Evaluation and Development of Consciousness in Artificial Cognitive Systems

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  - What is consciousness?
  - Working hypotheses
  - Objectives
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What is consciousness?

“The state of being characterized by sensation, emotion, volition, and thought”

“The quality or state of being aware especially of something within oneself”

Self-consciousness
Consciousness in Artificial Cognitive Systems

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What is consciousness?

Senses ↔ Conscious Experience
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What is consciousness?
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What is consciousness?
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What is consciousness?

Bistable Perception
What goes on inside the brain when we perceive the color RED?
What is consciousness?

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Light

Retina

Sensation

Spike Pattern

MIND

SESES

BRAIN

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What is consciousness?

How sensation is produced?

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What is consciousness?

Mind-Body Problem

Material Observable

Immaterial Private

BRAIN

MIND
What is consciousness?

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**Phenomenal Consciousness**

**Access Consciousness**

**Cognitive Skills**

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Phenomenal Consciousness

“Hard Problem”

Access Consciousness

“Easy Problems”

Qualia

Cognitive Functions

(Block, 1995)

(Chalmers, 1995)
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Cognitive Skills

- Functional dimension of:
  - Attention
  - Planning
  - Imagination
  - Emotions
  - Theory of Mind
  - Introspection
  - …

“Easy Problems”
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What are Qualia?

- "The redness of red"
- "Enjoying a song"
- "The taste of ice-cream"
- "A headache"
- "Hard Problem"

Integrated
Ineffable
Private
Structured
Presence
Sensations
What are Qualia?

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Working Hypotheses

What is consciousness.
How can it be scientifically studied.
How can it be measured.

Machine Consciousness
Objectives

Prove or refute the working hypotheses

Cognitive architecture based on a model of consciousness

Framework for the evaluation of the level of consciousness of artificial systems
Objectives

I. To demonstrate that phenomenal consciousness can be studied using artificial systems.
Objectives

II. To demonstrate that the functional role of consciousness is integration and adaptation.

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Objectives

III. To demonstrate that consciousness is a process, not a property of matter.
Objectives

IV. To demonstrate that there is no direct correlation between computational power and cognitive power.
Objectives

V. To demonstrate that consciousness can be scientifically studied using the *heterophenomenology* method.

(Dennett, 1991)
Objectives

V. To demonstrate that consciousness can be scientifically studied using the *heterophenomenology* method.
Objectives

VI. To demonstrate that the level of consciousness of an artificial system can be measured.
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Study of Consciousness

- Problems and Scientific Challenges
  - Applicability of the scientific method.
  - Relative immaturity.
  - Definition of consciousness.
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Study of Consciousness

Main levels of study:

- Physical Level.
- Neurobiological Level.
- Cognitive Level.
Machine Consciousness

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Human Consciousness

Analysis and Modeling

Comparison

Design and Implementation

Models of Human Consciousness

Adaptation to Computational Models

Models of Machine Consciousness

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Machine Consciousness

- Human Consciousness
  - Analysis and Modeling
  - Comparison

- Machine Consciousness
  - Design and Implementation

- Models of Human Consciousness
  - Adaptation to Computational Models

- Models of Machine Consciousness
  - Neural Networks
  - Hybrid Systems
  - Cognitive
Machine Consciousness

- Artificial Neural Networks

- Hybrid Systems
  - ANN, RBS, GA, ...

- Cognitive Architectures
  - IDA (Franklin, 1998), LIDA (Franklin, 2007),
  - CogPrime (Goertzel, 2009),
  - Haikonen (Haikonen, 2007),
  - CRONOS (Holland, 2007),
  - CiceRobot (Chella, 2009),
  - ...

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Machine Consciousness

Main Areas of Application

- Cognitive Robotics.
- Synthetic Phenomenology (Chrisley, 2009).

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Measuring Consciousness

- Main Approaches:
  - In humans.
  - In other animals.
  - In machines.

- Main Tools:
  - Verbal report.
  - Observed behavior.
  - Neurophysiologic markers (EEG, fMRI, JFK-revised, etc.).

