LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
CHAIR OF PHYSICS EDUCATION RESEARCH – FACULTY OF PHYSICS
Didaktik der Physik

# Learning about Quantum Technologies using Games: Interactive visualizations and the role of AI

Stefan Küchemann

Gefördert durch:
Bundesministerium für Forschung, Technologie und Raumfahrt

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# Our Collaborators

Didaktik der Physik

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TUM

MCQST

Munich Quantum Valley

MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

STUDIO MERKAS

GamingQ

# Typical instructions in Quantum Physics textbooks



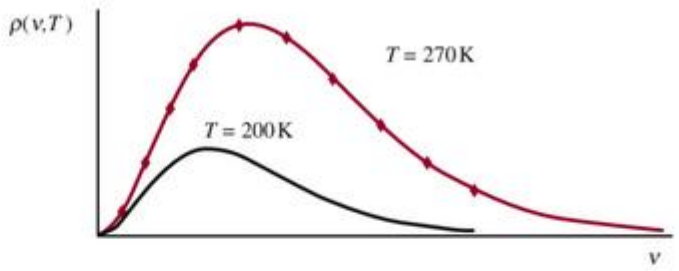


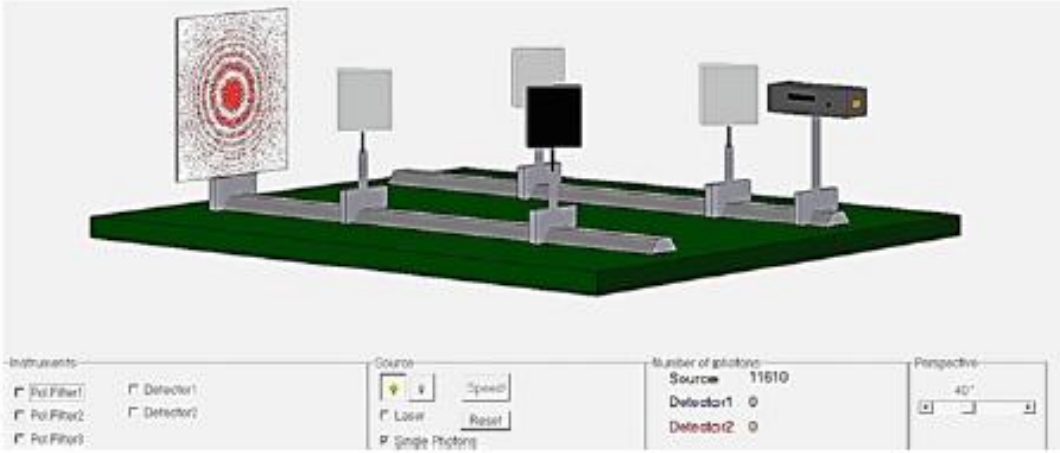

**Fig. 1.2** The experimental spectral distribution and the Planck distribution for different temperatures. The description is perfect from low to high frequencies

$$\bar{E} = \frac{E_\nu}{e^{E_\nu/k_B T} - 1}. \tag{1.14}$$

Using $e^x \simeq 1 + x$ for small $x$, this expression reduces to $k_B T$ in the high temperatures limit. Combining with the average energy of equation (1.4), we have

$$\rho_\nu(\nu, T) = \frac{8\pi\nu^2}{c^3} \frac{E_\nu}{e^{E_\nu/k_B T} - 1}. \tag{1.15}$$

For this distribution to satisfy the Wien displacement law, the characteristic energy $E_\nu$, the minimum energy, absorbed or emitted, must be proportional to the frequency $\nu$. Writing the characteristic energy as






Pereyra, P. (2012). *Fundamentals of quantum physics*. springer.

Marshman, E., & Singh, C. (2022). QuILTs: Validated teaching–learning sequences for helping students learn quantum mechanics. In *Physics Teacher Education: What Matters?* (pp. 15-35). Cham: Springer International Publishing.

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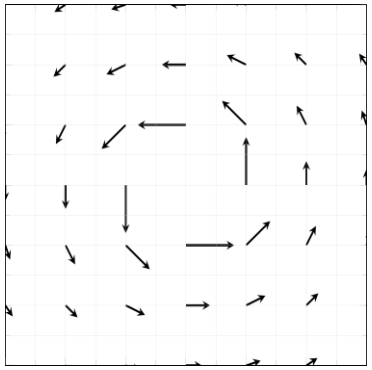
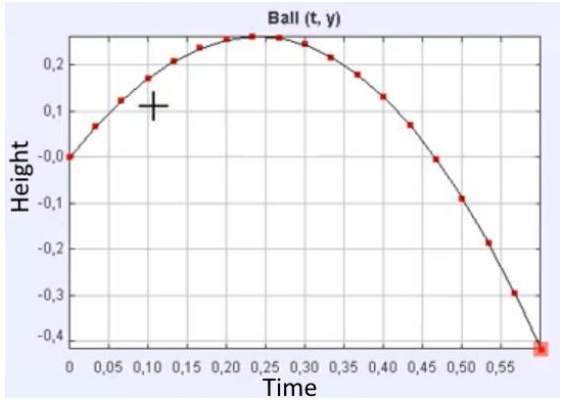
The trajectory of the ball follows a parabolic path

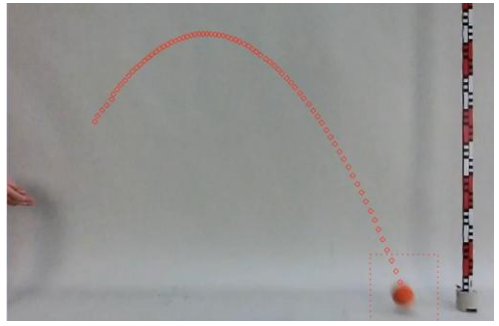
$$\vec{B} = \begin{pmatrix} \frac{-y}{x^2+y^2} \\ \frac{-x}{x^2+y^2} \end{pmatrix}$$

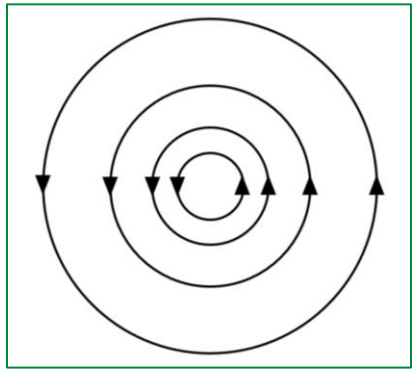





# Types of representations in Physics Education

$$\vec{r} = \begin{pmatrix} v_x t + x_0 \\ -\frac{1}{2} g t^2 + v_y t + y_0 \end{pmatrix}$$





The magnetic field runs circularly around the current-carrying conductor and the magnitude decays outward.

