Doctoral Thesis

Cognitive Architectures for Serious Games

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"The only true voyage of discovery, the only fountain of Eternal Youth, would be not to visit strange lands but to possess other eyes, to behold the universe through the eyes of another, of a hundred others, to behold the hundred universes that each of them beholds, that each of them is."

Marcel Proust

To my loves Agnese, Marta and Leonardo.

"The key question is, no matter how much you absorb of another person, can you have absorbed so much of them that when that primary brain perishes, you can feel that that person did not totally perish from the earth... because they live on in a 'second neural home'?... In the wake of a human being's death, what survives is a set of afterglows, some brighter and some dimmer, in the collective brains of those who were dearest to them... Though the primary brain has been eclipsed, there is, in those who remain... a collective corona that still glows."

Douglas Richard Hofstadter

To my parents

Abstract

This dissertation summarises a research path aimed at fostering the use of Cognitive Architectures in Serious Games research field.

Cognitive Architectures are an embodiment of scientific hypotheses and theories aimed at capturing the mechanisms of cognition that are considered consistent over time and independent of specific tasks or domains.

The theoretical approaches provided by the research in computational cognitive modelling have been used to formalise a methodological framework to guide researchers and experts in the game-based education sector in designing, implementing, and evaluating Serious Games. The investigation of cognitive processes involved during the game experience represents the fundamental step of the proposed approach.

Two different case studies are described to discuss the possible use of the suggested framework. In the first case study, the aim was to design a modified version of the Tetris game with the intention of making the game more effective in training the visual-spatial skill called mental rotation. In the second scenario, the framework was used as a basis for creating an innovative persuasive game. This case study provides an example of adopting cognitive architectures for implementing a non-player character with human-like behaviour developed using targeted cognitive theories.

List of publications

Findings from this research have been part of the following publications:

Allegra, M., Bongiovanni, A., Città, G., Cusimano, A., Dal Grande, V., Gentile, M., ... Signa, A. (2021). The role of metaphor in serious games design: the bubblemumble case study. In F. de Rosa, I. Marfisi Schottman, J. Baalsrud Hauge, F. Bellotti, P. Dondio, & M. Romero (Eds.), *Games and learning alliance* (pp. 198–207). Cham: Springer International Publishing.

Augello, A., Città, G., Gentile, M., & Lieto, A. (2021, December). A storytelling robot managing persuasive and ethical stances via act-r: an exploratory study. *International Journal of Social Robotics*, 1–17. Retrieved from https://doi.org/10.1007/s12369-021-00847-w doi: 10.1007/s12369-021-00847-w

Bono, A., Augello, A., Gentile, M., & Gaglio, S. (2020). Social practices based characters in a robotic storytelling system. In *2020 29th ieee international conference on robot and human interactive communication (ro-man)* (p. 90-95). doi: 10.1109/RO-MAN47096.2020.9223501

Gentile, M., Citta, G., Lieto, A., & Allegra, M. (2019). Some Notes on the Possibile Role of Cognitive Architectures in Serious Games. In A. Liapis, G. N. Yannakakis, M. Gentile, & M. Ninaus (Eds.), (Vol. 11899, pp. 231–241). SPRINGER INTERNATIONAL PUBLISHING AG. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85082450595&doi=10.1007%2f978-3-030-34350-7_23&partnerID=40&md5=c5352c9e0ae5cb23dff8227ca220cbb2 doi: 10.1007/978-3-030-34350-7\%5C_23

Gentile, M., & Lieto, A. (2022). The role of mental rotation in TetrisTM gameplay: An ACT-R computational cognitive model. *Cognitive Sys-*

tems Research, *73*, 1–11–1–11. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85122683826&doi=10.1016%2fj.cogsys.2021.12.005&partnerID=40&md5=d4191bd13ecb53d31fa536591b320e1c doi: 10.1016/j.cogsys.2021.12.005

Signa, A., Chella, A., & Gentile, M. (2021). Cognitive robots and the conscious mind: A review of the global workspace theory. *Current Robotics Reports*, *2*, 125 - 131.

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Spotorno, R., Picone, M., & Gentile, M. (2020). Designing an online dungeons & dragons experience for primary school children. In I. Marfisi-Schottman, F. Bellotti, L. Hamon, & R. Klemke (Eds.), *Games and learning alliance* (pp. 207–217). Cham: Springer International Publishing.

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Starting a doctoral programme at 44 was not so easy. Several factors and people influenced this choice, reinforcing convictions and motivations that came from deep within. Uncertainties, questions and a high-level curiosity are traits I found in many colleagues I had the pleasure of meeting during my twenty years of work at the National Research Council of Italy (CNR), which I also find in myself. It is these feelings, with which we often superficially associate a negative valence, that instead played a decisive role in the start of this adventure.

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somehow experiencing this emotion with me.

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1 Introduction

In 1998, in his seminal work, Windschitl (1998) provided an outline of the opportunities offered by the Web in education, in particular as a repository of knowledge capable of supporting students' processes of inquiry and discovery and as a tool capable of fostering communication between students.

Today, after about 25 years and several technological revolutions, the most debated topic both in research and in society is Artificial Intelligence (AI)[1], the benefits and potential risks associated with its use in the different spheres of human activity and thus also in the field of learning and teaching.

However, the current attention on AI seems to have forgotten how the research in the AI field has always looked at the world of education as one of its main fields of application. Since understanding how people learn is closely related to the idea of intelligence[2] or because knowledge representation has been one of the

[1] According to McCarthy (2007), artificial intelligence is "the science and engineering of making intelligent machines, especially intelligent computer programs. It is related to the similar task of using computers to understand human intelligence, but AI does not have to confine itself to methods that are biologically observable.".

[2] Determining what intelligence is and how it can be defined has always been and continues to be the goal of various communities of researchers operating in different fields. Among the studies in the literature, we can distinguish a few broad categories of approaches such as psychometric, cognitive and biological. The work from R. J. Sternberg (2012) analyses the state of the art of intelligence theories, from Cattel, Horn and Carrol's CHC theory to Gardner's theory of multiple intelligences, as well as his triarchic theory, also providing a review of advances in the biological and neuroscientific fields. Steinberg adopts a different approach based on metaphors to categorise the research on intelligence in the "The Cambridge Handbook of Intelligence" (R. Sternberg, 2020). Among the various metaphors, the computational one is certainly of interest to the aims of this thesis. According to the computational metaphor, the mind could be seen as a computing device analogous to a computer. Consequently, for many theorists of this approach, such as Newell and Simon, computer programmes implicitly define cognitive theories. Other researchers like Anderson propose a smoother point of view, seeing in computer programmes an attempt to operationalise cognitive theories. The wealth of approaches demonstrates how defining intelligence is undoubtedly a challenging task. However, many scholars agree on the central role of the ability to adapt to the environment in the definition of intelligence. For this reason, we refer in this thesis to the definition provided by Steinberg and quoted in the Encyclopaedia Britannica, which states that human intelligence is a "mental quality that consists of the abilities to learn from experience, adapt to new situations, understand and handle abstract concepts, and use knowledge to manipulate one's environment" (Britannica, 2023).

most prominent research topics in AI, the link between AI and Education has always been investigated.

In recent years, the research interest in AI and Technology-Enhanched Learning (TEL) has found a further common field of exploration: games.

Games have always been one of the favourite fields of experimentation for AI. They provide a controlled environment with precise rules where it is possible to compare the behaviours of intelligent agents with that of human players. Just think of the research on traditional board games like chess, backgammon, and, more recently, Go (Campbell, Hoane, & hsiung Hsu, 2002; Schaeffer & van den Herik, 2002). The emergence of the digital gaming industry has led to progressive interest towards the use of AI as a support for the realisation of games, resulting in the emergence of a research field called "games Artificial Intelligence" (games AI). A well-known seminar, that was held in 2012 in Dagstuhl (Lucas et al., 2012), represents a key milestone in shaping this research area. During the workshop, about 40 experts discussed and outlined the main challenges of the emerging research area, identifying different possible research themes. Other conferences have been contributing to shaping this field, such as the AAAI Artificial Intelligence and Interactive Digital Entertainment (AIIDE)[3], and the IEEE Conference on Games [4]. Moreover, in the book "Artificial Intelligence and Games", Yannakakis and Togelius (2018a) recently provided a systematical outline of the *games AI* field.

In educational research, the idea of games as an approach to foster the acquisition or creation of knowledge and meaning and the development of skills and competencies has been cultivated along the paths of human history until it came to full awareness with the creation of specific research fields like game-based learning and serious games.

Serious games (SGs) are typically defined as "games designed with a purpose other than mere entertainment" (Djaouti, Alvarez, Jessel, & Rampnoux, 2011; Michael & Chen, 2006).

Usually, such a goal, different from pure entertainment, is to enhance learning

[3]The AIIDE conference website is accessible at the following url https://aaai.org/conference/aiide-2/

[4]Since 2019, the IEEE Conference on Computational Intelligence and Games (CIG) has been renamed to IEEE Conference on Games (CoG). The website of the conference is accessible at the following url http://ieee-cog.org

or to foster the development of skills and abilities by exploiting the engagement and motivational characteristics inherent in the game (Gentile, Allegra, & Söbke, 2019).

It is precisely in the SGs research field that my doctoral path has been developed to contribute to its maturation, also thanks to the utilisation of research advances in the field of AI and, in particular, that part of AI that is more focused on the analysis of cognitive processes.

This need has emerged from a personal awareness, corroborated by the analysis of the literature, that it was necessary to propose a theoretically grounded research path to get out of an often sterile opposition between enthusiasts and sceptics of SGs. In fact, while enthusiasts claim that SGs would lead to a revolution in learning and teaching processes, promoting the idea that SGs can enhance learning at different ages and in various branches of knowledge, sceptics point out all the limitations of this approach in fostering effective learning. Although SGs are generally called upon for their ability to promote a rich set of skills (e.g., critical thinking, problem-solving, decision-making, etc.), most studies in this regard fail to prove the ability of the game to achieve "deep learning" (Gee, 2014)[5]. Further confirming the difficulty of proving their effectiveness, according to Ifenthaler, Eseryel, and Ge (2012b), research studies in this field often rely on a simple cross-sectional research design using tests administered before and after the game experience on small samples to test the educational effectiveness of game-based learning. Moreover, often the validation is performed with unvalidated measures, a sign of the discipline's lack of maturity. Furthermore, as suggested by Kim and Ifenthaler (2019), the results provided by the evaluation of game-based learning activities do not offer an interpretation capable of returning positive feedback to the design phase to improve their effectiveness.

