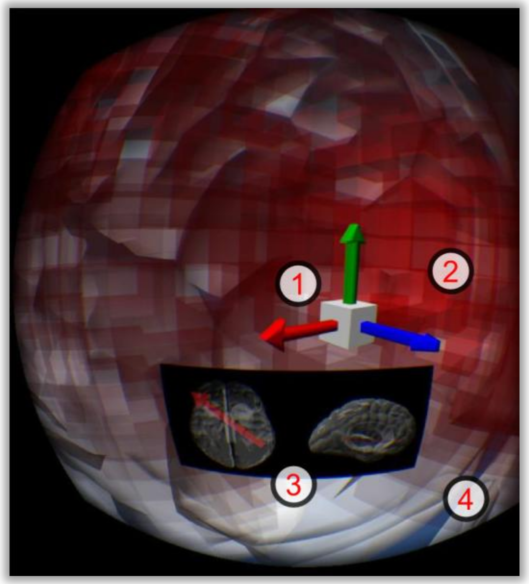
- Objective: brain activity visualization with a high immersion
- Approach:
  - Head-mounted display
  - Virtual environment

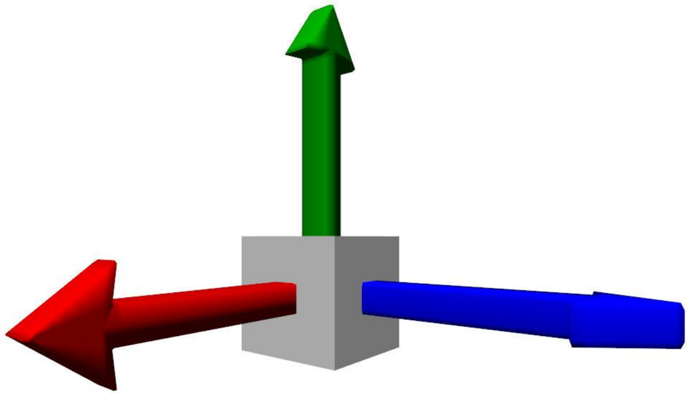
Virtual environment

1) Brain structure
2) Voxels displaying brain activity
3) Reference frame
4) Compasses

