

# Curiosity-driven learning: AI, cognitive sciences and education



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Collaborations:



# Open-ended and autonomous development

PHYSICAL DEVELOPMENT	Average age skills begin	3 months	6 months	9 months	1 year	2 years	3 years	5 years
Head and trunk control	lifts head part way up	holds head up briefly holds head up high and well	holds up head and shoulders	turns head and shifts weight	holds head up well when lifted NO YES	moves and holds head easily in all directions		
Rolling		rolls belly to back	rolls back to belly	rolls over and over easily in play				
Sitting		sits only with full support sits with some support	sits with hand support	begins to sit without support	sits well without support	twists and moves easily while sitting		
Crawling and walking		begins to creep	scoots or crawls	pulls to standing	takes steps walks runs	can walk on tiptoe and on heels	walks easily backward	hops on one foot
Arm and hand control	grips finger put into hand	begins to reach towards objects	reaches and grasps with whole hand	passes object from one hand to other	grasps with thumb and forefinger	easily moves fingers back and forth from nose to moving object	throws and catches ball	
Seeing	follows close object with eyes	enjoys bright colors/shapes	recognizes different faces	eyes focus on far object	looks at small things/pictures	Sees small shapes clearly at 6 meters (see p. 453 for test).		
Hearing	moves or cries at a loud noise	turns head to sounds responds to mother's voice	enjoys rhythmic music	understands simple words	understands simple words	hears clearly and understands most simple language		

# Curiosity-driven autotelic exploration



During exploratory play, children invent and pursue their own problems/goals



- What mechanisms for goal selection?
- What mechanisms for goal generation?
- What long-term consequences on learning and development?

Chu, J., & Schulz, L. E. (2020). Play, curiosity, and cognition. *Annual Review of Developmental Psychology*, 2.

Oudeyer, P. Y. (2018). Computational theories of curiosity-driven learning. In « *The New Science of Curiosity* », Nova Science Pub.



**Cognitive sciences**  
 Understand better humans  
 using AI models

Many collaborations with researchers in

- AI and machine learning
- Developmental psychology
- Neuroscience
- Educational sciences

Curiosity  
 and open-endedness

**Artificial Intelligence:**  
 autonomous lifelong learning



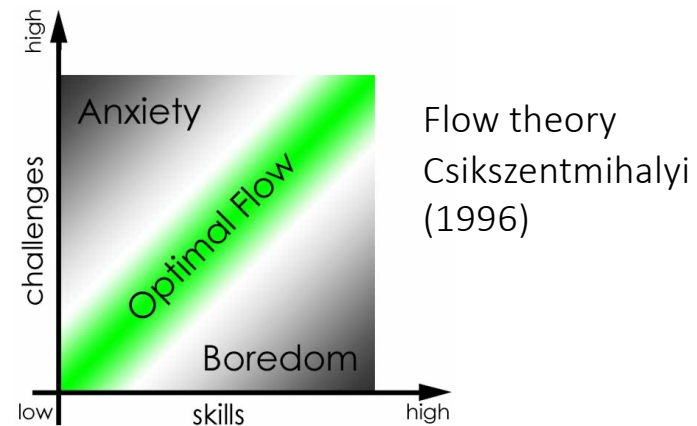
Applications in educational technologies, cognitive training, scientific discovery



Flowers AI & CogSci lab  
 Inria, Univ. Bordeaux



# Intrinsic motivation, curiosity and active learning



- ➔ Intrinsic drive to reduce uncertainty, and to experiencing novelty, surprise, cognitive dissonance, challenge, incongruences, ...
- ➔ Optimal interest = optimal difficulty = neither trivial nor too difficult challenges  
Berlyne (1960), White (1960), Kagan (1972), Csikszentmihalyi (1996), (Kidd et al., 2012), ...

NEUROSCIENCE



**THIS LOOKS INTERESTING**  
Understanding active sampling  
and curiosity

**Sharp wave-ripples**  
Role in memory retrieval and  
consolidation



J. Gottlieb  
(Columbia, NY)

L. Smith  
(Indiana Univ.)



C. Kidd  
(Berkeley)

## Towards a neuroscience of active sampling and curiosity

Jacqueline Gottlieb<sup>1,2,3\*</sup> and Pierre-Yves Oudeyer<sup>4,5</sup>

Development of a unified formal and theoretical framework  
in psychology and neuroscience

(Frontiers in Neuroscience 2007; IEEE TEC 2007; Trends in Cognitive Science, Nov. 2013; Progress in Brain Research, 2016; Frontiers in Neuroscience, 2014; Scientific Reports, 2016; PNAS, 2016; Nature Reviews Neuro. 2018; Nature Communications, 2021)



# Goal selection: What's an interesting problem/goal?

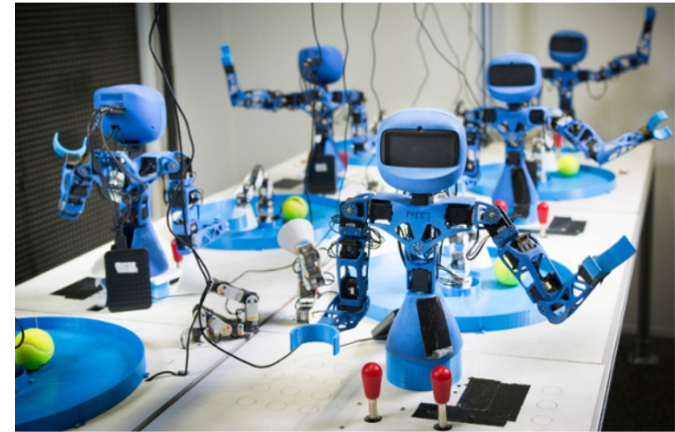
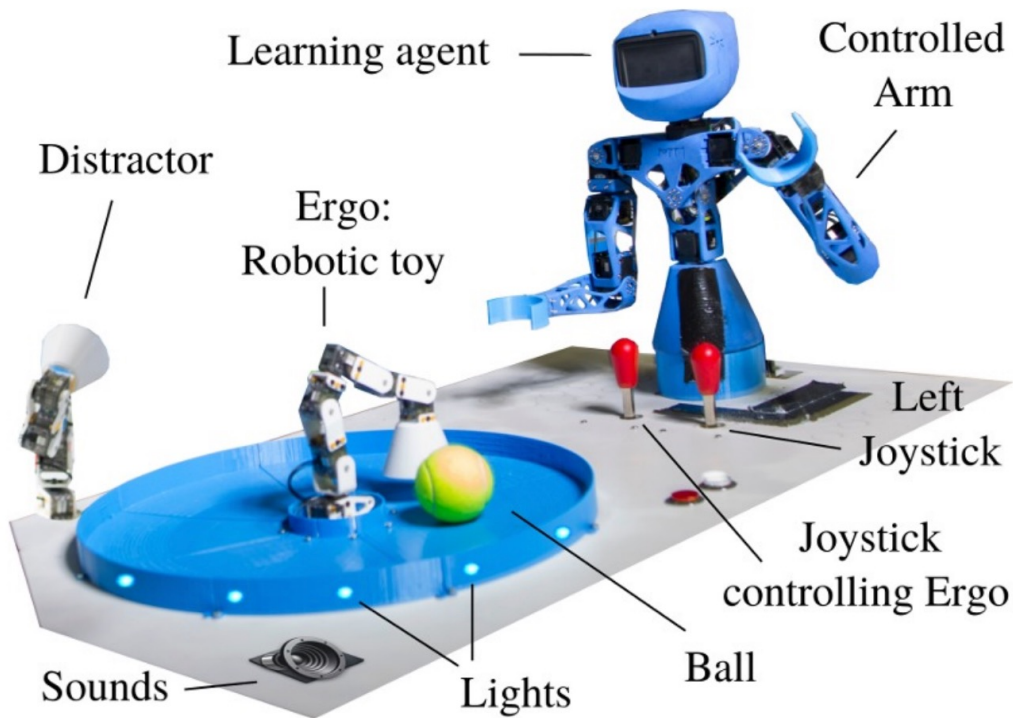
*(verbal) hypotheses from psychology and/or developmental biology:*