As recently stated by Mayer (2019), who analyses this phenomenon from the perspective of Cognitive Science (CS), there is very little clear evidence in favour of the fact that 'playing' SGs directly improves cognitive ability in general. In a seminal paper entitled "Do brain training programmes work?", Simons et al. (2016a),

[5] According to several authors (*The Cambridge Handbook of the Learning Sciences*, 2014; Council, 2000), "deep learning" is the condition in which learners show a deep understanding of subject matter and are able to transform factual information into usable knowledge in contexts different from the original one (transfer learning)

states that every game undoubtedly enhances and improves the ability to play the game itself (practice improves performance). However, he also emphasized that there is no scientifically sound evidence that playing SGs improves higher-level mental processes such as problem-solving and long-term remembering (E. Goldstein, 2011).

In the end, despite the progress achieved in this last decade, research on SGs lacks theoretically well-founded models that are able to guide the design and evaluation phases of the games themselves.

To this aim, some scholars (Frutos-Pascual & Zapirain, 2017; Greitzer, Kuchar, & Huston, 2007; Mayer, 2019; Vermillion et al., 2017) suggest that SG sector can benefit from a constructive dialogue with the CS field, which could and should provide an essential theoretical reference for dealing with some crucial issues such as modelling the player's behaviour and evaluate his/her interaction. Specifically, CS would be able to provide SG research with results and research methodologies on cognitive principles and models for explaining the cognitive processes that underlie learning through SG (Greitzer et al., 2007). This kind of research would help scholars in the design and the evaluation process of a SG giving valuable indications on how cognitive skills and in particular, according to J. R. Anderson, Corbett, Koedinger, and Pelletier (1995), declarative and procedural knowledge is acquired in the game phases.

On the other hand, SGs could provide CS with an appropriate experimental environment able to overcome the limitations of some cognitive experiments. In CS, experimental designs are generally carried out in aseptic environments (e.g., the laboratories) very distant from everyday reality to isolate all the factors that could influence the studies. Unfortunately, this approach leads to results often refuted when tested and analyzed in "real" contexts. SGs can represent a good compromise between structured experimental settings and less structured experimental settings closer to daily reality. In fact, SGs are generally designed to simulate reality, and research confirms that SGs can "immerse" the player in a cognitive flow (Csikszentmihalyi, 2014) that leads him to experience the situation as if it were real. In addition, the handcrafted nature of SGs allows the researchers to manipulate the game to stimulate/test and verify specific cognitive processes. The analysis of the

user's interactions collected during the gameplay would allow researchers to verify the validity of the theorized models, thus representing a promising research paradigm for the cognitive sciences of the computational approach.

For all of these reasons, this thesis work aims at an in-depth exploration of Cognitive Architectures (CAs) and the theoretical models on which they are built as a congenial tool for the explanation, representation, and reproduction of the cognitive processes and knowledge acquisition dynamics involved in the learning contexts provided by SGs.

The term "cognitive architecture" (CA), introduced by Allen Newell in 1990 (Newell, 1990), indicates both abstract models of cognition and the software instantiations of such models (Lieto, Bhatt, Oltramari, & Vernon, 2018).

In the serious games and educational technologies fields, various cognitive theoretical models proposed as cognitive architectures have found application, among them, for example, the "Schema Theory" from (Eckblad, 1981), the "Cognitive Load" by (Sweller, 1988), the theory of "Multimedia Learning" proposed by (Mayer, 2014), or the "Mental Models" from (Seel, 2001).

However, within the scope of this thesis, we are interested in exploring the part of CA research that investigates the computational instantiation of cognitive theories and that therefore intersects with the AI field.

The investigation starts with the exploration of the two research fields. Subsequently, the intersection of the two fields will be analysed through an in-depth analysis of the literature. In particular, at this stage, reference will be made to the broad field of games to draw inspiration for a systematisation of approaches in the specific area of serious games. The literature investigation will lead to the definition of a theoretical framework designed to support researchers, designers and experts in implementing and evaluating serious games according to a well-founded cognitive approach. Finally, the framework will be tested in two case studies, the first on Tetris and the second on the implementation of dialogue-based persuasive serious games.

2 A walk through the core concepts

This chapter presents two areas covered by this thesis work: serious games and cognitive architectures. Concerning serious games, after briefly reviewing the history of the research field, a summary of the evidence reported in the literature on their educational effectiveness is given. The section is completed by examining the leading frameworks for designing serious games available in the literature. With regard to cognitive architectures, after a high-level introduction to the field, two of the prominent architectures in the literature, ACT-R and Soar, are presented in detail.

2.1 Serious Games

Understanding what we mean by "serious games" is a fundamental step not only to comprehending the field of application that we are investigating but also to provide a complete interpretation of the results of this thesis work.

The concept of serious games consists of two words with seemingly contrasting meanings, which can be perplexing upon superficial reading. The term "game" naturally evokes fun and inherently motivating playful activities, while the adjective "serious" is attached to it, almost suggesting a distortion of the essence of the game.

The first author to introduce the concept of serious games was Clark Abt in 1970 in his book titled "Serious Game" (Abt, 1970). In his book, Abt proposed the following definition:

> Serious games are digital or analog games whose main objective is to combine learning and fun in order to achieve specific goals of education, training, or communication. (Abt, 1970)

Since 1970, different definitions of the concept of Serious Game have been proposed in literature, of which we present a non-exhaustive list below.

> Serious games are games designed for a primary purpose other than pure entertainment. The serious purpose can be education, training, advertising, or public policy.(Michael & Chen, 2006)

> Serious games are digital games designed to educate, train, or persuade players to engage in productive, real-world activities or to learn meaningful, transferable skills. (Susi, Johannesson, & Backlund, 2007)

> Serious games are games designed for a primary purpose other than entertainment, with a particular focus on applications such as education, training, health, and public policy.(Djaouti et al., 2011)

> Serious games are computer-based games that enable players to learn, improve, or maintain skills or knowledge while engaged in an activity that resembles a game. (Connolly, Boyle, Macarthur, Hainey, & Boyle, 2012)

> Serious games are interactive digital media designed to promote purposeful behavior change, support learning, and increase awareness by engaging players in entertaining game-play that serves a serious purpose. (DeSmet et al., 2014)

Notwithstanding more or less significant variations, all the definitions cited insist on the different primary objectives with which serious games are conceived and realised compared to traditional games.

However, it is fair to point out that throughout human history, games and the action of playing have attracted the attention of scholars of all ages[1].

Although with different nuances and points of view, academics who have analysed the game in its various forms have often identified in it some aspects that

[1] Although the same word is used in many languages to refer to the two concepts of play and play ("spielen ein Spiel" in German, "jouer à un jeu" in French, "giocare un gioco" in Italian, "ludere ludum" in Latin), the evolution of the English language has led to two different terms. Moreover, game theorists attribute different meanings to the two terms. The term "play" refers to free play instead of "game", which identifies goal-directed play activity. For a complete treatment of the topic, see (Galloway, 2006)

could be described as 'serious'. In ancient Greece, the game, in its broadest version, was considered intrinsically linked to a wide range of cultural activities (D'Angour, 2013). For instance, in his dialogue 'The Republic', Plato discusses the nature of the game and its role in education and character development, arguing that a game is essential for developing a child's physical, emotional and intellectual capacities. He believed that children should be allowed to play freely, but that their play should also be directed towards moral and intellectual ends and that play could be used as a tool for teaching and education (paidiá - play & paodeia - education).

In a context much closer to today, Huizinga (1950)[2] argues that play and games are not just frivolous activities but essential to developing and maintaining culture and society. Huizinga claims that games create a temporary world separate from everyday life, where players can freely and creatively explore different possibilities and outcomes according to the game's rules. Through play, individuals develop skills, learn social norms and values, and explore different forms of identity.

A similar approach can be found in Piaget (2013)[3]. He believed that games could effectively promote cognitive development. Games can help children develop problem-solving, logical thinking, and spatial reasoning skills.

This brief and, certainly, not exhaustive analysis of the role of play in human and social development is intended to broaden the scope of this paper not only to games specifically designed for a main use other than entertainment but also to a *practice of using games*, whether commercial or ad-hoc, that is aimed at a purpose other than entertainment.

In the following sections, the field of serious games is analysed from the point of view of research aimed at verifying its benefits and from the point of view of frameworks that are present in literature to support the design of serious games.

2.1.1 Cognitive benefits and limitations of serious games

An important question that naturally arises is, "What effects can Serious Games have on students and learning processes?". Although historically, it has been pointed out that there was a stressful need to investigate more thoroughly the effects that Serious Games have (e.g. Girard, Ecalle, & Magnan, 2012; Young et al., 2012), much

[2]The first edition of "Homo Ludens" was published in Dutch in 1938.
[3]The first edition of "Play, Dreams And Imitation In Childhood" was published in 1951.

has been accomplished over the years, with numerous studies carried out in different fields: Political Sciences (Jones & Bursens, 2015), Engineering (Chaves et al., 2015), Social Sciences (Cózar-Gutiérrez & Sáez-López, 2016), Management (Geithner & Menzel, 2016), Medicine (Dankbaar et al., 2015), Languages (Franciosi, 2015), Nursing (Sarabia-Cobo, Alconero-Camarero, Lavín-Alconero, & Ibáñez-Rementería, 2016), Physics (D. M. Adams, Pilegard, & Mayer, 2015).

In parallel to these works, several literature reviews and meta-analyses have attempted to identify, examine and classify the benefits and limitations associated with the use of SGs (Connolly et al., 2012). Some of these works thematised benefits and limitations of the use of SGs from the perspective of the learning outcomes[4] achieved (Boyle et al., 2015; Connolly et al., 2012; Vlachopoulos & Makri, 2017), others from the perspective of the research methodologies implemented (Mayer, 2019).

Most improvements in learning outcomes rely directly on the cognitive sphere or aspects strictly connected to cognition. According to Vlachopoulos and Makri (2017), improvements at learning outcome levels are reported and supported by empirical evidence about knowledge acquisition, conceptual application, content understanding and action-directed learning. The authors report findings related to the increased likelihood, in the context of problem-solving, of students learning when using games compared to traditional learning experiences. As an example, in the context of medical education, Serious Games prove to be effective training methods, both for single-player and multiplayer games.

The empirical evidence is also evident in other application areas, such as mathematics, history, languages, physical education, physics and marketing. Moreover, some studies present evidence of students' preference for visualized simulations in the context of laboratory activities. Specifically, the power of simulations emerges in the context of clinical skill practice, nursing practice knowledge, critical thinking and decision-making, as well as in terms of facilitators of flow experiences and learning. Furthermore, Boyle et al. (2015) point out that in addition to these benefits, classifiable as 'content benefits', the use of computer games and SGs contributes to enhancing attentional and visual perception, task switching, multi-

[4] According to (Shute, 1996) learning outcomes represent the results of a learning process (e.g., propositional knowledge, procedural skills, mental models).

tasking, implicit learning of sequential context, and the ability to deploy attention over space, time and objects. These results also include improvements in performance regarding working memory, addition, auditory perception, selective attention tasks, and higher-level thinking skills (Connolly et al., 2012).