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Measuring Consciousness

- Problems
  - Verbal report?
  - Neurophysiologic markers?
  - Observed behavior?

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Measuring Machine Consciousness

- Extant proposals:
  - Turing Test (Turing, 1950).
  - Cognitive tests (mirror test [Gallup, 1977]).
  - Axioms (Aleksander, 2003).
  - Ordinal Probability Scale (Gamez, 2005).
  - Information Integration $\Phi$ (Tononi, 2008).
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CERA-CRANIUM

- Framework for the experimentation with Cognitive Models of Machine Consciousness (CMMC).

- Applicable to different agents.
- Applicable to different domains.

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CERA-CRANIUM

- CERA
  (Conscious and Emotional Reasoning Architecture)
  - Layered control architecture.

- CRANIUM
  (Cognitive Robotics Architecture Neurologically Inspired Underlying Manager)
  - Runtime environment for the creation and management of large amounts of parallel processes that share a common workspace.

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CERA-CRANIUM

- Inspired by cognitive theories
  - Global Workspace Theory (Baars, 1988, 1997).

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CERA-CRANIUM

- Inspired by cognitive theories
- Multiple Draft Model (Dennett, 1991)
CERA-CRANIUM

- Both metaphors agree that:

  “A set of specialized processors compete/collaborate in order to generate the conscious contents of the mind”.

- CERA-CRANIUM provides a specific design and implementation.
CERA provides answers for these questions:

- What should be the next action?
- What should be the next conscious content of the mind?
CRANIUM

- SWS (Shared Workspace).

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CERA supports two flows of information:

- **Bottom-Up**: Perception.
- **Top-Down**: Action.

CERA

- **Introduction**
- **State of the Art**
- **CERA-CRAINUM**

Consciousness in Artificial Cognitive Systems
Consciousness in Artificial Cognitive Systems

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![Diagram of Bottom-Up Flow]

- **Bottom-Up Flow:**
  - Percept Generation.

---

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CERA-CRANIUM

- Top-Down Flow:
- Action Generation.

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- Specialized Processors
  - Preprocessors
  - Aggregators
  - Planners
  - Forecasters
  - ...

WORLD

AGENT

CERA S-M

Crash

Contact Sensor

Contact Sensor Service

Simple Percepts

Actions

Simple Behavior

CERA Physical Layer

(1)

ETC

Complex Percepts

(2)

Simple Percepts

Reactive Processor

Percept Aggregator

Action Planner

Crash

Contact Sensor

Motor Control

Contact Sensor Service

Simple Percepts

Actions

Simple Behavior

CERA Physical Layer

(1)

ETC

Complex Percepts

(2)

Simple Percepts

Reactive Processor

Percept Aggregator

Action Planner

Contact Sensor

Simple Percepts

Actions

Simple Behavior

CERA Physical Layer

(1)

ETC

Complex Percepts

(2)

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Reactive Processor

Percept Aggregator

Action Planner

Contact Sensor

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Action Planner
CC-Bot Example
CERA-CRANIUM

- Control loops:
  - Adaptive responses at different levels.

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  - Representation

Knowledge Representation

- Readings → Simple P. → Complex P.
- Indexed percepts: $j, t \rightarrow J \rightarrow CJ$

---

**CERA-CRANIUM**

- **Sensor Preprocessors**
  - $N(\delta S_j)$
  - Timer
  - Proprioception

- **Percept Aggregators**
  - Physical Layer
  - $M(S_{C,j})$

---

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Knowledge Representation

- Simple Behavior $\rightarrow$ Atomic A. $\rightarrow$ Simple A.
- Indexed Behaviors: $CI \rightarrow I \rightarrow j, t$
Contextualization

- **Bottom-Up:**
  - “Native” context application, such as spatiotemporal contexts.

- **Top-Down:**
  - Specific context induction from the Core Layer.
Modulation

- Modulation induced by Core Layer:
  - Context Commands.
  - **CJ-index**: Region of interest within the sensorimotor space of the agent.