- High novelty/high uncertainty? (many)
- Knowledge gap, cognitive dissonance? (Kagan, Festinger, Lowenstein)
- Intermediate novelty, intermediate complexity? (Berlyne, Kidd)
- Intermediate challenge? (White, Csikszentmihalyi)

*Technical ideas from cognitive modeling or ML:*

- High novelty/high uncertainty? (many)
- Surprise? (Itti and Baldi)
- Free energy? (Friston)
- Different forms of information gain/learning progress, e.g.:
  - KL-divergence between prior and posterior probabilistic model
  - Predictive information (Martius), predictive information gain (Little & Sommer)
  - Compression progress (Schmidhuber)
  - Epistemic uncertainty
  - **Empirical improvement of prediction or control (Oudeyer et al.)**

# Testing theories by building real world robots



Journal of Machine Learning Research 23 (2022) 1-41

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## Intrinsically Motivated Goal Exploration Processes with Automatic Curriculum Learning

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# The Learning Progress hypothesis

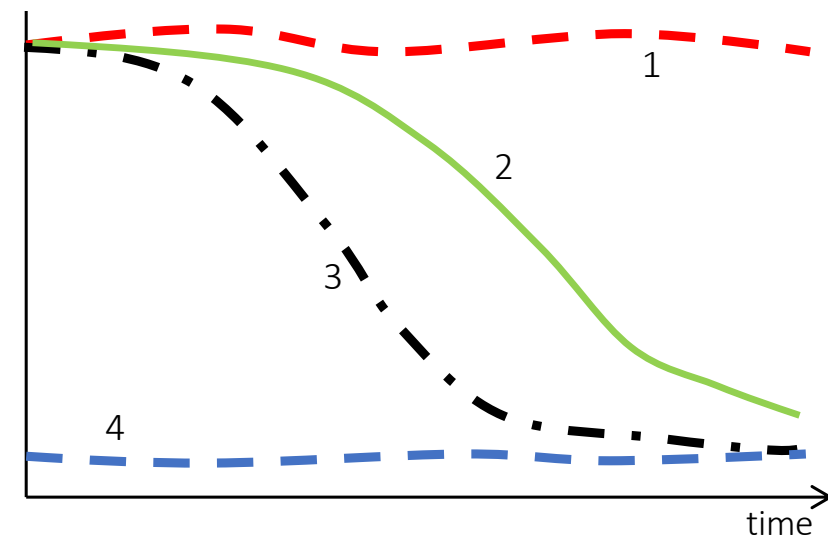
Interestingness of goal  
=  
proportional to  
empirical  
absolute learning progress  
(absolute value of derivative)

## → Automated Curriculum Learning

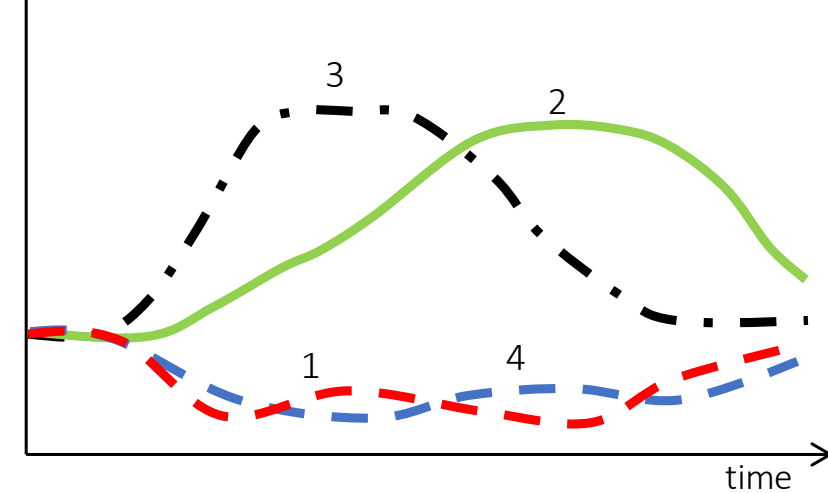
(Oudeyer and Kaplan, 2003; 2007 *Frontiers in Neuroscience*;  
Gottlieb et al., 2013 *Trends in Cognitive Science*; Oudeyer and  
Smith, 2016, *Topics in Cognitive Science*)

<https://www.frontiersin.org/articles/10.3389/neuro.01.1.1.017.2007/full>

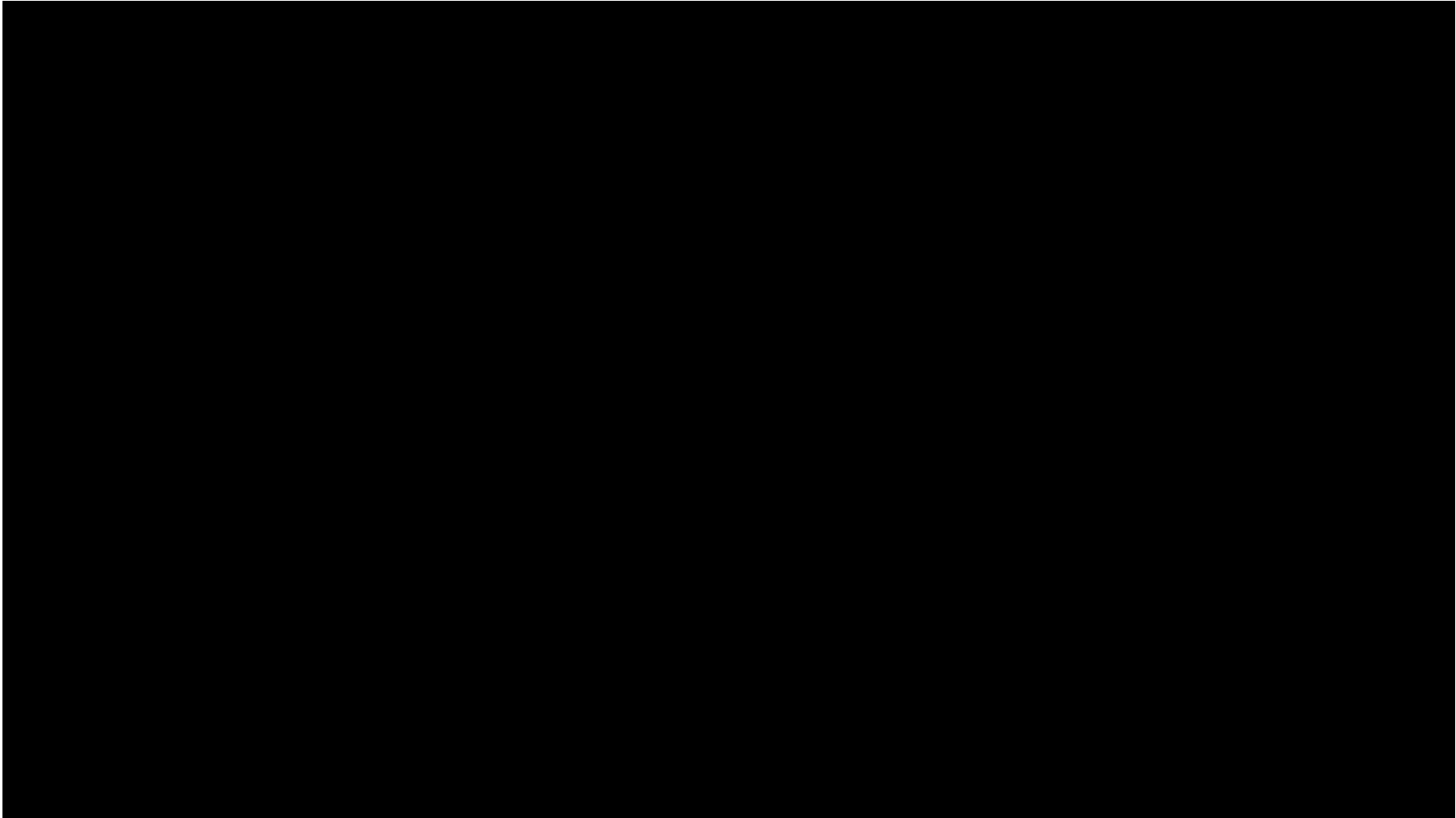
Evolution of empirical errors in 4 activities/goal types