# Types of representations in Physics Education

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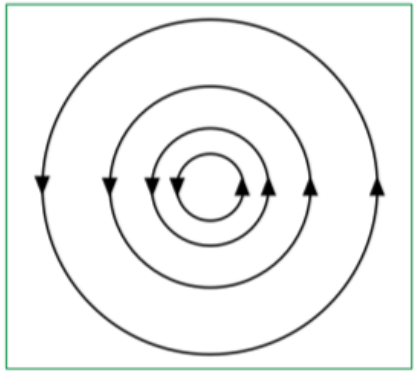
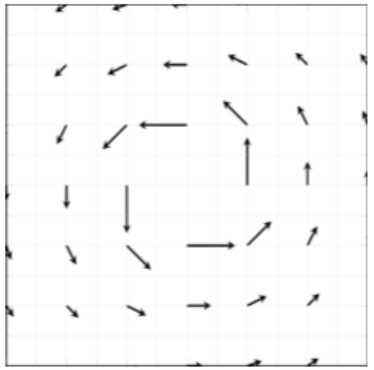
Actional-operational

Visual-graphical

Verbal-textual

Symbolic-mathematical





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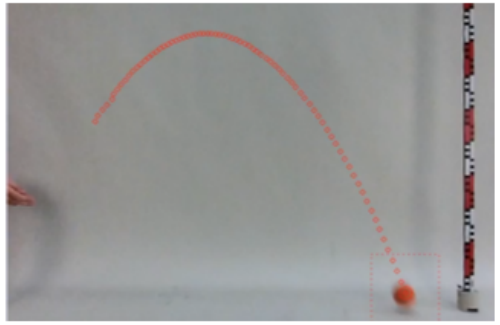
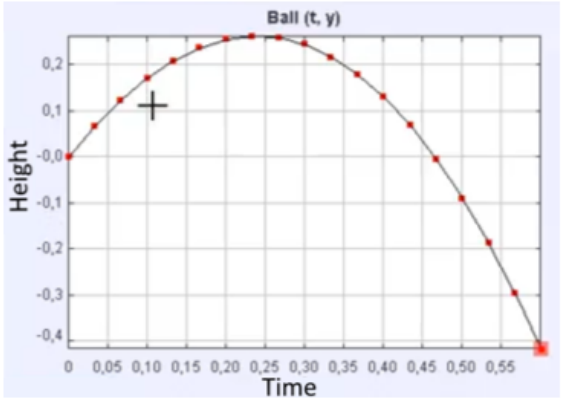





The trajectory of the ball follows a parabolic path

$$\vec{r} = \begin{pmatrix} v_x t + x_0 \\ -\frac{1}{2} g t^2 + v_y t + y_0 \end{pmatrix}$$

Wu, Puntambekar, J Sci Educ Technol (2012) 21:754–767

# Students experience different types of Cognitive Load during learning

- Three kinds of CL

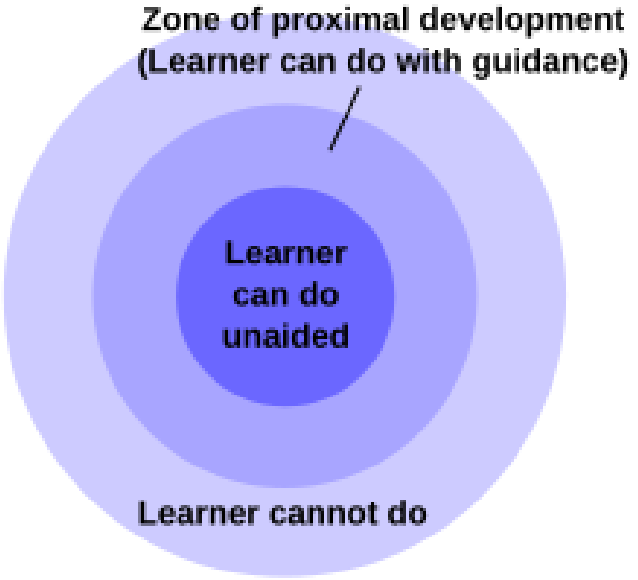

**Intrinsic Cognitive Load**:
inherent difficulty of the subject matter


**Extraneous Cognitive Load**:
unnecessary cognitive burden due to poor instructional design

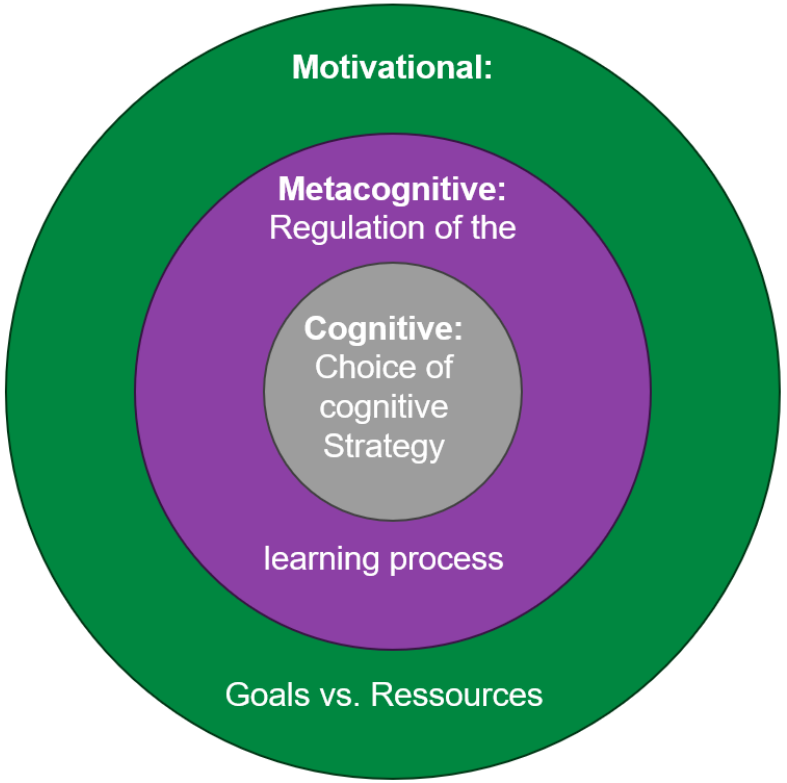

**Germane Cognitive Load**:
effort required for schema construction and automation

# How can we regulate cognitive load?

- Scaffolding = support given to learner by instructor; tailored to learner
- Three essential features:
  1. Interaction between learner and expert should be collaborative
  2. Learning should take place in the learner's zone of proximal development
  3. Scaffold, support and guidance are gradually removed as the learner becomes more proficient