The use of SGs can also have effects in the area of affective and behavioural change. According to Boyle et al. (2015), specific studies report improvements related to the use of games regarding levels of arousal, feeling of presence, situation awareness and faster performance when needed. Improvements connected to the use of specialized games are also reported relative to the development of prosocial behaviours, resistance to relapse in alcohol dependence, and the improvement of relationship satisfaction and intimacy motives in relationships with partners.

Some research works, moreover, focus on the effects of the use of computer games and SGs on social and soft skills showing, through specific case studies, improvements in emotional expressivity, control, empathy and self-efficacy (Connolly et al., 2012).

However, what is reported does not show the 'dark side of the moon'. Indeed, there are several objections in the literature regarding the actual effectiveness of SGs in procuring the benefits described above or, at least, in deeply procuring them. Several concerns have been raised about the theoretical and procedural soundness of the research conducted to demonstrate the effectiveness of games.

Among the various criticisms advanced (Girard et al., 2012; S. I. Gray, Robertson, Manches, & Rajendran, 2019), one, in particular, shows maybe the most problematic limitations of SG use: the lack of adequate and effective generalisation from in-game performance to real-world cognitive gains (Morra & Borella, 2015; Simons et al., 2016b). A problem closely related to the long-discussed within psychology and education, and more general problem of transfer learning (Barnett & Ceci, 2002; Birney & Grose, 1963). J. A. Adams (1987) define transfer learning "as the extent to which learning of a response in one task or situation influences the response in another task or situation".

Such a substantial limitation would not provide convincing evidence that SGs can improve learning. It is ultimately impossible to come to generalisable conclusions as there are different games, designed according to different models, gener-

ated in different environments (Ke, 2009). The most significant risk, therefore, is that the cognitive benefits produced by each game remain strictly limited to the specific game context.

Accordingly, Fu, Hainey, and Baxter (2016) argue that although game-mediated learning is able to offer enjoyable and motivating experiences, there is a lack of robust evidence that games lead to real and shareable learning outcomes. Several studies seem to successfully demonstrate that when comparing a test group that learns with games with a control group that learns in an ordinary school context, the results do not differ (Giessen, 2015).

The field of debate is intricate, and probably simply asking whether SGs work is the wrong question. A critical attitude to the problem begs more pointed research questions that open up a new and much-needed avenue toward a deeper understanding of the cognitive theories and cognitive models underlying how games work and the design principles adopted.

In this direction, approaches that study the effects of SGs from a careful analysis of the implemented research methodologies seem to bring the terms of the controversy outlined above into clear focus. Mayer (2019) identifies three fundamental research questions related to the use of computer games and SGs in education: (a) "Does adding feature X to a game cause improvements in learning?"; (b) "Does playing game X cause improvements in skill Y?"; (c) "Do people learn academic material better with a game or with a conventional media?". Each question forms the basis of three different genres of research on computer games for education: (a) *Value-added research*; (b) *Cognitive consequence research*; (c) *Media comparison research*.

According to Mayer, under the label of *value-added*, it is possible to collect works that compare the learning outcomes obtained by groups playing a basic version of a video game with the learning outcomes of groups playing the same game modified, however, through the inclusion of a specific feature. The objective of this line of research is to identify precisely which features most enhance the effectiveness of a game in terms of learning outcomes. *Cognitive consequence research* includes research works that compare the positive effects obtained on the cognitive skills of groups that play video games with the effects obtained on the same skills of control groups engaged in activities that do not involve the use of games. The aim of

this line of research is to establish which types of games have an effect on different cognitive skills. *Media comparison research*, finally, groups together research works that compare learning outcomes obtained in groups that learn educational content through games with learning outcomes obtained in groups that learn the same content through conventional tools. The aim of this line of research is to establish whether playing video games enables learning content more effectively than using conventional tools.

It is clear that all three genres of research once again rely on the cognitive sphere (*Cognitive consequence research*) or on spheres strictly connected to cognition (*Value-added research* and *Media comparison research*). Sticking to an approach that analyses studies on the benefits of the use of computer games and SGs from the methodologies used to conduct them, Mayer (2019) shows how, in practice, these benefits while being undeniable are much more limited in both quantity and quality. For example, with regard to *cognitive consequence research*, it appears that clearly and solidly demonstrated beneficial effects can only be found in an improvement of perceptual attention through the use of first-person shooter games and in an improvement of two-dimensional mental rotation ability through the action of spatial puzzle games.

According to this perspective, research that wants to overcome these limitations and aims to bring greater precision to experimental work should invest in the design and analysis of games only after having developed or referred to solid methodological frameworks. Such frameworks can only be able to provide those who design and/or use games to foster learning with an adequate knowledge of cognitive and learning principles and theories.

2.1.2 Frameworks for Serious games design

Several efforts have been made to provide theoretical frameworks for supporting games and serious game design. The goal is to provide techniques for the specification of games capable of giving the designer sufficient control during a process that is intrinsically creative and, therefore, prone to inefficacy.

Generally, a wide range of professions is engaged in the design process, including writers, graphics designers, software developers, video makers, marketing and

sales professionals, and recently even AI experts. Due to this innate variability and the plethora of approaches adopted, this domain is typically seen as highly fragmented and inconsistent (Björk & Holopainen, 2005).

Some research in this field is restricted to support the analysis and description of games. A well-developed conceptual framework for examining games has been constructed by Salen Tekinbas and Zimmerman (2003). Hunicke, LeBlanc, Zubek, et al. (2004) developed the *MDA* framework based on three different levels of abstraction for comprehending and designing games: the game mechanics adopted in the game implementation (Mechanics), the dynamics in the games (Dynamics), and the player's emotional response evoked by the game (Aesthetics). Within the *Game Ontology Project (GOP)*, Zagal, Mateas, Fernández-Vara, Hochhalter, and Lichti (2005) propose a structured vocabulary that identifies the elements of games and the relationships between them.

Some authors adopt visual approaches to describe games (Koster, 2005). Inspired by Propp's approach to analysing Russian fairy tales, Djaouti, Alvarez, Jessel, Methel, and Molinier (2007) presented a diagram language to identify the game's core elements (*"Game Bricks"*).

In some cases, the objective of the proposed frameworks is wider than the game analysis and looks towards providing tools to assist in the design and prototyping of games. This is the case of *Machinations*, a graphical framework aimed at prototyping and validating the game dynamics (E. Adams & Dormans, 2012; Dormans, 2013).

Taking its cue from computer science, Björk and Holopainen (2005) focus on game design patterns to characterise well-identified recurrent problems and provide reusable solutions. The authors provide a shared vocabulary of game elements enabling structured comparisons and facilitating the implementation of component-based design support tools.

Some studies (Marsh, 2010; Marsh, Yang, & Shahabi, 2006) adopt the activity theory to investigate games from the perspective of narrative and players' experiences by formalizing the *Hierarchical Activity-Based Scenario (HABS)* framework, which they then refined to increase the emphasis on users' engagement and serendipity analysis (Marsh & Nardi, 2014).

Specifically looking at serious game design, several approaches should be mentioned.

In 2006, de Freitas and Oliver (2006) highlighted the need for a framework explicitly conceived for educational games. They proposed the *Four-Dimensional framework* identifying the core dimensions a designer has to consider in designing an educational game. Another model conceived to offer guidelines to game designers is the *RETAIN* model proposed by Gunter, Kenny, and Vick (2006). The *RETAIN* model, based on classical instructional design theories, supports the analysis of a game from the point of view of educational effectiveness.

One of the fundamental frameworks used in the game field to analyse a game from an educational perspective is the *Game Object Model II*[5] proposed by Amory (2006). The *GOM* model identifies five distinct state spaces (i.e., Game Space, Visualisation Space, Elements Space, Actor Space, and Problem Space), within which it allows the designer to highlight the relationships between the pedagogical dimensions of learning and game elements using an object-oriented approach.

A prominent framework with a goal similar to the *GOM* model is the *Learning Mechanics-Game Mechanics (LM-GM)* (Arnab et al., 2014). The *LM-GM* model is based on recognising game mechanics as a fundamental element for conveying learning. According to this approach, the model guides the designer in connecting game mechanics and pedagogical practices (learning mechanics). However, the model does not allow for different levels of abstraction and does not offer the possibility of explicitly linking high-level educational objectives with game design.

More recently, Carvalho et al. (2015) proposed the *Activity Theory-based Model of Serious Games (ATMSG)*. Compared to the *LM-GM* model, *ATMSG* goes into more detail concerning the game's inner components, allowing a better understanding of the game structure.

Finally, some attempts support the design of specific game types by providing software tools. For example, in the context of scenario-based games, Westera, Nadolski, Hummel, and Wopereis (2008) proposed a design framework based on the Emergo toolkit (Nadolski et al., 2007).

[5]The *Game Object Model II* is an evolution of the original version. (Amory, 2001; Amory, Naicker, Vincent, & Adams, 1999)

2.2 Cognitive Architectures

In this thesis, the term "cognitive architecture" refers to the computational implementation of human cognition theories aimed at realising artificial systems exhibiting intelligent behaviour in a general setting (Lieto, Bhatt, et al., 2018).

As a result, CAs provide a foundation of fundamental processes and computational limitations upon which designers may build formalisations of targeted cognitive processes.

According to this point of view, the research on CA mainly falls within the field of artificial intelligence. However, research on CAs is widely explored and spans various disciplines, such as Cognitive Sciences, Educational Psychology, and in the last years Cognitive and Social Robotics. Despite their differences, the joint effort of the various disciplines to unravel the mystery of the mind has found cognitive architectures a powerful investigation tool.

In particular, CAs allow researchers in cognitive sciences to validate cognitive theories and revealing underlying aspects of human mind through experimentation on computational models. At the same time, CAs enhance the progress of AI by implementing artificial agents that take inspiration from cognitive approaches and employ cognitive-inspired decision-making and behavioural heuristics (Lieto, 2021; Lieto, Bhatt, et al., 2018).

CAs have been defined as an embodiment of scientific hypotheses and theories aimed at capturing the mechanisms of cognition which can be considered consistent over time and are independent of specific tasks or domains (Lieto, 2021). This objective definitely includes investigating the various cognitive processes such as perception, attention, reasoning and decision-making, memory, learning, and metacognition (Lieto, 2021; Lieto, Chella, & Frixione, 2017; Oltramari & Lebiere, 2012).