% of time exploring each activity/goal type  
proportional to abs(learning progress)

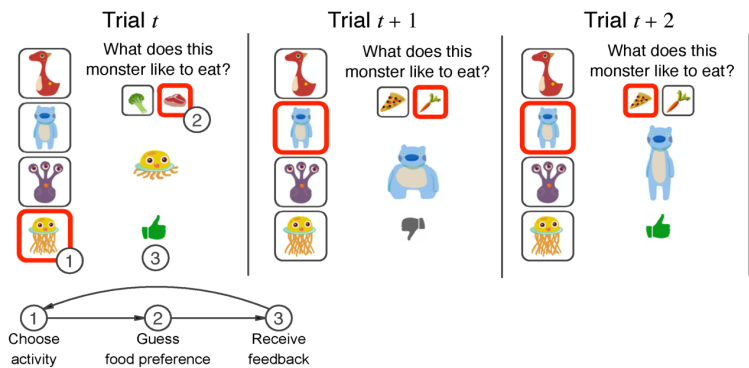


# Curiosity-driven autotelic robots



Forestier, Portelas, Mollard, Oudeyer (2016/2022) Intrinsically Motivated Goal Exploration Processes with Automatic Curriculum Learning, JMLR  
<https://www.jmlr.org/papers/volume23/21-0808/21-0808.pdf> <https://www.youtube.com/watch?v=NOLAwD4ZTW0>

# Testing the learning progress hypothesis in human experiments



382 adults (Mturk)

Utility functions:

$$U_{i,t} = w_{PC} \times PC_{i,t} + w_{LP} \times LP_{i,t} \quad (2.1)$$

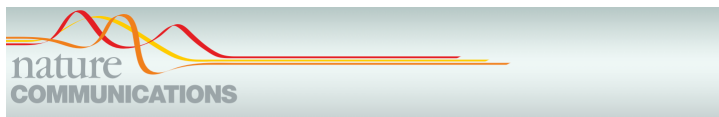
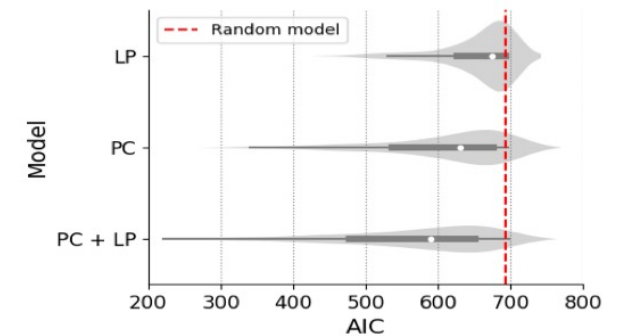
Percent correct  
(mean errors)

Learning progress  
(error derivative)

Softmax decision model (bandit):

$$p_t(\text{choice}_i) = \frac{e^{U_{i,t}/\tau}}{\sum_{\forall k \in K} e^{U_{k,t}/\tau}}$$

Model fits:



ARTICLE

2021

<https://doi.org/10.1038/s41467-021-26196-w>

OPEN

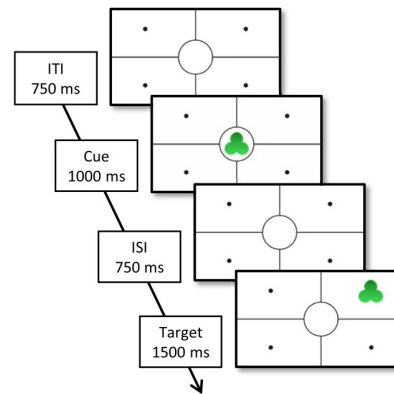
## Humans monitor learning progress in curiosity-driven exploration

Alexandr Ten<sup>1</sup>, Pramod Kaushik<sup>1</sup>, Pierre-Yves Oudeyer<sup>1</sup> & Jacqueline Gottlieb<sup>2</sup>

DEVELOPMENTAL NEUROSCIENCE

# Infants tailor their attention to maximize learning

F. Poli<sup>1\*</sup>, G. Serino<sup>1,2</sup>, R. B. Mars<sup>1,3</sup>, S. Hunnius<sup>1</sup>



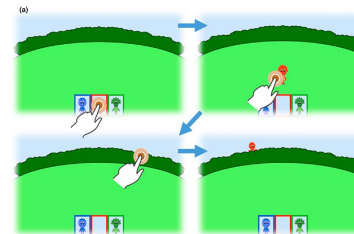
50 8-months old infants

- Sequence of (learnable) patterns
- Looking time/engagement correlates with LP, not with surprise and prediction error

# Exploration in 4-year-old children is guided by learning progress and novelty

Francesco Poli<sup>1,2</sup> | Marlene Meyer<sup>1</sup> | Rogier B. Mars<sup>1,3</sup> | Sabine Hunnius<sup>1</sup>