# Supporting students during self-regulated learning using AI

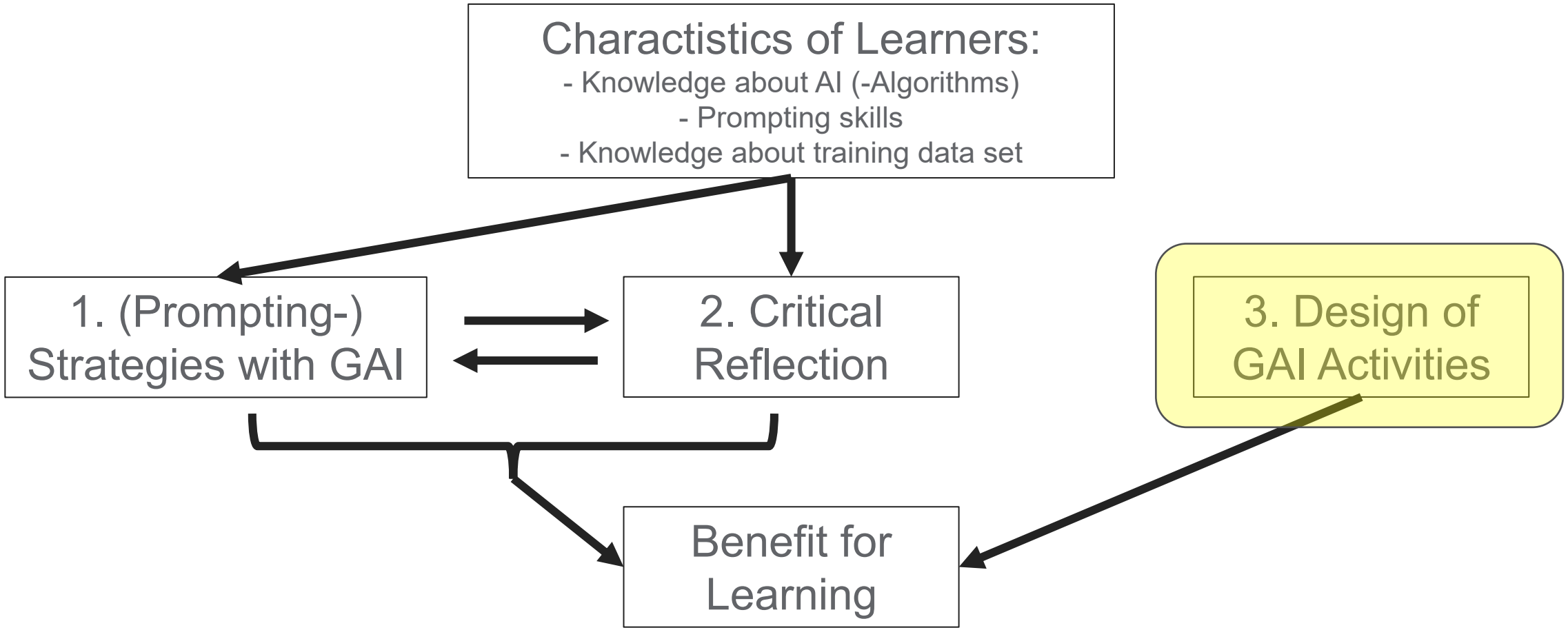



| Theoretical aspect | Prompt for the LLM | The LLM feedback |
|---|---|---|
| Cognitive Sense-making (Smy et al., 2016) | If the student's answer is incomplete or incorrect, encourage the student to organize and make sense of the concepts that they misunderstood or that was missing without giving the correct answer | You're right, the metal balls hit each other. But that is only one part of the whole. Think about what happens when the balls hit each other. What happens to the energy and momentum? And why does only the last ball move and not the others? Try to answer these questions to get a better understanding of Newton's cradle |
| Cognitive Elaboration (Berthold & M. Nückles et al., 2007) | If the student's answer is incomplete, encourage the student to elaborate on aspects that were missing without giving the correct answer | You're right, the metal balls hit each other. But that's only part of the story. Can you perhaps say a little more about this? For example, what happens when one ball hits the others? And why does the last ball move even though it wasn't hit directly by the first ball? Think about the laws of physics that we discussed in class |
| Cognitive Self-explanation (Hofer et al., 1175) | If the answer of the student is incomplete or incorrect, give an example of a simpler situation in which the incorrect or missing concept plays a central role and ask the student how he would explain the situation. Do not give the correct answer | You're right about the metal balls hitting each other. But what happens after that? Think of a row of dominoes. What happens when you knock over the first domino? |

Steinert, S., Avila, K. E., Ruzika, S., Kuhn, J., & Küchemann, S. (2024). Harnessing large language models to develop research-based learning assistants for formative feedback. Smart Learning Environments, 11(1), 62.

Scheiter et al., J. (2017). How to Design Adaptive Information Environments to Support Self-Regulated Learning with Multimedia

# Challenges when using AI in education

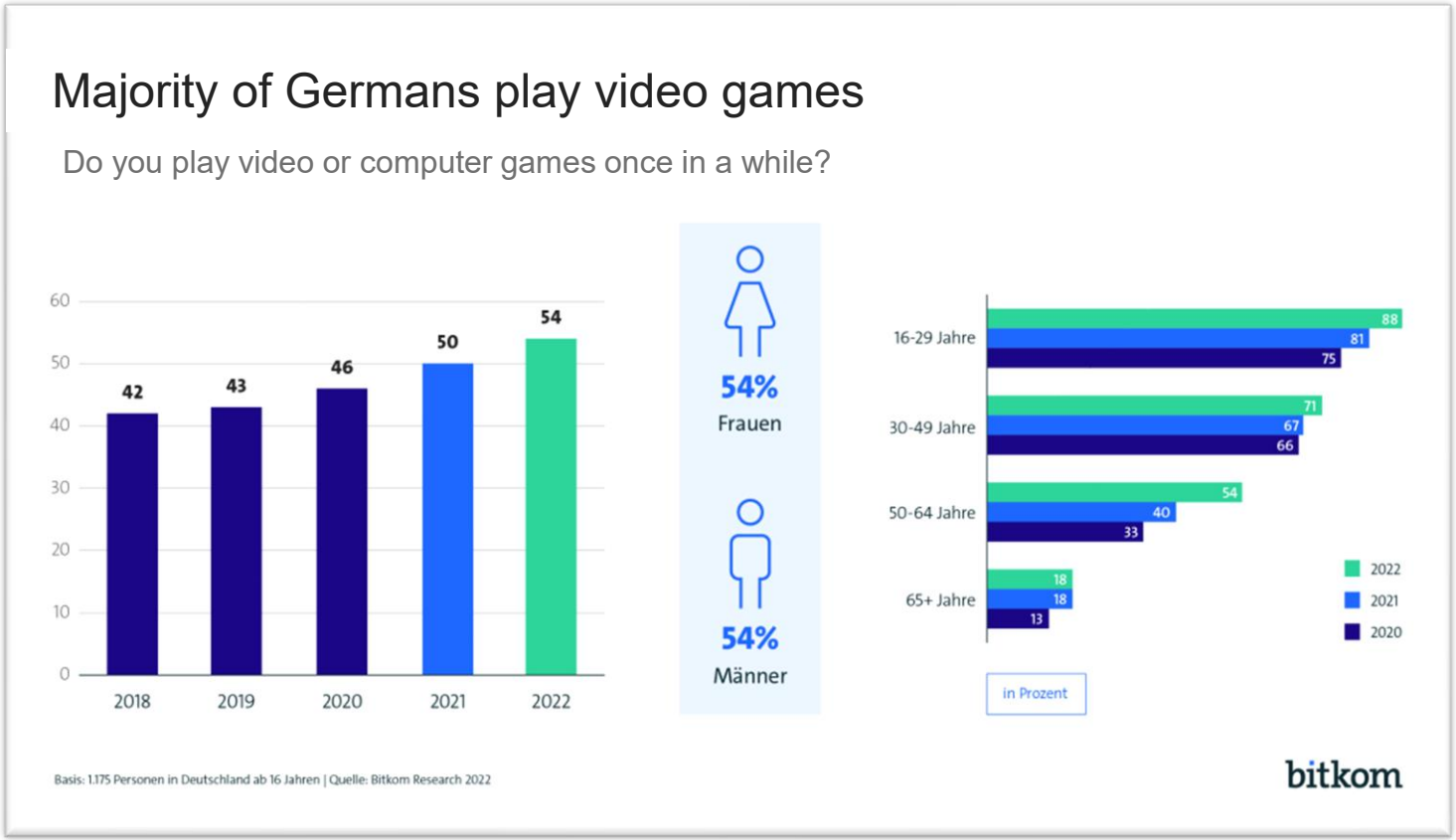



**What about digital games?**

# Why Video Games?

## Gaming Industry in Germany

The video gaming industry has grown into being one of the biggest multimedia industries in the world.