![Diagram showing the Modulation process]

- **Context Commands**
- **Calculation of next Contextual CJ-index**
- **Core Layer implementation of the Cognitive Model**
- **M(S_cj)**
- Mission percepts, Complex percepts, Novelty percepts, Mismatch percepts, ...

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Sensory Fusion Example

- Left j referent vector
- Right j referent vector
- j referent vector
- Impact
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Sensory Fusion Example

Left j referent vector
Right j referent vector

Impact

$j$ referent vector

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ConsScale

- Scale designed to measure the cognitive development of consciousness in agents.

- Based on cognitive functions synergy and the heterophenomenology approach.

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ConsScale allows the characterization of the level of development of consciousness based on:

1. An ordered list of levels (from -1 to 11).
2. A quantitative score (CQS: from 0 to 1000).
3. A graphical cognitive profile.
Consciousness in Artificial Cognitive Systems

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  - Introduction
  - Levels
  - CQS
  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
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- Conclusions

---

ConsScale

- Evaluation of the cognitive development of an agent using *ConsScale*.

![Diagram](image)

**Level:**

(3) Adaptive
Abstract Architecture

Abstract architectural components (Wooldridge, 1999):

- B, E, S, A, R, M
- Att, M^n, SsA, I, O, AR, AVR, R^n

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Cognitive Skills (CS\textsubscript{i,j})

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<th>Cognitive Skills</th>
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<td>CS\textsubscript{2,1}: Fixed reactive responses (&quot;reflexes&quot;).</td>
</tr>
<tr>
<td>3</td>
<td>CS\textsubscript{3,1}: Autonomous acquisition of new adaptive reactive responses.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{3,2}: Usage of proprioceptive sensing for embodied adaptive responses.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{3,3}: Selection of relevant sensory / motor / memory information.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{3,4}: Evaluation (positive or negative) of selected objects or events.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{3,5}: Selection of what needs to be stored in memory.</td>
</tr>
<tr>
<td>4</td>
<td>CS\textsubscript{4,1}: Trial and error learning. Re-evaluation of selected objects or events.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{4,2}: Directed behavior toward specific targets like following or escape.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{4,3}: Evaluation of the performance in the achievement of a single goal.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{4,4}: Basic planning capability: calculation of next n sequential actions.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{4,5}: Ability to build depictive representations of percepts for each available sensory modality.</td>
</tr>
<tr>
<td>5</td>
<td>CS\textsubscript{5,1}: Ability to move back and forth between multiple tasks.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{5,2}: Seeking of multiple goals.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{5,3}: Evaluation of the performance in the achievement of multiple goals.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{5,4}: Autonomous reinforcement learning (emotional learning).</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{5,5}: Advanced planning capability considering all active goals.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{5,6}: Ability to generate selected mental content with grounded meaning integrating different modalities into differentiated explicit percepts.</td>
</tr>
<tr>
<td>6</td>
<td>CS\textsubscript{6,1}: Self-status assessment (background emotions).</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{6,2}: Background emotions cause effects in agent’s body.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{6,3}: Representation of the effect of emotions in organism and planning (feelings).</td>
</tr>
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<td>CS\textsubscript{6,4}: Ability to hold a precise and updated map of body schema.</td>
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<tr>
<td></td>
<td>CS\textsubscript{6,5}: Abstract learning (learned lessons generalization).</td>
</tr>
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<td></td>
<td>CS\textsubscript{6,6}: Ability to represent a flow of integrated percepts including self-status.</td>
</tr>
<tr>
<td>7</td>
<td>CS\textsubscript{7,1}: Representation of the relation between self and perception / action / feelings.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{7,2}: Self-recognition capability.</td>
</tr>
<tr>
<td></td>
<td>CS\textsubscript{7,3}: Advance planning including the self as an actor in the plans.</td>
</tr>
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<td></td>
<td>CS\textsubscript{7,4}: Use of imaginational states in planning.</td>
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### Cognitive Skills (CS_{i,j})

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Cognitive Skills

- Cognitive skills associated with consciousness:
  - Theory of Mind (Vygotsky, 1980).
  - Executive Function (Perner, 1999).
  - Modulating Function of Emotions (Damasio, 1999).
  - Learning Mechanisms.
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Cognitive Skills