Nevertheless, due to the absence of a universally accepted theory of cognition, there remains a lack of consensus regarding the precise definition of cognitive architecture and the specific cognitive processes or essential attributes that qualify a system to be classified as such (Kotseruba & Tsotsos, 2018).

Although there is no magic list of constraints, as stated by Newell (2018), some researchers have proposed lists of essential characteristics that a system must pos-

sess to be identified as a cognitive architecture.

Langley, Laird, and Rogers (2009) proposed criteria like the ability to explain psychological phenomena, robustness, and providing a distinctive approach to constructing integrated intelligent systems.

Newell (1980) points out mandatory criteria a cognitive architecture should possess, including:

- flexible behaviour, that is the ability "to cope with environments whose demands are not known at the time the system is designed";
- real-time operation, which represents the need for these systems to operate with limited resources also in terms of time and the resulting need to manage the imperfect choices performed by the same system;
- rationality, although the nature of rational action is not yet sufficiently understood this constraint refers to the ability of these systems to operate according to action plans aimed at achieving clear objectives;
- large knowledge base, these systems should be able to quickly and reliably access large amounts of encoded knowledge;
- learning, the capacity of a system to enhance its performance over time.

Instead, Sun (2004) desiderata encompass realism from an *ecological, cognitive, and bio-evolutionary* point of view. According to Sun (2004), a cognitive architecture to be ecologically realistic must consider the essential functions of human agents in their natural environments. Cognitive realism refers to the ability of these systems to understand cognition by abstracting from the infinity of observable details. Finally, bio-evolutionary realism states that "a cognitive model of human intelligence should be reducible to a model of animal intelligence". Other characteristics listed by Sun (2004), like adaptation, modularity, routineness, and synergistic interaction, can also be found under different names in Newell's criteria.

A different approach to characterize CAs is to examine the skills and actions that the system exhibits (Kotseruba & Tsotsos, 2018). In this case, the goal could be to check whether a CA exhibits human-like behaviour and infer that it resembles a human cognitive mechanism.

Another possibility is to evaluate CAs behaviours in various domains, where the assumption is that if the architecture can be used in multiple domains, it is possible to conclude that it is a general cognitive architecture (Ichise, 2016). Vernon (2022) emphasises fundamental cognitive skills, including attention, perception, learning, memory, reasoning, actions selection, and meta-reasoning, examining how architectures exhibit these abilities.

Ichise (2016) presents a method for comparing CAs using the CHC model — a psychological model of human intelligence — and the metrics relative to the four categories used to classify its components. Desirable characteristics for a cognitive architecture include ecological, bio-evolutionary, and cognitive realism, as well as eclecticism of methodologies and techniques.

Concerning the specific case of developing cognitive architectures in the view of the emergent paradigm, Vernon (2022) highlights the importance of identifying a value system that considers exploratory and social motives to select and pursue the goals to achieve.

Three main perspectives derived from different cognitive science paradigms drive the design and development of a CA: cognitivist, emergent, and hybrid (Vernon, 2022). The intelligent agent developed within the cognitivist perspective relies on a computational model that requires symbolic knowledge to perform a given task. On the opposite, the emergent perspective focuses on the development of an agent for developing cognitive abilities through ontogeny over an extended period (Vernon, 2022).

The most mature approach in the literature to developing CAs is hybrid computational models. Such a hybrid perspective integrates symbolic and sub-symbolic processing, leveraging their individual strengths (Vernon, 2022). Hybrid CAs include low-level neural elements to simulate perception and more advanced logical and symbolic elements to perform automated reasoning and planning tasks (Lieto, 2021; Lieto, Lebiere, & Oltramari, 2018).

Many different CAs have been created and tested for various cognitive tasks. In the past 30 years, various application domains, including robotics and tutoring systems, have extensively exploited CAs (Augello, 2022; Augello, Città, Gentile, & Lieto, 2021; Lopes & Bidarra, 2011a).

Kotseruba and Tsotsos (2018) present a comprehensive and up-to-date summary of four decades of cognitive architecture studies.

The design of a CA is influenced by the pursued scientific aim, generally following a "structural" approach to identify an equivalence between the computational and cognitive processes. Moreover, existing CAs differ in their assumptions about important issues such as knowledge representation, memory types, learning mechanisms, and the functional processes operating on these structures. These assumptions are crucial for a cognitive architecture to function effectively in its environment, and they can be achieved through various approaches (Langley et al., 2009). A CA is then computationally designed by modelling the components necessary for a system to exhibit cognitive capabilities, their relationships, and their algorithmic and representational details.

Over the past decades, various cognitive architectures like SOAR (J. Laird, 2012) ACT-R (J. R. Anderson et al., 2004), CLARION (Sun, 2006), LIDA (Franklin, Madl, D'mello, & Snaider, 2013), PSI (Dörner & Güss, 2013), SIGMA (Rosenbloom, Demski, & Ustun, 2016), to make few meaningful examples, have been proposed. ACT-R and SOAR are the CAs more extensively evaluated in several cognitive tasks like learning, reasoning, recognition, and selective attention.

The following sections examine ACT-R and SOAR in detail as two of the most prominent CAs exploited in literature.

2.2.1 ACT-R: Adaptive Control of Thought—Rational

ACT-R (Adaptive Control of Thought-Rational) has been developed by John Anderson and colleagues from Carnegie Mellon University according to theoretical assumptions and experimental findings from human cognition research (J. R. Anderson et al., 2004; J. R. Anderson, Matessa, & Lebiere, 1997). This architecture has been successfully used to create models in fields such as memory and learning, perception and attention, language processing, decision-making, problem-solving, and cognitive development. The primary basis for defining ACT-R comes from the rational analysis theory, which suggests that every aspect of the cognitive system is optimised based on the surrounding environment's requirements while considering its computational constraints (Taatgen, Lebiere, & Anderson, 2005).

ACT-R includes several modules that allow the modelling of perceptual and cognitive abilities of human beings and a production system. It can be considered a hybrid architecture since symbolic and sub-symbolic components characterize it.

The symbolic structure comprises a set of modules with dedicated buffers while the sub-symbolic structure involves multiple simultaneous processes based on mathematical equations, which are responsible for the majority of the learning processes employed in ACT-R.

More specifically, each module is devoted to processing different kinds of information and interacts with a production system responsible for coordinating their behaviour through the buffers. The main function of the buffers is to forward action requests to their corresponding module. Although actions are forwarded simultaneously, they require different times. The necessary time is based on a measure of human performance in the real-time execution of specific actions.

These modules work together in a coordinated way and in collaboration with their respective buffers, resulting in the ability to define ACT-R activities that are interactive and that can involve if required, a keyboard for typing and a screen.

The primary connections between the ACT-R framework and the external world are established through the perceptual and motor modules, which include components for audio, visual, motor, and speech processing.

The visual module has been integrated since version 5.0 to create a model of how visual attention and perception collaborate to form higher-level representations that align with the ACT-R theory of cognition. It includes a visual-location buffer, keeping track of an object's location (where) on the screen, and a visual buffer which identifies its symbolic expression (what). Therefore, it creates a memory that stores a representation of the environment that takes into account its distinguishing features.

According to the theoretical perspective on visual attention that is employed in ACT-R [6], this module allows for the focus of attention to be moved to a particular area on the screen, enabling the sequential creation of a chunk representing the object in question. It allows shifting attention to a particular scene on the screen

[6] As reported in (J. R. Anderson et al., 1997), the visual attention theory used in ACT-R is a synthesis of Posner's (1980) spotlight metaphor, Treisman and Gelade's (1980) feature-synthesis model, and the Wolfe's (1994) attentional model.

identified through its spatial position. This module could be used to simulate eye movements or to hold visual attention to a particular object in the scene.

The exploitation of it has proven to be effective in simulating well-known classic perceptual experiences, like the Sperling task (Sperling, 1963) and visual search activities. Nevertheless, according to Peebles (2019), both the ACT-R visual component and its suggested developments, such as ACTR/E project (Trafton et al., 2013), lack the ability to address issues related to spatial imagination. In order to address this need, Peebles (2019) proposes an ACT-R extension that provides specific chunk types and imagery operations for the representation and manipulation of mental visual objects.

The audio component is aimed to perceive sounds. It has two buffers: one that deals with the location of the sound source (where), precisely the so-called aural-location buffer, and another, named the aural buffer, which stores information about what has been heard (what). Every audio input is processed by this module and translated into chunks that can be accessed by the model when needed.

The speech module enables the model to speak, allowing it to communicate words and short phrases to other models through the vocal buffer. The function of this module involves progressing through three internal stages: preparation, processing of word sounds, and execution. It differs from other modules in that it does not monitor spoken words. With the assistance of the motor module, the model is equipped with the ability to operate tools like a keyboard and mouse, thereby obtaining motor skills.

The goal module is the simplest module. It manages the current task state and relevant information. The goal buffer is usually exploited to store the current activity state. The module has a limited set of functions which include creating a new goal block upon request, modifying and updating the information in any slot, and removing or storing the goal block in declarative memory.

Along with the goal module, the imaginal module could also be used to store the model's internal state for achieving the goal. The ability to create new blocks at runtime is useful in several cases, for example when the model needs to keep track of internal changes to its state during model execution.

One of the fundamental components of ACT-R is memory. The architecture

includes two types of knowledge, one is declarative and the other procedural. It also includes a central production system that connects the modules by using IF-THEN production rules.

The smart behaviour exhibited by computational agents results from the interplay between these two components, which have been analyzed at a knowledge level in the work of (Lieto, Lebiere, & Oltramari, 2018).

Declarative memory handles the creation and storage of facts, storing explicit fundamental units of information possessed by the model with respect to its environment. These units, the so-called "chunks", are composed of key-value pairs. The values of these pairs are based on a set of symbols, such as constants or references to other blocks, and are used to represent atomic knowledge. The slots within them include an *isa* slot that identifies their category, as well as other slots that encode other information. The "declarative module" is a dedicated component that is responsible for managing and storing declarative knowledge.

While declarative knowledge refers to the information that a system has in the form of explicit facts, procedural knowledge entails the set of rules that guide the processing of declarative knowledge. The procedural module performs a function similar to the declarative module, but instead of generating and storing declarative knowledge, it produces and retains procedural knowledge, also known as production rules, for the model.

ACT-R utilizes a process of spreading activation, that relies on the continuous interaction between long-term and short-term memories to activate relevant pieces of knowledge.