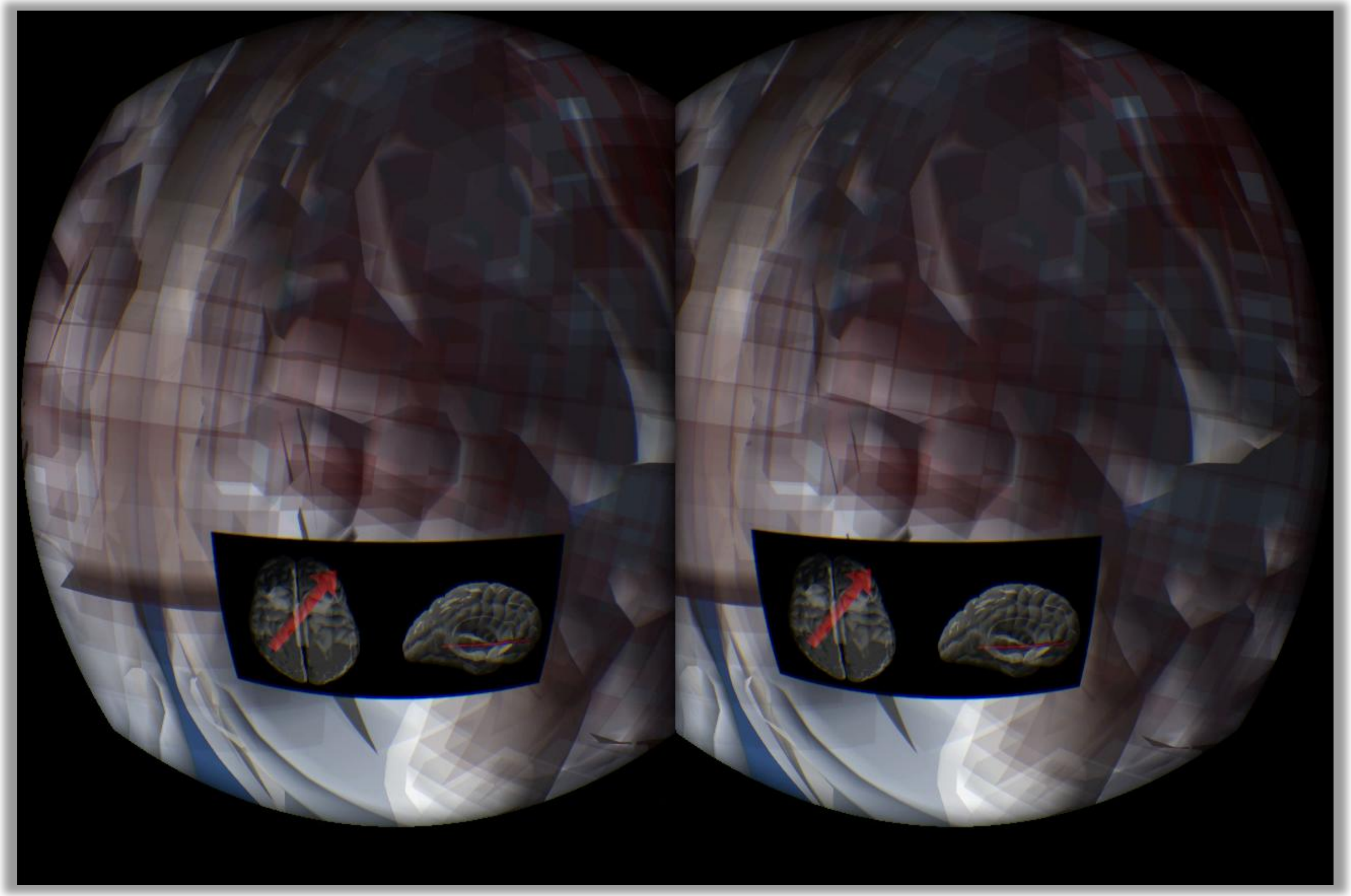