- Cognitive Hierarchy for the Theory of Mind (Lewis, 2003):

  - “I know”
  - “I know I know”
  - “I know you know”
  - “I know you know I know”

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Cognitive Skills

- Cognitive Hierarchy of the Executive Function:

- Perception
- Adaptation
- Attention
- Set Shifting
- Planning
- Imagination

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Cognitive Skills

- Cognitive Hierarchy of Emotions:
Cognitive Skills

- Cognitive Hierarchy of Learning:
Cognitive Skills

- Cognitive Hierarchy characterizes as a poset \((\text{CSS}, <)\).

\[
\text{CS}_{6,1-6} < \text{CS}_{7,1-5} < \text{CS}_{8,1-4} < \text{CS}_{9,1-2}
\]

- \(\text{CS}_{6,1-6}\) ("I know") < \(\text{CS}_{7,1-5}\) ("I know I know")
- \(\text{CS}_{7,1-5}\) ("I know I know") < \(\text{CS}_{8,1-4}\) ("I know you know")
- \(\text{CS}_{8,1-4}\) ("I know you know") < \(\text{CS}_{9,1-2}\) ("I know you know I know")

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Cognitive Skills

CS7,4: Self-recognition capability.

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Habilidades Cognitivas

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ConsScale Levels

- **Super-conscious**
- **Human-like**
- **Social**
- **Empathic**
- **Self-conscious**
- **Emotional**
- **Executive**
- **Attentional**
- **Adaptive**
- **Reactive**
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**Level -1. Disembodied**

- Behavior: not a situated agent.
- Phylogeny: amino acid.
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Level 0. Isolated

- Behavior: not a situated agent.
- Phylogeny: isolated chromosome.
Level 1. Pre-Functional

- Behavior: not a situated agent.
- Phylogeny: dead bacteria.

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Level 2. Reactive

- Behavior: reflexes.
- Phylogeny: virus.
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Level 3. Adaptive

- Behavior: learning of new reflexes.
- Phylogeny: earthworm.
Level 4. Atenttional

- Phylogeny: fish.
Level 5. Executive

- Phylogeny: quadruped mammal.
Level 6. Emotional

- Behavior: modulated by feelings. “I know”.
- Phylogeny: monkey.
Level 7. Self-conscious

- Phylogeny: monkey.
Level 8. Empathic

- Behavior: making of tools and social. “I know you know”.
- Phylogeny: chimpanzee.

“others”

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Level 9. Social

- Behavior: linguistic capabilities. Culture. “I know you know I know”.
- Phylogeny: human.

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Level 10. Human-like

- Phylogeny: human.

Introduction

State of the Art

CERA-CRANIUM

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Artificial Qualia

Experimentation

Conclusions
Level 11. Super-conscious

- Behavior: several coordinated threads of consciousness.
- Phylogeny: n/a.
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<tr>
<td>745.74</td>
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<tr>
<td>524.54</td>
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<td>341.45</td>
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<td>200.03</td>
<td>7</td>
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<td>101.08</td>
<td>6</td>
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<tr>
<td>41.23</td>
<td>5</td>
</tr>
<tr>
<td>12.21</td>
<td>4</td>
</tr>
<tr>
<td>2.22</td>
<td>3</td>
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**CQS Quantitative Score**

- $L_i$  
  Score for each $i$ level.

- **CLS**  
  Cumulative score.

- **CQS**  
  *ConsScale* Quantitative Score.
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CQS Quantitative Score

\[ L_i = \begin{cases} 0 & \text{if } ncsf \text{ is 0} \\ \frac{(ncsf + (J - J_i))^3}{10^3} & \text{otherwise} \end{cases} \]

\[ J_i = 10 \]

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CQS Quantitative Score

\[ CLS = \sum_{i=2}^{11} \left( \frac{L_i}{i - 1} \right)^2 \]
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CQS Quantitative Score

\[ CQS = \frac{e^{(CLS^5/K)}}{10} + a \]
An agent is said to comply with level $n$ if and only if it satisfies both $n$ and all lower levels.