https://www.bitkom.org/Presse/Presseinformation/Gaming-Trends-2022#_

# Pros and Cons of Video Games

| Pros | Cons |
| --- | --- |
| Enhances **cognitive functions** such as **attentional control and memory**.<br>Chaarani B, et al., "Association of Video Gaming With Cognitive Performance Among Children", *JAMA Netw Open* (2022). | Can lead to **addiction**, recognized as a mental health disorder.<br>Porter, Guy, et al. "Recognizing problem video game use." *Australian & New Zealand Journal of Psychiatry* 44.2 (2010) |
| May **improve vision** by increasing the ability to distinguish colors.<br>Li, et al "Video-Game Play, Induces Plasticity in the Visual System of Adults with Amblyopia." *PLoS Biology* 9. (2011) | Encourages a **sedentary lifestyle**, which can be detrimental to physical health. |
| Encourages **social connections** through multiplayer games and online networks. | Risk of increased **aggression**, especially from violent video games.<br>Prescott AT, et al., "Metaanalysis of the relationship between violent video game play and physical aggression over time" *Proc Natl Acad Sci U S A*. 115(40) (2018). |
| Offers **educational benefits** by sparking interest in subjects and interactive learning.<br>Whitton, Nicola, and Alex Moseley, eds. "*Using games to enhance learning and teaching*". New York: Taylor & Francis, (2012). | Can lead to mental health concerns like **decreased focus and concentration issues**. |
| Promotes **physical activity** in interactive games, contributing to fitness. | Can **interfere with real-life responsibilities**, leading to neglect of important tasks. |

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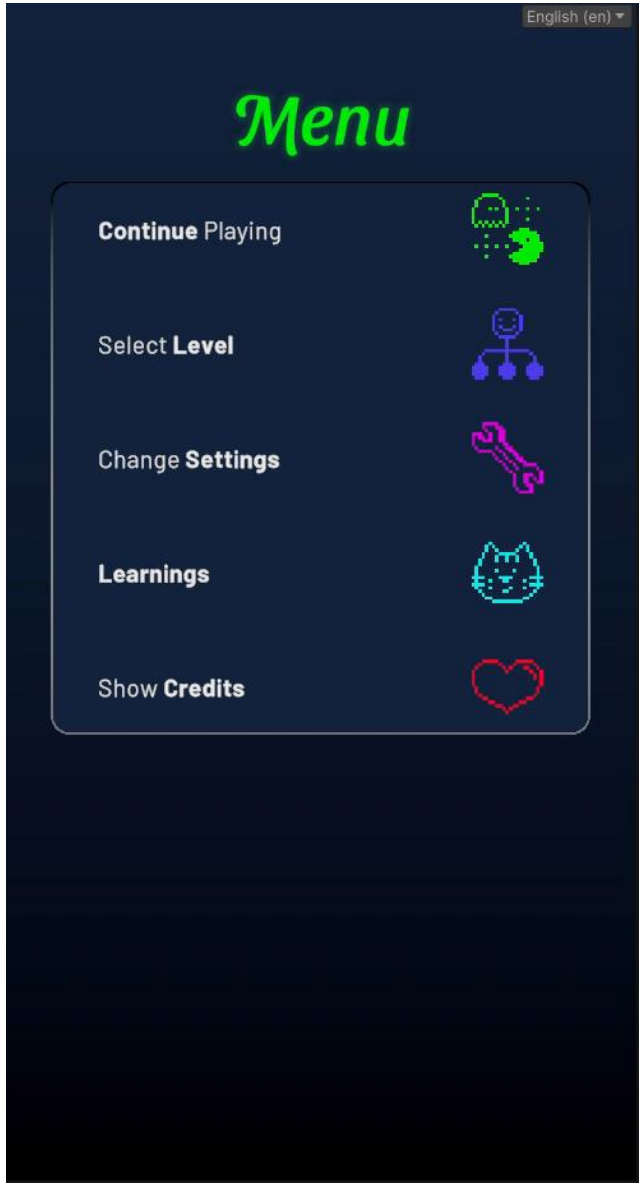
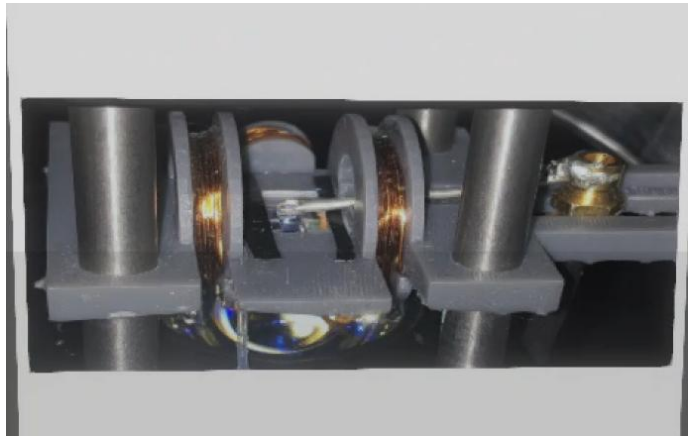
# Game play in Qookies