CHILD DEVELOPMENT



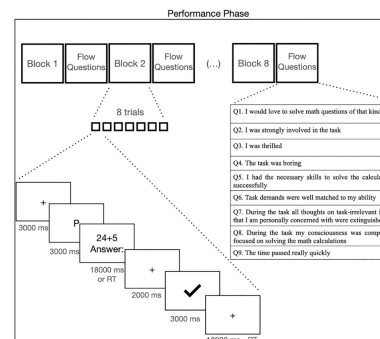
102 4-years old

- Free exploration of tasks
- Exploration decisions depend on LP + novelty



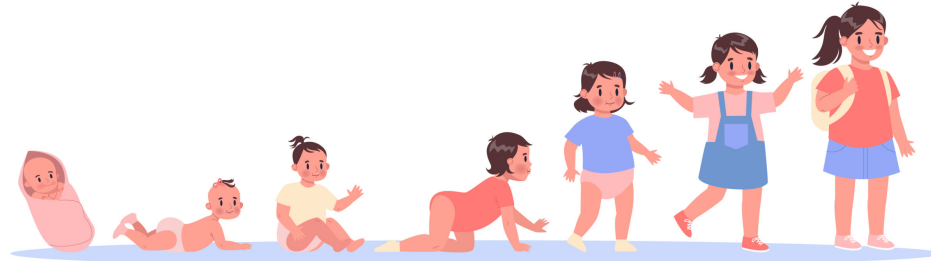
# Learning progress mediates the link between cognitive effort and task engagement

Ceyda Sayalı<sup>a</sup>, Emma Heling<sup>b,c</sup>, Roshan Cools<sup>b,c</sup>



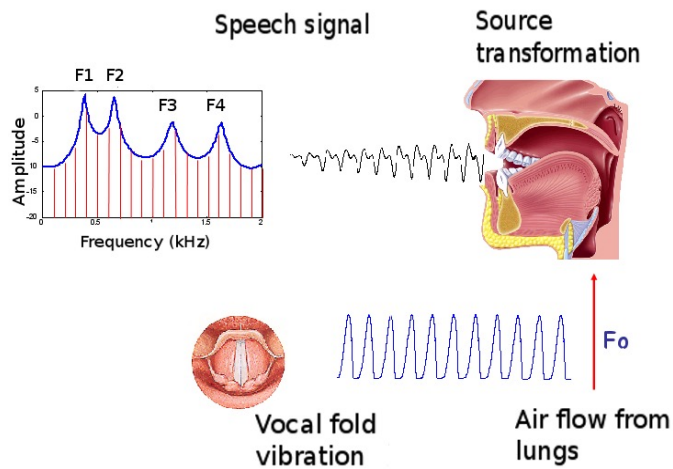
40 adults

Engagement and flow experience correlated with LP

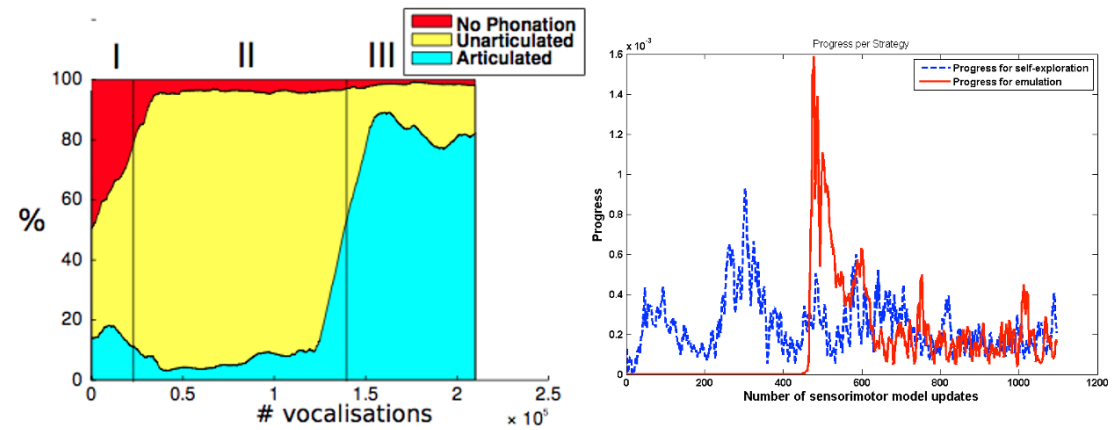


What are the long term consequences of curiosity on developmental learning trajectories ?

# Curiosity-driven self-organization of vocal development



DIVA Vocal tract model (Guenther et al.)



0-3 mo:  
squeals, growls,  
yelps ...

3-7 mo:  
quasi-vowels

7-10 mo:  
language-independent  
proto-syllables

10 mo:  
influence by  
ambient language

12 mo:  
first words

Approximate age  
(Oller, 2000)



# Mechanisms for open-ended goal generation ?



From robots and sensorimotor exploration...

# Language as a creative tool to imagine new goals and plans

## nature machine intelligence

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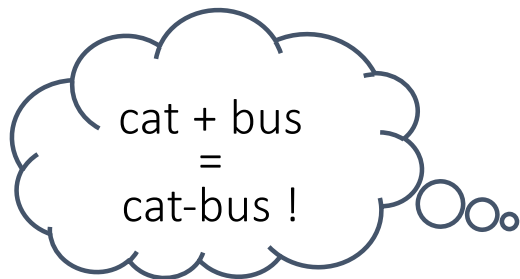
[nature](#) > [nature machine intelligence](#) > [perspectives](#) > [article](#)

Perspective | [Published: 20 December 2022](#)

### Language and culture internalization for human-like autotelic AI

[Cédric Colas](#) , [Tristan Karch](#), [Clément Moulin-Frier](#) & [Pierre-Yves Oudeyer](#)