Agent L3
Level: 3 – Adaptive (canonical)
CQS: 2.22

Agent L3+
Level: 3 – Adaptive (non-canonical)
CQS: 9.04

Agent L4
Level: 4 – Attentional (canonical)
CQS: 12.21
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**ConsScale Instantiation**

![Diagram](https://example.com/diagram.png)

- **Agent**
- **Problem Domain Definition**
- **Analysis of the Architecture**
- **Domain-specific Cognitive Tests**

**ConsScale**

- **Cognitive Skills**
  - **Instantiation**
    - \( \text{CS}_{i,j} \rightarrow \text{BP}_{i,j} \)

**Generic Cognitive Skills** (\( \text{CS}_{i,j} \)) \rightarrow **Domain-specific** (\( \text{DCS}_{i,j} \))

**Domain-specific CS \rightarrow Behavior Profiles** (\( \text{BP}_{i,j} \))

**Behavior Profiles \rightarrow Behavioral Tests**

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ConsScale FPS
First-Person Shooter Video Game Bots

- **DCS\textsubscript{3,3}**: Ability to ignore sensory input not critical to current task.
- **BP\textsubscript{3,3}**: Bot ignores detected ammo reloading kits when involved in a firefight and no more ammo is needed.
Consciousness in Artificial Cognitive Systems

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  - Cognitive Profiling
  - Instantiations
- Artificial Qualia
- Experimentation
- Conclusions

**ConsScale Calculator**

![ConsScale Calculator](image)

- **Architectural Level**
  - (5) Executive
- **ConsScale Level**
  - (3) Adaptive

**CQS (0 - 1000)**

<table>
<thead>
<tr>
<th>Level</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.27086319</td>
<td>2.94</td>
</tr>
</tbody>
</table>

**Remarks**

- Potential arch. level: 5
- Level3
- Reset
- Report

**Level 4, Attentional**

- $L_1 = 0.421875$
- Check/Uncheck All
- $CS_{5,1}$: Trial and error learning. Re-evaluation of selected objects or events.
- $CS_{5,2}$: Directed behaviour toward specific targets like following or escape.
- $CS_{5,3}$: Evaluation of the performance in the achievement of a single goal.
- $CS_{5,4}$: Basic planning capability: calculation of next $n$ sequential actions.
- $CS_{5,5}$: Depictive representations of percepts.

**Level 5, Executive**

- $L_5 = 0.125$
- Check/Uncheck All
- $CS_{5,1}$: Ability to move back and forth between multiple tasks.
- $CS_{5,2}$: Seeking of multiple goals.
- $CS_{5,3}$: Evaluation of the performance in the achievement of multiple goals.
- $CS_{5,4}$: Autonomous reinforcement learning (emotional learning).
- $CS_{5,5}$: Advanced planning capability considering all active goals.
- $CS_{5,6}$: Ability to generate selected mental content with grounded meaning.
Contents

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✓ Artificial Qualia
☐ Experimentation
☐ Conclusions
Artificial Qualia

- How qualia can be generated in a machine?

- Would artificial qualia be comparable to human subjective experience?
Hypotheses about qualia

- They are processes that are present in relation with cognitive abilities.
- They have associated functionality.
- Qualia are the ultimate result of the perception process.
Proposed model

Stage 1
Perceptual representation of content

Stage 2
Introspective perceptual representation

Stage 3
Self-modulation and report

Sensory Data

Perceptual Content

Meta-Representation

Meta-Management

World Reconstruction

Introspection

Exteroceptive Detection

Proprioceptive Detection

Sensors (stimuli)

Somatosensory System (sensors position)

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Application to Visual Experience

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Proposed model

Stage 1
Moving dot

Stage 2
What is it like to see a moving dot

Stage 3
I report I see a moving dot ("movement")

Sensory Data
(left dot – ISI – right dot – ISI)