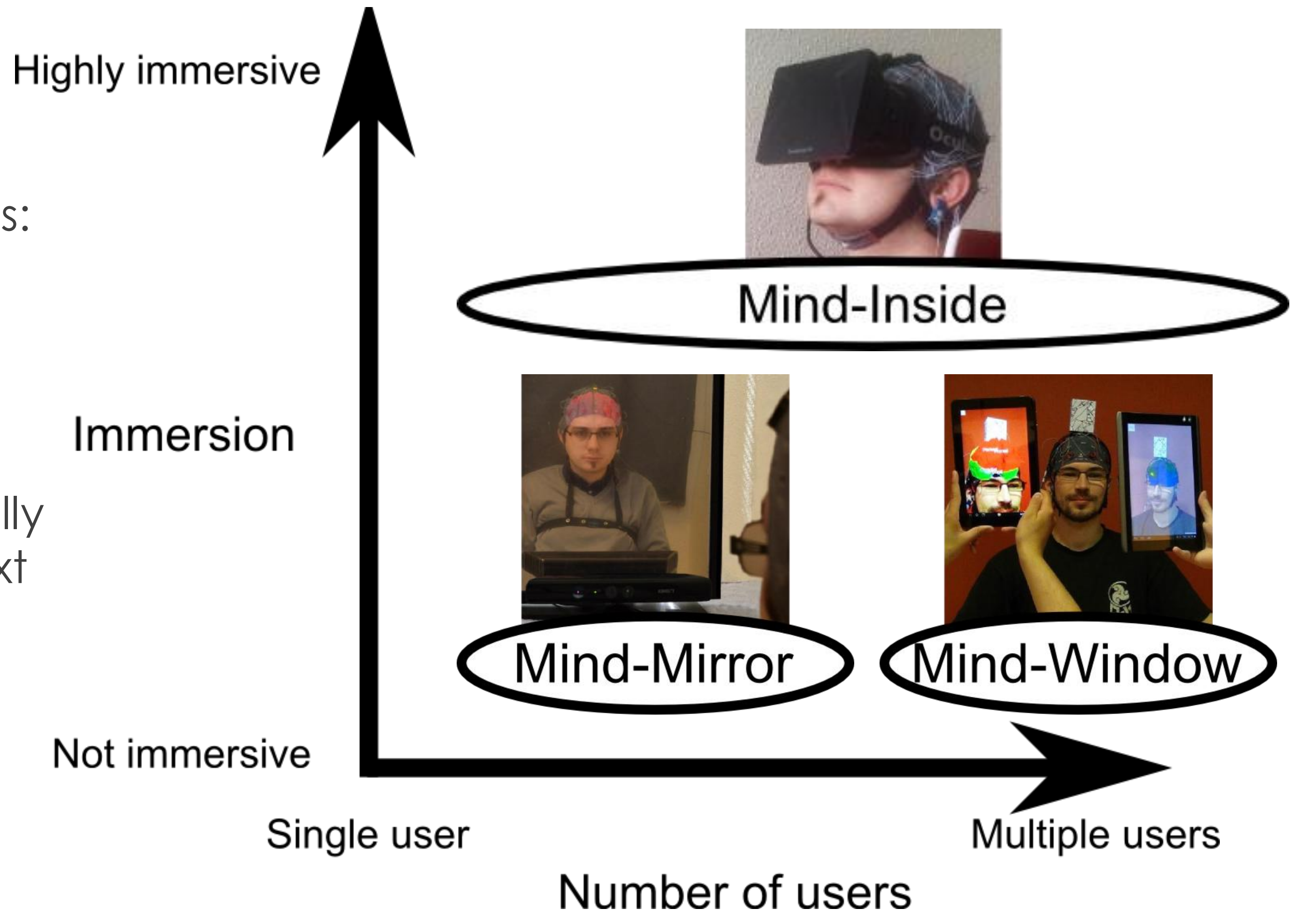
Mind-Inside (video)