Creativity = novelty + relevance



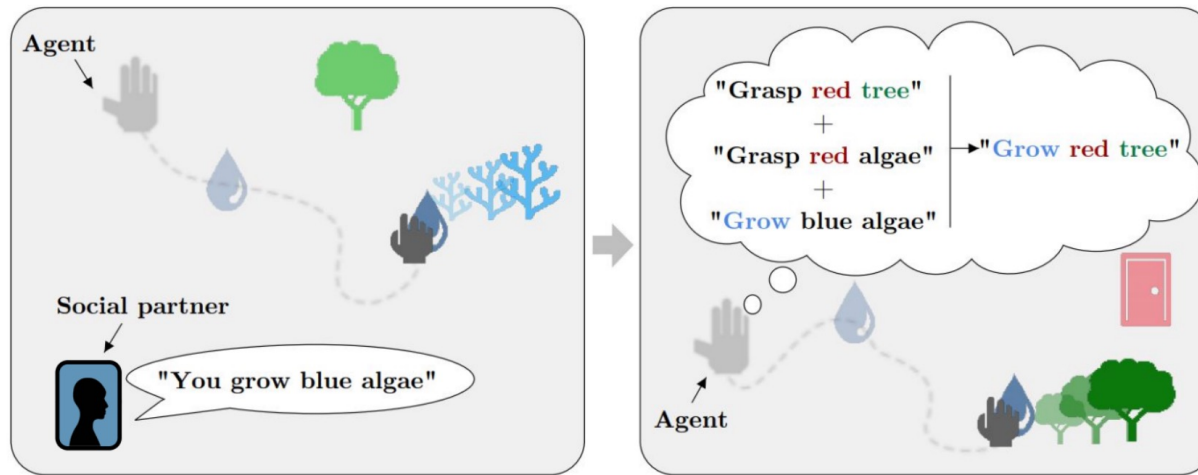
Lev Vygotsky

# Language as a creative tool to imagine new goals and plans



Complex open environments with social peers

Language as a cognitive tool for creative exploration of abstract goals

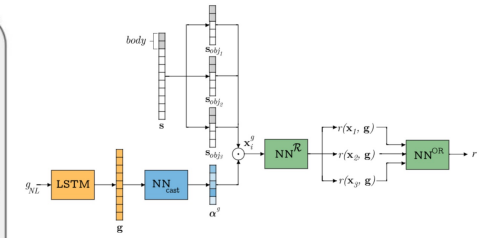


## 1. Guided exploration with a social partner:

Learning the meaning of sentences through interaction with a social peer

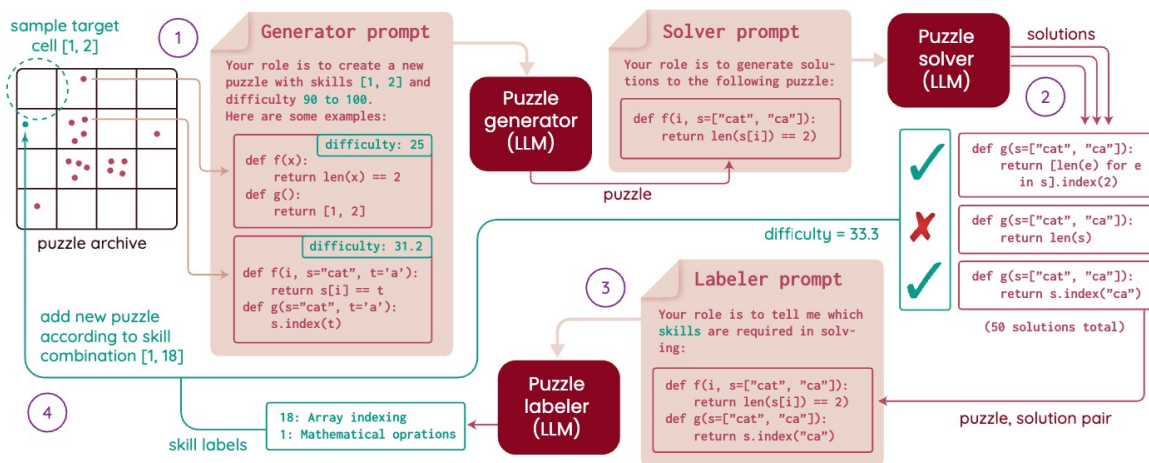
## 2. Creative autonomous exploration:

Imagining new goals by composing known sentences

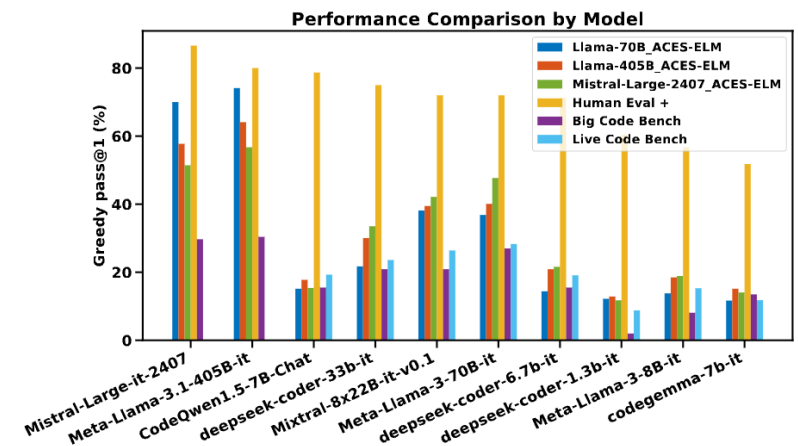


Deep sets and transformers for compositional learning and generalization

# Self-improving autotelic generative models for code



Eval correlates with Big Code Bench and Live Code Bench



## Generating a Diversity of Challenging Programming Puzzles with Autotelic Generative Models

Julien Pourcel  
Inria

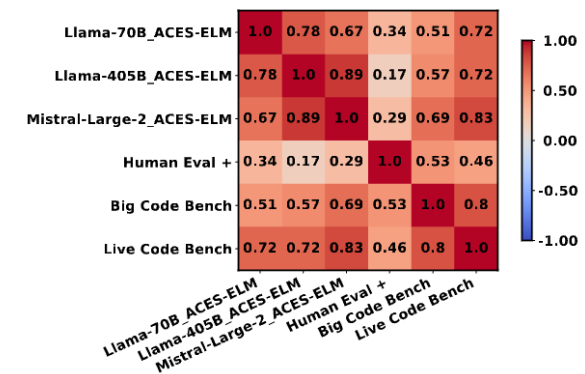
Cédric Colas  
MIT, Inria

Gaia Molinaro  
University of California, Berkeley

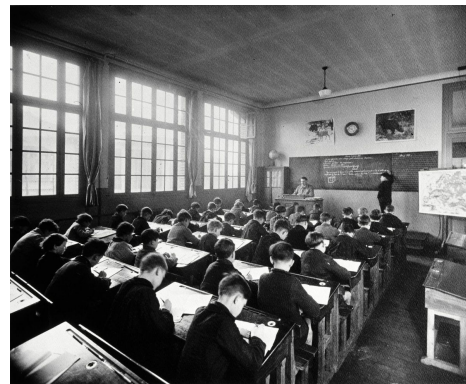
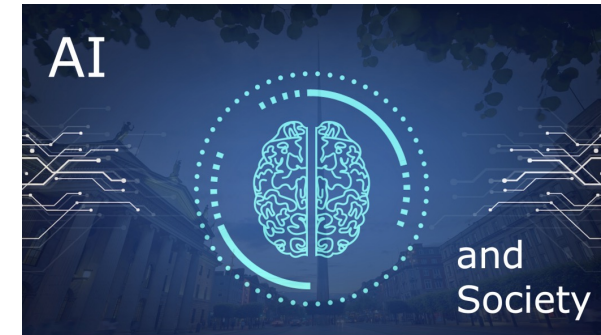
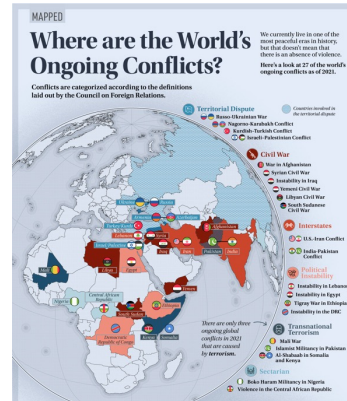
Pierre-Yves Oudeyer  
Inria

Laetitia Teodorescu  
Inria

Neurips 2024

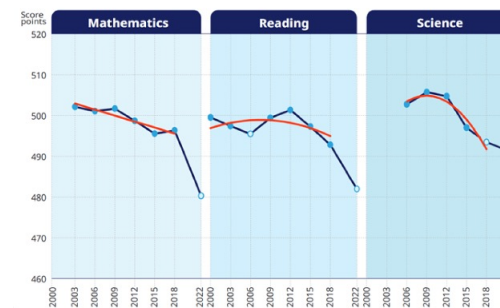


# From societal to educational challenges



OECD average trends in mathematics, reading and science

In 23 OECD countries up to 2022



👤 How to educate children to build a better world and thrive?