Perceptual Content

World Reconstruction

Modulation/Report

Meta-Management

Meta-Representation

Exteroceptive Detection

Proprioceptive Detection

Sensores Visuales (estímulo: punto blanco)

Sistema Somatosensorial (posición de los sensores)
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Domains of Experimentation

- Application of CERA-CRANIUM to the control of autonomous agents.
- Application of CERA-CRANIUM to synthetic phenomenology.
- Application of ConsScale to the evaluation of machine consciousness models and implementations.
Domains of Experimentation

- Application of CERA-CRANiUM to the control of autonomous agents.
  - CERA-CRANiUM Explorer (CC-Explorer) → Exploration task.
  - CERA-CRANiUM Chaser (CC-Chaser) → Chasing task.
  - CERA-CRANiUM Bot (CC-Bot) → FPS playing task.
CERA-CRANIUM Explorer

- Autonomous exploration (no SLAM).
- Using both simulated and real P-3DX robots.
CERA-CRANIUM Explorer

- Autonomous exploration (no SLAM).
- Use of frontal sonar ring for mapping.

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CERA-CRANIUM Explorer

- CC-Explorer implementations
  - **CCE-1**: physical layer only (obstacle avoidance reflex).
  - **CCE-2**: Attention focus toward areas free of obstacles.
  - **CCE-3**: Attention focus toward unexplored areas.
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CERA-CRANIUM Explorer

- Calculation of contextual $CJ$-index
- Rule-Based System
- Core Layer
- Global Status
- Context Commands

- SWS
- Mission Layer
- Physical Layer

- $M(S_C)$
  - Mission Percepts, Complex Percepts, Mismatch Percepts, Novelty Percepts, ...
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CERA-CRANIUM Explorer

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CERA-CRANIUM Explorer

- Physical Layer
  - SWS
- Mission Layer
  - SWS
- Context Commands
- Calculation of contextual $C_i$-index
- Rule-Based System
- Core Layer
- Global Status

Consciousness in Artificial Cognitive Systems

- Mission Percepts
- Complex Percepts
- Mismatch Percepts
- Novelty Percepts...

$M(S_C)$
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CERA-CRANIUM Explorer

CCE-2: Attention to Open Areas

- 100 sec.
- 500 sec.
- 1000 sec.
- 2000 sec.

CCE-3: Attention to Unexplored Areas

- 100 sec.
- 500 sec.
- 1000 sec.
- 2000 sec.

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CERA-CRANIUM Explorer

CCE-1 (no attention): 0.19 m²/s
CCE-2 (open areas): 0.29 m²/s
CCE-3 (unexplored): 0.36 m²/s

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CERA-CRANIUM Chaser

- Simple pursuing task.
CERA-CRANIUM Chaser

- Additional parameter for context formation:
  - \( t \) (time), \( j \) (relative position),
  - \( c \) (color), \( m \) (movement).

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CERA-CRANIUM Chaser
Multimodal Sensory Fusion

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CERA-CRANIUM Bot

- Environment
  - Unreal Tournament 2004
  - Pogamut

- Implementations
  - CC-Bot1:
    - Qualification trials at 2K BotPrize 2009.
  - CC-Bot2:
    - Winner of the 2K BotPrize 2010.
Consciousness in Artificial Cognitive Systems

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CERA-CRANIUM Bot

Mission Percepts

Simple Percepts

Mission Percepts

Sensors (game)

Proprioception (game)

Timer (game)

Attacker Detector

"I am being damaged"

"I see an enemy"

"Enemy is approaching"

"Enemy attacking"
Consciousness in Artificial Cognitive Systems

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CERA-CRANIUM Bot

BotPrize – Turing Test Adapted to FPS game

Human judges

Artificial Bots

Unreal Tournament deathmatch game

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Consciousness in Artificial Cognitive Systems

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2K BotPrize 2010 Results

- CC-Bot2 (Spain): 31.81%
- UT^2 (USA): 27.27%
- ICE-2010 (Japan): 23.33%
- Discordia (USA): 17.77%
- w00t (Germany): 9.30%

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CERA-CRANIUM Observer

Synthetic Phenomenology

- Specification of the content of conscious experience.