Conclusion: highly immersive brain activity visualization tool

Summary

- Objective: brain activity visualization using VR/AR
- 3 systems with different objectives:
  1) Mind-Mirror
  2) Mind-Window
  3) Mind-Inside
- User study: Mind-Mirror successfully used in a neurofeedback context



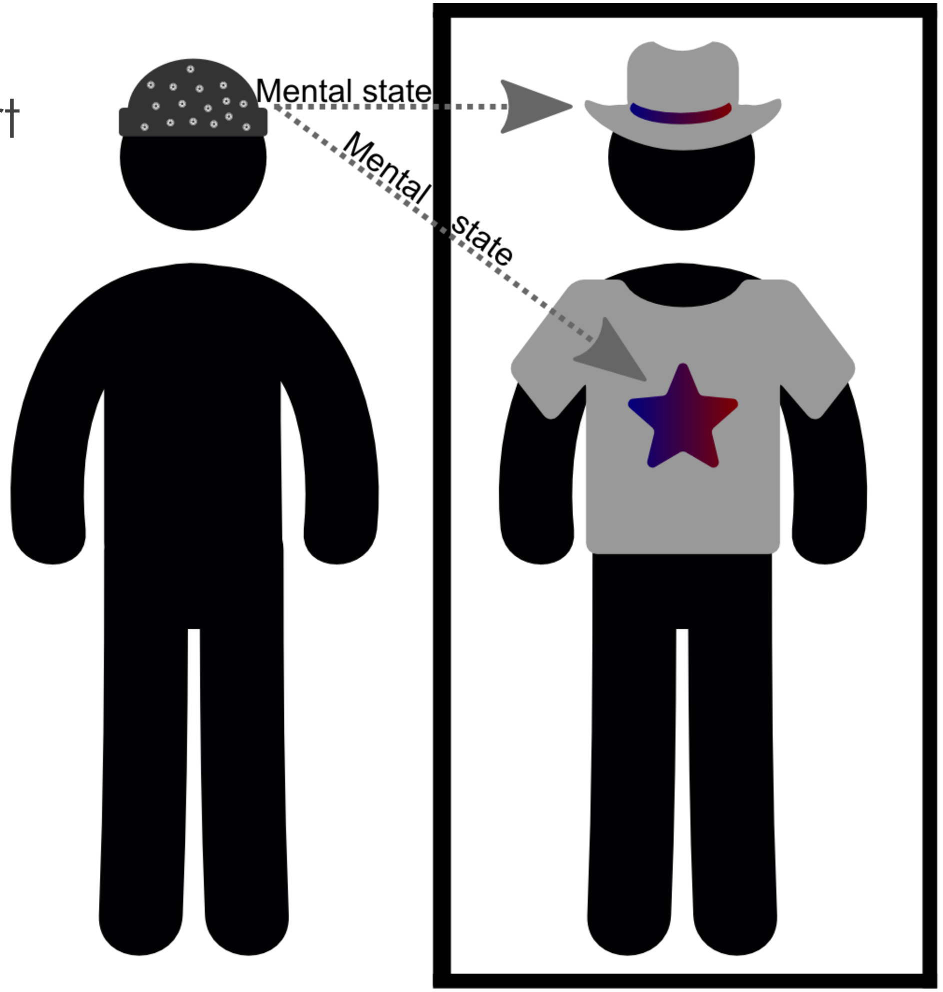
Outline

1) Related work
2) Contribution 1: compatibility study between a brain-computer interface and another input device
3) Contribution 2: real-time brain activity visualization techniques using virtual or augmented reality
4) **Contribution 3: designing novel usages of BCIs combined with virtual/augmented reality for smart clothes**
5) Conclusion

Towards smart clothes based on brain-computer interfaces and augmented reality

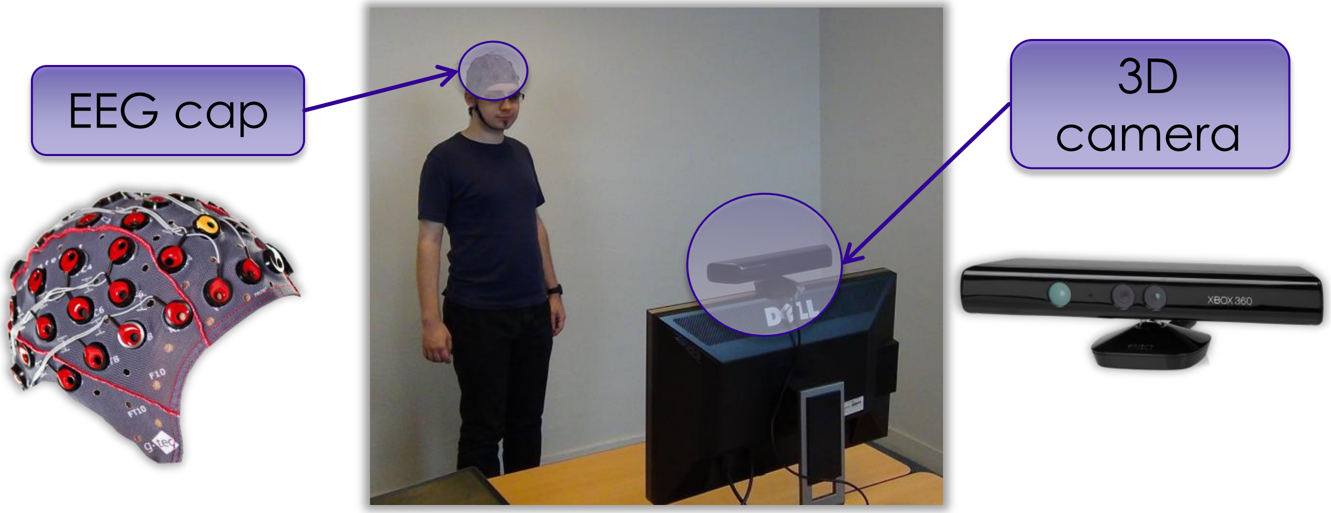
Our approach for designing virtual smart clothes using a BCI