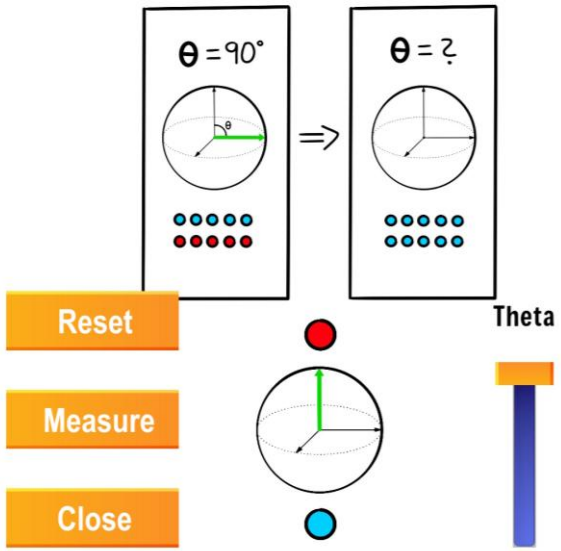


# How do we „represent“ concepts in Quantum Physics

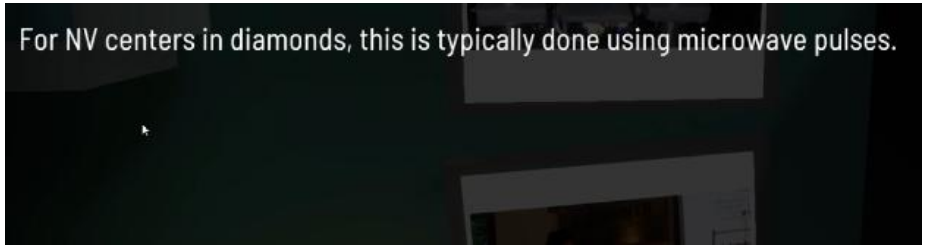
## Real images from the lab



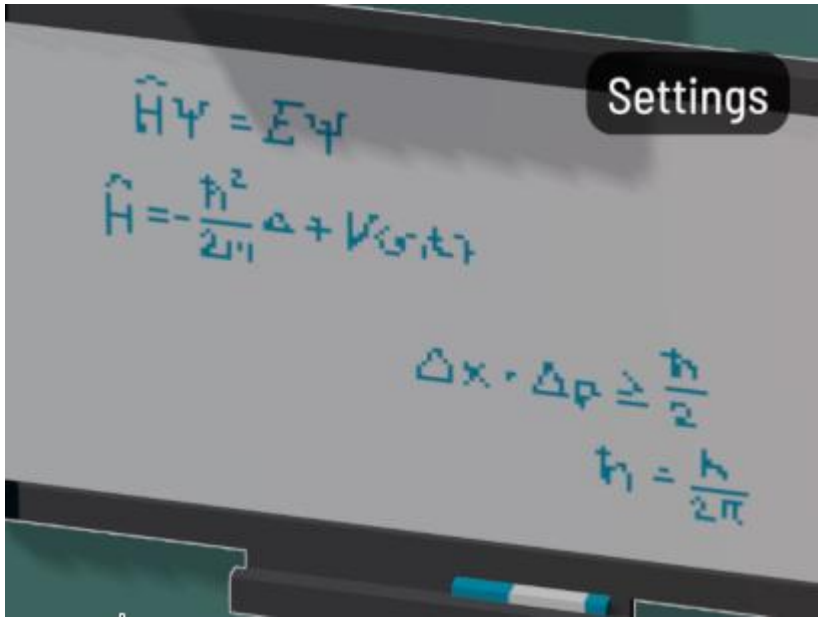

## Convention-based representation




## Verbal explanations

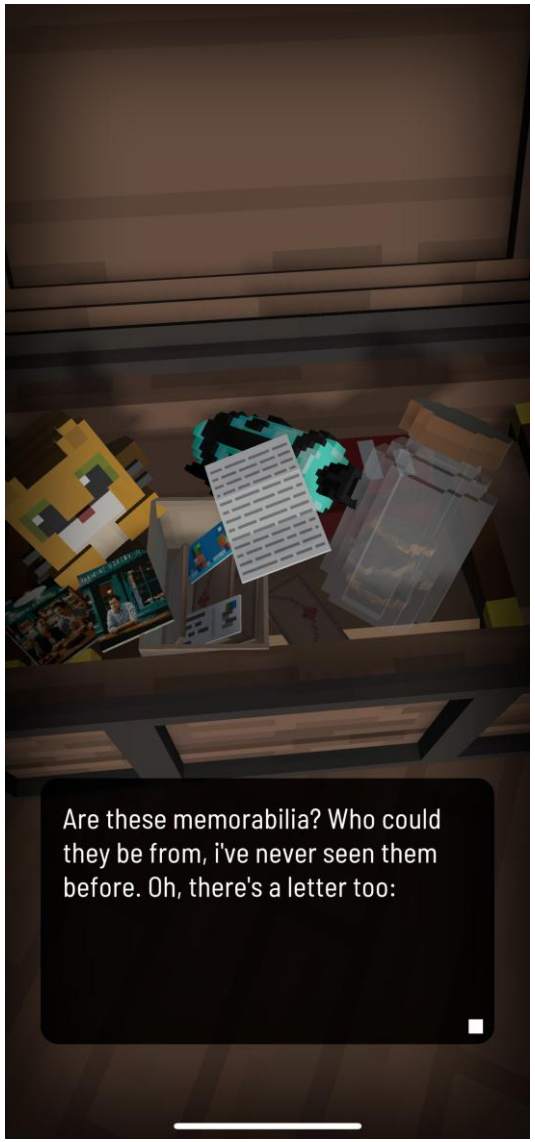


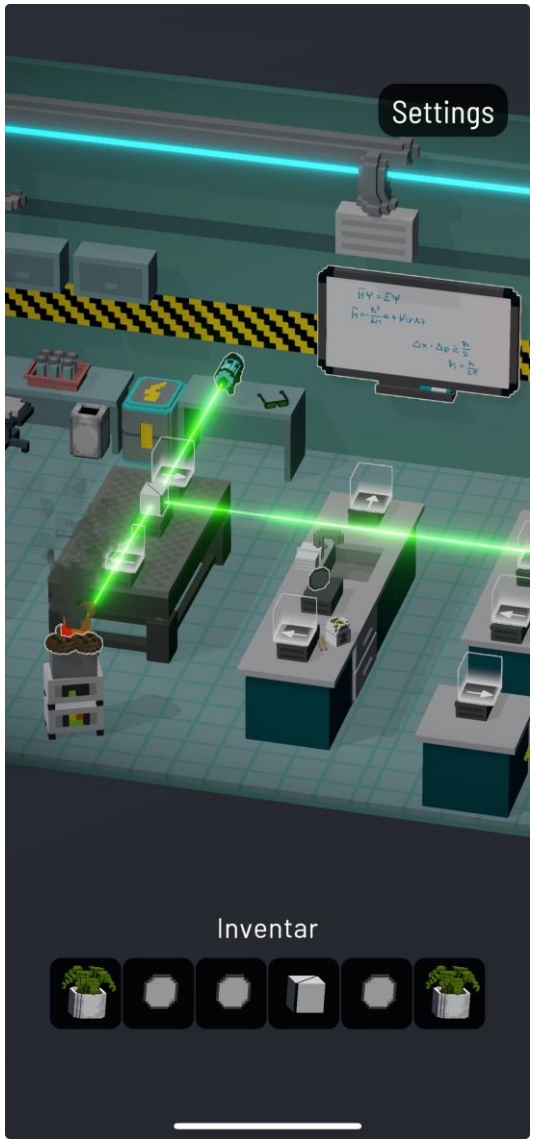

## Equations



# How do we keep students engaged?

## Regular interactions with parts of the story



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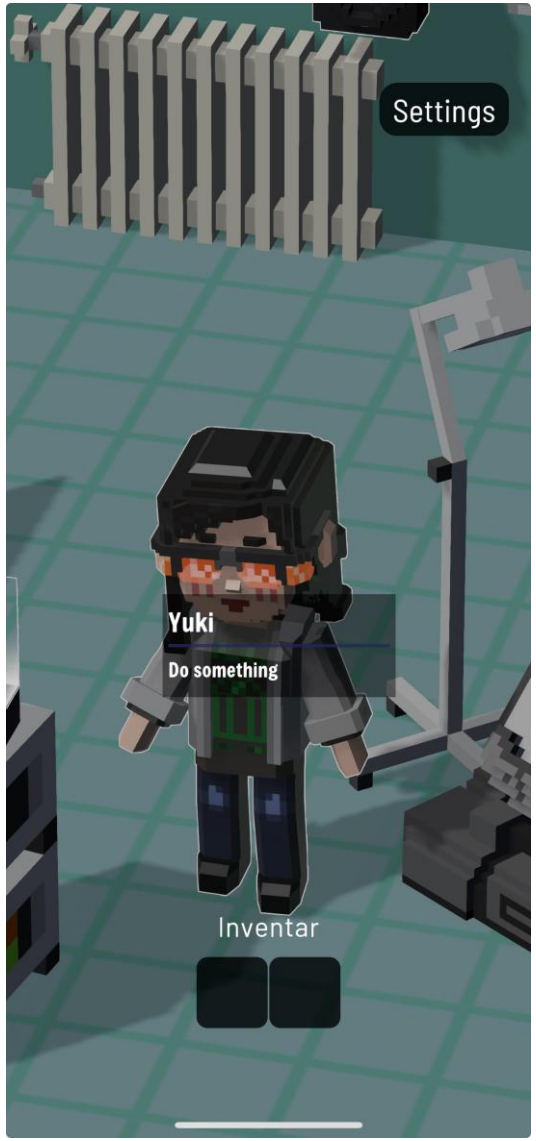
# Different levels of concept-based interaction