- Minimal implementation CERA-CRANIUM.

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CERA-CRANIUM Observer

Visual Experience

Three visual stimuli:

- **S1**: Static white object resting on a dark background.
- **S2**: White object moving along a linear trajectory.
- **S3**: Two white stationary blinking dots.
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CERA-CRANIUM Observer

Results

(a) “Object resting on the ground”

(b) “Object moving uniformly from left to right”

(c) “Ball moving back and forth”

RDS SIMULATOR

SIMULATED CAM

CERA VIEWER
Agent evaluation using ConsScale

Simplified Rating Process

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Agent evaluation using ConsScale

- LIDA. Cognitive architecture based on the GWT (Franklin, 2007).
- Haikonen. Haikonen cognitive architecture (Haikonen, 2007).
Agent evaluation using ConsScale

<table>
<thead>
<tr>
<th>ELIZA</th>
<th>CC-Bot1</th>
<th>MAFI</th>
<th>LIDA</th>
<th>Haikonen</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS2,1; CS3,3; CS3,4; CS3,5; CS9,3.</td>
<td>CS2,1; CS3,1; CS3,2; CS3,3; CS3,4; CS3,5; CS3,6; CS4,1; CS4,5; CS5,2; CS5,4.</td>
<td>CS2,1; CS3,1; CS3,2; CS3,3; CS3,4; CS3,5; CS3,6; CS3,7; CS4,1; CS4,2; CS4,3; CS4,4; CS4,5; CS5,1; CS5,2; CS6,3; CS5,4; CS5,5; CS5,6; CS6,1; CS6,2; CS6,3; CS6,4; CS6,5; CS6,6; CS7,1; CS7,2; CS7,3; CS7,6; CS8,1.</td>
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<td></td>
</tr>
<tr>
<td>CQS: 0.19</td>
<td>CQS: 0.51</td>
<td>CQS: 12.37</td>
<td>CQS: 102.27</td>
<td>CQS: 114.39</td>
</tr>
<tr>
<td>2 (reactive)</td>
<td>2 (reactive)</td>
<td>4 (attentional)</td>
<td>6 (emotional)</td>
<td>6 (emotional)</td>
</tr>
</tbody>
</table>

Consciousness in Artificial Cognitive Systems

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Consciousness in Artificial Cognitive Systems

Agent evaluation using ConsScale

<table>
<thead>
<tr>
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<th>Haikonen</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS₂,₁; CS₃,₃; CS₃,₉,3; CS₉,3.</td>
<td>CS₂,₁; CS₃,₁; CS₃,₂; CS₃,₃; CS₃,₄; CS₃,₅; CS₃,₆; CS₄,₁; CS₄,₅; CS₅,₂; CS₅,₄,4.</td>
<td>CS₂,₁; CS₃,₁; CS₃,₂; CS₃,₃; CS₄,₁; CS₄,₂; CS₄,₃; CS₄,₄; CS₄,₅; CS₅,₂; CS₅,₄; CS₆,₄; CS₇,₁; CS₇,₂; CS₇,₅; CS₇,₆.</td>
<td>CS₂,₁; CS₃,₁; CS₃,₂; CS₃,₃; CS₃,₄; CS₃,₅; CS₃,₆; CS₃,₇; CS₄,₁; CS₄,₂; CS₄,₃; CS₄,₄; CS₄,₅, CS₅,₁; CS₅,₂; CS₅,₃; CS₅,₄; CS₅,₅; CS₅,₆; CS₆,₁; CS₆,₂; CS₆,₃; CS₆,₄; CS₆,₅; CS₆,₆; CS₇,₁; CS₇,₂; CS₇,₃; CS₇,₆; CS₈,₁.</td>
<td>CS₂,₁; CS₃,₁; CS₃,₂; CS₃,₃; CS₃,₄; CS₃,₅; CS₃,₆; CS₃,₇; CS₄,₁; CS₄,₂; CS₄,₃; CS₄,₄; CS₄,₅; CS₅,₁; CS₅,₂; CS₅,₃; CS₅,₄; CS₅,₅; CS₅,₆; CS₆,₁; CS₆,₂; CS₆,₃; CS₆,₄; CS₆,₅; CS₆,₆; CS₇,₁; CS₇,₂; CS₇,₃; CS₇,₄; CS₇,₈; CS₉,₃.</td>
</tr>
</tbody>
</table>