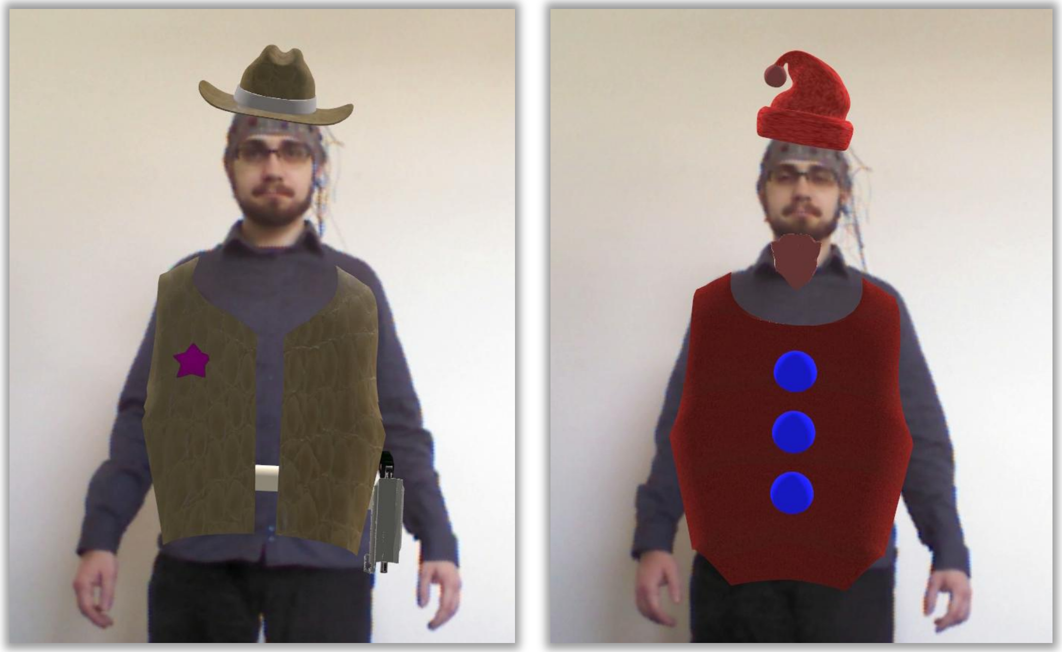
- Objective: design new concepts of smart clothes using a BCI
- Approach: use of AR
- Two-step approach:
  1. Virtual dressing room
  2. Novel smart clothes: Invisibility Cloak



Virtual dressing room

- Objective: design a testbed for virtual smart clothes controlled using mental state
- Approach: use AR and a BCI
- Components: 3D camera, EEG headset





Virtual dressing room: other rendering effects

The Invisibility Cloak

- Context: Homo Textilus and new generations of smart clothes
- Objective: novel smart clothes introducing the feeling of having an invisibility super-power, "the B-C-Invisibility Power"
- Approach: use of a BCI combined with AR
- Same system architecture as the Mind-Mirror
- Camouflage effect:
  - Camouflaging objects [Inami, 2000]
  - Camouflaging humans [Inami, 2003]

[Inami, 2000]

[Inami, 2003]

The Invisibility Cloak

- Inspiration: Harry Potter universe
- Objective: being invisible when seeing a ghost, visible when seeing an owl
- Activation: putting a hood and reaching a mental state
- Virtual elements: owl and ghost

["Harry Potter and the Philosopher's Stone", Warner Bros, 2001]