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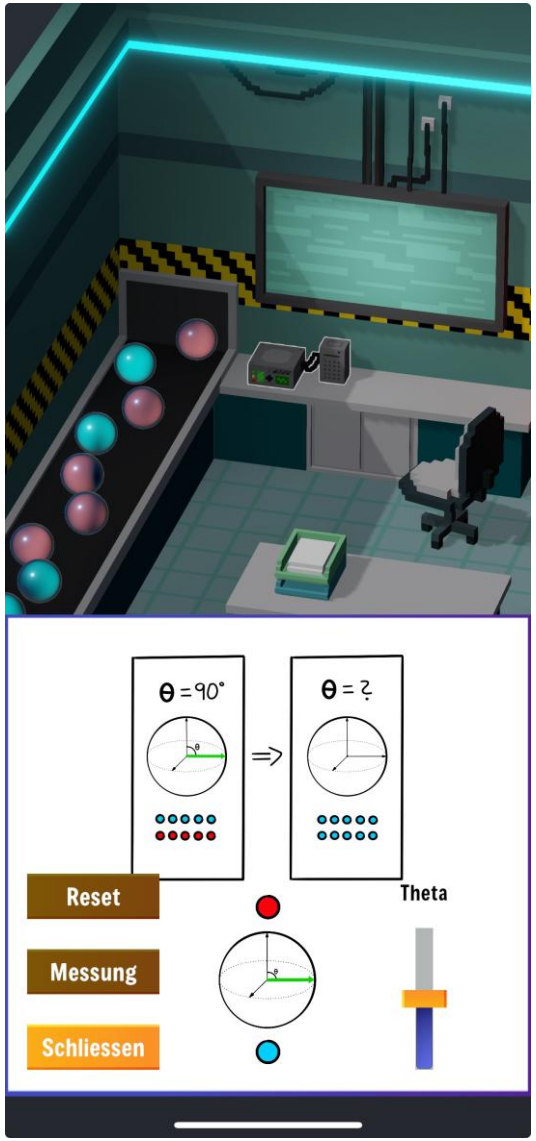
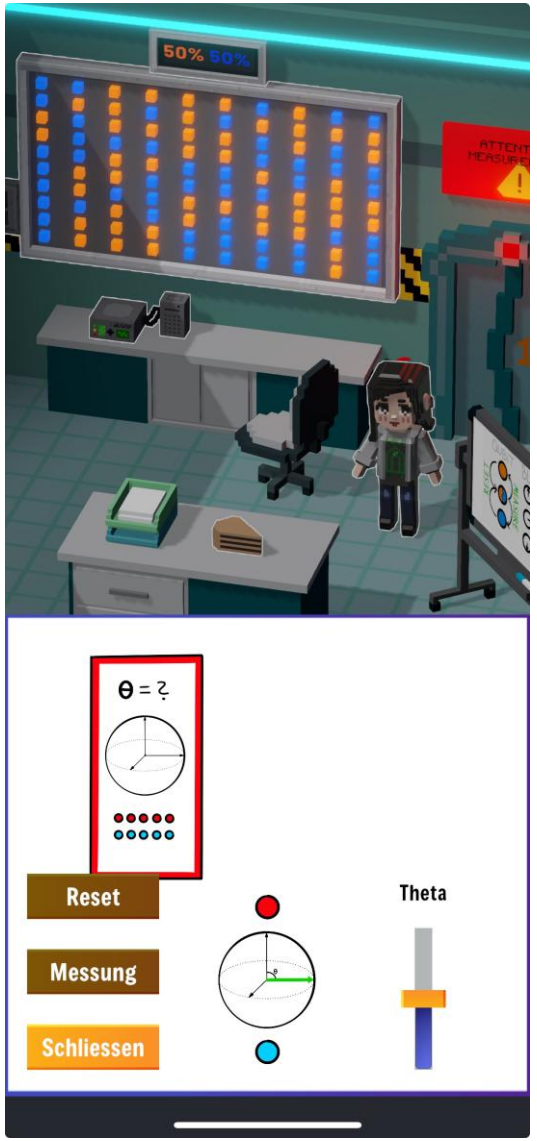
# How do we include concepts of quantum physics?

## Example: the effect of a measurement



# How do students gain conceptual understanding of Quantum physics

*Learn* + *apply*

*learning nuggets* + *solve the level*

# Research Questions and Hypotheses

1. How can an AI character effectively support a player in learning QT content?

- Scaffolding in digital game-based learning can effectively improve learning (Cai et al. 2022)
- Scaffolding usefulness has a significant positive correlation with game usefulness and game ease of use (Chein et al. 2024)

2. How does the AI character influence the player's cognitive load?

- Scaffolding can reduce cognitive load (Arnold et al. 2017)
- Adaptive scaffolding has a positive impact on cognitive load (Faber et al. 2023)
- Use of generative AI places high demands on metacognition (Tankelevitch et al. 2024)

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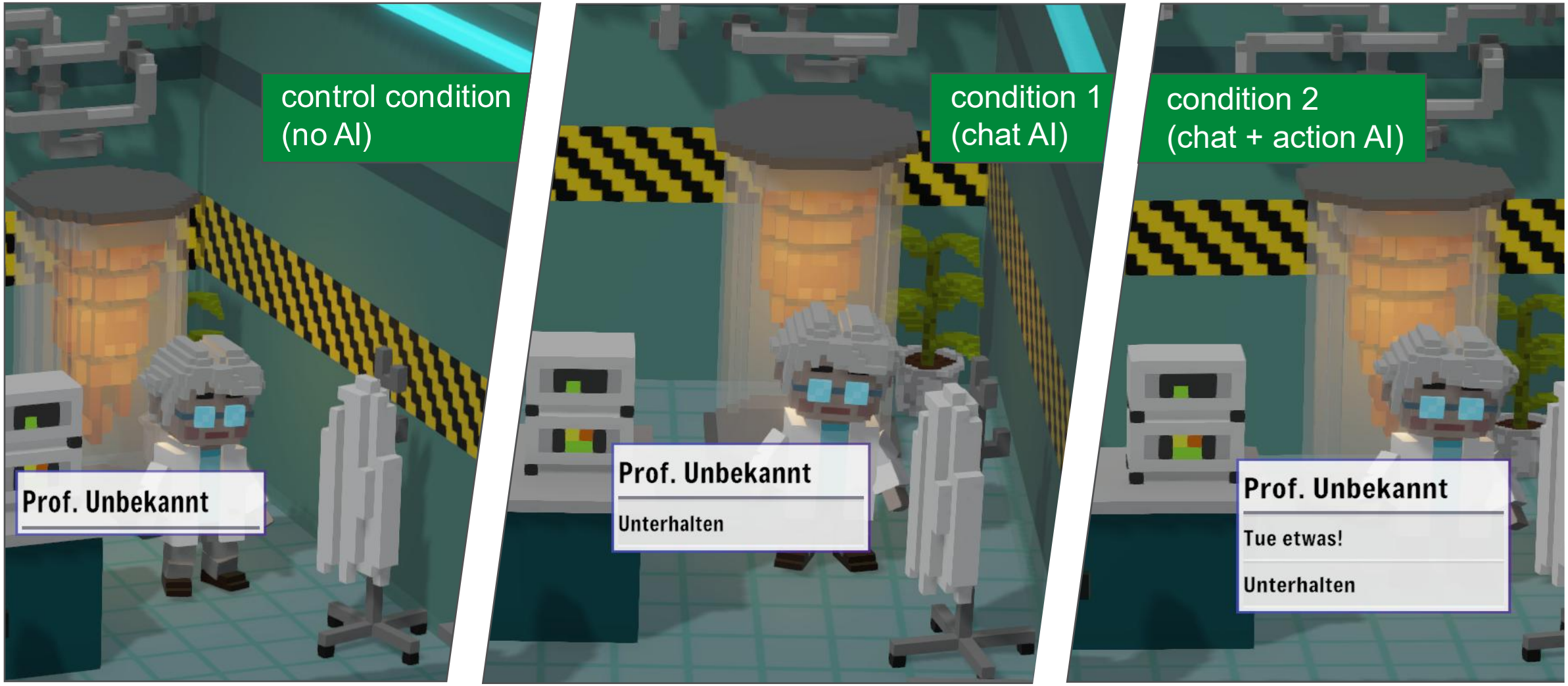
# Conditions