➔ Design and disseminate methods that educate (using) curiosity and metacognition

# Educational technologies for fostering efficient learning and intrinsic motivation



PhD  
Benjamin Clement



Experiments with  
> 1000 children in more than 30  
schools in Aquitaine

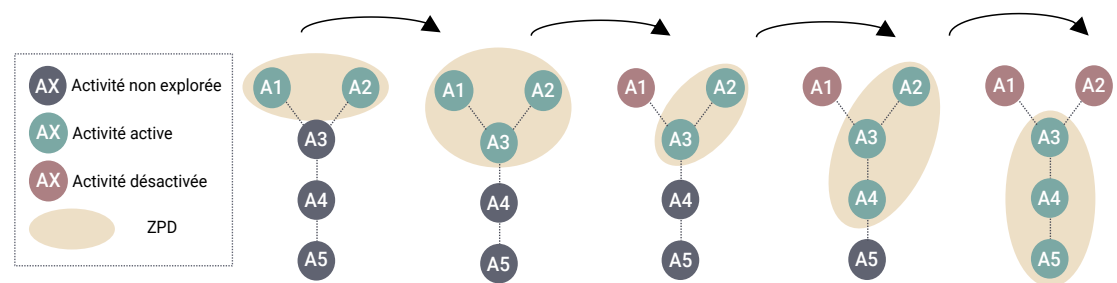
KidLearn project:

Personalization of teaching sequences  
(curriculum) in Intelligent Tutoring Systems

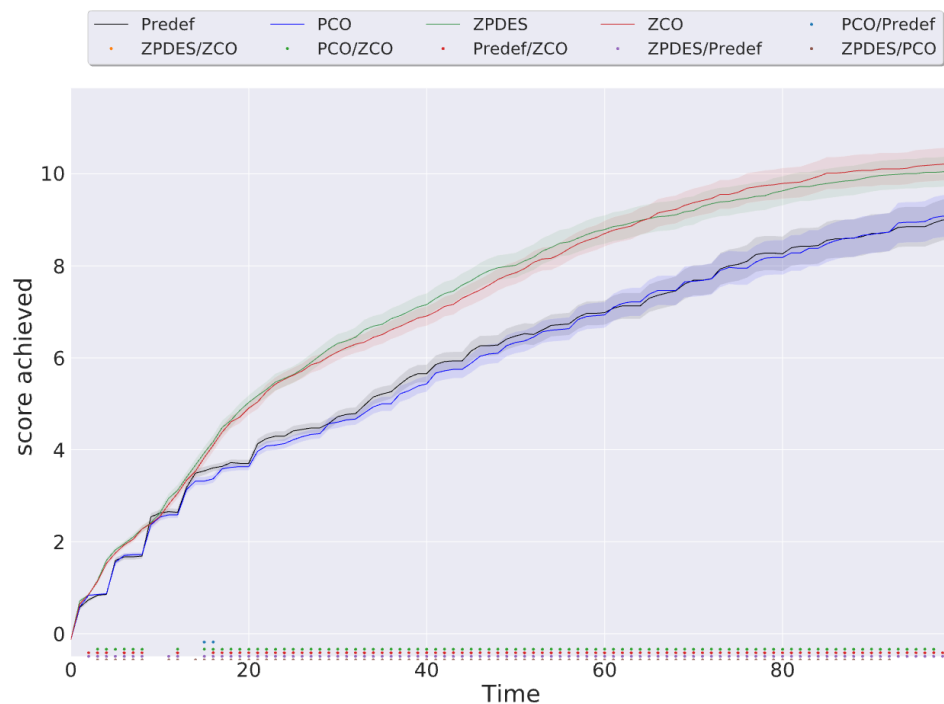
(Clement et al., Journal of Educational Data Mining,  
2015; 2024)

<https://arxiv.org/abs/1310.3174>

<https://www.theses.fr/2018BORD0373>



## Score for achieved activities

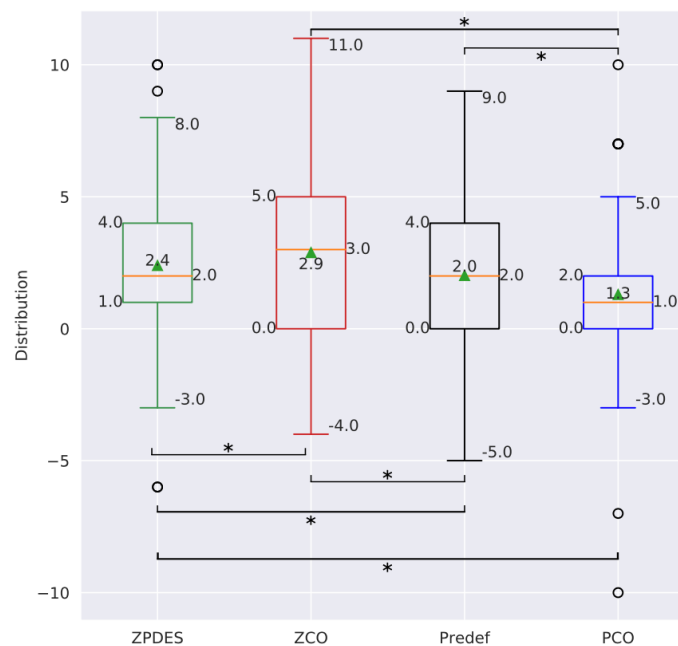


# Learning impact

← ZPDES and ZPDES + choice/gamification (ZCO)

← Hand designed curriculum  
Hand designed + choice/gamification (PCO)

"Learning Score"



## Improved Performances and Motivation in Intelligent Tutoring Systems: Combining Machine Learning and Learner Choice.

Benjamin Clément<sup>1,3,×</sup>, H el ene Sauz eon<sup>1,2,+</sup>, Didier Roy<sup>1</sup>, and Pierre-Yves Oudeyer<sup>1,+ ,×</sup>