Invisibility rendering and camouflage effect

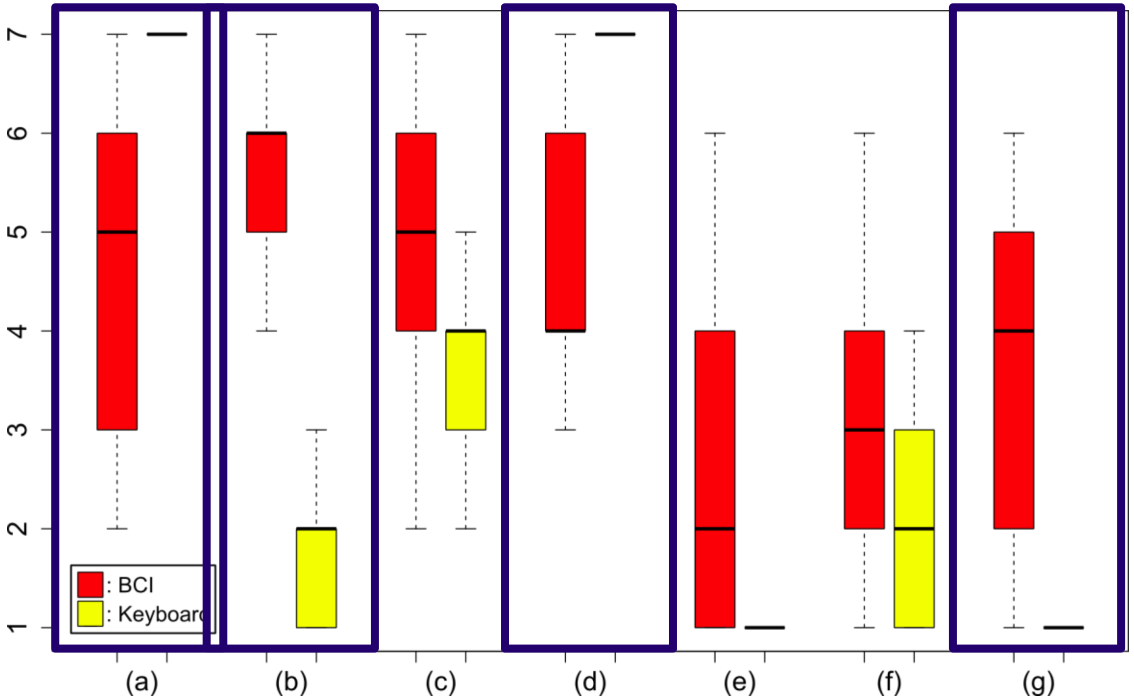
- Pre-recorded background image (camera)
- Progressive transparency of the user's cut-out image
- Occlusion with real objects
- 3D elements displayed around the user (AR)

User study

- Objective: compare a BCI to a more classical interface (keyboard) for controlling an optical camouflage
- Conditions: BCI vs. keyboard
- Task: become visible when seeing an owl, invisible when seeing a ghost
- Participants: 12 (3 females/9 males), mean age: 28
- Experimental design: 12 seconds per trial, 80 trials, total duration: 25 minutes

Results

- BCI classification: (statistical analysis using a mixed ANOVA model)
  - Significant difference between concentration / relaxation (F(1.11)=14.37, p=0.003)
  - No significant difference between visibility goals (F(1.11)=0.365, p=0.56)
- Trial success:
  - BCI: 66.9% (SD: 17.6%)
  - Keyboard: 99.15% (SD: 1,9%)
- Questionnaire: (paired-wise t-test)
  - BCI pros: innovative (b), feeling of having super-powers (g)
  - Keyboard pros: controllable (a), enough time to become (in)visible (d)



(a) Controllability, (b) Innovation, (c) Motivation, (d) Enough time to become invisible, (e) Stress level, (f) Fatigue level, (g) Feeling of having a super-power

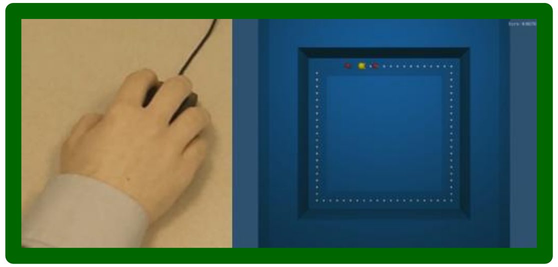
Summary

- Objective: novel concepts of smart clothes using a BCI
- Framework for designing virtual smart clothes driven by BCI: virtual dressing room
- Novel approach: the Invisibility Cloak
  - Augmented Reality-based camouflage
  - Mental “power” (B-C-Invisibility Power) based on concentration/relaxation tasks
  - User study result: BCI successfully used, BCI found innovative and closer to the “feeling of having a super-power”