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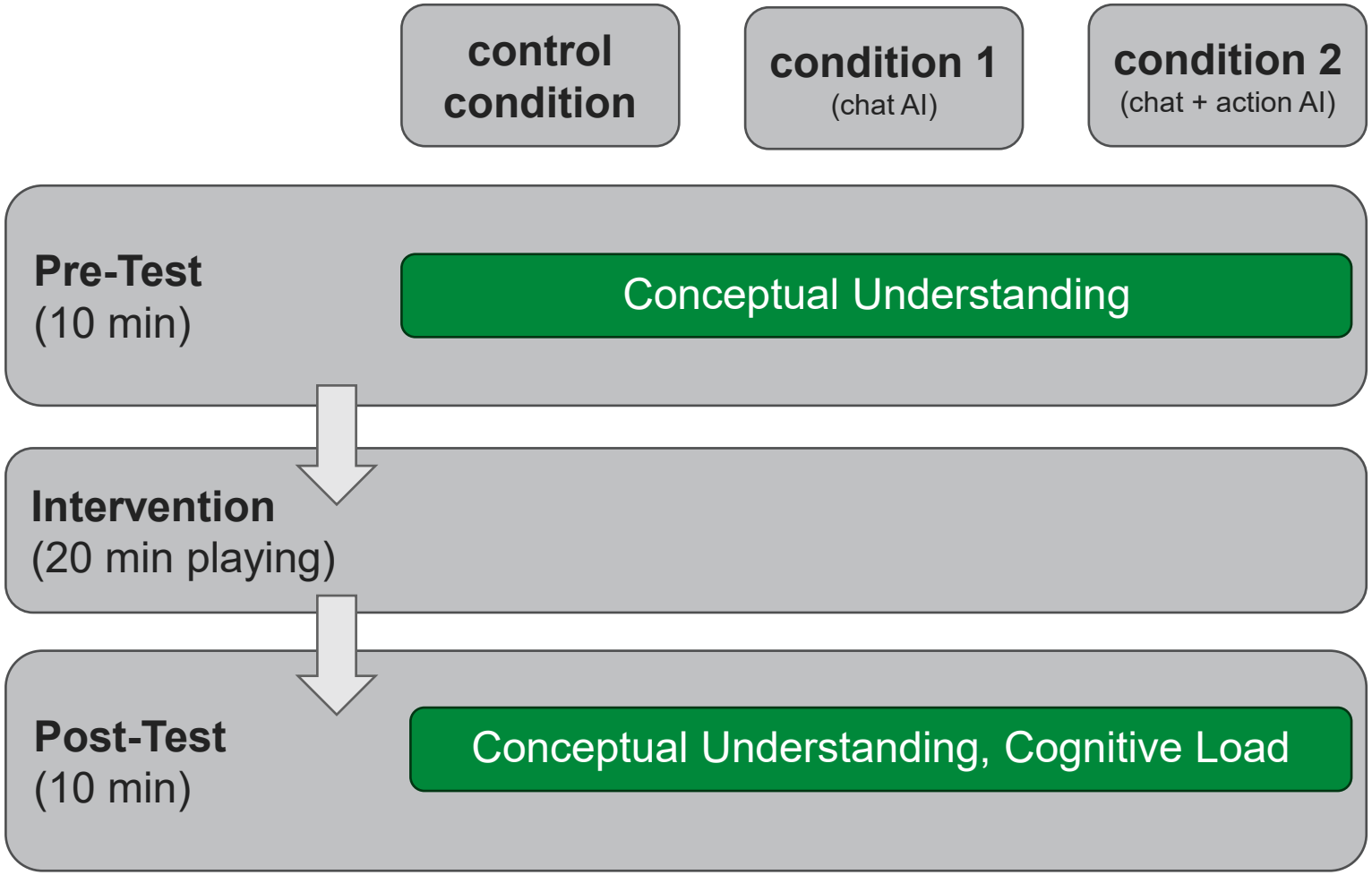
# Studydesign and Methods



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# Participants

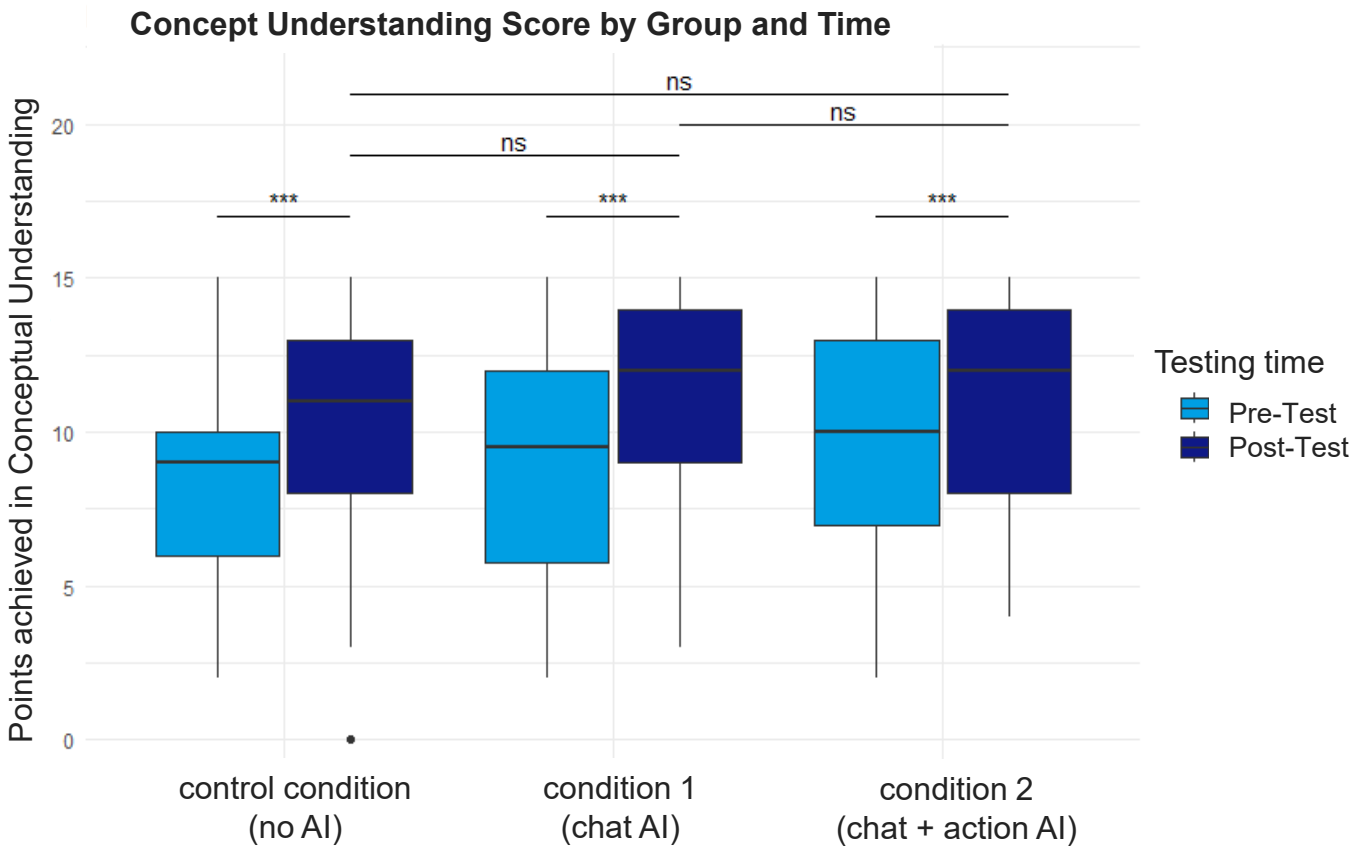
| | **Control condition** (no AI) | **Condition 1** (chat AI) | **Condition 2** (chat + action AI) |
|---|---|---|---|
| Number | 47<br>65 | 50<br>32 | 55 |
| Gender (m/f/d) | 26/20/1<br>33/28/4 | 24/23/3<br>17/15/0 | 31/20/4 |
| Occupation (pupil/student/employee/other) | 35/ 7/3/2<br>43/22/5/5 | 26/27/4/3<br>18/12/2/0 | 34/15/4/2 |

We reach significantly fewer people from the interested public.