It constantly checks the sub-symbolic information of the chunks by updating the activation values, i.e. the values that depend on how often and how recently that particular chunk was accessed. The activation of a chunk A_i is characterised by the equation:

$$A_i = B_i + \sum_j W_j S_{ji} + e$$

In the above formula, B_i represents the base-level activation of a chunk, or the strength of the association between a production and its context, based on how frequently that production has been utilized in the past in analogous situations.

$\sum_j W_j S_{ji}$ is the activation from spreading, the weighting W_j is the amount of activation from source j, it is the attentional weighting of the elements that are part of the current goal, and S_{ji} refers to how strongly source j is linked to chunk i and finally, e is the noise, it represents random fluctuations in activation levels, it is described in (J. R. Anderson et al., 2004) as a stochastic noise value.

The idea of activation is derived from rational analysis and it indicates the likelihood of a chunk being necessary. The approximations given by ACT-R's learning equations accurately represent the probabilities in the surrounding environment (Taatgen et al., 2005). The total activation determines the probability that the chunk will be selected for execution. The greater the activation, the more probable it is that the production will be chosen. If a chunk has higher activation, it can be retrieved more quickly and there is a greater chance that the activation will surpass the retrieval threshold (Taatgen et al., 2005).

It's worth noting that the exact parameters of the activation equation may differ based on the particular ACT-R implementation employed. Nevertheless, the fundamental concept of combining base-level activation, spreading activation, and noise to model the competition between distinct cognitive processes remains uniform in the majority of the architecture's versions.

To represent the sub-symbolic information in production rules, an expected utility is employed, which is gradually learned through a reinforcement learning procedure.

Another essential component of the architecture as introduced before is the centralised production system, which employs production rules (if-then rules) to synchronize communication and performance among its modules. The conditions of the rules are influenced by the state of the buffers of the different modules. Finally, the system itself provides algorithms that compare the current buffer contents to the production rules, and then choose the most powerful match (which has been adjusted based on its anticipated usefulness).

A partial matching mechanism can be enabled: in that case the tests conducted on buffer values can be somewhat eased even though most conditions in a production are still tested explicitly. More specifically, all queries that match inequality tests must still be verified, while equality tests for slots within a buffer block can be

relaxed, meaning tests that specify a specific value for a slot or tests with variables that compare two or more slot values. If more than one production satisfies the match, the production that has the greatest level of utility will be utilized.

To obtain a comprehensive and current understanding of ACT-R, we would like to draw your attention to (F. E. Ritter, Tehranchi, & Oury, 2019).

2.2.2 Soar: State, Operator, and Result

Soar is a general cognitive architecture aimed at creating AI agents with human-like cognitive characteristics and capabilities. It has been used extensively to model human behaviour and to create agents in various settings, such as real-world robots, computer games, and large-scale distributed simulation environments. Originally designed as a symbolic architecture, it can now be considered a hybrid CA (Kotseruba & Tsotsos, 2018). In fact, Soar uses symbol structures to represent knowledge, but it also includes non-symbolic reasoning through its spatial-visual system.

Initially developed in the 1980s to support multi-task and multi-method problem-solving, over time, the architecture has incorporated features such as episodic and semantic memory, reinforcement learning and a spatial visual system.

It shares similarities with other architectures such as ACT-R and Sigma and has contributed to the development of the Common Model of Cognition (J. E. Laird, Lebiere, & Rosenbloom, 2017).

It consists of various modules that are independent of the specific tasks and interfaces between them. Long-term knowledge is stored in different types of memory, including procedural, semantic, and episodic memory. Semantic memory stores general knowledge about the world, the agent's environment, abilities, and long-term goals. It is different from procedural memory in terms of how it stores and accesses information, what type of information is retrieved, and how it is learned. Semantic memory can be built up incrementally by an agent during its operations, or it can be initialized with pre-existing knowledge from curated knowledge bases.

Episodic memory stores memories of past experiences, enabling an agent to recall the context and temporal relationships between those experiences. Procedural knowledge creates a cue in the episodic memory buffer, which is used to

retrieve the best match of the memory. Both semantic and episodic memories are represented as symbolic graph structures and are accessed using a combination of base-level activation and spreading activation.

A key component is represented by the Spatial-Visual System (SVS). It acts as a mediator between symbolic working memory and non-symbolic perception and motor control. It is responsible for processing non-symbolic information in 2D and 3D space by supporting modality-specific representations, like mental imagery. This is important for the efficient processing of visual data. SVS allows information to flow both bottom-up from perception through SVS into working memory and top-down from working memory to SVS to enable reasoning over hypothetical non-symbolic representations. By using filters, SVS is capable of automatically extracting symbolic properties and relationships from visual input, and it can also support reasoning over spatial-visual representations. Additionally, SVS is responsible for facilitating interactions between motor actions and perception in 3D robotic environments.

Soar organizes knowledge related to conditional action and reasoning into operators that can be internal or external actions. Dynamic integration of knowledge is facilitated by breaking down the knowledge associated with an operator into three distinct functions: proposing potential operators, evaluating proposed operators, and applying the operator. This approach differs from rule-based systems, where a single rule is selected and fired during the processing cycle and where the knowledge for these functions is permanently linked as conditions and actions. In contrast, Soar represents the knowledge for each of these functions as separate rules, which are fired in parallel when they match the current situation. Rules in Soar do not represent alternative actions but are instead units of context-dependent knowledge that contribute to making a decision and taking action.

Soar facilitates decision-making, impasses, sub-states, and learning through chunking, reinforcement learning, semantic and episodic memory, as well as spatial-visual reasoning. The decision-making process in Soar is focused on the operators and involves a working memory that contains various types of information such as goals, data from long-term memory, perception, and the results of internal operators. The preference structure supports the selection of operators, which are created

by rules and added to preference memory. The decision cycle has five phases, including input, elaboration, operator proposal, operator evaluation, and operator application. Elaboration rules create new structures based on existing knowledge, while operator proposal rules determine if an operator is applicable and create a representation of it in working memory. Operator evaluation rules select an operator based on preferences, and operator application rules apply to the selected operator. The output phase sends any new structures to the relevant modules. If there is not enough information to apply an operator, an impasse occurs during the cycle.

Soar employs impasse-driven processes to address situations where available knowledge is insufficient to select or apply an operator. It uses a strategy called "going meta" to gain more useful information by actively reasoning and retrieving knowledge from other sources. If there is insufficient or conflicting information during operator selection, an impasse occurs. Soar deals with three kinds of impasses: state no-change, operator tie/conflict, and operator no-change. To focus on impasse reasoning, Soar arranges data in working memory into states and sub-states. Procedural memory looks for matches in the sub-state just like in the top state. When an impasse is resolved, the sub-state ends and all non-result sub-state structures are automatically deleted. By following this process, Soar agents can quickly adapt to any relevant changes in their environment, even when multiple sub-states are active.

Soar's approach to hierarchical decomposition allows for dynamic combinations of primitive and abstract operators, with procedural knowledge that proposes operators for implementation when an impasse arises. The deliberate operator selection process supplements automatic parallel processing when preferences are insufficient to pick a single operator. Impasse-driven sub-states allow for metacognitive reasoning, incorporating any and all types of reasoning that are possible in Soar, including deliberate access to semantic and episodic memories, non-symbolic reasoning, planning, and reasoning about others. The learning mechanism in the Soar cognitive architecture is based on chunking: when there is a lack of knowledge to select or apply an operator and impasses occur, chunking creates rules from historical traces of processing in sub-states to resolve impasses and eliminate fu-

ture processing. Chunking can learn various types of rules, including elaboration, operator proposal, operator evaluation, and operator application rules. However, chunking requires deterministic sub-state decisions and may have some overhead costs. The new approach to chunking is called explanation-based behaviour summarization (EBBS). Reinforcement Learning (RL) can be used to allow an agent to modify its operator selection to maximize future rewards based on feedback received through achieving goals, failures, or other rewards. RL rules are created to encode the expected reward for specific states and operators, and they are updated based on the reward associated with the state and the expected future reward. RL rules can be learned by chunking and can support hierarchical reinforcement learning.

The mapping from state and operator to expected reward is represented as collections of relational rules, supporting tile coding, hierarchical tile coding, and other combination mappings. RL in Soar applies to every active sub-state, allowing for hierarchical reinforcement learning across different types of problem-solving and reasoning.

The key features of the Soar architecture motivated its use in developing cognitive models of various human behaviours, such as decision-making in dynamic environments, language comprehension, and learning. It is particularly useful for modelling complex, real-world problems but may not be the best choice for all applications.

As a general cognitive architecture, Soar is positively evaluated in most capabilities, such as flexible behaviour, adaptive behaviour, real-time operation, rich environment interaction, symbolic reasoning, language use, and learning from experience. Limitations and room for improvement are in language use and perceptual category learning.

3 Cognitive Architectures and Games: The state of the art

This chapter provides a detailed picture of the applications of cognitive architecture in games.

Games have always been one of the main fields of application in studies on cognitive architectures. The pioneer in linking cognitive architectures and games was Newell in a seminal work published in 1973 (Newell, 1973). In his review of the state of research in experimental psychology, Newell (1973) proposed the development of computational models capable of performing and explaining complex tasks. And it was precisely in this context that he suggested using games as practical and concrete examples of complex tasks that could be analysed with such cognitive computational models. In his last book, Newell (1990) further developed this approach by introducing the "Unified Theories of Cognition" (UTCs), proposing Soar as the first cognitive architecture to model human cognitive activities.

Around the turn of the last century, Laird and Van Lent began the Soar/Game project (J. Laird & VanLent, 2001; J. E. Laird & Lent, 1999; van Lent et al., 1999) confirming the existence of a strong link between cognitive architectures and games. The project recognised the opportunities offered by computer games as a domain in which advances in AI could be safely explored and tested. Moreover, the authors emphasised the benefit of computer game realism that would derive from using AI techniques.

More recently, W. D. Gray (2017) relaunched Newell's programme, highlighting how action games allow researchers to develop comprehensive cognitive theories that could consider a full range of competencies.

A systematic literature analysis was carried out to build this overview of the intertwining of cognitive architectures and games.

The study was done according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses reporting guideline (PRISMA Checklist) (Page et al., 2021).

The analysis has been conducted by exploring the primary scientific databases such as Web of Science and Scopus. Moreover, the ACM Digital Library (DL) and IEEE Digital Library have been included to consider the literature covering computer science and information technology.

To define the query to be used in the bibliographic search, I started by considering the group of architecture (i.e. SOAR, ACT-R, CLARION, EPIC and LIDA) to look at the cognitive architecture domain. These architectures are referenced in most of the sources analysed in the recent and comprehensive review realised by Kotseruba and Tsotsos (2018). Moreover, the general term "cognitive architecture" was added to the query to include those papers in which the authors depicted the proposed systems as cognitive architecture.