<sup>1</sup>Inria, FLOWERS team, Talence, 33405, France

<sup>2</sup>Universit e de Bordeaux, BPH lab, Bordeaux, 33076, France

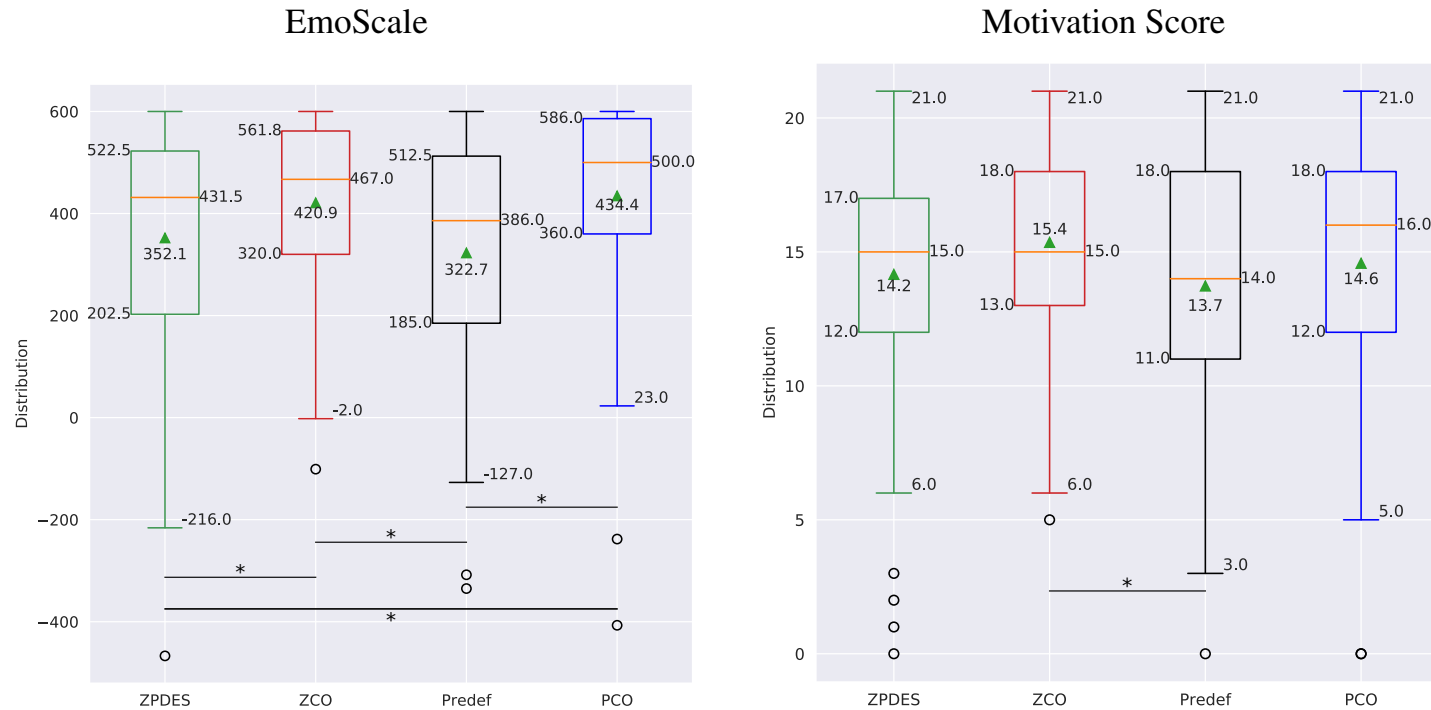
<sup>3</sup>EvidenceB, Paris, 75018, France

<sup>+</sup>corresponding authors

<sup>×</sup>these authors equally supervised this work

<https://arxiv.org/abs/2402.01669>

# Motivational impact



**Figure 6.** Boxplots presenting the Emotional Scale score on the left and the Motivation score on the right. Students working with ZCO and PCO show the highest EmoScale scores while students working with ZCO show the highest Motivation score, followed by PCO and ZPDES and Predef present the lowest score.

Conclusions: 1) learning-progress based personalization > hand-made curriculum  
 2) gamification boosts personalized learning; but degrades non-personalized learning

# Societal and industrial impact: educational technologies

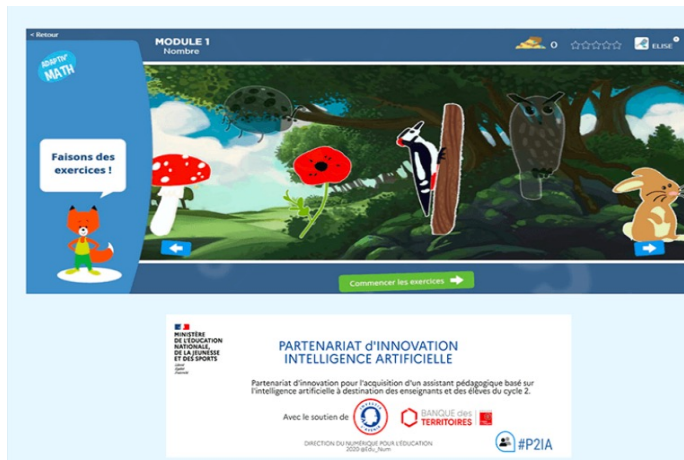


Large scale industrial deployment (available to all schools in France) with major edTech actors (evidenceB, Nathan, etc)

- Primary, middle, high-school
- 30000 exercices
- > 100 000 classrooms



PARTENARIAT D'INNOVATION INTELLIGENCE ARTIFICIELLE



All stakeholders involved !

# Training curiosity and metacognition by training children to ask curious questions

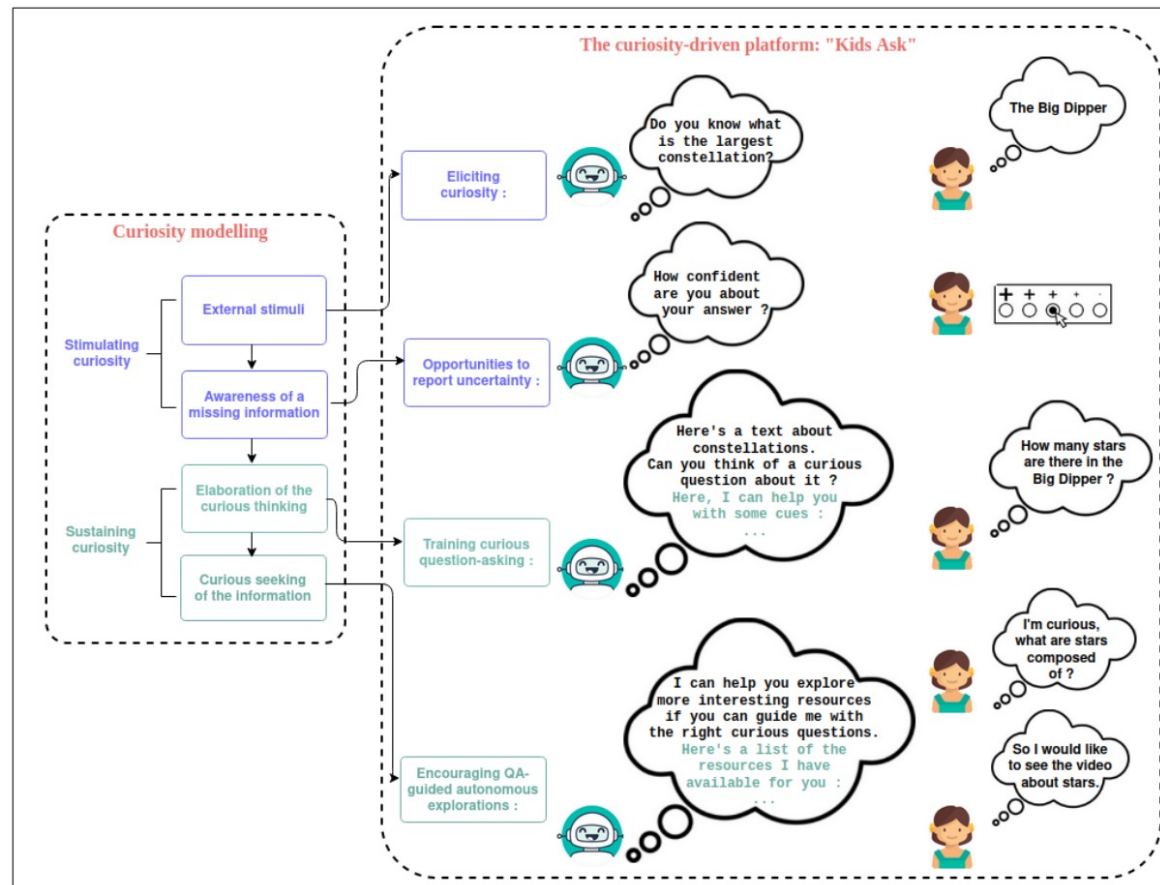


Figure 1: Illustration of the study's general idea and the platform's main features