- CQS: 0.19
  - 2 (reactive)

- CQS: 0.51
  - 2 (reactive)

- CQS: 12.37
  - 4 (attentional)

- CQS: 102.27
  - 6 (emotional)

- CQS: 114.39
  - 6 (emotional)
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Agent evaluation using ConsScale FPS

Standard Evaluation Process

- Agent
- Analysis of the Architecture
- ConsScale
- Architectural Components
- Cognitive Skills
- Level of Cognitive Development
- Domain-specific Cognitive Tests
- Problem Domain Definition
Consciousness in Artificial Cognitive Systems

Agent evaluation using ConsScale FPS

Raúl Arrabales Moreno (PhD Defense)
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Conclusions

- Several cognitive functions associated with consciousness have been identified and integrated in an artificial architecture.

- Consciousness has been characterized as an integrative “super-function”.

- A practical framework for the assessment of the level of consciousness of artificial agents has been proposed.
Conclusions

- CERA-CRANIUM application to:
  - Simple tasks (autonomous exploration and target following).
  - Human-like video game bots (2K BotPrize).
  - Synthetic phenomenology.

- ConsScale application to:
  - Assessment and comparison of models and implementations designed for different domains.
Conclusions

- We don’t know yet what phenomenal states exactly are, however:
  - Artificial Qualia can contribute to the understanding of human consciousness.
  - Qualia have been functionally characterized proposing a model of consciousness as an integrator and self-regulating function.

- The heterophenomenology approach has been put in practice.

- It is possible to characterize and measure the level of consciousness of artificial agents.
Future Work

- CERA-CRANIUM mechanisms:
  - Attention
  - Global Access
  - Preconscious Management
  - Contextualization
  - Self-Regulation
- Self-state Assessment
- Sensorimotor Prediction
- Long Term Memory Management
- Learning Mechanisms
- Verbal Mental State Report
Future Work

- To enhance the experimentation in synthetic phenomenology with more complex stimuli and better representation mechanisms.
- To improve the believability of CC-Bot.
- To refine the definition of ConsScale and to use it in other problem domains.
- To use ConsScale as a roadmap.

Introduction
State of the Art
CERA-CRANIUM
ConsScale
Artificial Qualia
Experimentation
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Conclusions
Future Work
Publications
Thank you for your attention
References

ANNEXES

Additional Slides
CERA-CRANIUM

Software Architecture

Based on *Robotics Developer Studio*

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Consciousness in Artificial Cognitive Systems

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CERA-CRANIUM

- Software Architecture
  - Service-Oriented Architecture

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Calculation of $a$ and $K$

\[
\begin{align*}
\frac{e^{0/K} + a}{10} &= 0 \\
\frac{e^{c^5/K} + a}{10} &= 1000
\end{align*}
\]
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- **Experimentation**
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**ConsScale as a Roadmap**

- Consciousness in an integrator.
- Inspired by evolution and development.
- Cognitive functions are considered synergistically. Cognitive dependency.

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Consciousness in Artificial Cognitive Systems

CERA-CRANIUM Bot
2k BotPrize 2010 Judging Results

Percentage of votes wrongly classifying bots as human players

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Aplicación a la Experiencia Visual

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Aplicación a la Experiencia Visual

![Diagram](image-url)
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  - **ConsScale**
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**CERA-CRANIUM Observer**

Synthetic Phenomenology

-GOALS
- Artificial Qualia
- Multimodal integrated representation
- Low bandwidth Serial
- High bandwidth Asynchronous
- Raw monomodal sensory data
- Specialized Processors
- Context
- “Spotlight”
- Coordination and Context Formation Processes
- Control Signal
- Sensors
- Working Memory (SWS)