About the game, the general terms *games* and *serious games* have been used to collect studies regarding all types of games and playful activities looking.

The query defined to perform the search in Scopus and the other databases [1] is the following:

```
TITLE-ABS-KEY ( ( games OR "serious game*" ) AND (
↪ "cognitive architecture*" OR "ACT-R" OR Soar OR
↪ LIDA OR CLARION OR EPIC OR ICARUS ))
```

The search produced a list of 590 articles, which was then reduced to 166, by removing irrelevant articles as a consequence of titles and abstract analysis. The list of selected papers was increased to the final set of 199 eligible articles by adding the key papers presenting the Soar/Game project and the papers that directly cited those papers. The full-text analysis led to the final list of 118 selected papers. Figure 3.1 summarises the article selection and analysis process results.

The 118 selected papers were analysed through a multi-dimensional approach to considering the different possible points of view inherent to the investigated research field. Specifically, the following dimensions were considered:

- Games genres;

[1] The query syntax was adapted according to the formalism required by each database.

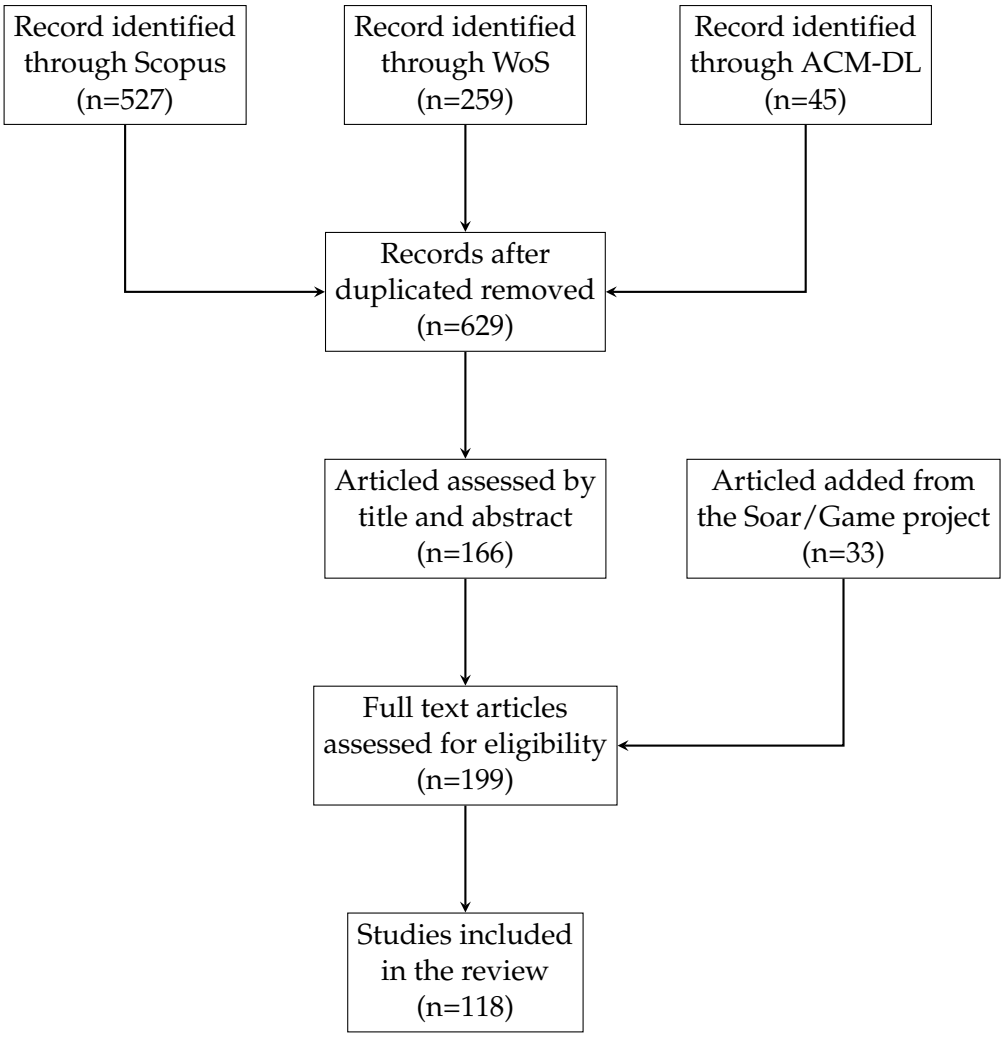

Figure 3.1: Prisma Flow Diagram

- Cognitive architectures;
- Mental processes;
- AI for games.

The following sections report the analysis of the 118 selected articles for each dimension. Next, a combined examination is reported to provide a greater comprehension of the field to provide the base on which we derive our framework.

3.1 Game genres

For the aim of this thesis, the analysis of *games genre* investigated with or by cognitive architecture represents an essential dimension.

GameTypeLevel1	GameTypeLevel2	Examples
Action games	combat	Tag, Paintball, Space Invaders, Street Fighter series, Doom, Halo
	space	Pitfall, Super Mario Bros., Pac-Man, Super Monkey Ball
	adventure	Metroid series, Tomb Raider series
	rhythm	Dance Dance Revolution, Parappa the Rapper, EyeToy: Play
Game simulations	management	SimCity series, Animal Crossing
	transport	MS Flight Simulator, Densha de Go!
	social	SIMSOC, The Sims series, Dating sims
	sports	Formula Dé , Gran Turismo series,Track & Field , Madden series, Championship Manager series, Pro Evolution Soccer series
Games of chance	draw	Lotto, Keno, Bingo, Roulette, Slot machines, Scratch tickets
	betting	Sports, elections, contests
Puzzle games	movement & arrangement	Rush Hour, 14/15 Puzzle, Tetris, Chu Chu Rocket, Puyo Puyo
	mechanical & assembly	Rubik's Cube, Hex, jigsaw puzzles, polyminoes
	adventure	Zork, Myst, Broken Sword series, Grim Fandango, ICO
Role-Playing games	tabletop	Dungeons & Dragons, White Wolf
	live-action (larp)	White Wolf: Mind's Eye Theatre
	digital	Ultima series, Final Fantasy series, Baldur's Gate
Sports games	race	Athletics, Tennis, Soccer, Basketball, Motor sports, Billiards, Golf, Boxing
	comparison	Figure Skating, Gymnastics
Strategy games	race	Backgammon, Snakes & ladders, Monopoly, Fantasy leagues
	space	Solitaire/Patience, Tic-tac-toe, Connect-4, Go, Scrabble
	chase	Fox & Geese, The Three Musketeers, Lord of the Rings: Sauron
	displace	Draughts, Chess, War games, Risk, Civilization, Starcraft
	outplay	Cribbage, Casino, Uno, Dominoes, Lost Cities
	exchange	Rummy games: Gin, Canasta, Magic the Gathering, Pokemon
	comparison	Poker, Black Jack, Quiz shows, Magic the Gathering, Pokemon,

Table 3.1: Games genre classification adapted from Järvinen (2008).

Identifying the type of game used in the different studies allows us to analyse all possible intersections with the other dimensions of analysis, such as the examined mental processes, the used cognitive architectures and the purposes of the studies.

Nevertheless, providing a comprehensive categorisation of game genres is a non-trivial task. First, game genres are not stable, but they evolve through time. The game's literature shows that each of the present classifications refers to a unique perspective strictly dependent on the observer's point of view. Games could be classified according to different dimensions, such as the main game mechanics that characterise them, the game context, the theme of the game, the rule system or the interface, whether physical or digital. In this work, the analysis of games focused on the literature is based on the proposal by Järvinen (2008) that summarises several classifications available in the literature (see table 3.1).

Nevertheless, it was necessary to consider also the categories *Cognitive games*, *Game-theory games*, and *Mental tasks* to cover all the investigated sorts of games.

Figure 3.2 provides an overview of the types of games referred to in the literature under review. The two main types of games on which the selected articles focus are *Action games* and *Cognitive games*.

In the *Action games* category, the most commonly used games in this field of research are the so-called first-person-shooter games (e.g., *QuakeII*, *Descent III*, *Unreal Tournament 2004* and *Gears of War 3*). Another game in this category is *Super Mario*

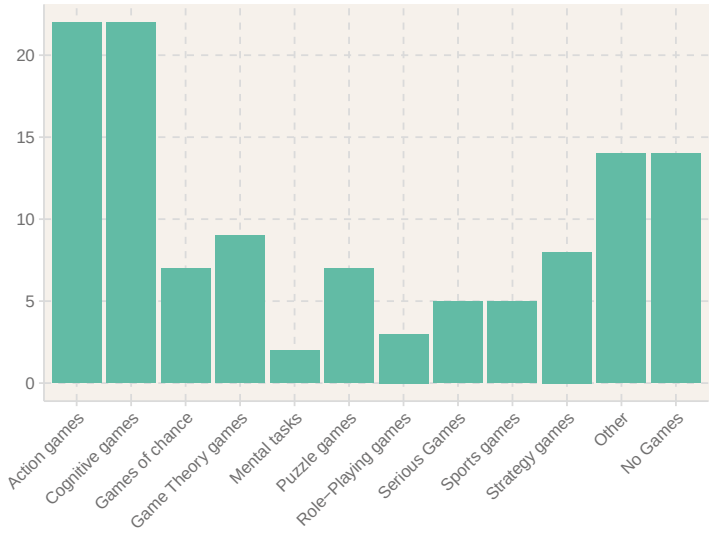

Figure 3.2: Game genres investigated in the analyzed literature.

Bros along with some of its variations (Derbinsky, Li, & Laird, 2012).

The category *Cognitive games* includes all those games designed explicitly in the field of cognitive sciences to favour the analysis of mental processes. In particular, in this category, great attention has been paid to the game *Space Fortress* and its various variations, developed in the works of Anderson and colleagues (J. R. Anderson, Betts, Bothell, Hope, & Lebiere, 2019; J. R. Anderson, Betts, Bothell, & Lebiere, 2021; Dimov, Anderson, Betts, & Bothell, 2020). These studies are analysed in detail in section 3.3.3.

A substantial number of works fall in the *Game theories game*, where many digital games are representations in the playful form of strategic interaction between two players. Cognitive architectures allow the researchers to study those interactions, also investigating alternative strategies to the optimal rationality approach typically used in this context. A typical example is the *Prisoner's Dilemma*, in which two rational agents are faced with a dilemma, to cooperate with their partner and obtain a mutual benefit or to betray their partner to receive an individual reward. Researchers analyze such games to study the decision-making strategies reproducing the typical limitations and bias of human reasoning.

In the category *Games of chance*, the attention goes to dice games or games like "Paper Rock Scissors".