PhD of Rania Abdelghani (collab. Inria  
Flowers/EvidenceB)

55 7–8-years old (Nouvelle Aquitaine)



International Journal of Human-Computer  
Studies

Volume 167, November 2022, 102887



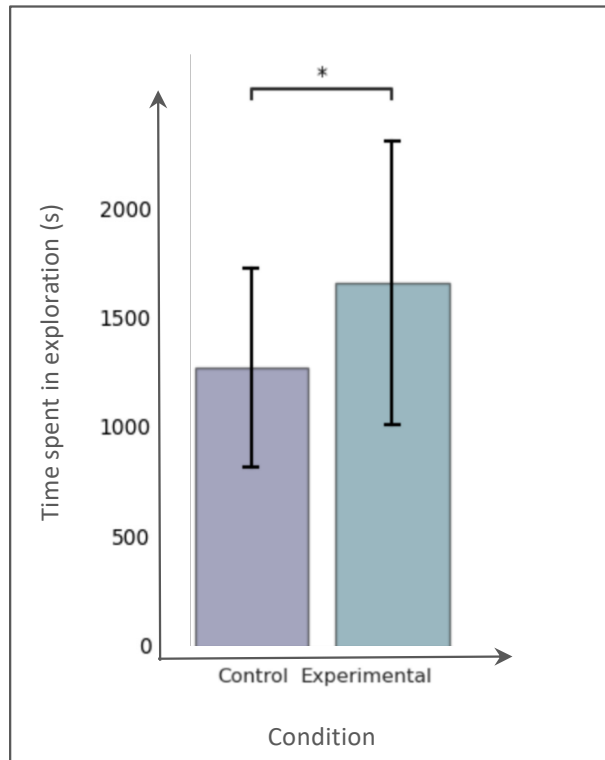
## Conversational agents for fostering curiosity-driven learning in children

Rania Abdelghani<sup>a, b</sup>, Pierre-Yves Oudeyer<sup>a</sup>, Edith Law<sup>c</sup>,  
Catherine de Vulpillières<sup>b</sup>, H  l  ne Sauz  on<sup>a</sup>

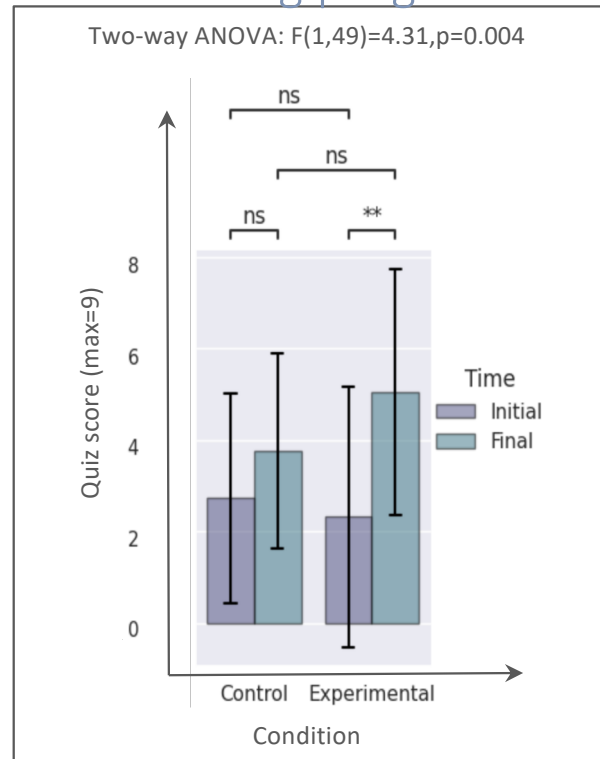
<https://arxiv.org/abs/2204.03546>

## Some highlight results

### Time spent in exploration



### Pre-post intervention learning progress



**Experimental: With KG propositions**  
**Control: No KG propositions**

- Time spent in exploration was correlated to the QA performance in the training (ANCOVA:  $F=4.1, p=0.04$ )
- Learning progress was correlated to the QA performance in the exploration (ANCOVA:  $F=3.67, p=0.05$ )

→ Longer exploration and stronger domain-knowledge learning progress

# Training children to appreciate curiosity

## Metacognitive workshop

### Declarative training



4 vidéos over 2 or 3 sessions

- 1 - Intrinsic motivation
- 2 - Importance of curiosity in learning
- 3 - Introduction to 4 metacognitive skills
- 4 - Metacognition and learning

### Procedural training

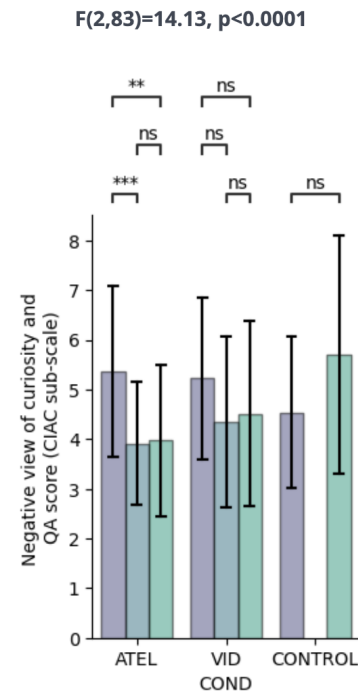


Application  
4MC

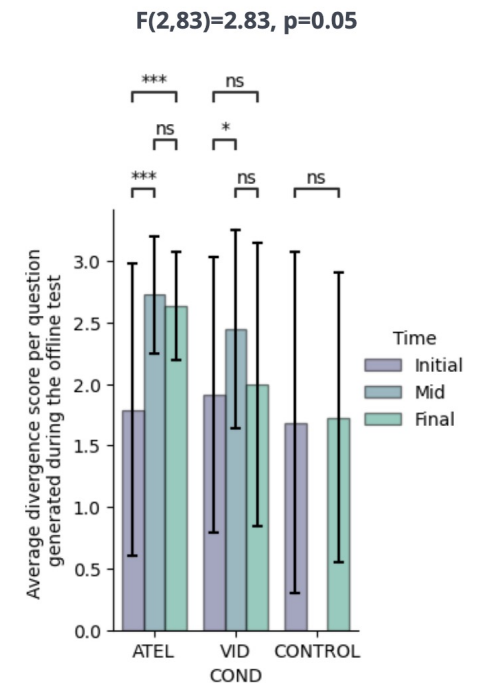
8 pedagogical texts to foster  
divergent question asking

Practice of the 4 metacognitive skills :  
Identify, Guess, Seek, Assess

Improvement of  
curiosity  
perception



Improvement of  
divergent question  
asking



Abdelghani, R., Law, E., Desvaux, C., Oudeyer, P. Y., & Sauz on, H. (2023). Interactive environments for training children's curiosity through the practice of metacognitive skills: a pilot study. In *Proceedings of the 22nd Annual ACM Interaction Design and Children Conference*

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*Senior colleagues:* C. Moulin-Frier, H. Sauzéon, D. Roy, O. Sigaud, J. Gottlieb, C. Mazon, K. Hofmann, P-F. Dominey, E. Nisioti, M. Nguyen, F. Kaplan, M. Lopes, S. Lamprier, O. Ly, L. Smith

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