Outline

Conclusion

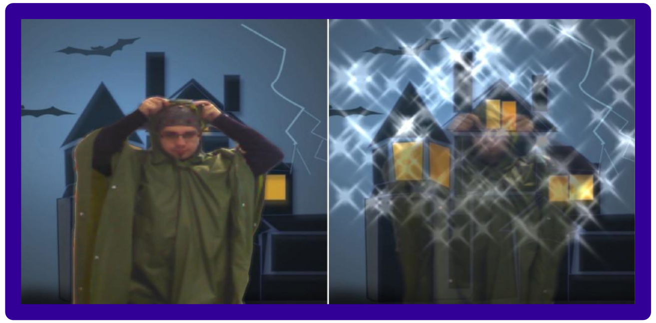
- Thesis objective: study the combination of brain-computer interfaces with virtual/augmented reality
- Contribution 1: compatibility study between a brain-computer interface and another input device



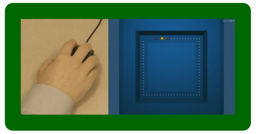
  - User study: evaluation of the performance of a brain-computer interface when performing a motor activity
  - Result: a simple BCI can be used even when performing a highly demanding motor activity

Conclusion

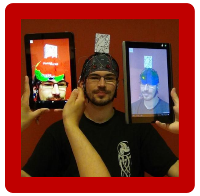
- Contribution 2: real-time brain activity visualization techniques using virtual or augmented reality
  - Mind-Mirror: in situ visualization of brain activity as in a mirror
  - Mind-Window: multi-user visualization of brain activity
  - Mind-Inside: immersive visualization of brain activity using VR
  - User study: Mind-Mirror usable in Neurofeedback context
- Contribution 3: designing novel usages of BCIs combined with virtual/augmented reality for smart clothes
  1. Framework for designing virtual smart clothes driven by BCI: virtual dressing room
  2. Invisibility Cloak: "feeling of having an invisibility super-power", inspired by Harry Potter universe



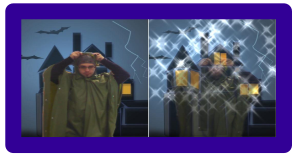
Future work



- Contribution 1: compatibility study between a brain-computer interface and another input device
  - Study more complex muscular activity: 3D motion, bimanual activities
  - Other kinds of devices: 3D user interfaces (Wii, Kinect, etc.)



- Contribution 2: real-time brain activity visualization techniques using virtual or augmented reality
  - Visualize previous brain states (temporal evolution)
  - Perform further user studies to evaluate the Mind-Window and Mind-Inside systems



- Contribution 3: designing novel usages of BCIs combined with virtual/augmented reality for smart clothes
  - Add other tracking or display devices (smartphone)
  - Combine with real smart clothes
- Long term objective: Study the impact of a rich virtual environment on the BCI performance
  - Improvement or impediment?

Publications

- **International conference papers**
  - Mercier-Ganady, J., Loup-Escande, E., George, L., Busson, C., Marchal, M., and Lécuyer, A. Can We Use a Brain-Computer Interface and Manipulate a Mouse at the Same Time?, ACM VRST, Singapore, 2013
  - Mercier-Ganady, J., Lotte, F., Loup-Escande, E., Marchal, M., and Lécuyer, A. The Mind-Mirror: See Your Brain in Action in Your Head Using EEG and Augmented Reality, IEEE VR, Minneapolis, USA, 2014
  - Mercier-Ganady, J., Marchal, M., and Lécuyer, A. B-C-Invisibility Power: Introducing Optical Camouflage Based on Mental Activity in Augmented Reality, ACM AH, Singapore, 2015
- **International conference poster**
  - Mercier-Ganady,J.,Marchal,M.,andLécuyer,A. The Mind-Window: Brain Activity Visualization Using Tablet-Based AR and EEG for Multiple Users, ACM AH, Singapore, 2015
- **Patent**
  - Lécuyer, A., Mercier-Ganady, J., Lotte, F., and Marchal, M. (2013). Système d'affichage de données caractérisant l'activité cérébrale d'un individu, procédé et programme d'ordinateur associé. Patent FR3015710A1.

Thank you for your attention

Contribution to the Study of the Use of Brain-Computer Interfaces in Virtual and Augmented Reality

Jonathan Mercier-Ganady