Marginal is the presence of works that focuses on *Serious games*. In this area,

we mainly find research investigating the use of emotions to improve the reasoning and dialogue skills of NPCs (Djordjevich et al., 2008; Guimarães, Mascarenhas, Prada, Santos, & Dias, 2019; Mascarenhas et al., 2022).

For the purposes of this thesis, the works from Janssen and van Rijn (2007) and Streicher, Busch, and Roller (2021) are worth mentioning. They investigate the user modelling topic for adaptive training. In particular, Streicher et al. (2021) examines a cognitive approach to user modelling that exploits memory activation levels of learned concepts to generate an adaptive learning path.

Different research papers do not analyse a specific game (*No Game*), especially those that present new cognitive architecture or systems aimed to support the integration of cognitive architectures and game engines. Finally, some studies focus on virtual environments to test the models/systems created (*Other*).

3.2 Cognitive Architectures

Providing an overview of the cognitive architectures used in the field is one of the main objectives of this literature review. The inventory proposed by Kotseruba and Tsotsos (2018) represents the base framework for this analysis.

Figure 3.3 shows the distribution of the papers according to the specific cognitive architecture used. Only nine of 84 architectures reported in the Kotseruba and Tsotsos (2018) review, have been identified in the investigated literature.

The distribution shows that, even in the specific field of games, ACT-R and Soar are the most widely used. The validity of the theoretical approaches on which ACT-R and Soar are defined and their features allow them to be used in various fields.

The investigated literature also presents a substantial number of works where authors describe as cognitive architectures, new systems developed from scratch (*From scratch*) or platforms not listed by Kotseruba and Tsotsos (2018) (*Other*).

The investigated literature also presents a substantial number of works in which authors present new systems (*From scratch*) or platforms not listed by Kotseruba and Tsotsos (2018) (*Other*) that are presented by the authors as cognitive architectures.

For instance, the study by Spraragen (2011) introduces a research direction fo-

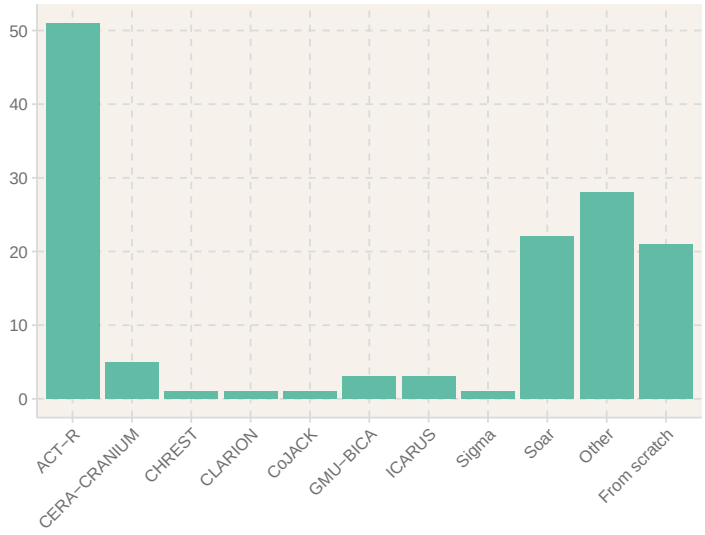

Figure 3.3: Distribution of the cognitive architectures employed in the investigated literature.

cused on establishing a novel framework known as EmoCog, which is adept at simulating a diverse range of emotional influences on human cognitive functions.

Arrabales proposed the CERA-CRANIUM architecture to implement virtual agents capable of displaying a level of consciousness and thus being more credible to the player (Arrabales, Ledezma, & Sanchis, 2009; Arrabales, Muñoz, Ledezma, Gutierrez, & Sanchis, 2012; Chella & Manzotti, 2013).

Li, Ma, and Principe (2020) present a new cognitive architecture inspired by the human functioning of vision and learning strategies. The architecture exploits frame-oriented reinforcement learning for understanding the content of raw frames in the context of *Super Mario Bros* game.

3.2.1 Supporting the integration of cognitive architecture and game engines

Another theme that emerges from the literature review is the issue of improving systems integration of cognitive architectures with games and game engines in particular. Starting from the result of previous research (Smart & Sycara, 2015a), Smart, Scutt, Sycara, and Shadbolt (2016) present specific Unity components designed to allow ACT-R models to control virtual characters. Smart and Sycara (2015b) analyses the problem from a more theoretical point of view, providing guidance on how to find the right balance of responsibilities between the two systems. While most

integration mechanisms refer to peer-to-peer schemes, a recent study (Morita, Nagashima, & Takeuchi, 2020) realises such integration through a blackboard server provided with slots for storing action commands from agents and slots for storing visual information obtained from the environment. The ACT-R and game engine continuously update each slot via a periodic socket communication. The underlying idea is to allow ACT-R ad the game engine to operate in parallel, which leads to novel agent behaviours. The study of Salt, Wise, Sennersten, and Lindley (2016) presents an extension of ACT-R called REACT-R, designed to facilitate integration with real and simulated robotic embodiments, which is then tested in playful contexts.

3.3 Mental processes

One of the primary applications emerging from analysing the selected literature is using computational cognitive models implemented through cognitive architectures to explore mental and cognitive processes.

Before going into detail, it is necessary to disambiguate the two terms mental and cognitive processes, which are frequently used as synonymous despite the fact they refer to slightly distinct facets of human functioning.

Mental processes refer to the overall operation of the mind and the subjective experiences of thought, emotion, and consciousness.

On the other hand, cognitive processes refer to the mental activities involved in acquiring, processing, storing, and applying information. They are more concerned with the cognitive processes of knowing, reasoning and comprehending. Perception, attention, memory encoding and retrieval, learning, problem-solving, decision-making, and language comprehension are examples of cognitive processes (J. Anderson, 2020; E. Goldstein, 2011).

However, the separation line between the two concepts is thin and constantly evolving, so we focus on the broader field of mental processes.

In this context, the goal could be to test and validate specific hypotheses on such processes.

Generally, those works use real data collected through analysis of the behaviours of human users. In this regard, games and in particular digital games, offer several

beneficial features because through them it is easy to collect the data needed to validate proposed hypotheses. Moreover, it is often possible to compare the emerging abilities of a computational model with those of a human user, also in real-time.

Nevertheless, providing a comprehensive taxonomy of cognitive processes is a non-trivial task, mainly due to the low consensus in identifying basic mental units that characterise the field of cognitive science. According to Poldrack et al. (2011), terminological ambiguity and confusion between mental processes and psychological tasks constitute two significant barriers to creating a taxonomy in this scientific domain.

For the aim of this work, the formal ontology proposed by Poldrack et al. (2011) has been used as the reference framework for the analysis of the mental process.

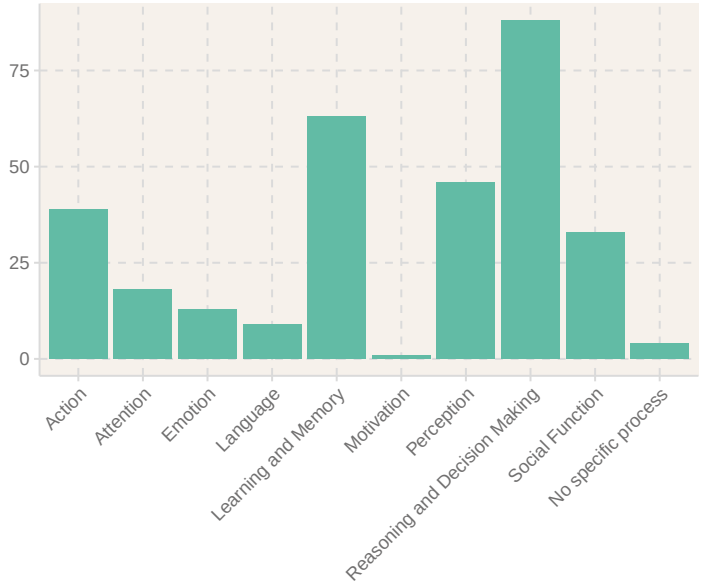

Figure 3.4: Distribution of the cognitive process investigated in the selected literature.

Figure 3.4 presents the distribution of the mental processes analysed using the first classification level proposed by Poldrack et al. (2011) as a reference. Following, a detailed analysis of the selected works for each category of mental processes shown in figure 3.4 is provided.

3.3.1 Attention and action

The research investigating the attention and action mental processes focuses on creating intelligent agents capable of operating in highly dynamic contexts, such

as those identified by first-person shooter (FPS) computer games and generally by simulation games in combat or battle contexts.

The interest in this type of game in the AI field is partly due to the possibility of controlling virtual characters through external software offered by various game producers such as Quake II and Unreal Tournament (J. E. Laird, 2001a, 2001b; J. E. Laird & Lent, 1999; van Lent et al., 1999; Yin, Feng, Hu, Zhang, & Zha, 2009). Moreover, these games take place in 3D environments where agents must demonstrate both spatial exploration skills and the ability to interpret and often anticipate the opponent's moves.

The definition of intelligent agents in such contexts represents an exciting challenge for researchers in the AI area, both as a laboratory and as an environment in which to demonstrate how AI can further enhance the degree of realism of games by fostering the realisation of intelligent virtual reality agents. For example J. E. Laird and Lent (1999), in the context of the Soar/Games project, have developed over time developed several bots capable of playing both Quake II and Descent 3 (J. E. Laird, 2001a, 2001b; van Lent et al., 1999)

Soar application is clearly prevalent in the context of first-person shooter games. One exception is the study realized by Choi, Konik, Nejati, Park, and Langley (2007), who developed an agent capable of playing the Urban Combat game in a human-like manner by means of the ICARUS cognitive architecture. Gemrot et al. (2009) describes the open-source platform Pogamut 3, designed for the rapid development of embodied virtual agent behaviour within the Unreal Tournament 2004 video game. Pogamut 3 features extensions such as integration with the ACT-R architecture and the ALMA emotion model and support for gesture-level avatar control, making it a comprehensive tool, attractive not only for researchers.

3.3.2 Emotions

One of the main objectives explored in the selected literature is to provide virtual agents (both virtual players and NPCs) with the ability to display emotions and, above all, to use internal emotion management as one of the main factors influencing their decisions.

Septseault and Nédélec (2005) proposed a Soar agent using actual internal state and episodical memory to evaluate the anticipated situations from the emotional point of view. Djordjevich et al. (2008) used the SHERCA-driven cognitive models to design NPCs for the game "Ground Truth" exhibiting consistent emotional states. Liu (2008) presents an emotion model for virtual humans based on psychology and neural science that integrates stimuli, motivation, personality, and mood together.