Only a fraction of the participants who had the opportunity accessed the functions of the AI.

# AI and Learning QT content

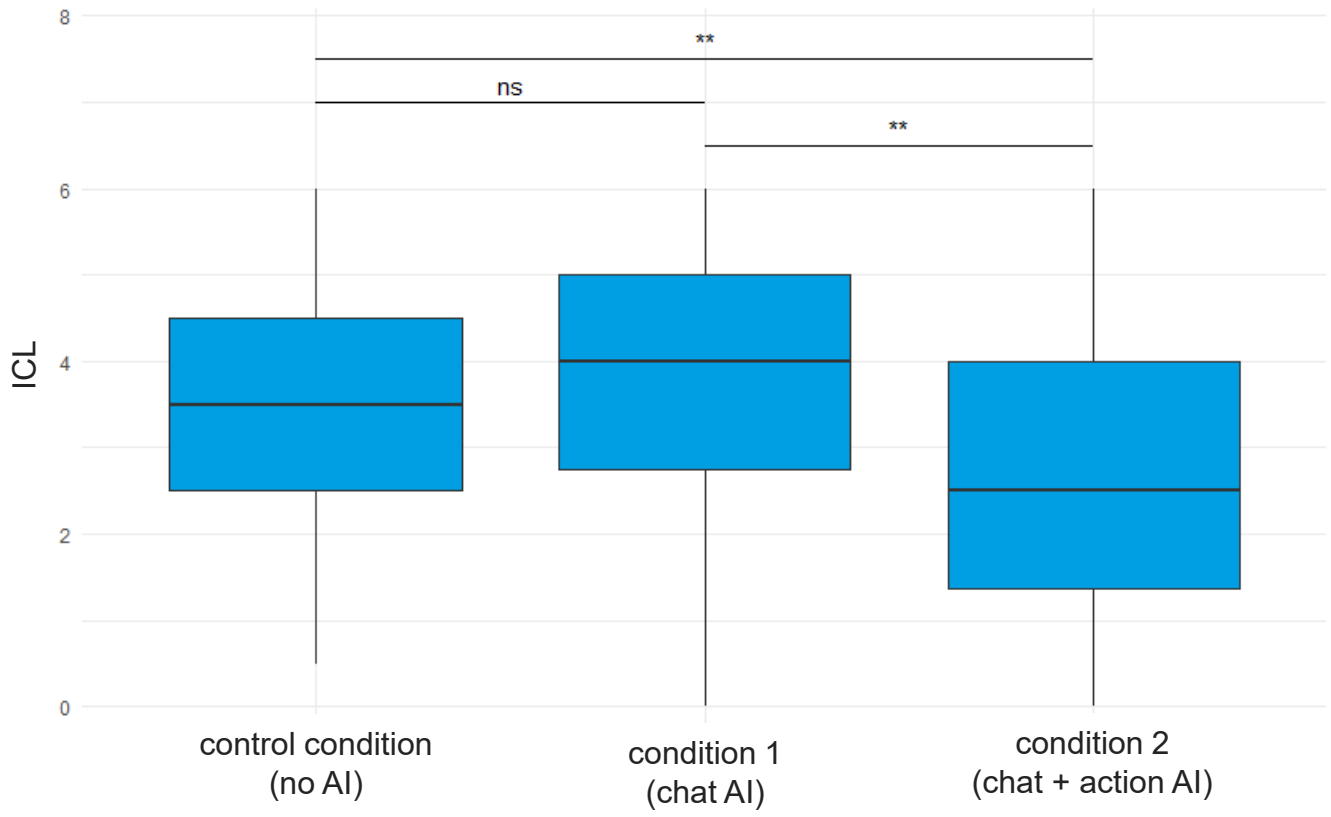
How can an AI character effectively support a player in learning QT content?




Participants learn through our game, regardless of the kind of scaffolding.

# AI and Cognitive Load

How does the AI character influence the player's cognitive load?




Compared to the other two groups, the ICL is significantly reduced in the condition 2.
ECL and GCL do not differ between the groups.

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# Takeaways

- Games are an effective way to engage even young learners about quantum physics
- Only a fraction of the participants who had the opportunity accessed the functions of the AI.
- Participants learn through our game, regardless of the kind of scaffolding.
- Compared to the other two groups, the ICL is significantly reduced in the condition 2.
- ECL and GCL do not differ between the groups.
- So far, we have not included a high level of interaction with mathematical equations

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# Thank you!

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**Galaqsci.de**

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# Literature


Arnold, J., Kremer, K. & Mayer, J. (2017). Scaffolding beim Forschenden Lernen. *ZfDN*, 23, pp. 21–37

Bawa, P., Watson, S. L., & Watson, W. (2018). Motivation is a game: Massively multiplayer online games as agents of motivation in higher education. *Computers & Education*, 123, pp. 174–194

Cai, Z., Mao, P., Wang, D., He, J., Chen, X. & Fan, X. (2022). Effects of Scaffolding in Digital Game-Based Learning on Student's Achievement: a Three-Level Meta-analysis. Educ Psychol Rev 34, pp.537–574.

Chang, C.-C, Liang, C., Chou P.-N. & Lin G.-Y. (2017). Is game-based learning better in flow experience and variozs types of cognitive load than non-game-based learning? Perspective from multimedia and media richness. *Computers in Human Behavior*, 71, pp. 218-227

Chien, C.-C., Chan, H.-Y. & Hou, H. T. (2024). Learning by playing with generative AI: design and evaluation of a roleplaying educational game with generative AI as acaffolding for instant feedback interaction. *Journal of Research on Technology in Education*, pp. 1-20

Chien, C. C., Ho, Y.-T., & Hou, H.-T. (2023). Integrating immersive scenes and interactive contextual clue scaffolding into decision-making analysis ability training game. *Journal of Educational Computing Research*, 62(1), pp. 376– 405.

Faber, T. J., Dankbaar, M. E., van den Broek, W. W., Bruinink, L. J., Hogeveen, M., & van Merriënboer, J. J. (2024). Effects of adaptive scaffolding on performance, cognitive load and engagement in game-based learning: a randomized controlled trial. *BMC Medical Education*, 24(1), 943.

Mayer, R. E. (2002). Multimedia learning. *Psychology of Learning and Motivation*, 41, pp.85-139

Plass, J. L., Perlin, K., & Nordlinger, J. (2010, March). The games for learning institute: Research on design patterns for effective educational games. *In Game Developers Conference*, San Francisco, CA (pp. 5-10).

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# Literature


Shaffer, D. W., Squire, K. R., Halverson, R., & Gee, J. P. (2005). Video games and the future of learning. *Phi delta kappan* 87(2), 105-111.

Sweller, J. (1988). Cognitive Load During Problem Solving: Effects on Learning. *Cognitive Science*. 12 (2), pp. 257–285.

Tankelevitch, L., Kewenig, V., Simkute, A., Scott, A. E., Sarkar, A., Sellen, A., & Rintel, S. (2024). The metacognitive demands and opportunities of generative AI. In *Proceedings of the CHI Conference on Human Factors in Computing Systems.* pp. 1-24

Wouters, P., van Nimwegen, C., van Oostendorp, H. & van der Spek, E. D. (2013). A meta-analysis of the cognitive and motivational effects of serious games. *Journal of Educational Psychology* 105 (2), pp. 249-265.