In some cases, the goal of providing agents able to show emotions guide the design of new cognitive architectures. For example, Spraragen (2011) present a research path oriented towards defining a new architecture called EmoCog. This architecture has been proposed to model various emotional effects on human cognitive processes for emotion-enabled game engines and virtual training environments.

Belle, Gittens, and Graham (2019) proposed a different approach for NPCs' mood simulation using the lightweight version of the ALMA cognitive architecture to overcome the cost of a heavy-weight system like generally designed CAs.

Finally, the FAtiMA toolkit is one of the leading solutions among several approaches to equip a virtual agent with social-emotional skills (Guimarães et al., 2019; Mascarenhas et al., 2022). FAtiMA provides a computational model of emotions based on the OCC appraisal theory and an explicit dialogue structure to help game designers to define role-play characters.

3.3.3 Learning and Memory

One of the most exciting areas is the investigation of learning and skill acquisition processes. The Anderson research program on skill acquisition is extremely interesting in this context. Anderson transposed the Cognitive, Associative, and Autonomous phases of the skill acquisition process proposed by Fitts to the primary learning mechanics of the ACT-R architecture. J. R. Anderson et al. (2019) shows how the production compilation mechanism of ACT-R and a new "Controller module" characterize the process of skill acquisition related to two games. In the "Space Track" game, Andreson focused on modelling the acquisition of the skills needed to control the ship in a frictionless environment. In the "Space Fortress" game, he

focused on navigational skills when the player had to destroy the fortress.

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The Autoturn game (a variant of Space Fortress) was used by J. R. Anderson et al. (2021) to extend the original skill acquisition model of J. R. Anderson et al. (2019).

The Space track game has recently been used to investigate the players' adaptation ability to parametric changes in learning and mastering the navigation complex skills (Seow, Betts, & Anderson, 2020, 2021). The first study (Seow et al., 2020) reveals that models which take more into account the adverse events best-fit human data. In the second study (Seow et al., 2021), the analysis of how players adapt to the changes in the acceleration parameter of the Space Track game reveals that considering past experiences with a constant time-based decay best fits human data.

A slightly different version of Space Fortress named AutoOrbit has been investigated by Gianferrara, Betts, and Anderson (2021) to further the understanding of cognitive and motor skill transfer across speeds. Results suggest that skill transfer across speed perturbations of the environment required the recalibration of action timing skills. Moreover, progressive action chunking and production compilation characterize skill transfer and facilitated transfer.

In a parallel research path, Dimov et al. (2020) focus on Coop Space Fortress, a cooperative version of Space Fortress, to analyze teamwork in a dynamic task. Coop Space Fortress requires pairs of subjects to cooperate to earn points. The results show that subjects improved their game score by becoming more skilled at controlling their ship and typically settling on a role. Role selection allows the players to focus on a single task and avoids switching costs.

The issue of skill acquisition was also analysed by studies using Soar. For example, John and Vera (1992) uses Soar's learning mechanisms to investigate how an

agent might acquire strategies and selection rules through experience in interactive behaviours.

Several selected papers analyse processes related to memory management. As mentioned above, Choi et al. (2007) has exploited the features of the ICARUS cognitive architecture, like the support of different aspects of knowledge and the specialisation of different types of memories, to develop an Urban Combat game virtual player. Specifically, ICARUS architecture organises knowledge in long-term memories at different levels of abstraction, provides a specific memory containing a prioritised list of goals the agent should attempt to achieve, and improves the retrieval mechanisms and the learning processes by indexing the procedural skills by the goals they achieve.

Derbinsky et al. (2012) present a review of the implementation of episodic memory in Soar to make it computationally functional and efficient, even for intelligent agents with a long life cycle. The authors use three games — TankSoar, Infinite Mario and Eaters (a game inspired by the classic PacMan) — to evaluate the scaling capability of episodic memory in the case of long agent lifecycles. In the following work, Derbinsky and Laird (2013) explored an approach that involves forgetting inactive knowledge that can be reconstructed when needed.

3.3.4 Perception

The process of perception is a complex cognitive function that involves collecting, interpreting and understanding sensory information from our environment. In the game context, perception refers to how players interpret and understand the game environment and its elements. It involves using sensory information and cognitive processes to make sense of the game world and make decisions based on that understanding. Several works analyse the perception problem from a visual and spatial point of view.

Wintermute (2012) analyses the problem of creating a unique perception system capable of inducing appropriate descriptions in each task an agent encounters. The authors address the issue of perceptual abstraction through mental imagery. The SOAR-based implementation was tested in the context of an arcade game (Frogger II) in which the agent is engaged in a motion-planning task to demonstrate the

effectiveness of the proposed approach.

Schrodt, Kneissler, Ehrenfeld, and Butz (2017) focus on the Super Mario Bros game environment to test the functional and computational modelling features of the SEMLINCS architecture in the context of embodied cognitive development to explore how conceptual, rule-like structures can be learned from continuous sensorimotor experiences.

The perception process is also central in those embodied games in which it is necessary to interact with a real context and human users. In this context, Alderisio, Antonacci, Zhai, and di Bernardo (2016); Zhai, Alderisio, Słowiński, Tsaneva-Atanasova, and di Bernardo (2018); Zhai, Alderisio, Tsaneva-Atanasova, and di Bernardo (2014) delineate a path of research that led to the development of a cognitive architecture capable of guiding or following a human player during a mirroring game. This game is considered a good task for studying interpersonal interactions and effective rehabilitation methods to help people suffering from social disabilities.

Ramiŕez, López, and Flores (2013) introduce a hybrid cognitive architecture developed based on ACT-R and SOAR. The main feature of the proposed system is a sensing modelling component designed to support the creation of intelligent virtual agents showing realistic behaviours.

Visuospatial processes play an essential role in various types of play. Smart and Sycara (2015a) combine the use of ACT-R with a virtual environment implemented through the Unity3D game engine to study a virtual cognitive robot's maze learning and place recognition abilities. The cognitive model combines different information (visual, tactile, and kinesthetic) to represent the topological structure of the environment.

Visuospatial and mental imagery skills are central in many games. We analysed this theme regarding the Tetris game (Gentile & Lieto, 2022), and it represents one of the two case studies examined in this thesis (see section 5.1).

3.3.5 Reasoning and decision-making

As shown in figure 3.4, reasoning and decision-making are among the most studied mental processes in the literature under review. Almost all selected works refer

more or less directly to reasoning processes.

For example, studies that exploit cognitive architectures in cognitive games or game theory games analyse the player's game strategies. For instance, Lebiere and West (1999) propose an ACT-R model of humans playing "Paper Rock Scissors" that does not rely on the classical game theory approach. The authors define the model according to the principle of reciprocal causation as an emergent property of the interaction between the players.

In the same context, R. L. West, Lebiere, and Bothell (2005) compares the optimal player strategy with the maximisation strategy in the game Rock, Paper and Scissor, arguing that the latter is consistent with scientific evidence and is the result of the evolutionary process.

Wintermute and Laird (2007) present a bimodal reasoning system in which quantitative representations are integrated with qualitative ones represented in Soar. The system was tested in the ORTS real-time gaming environment.

J. E. Laird, Derbinsky, and Tinkerhess (2011) introduces probabilistic reasoning into the SOAR symbolic architecture and tests it in the context of a multiplayer game called Liar's Dice.

Juvina, Lebiere, Martin, and Gonzalez (2011) present a cognitive model in ACT-R based on the Instance-Based Learning Theory of human decision-making within a more complex version of the game Prisoner's Dilemma. The authors modified a version of the Repeated Prisoner's Dilemma by adding the intra-group power concept in order to improve the opportunities for studying human behaviour in conflict situations.

De Obeso Orendain and Wood (2012) propose a complex problem-solving model realised in ACT-R that exploits a level of competition between strategies that can show more cognitive flexibility than limited ones to learning. The context of use is that of a game called FireChief, which defines a dynamic microworld in which the player counteracts the spread of fires using different types of mobile units.

Finally, in the area of complex reasoning processes, the works of Arrabales are noteworthy (Arrabales, 2012; Arrabales et al., 2009, 2012). In those studies, the author defined computational models capable of simulating high-level processes such as those related to conscious reasoning (Chella & Manzotti, 2013) to create virtual

agents capable of simulating human-like behaviour (Arrabales, 2012; Arrabales et al., 2009, 2012).

3.3.6 Social Function

This category includes all studies that deal with aspects related to social interaction.

One of the main topics is the study of the ability to read the opponent's thoughts and interpret his or her behaviour, enabling the agent to predict the opponent's possible future moves and then adapt his or her reasoning accordingly.

Several works analyse this aspect.Van Maanen and Verbrugge (2010) explored the *Marble Drop* game to validate a second-order social reasoning computational model, allowing the player to decide the next moves by considering the opponent's ability to predict it. Pynadath, Rosenbloom, Marsella, and Li (2013) present an extension of the Sigma cognitive architecture aimed at endowing it with the capacities associated with the *Theory of Mind* considered a critical component of human intelligence.

Another theme in this area is the analysis of agents' social coordination in reasoning. Schrodt, Röhm, and Butz (2017) exploit the Super Mario Bros game environment to demonstrate the capabilities of the SEMLINC architecture in understanding cooperative mechanisms between agents. To force collaboration, the authors equipped those agents with different skills, requiring each agent to learn the capabilities of the others through observation to obtain effective coordination.

A topic undoubtedly related to the previous one is the study of persuasive processes. In this area, a fair number of works analyse the deception process in the context of cybersecurity-related games.

According to Rowe and Rrushi (2016), a deception process is "a form of persuasion where one intentionally misleads an agent into a false belief to gain an advantage over the other agent".

The deception process typically involves an agent presenting false or truthful information (i.e. a signal) to an opponent to gain an advantage over him.

In the cybersecurity context, many studies analyse the *Insider attack game*, which was explicitly designed to investigate the interaction between a human attacker and a defence algorithm. The study from Cranford et al. (2018) represents the initial

step in their research programme on developing a cyber deception psychological theory. The ACT-R cognitive architecture was used by the authors to define an Instance-Based Learning (IBL) model of the attacker. The same authors developed the model in several research papers (Cranford, Aggarwal, et al., 2020; Cranford, Gonzalez, et al., 2020; Cranford et al., 2021). For example, in (Cranford, Gonzalez, et al., 2020), the authors define models for tracking an opponent's knowledge in a game to optimise strategies for reporting bogus data in an active defence strategy process. Recently, Katakwar, Uttrani, Dutt, and Aggarwal (2022) focused on the influence of network size on adversarial decisions using an ACT-R model.

In the study of persuasion processes, it is worth mentioning the work of Augello et al. (2021) that represents the basis of the second case study of this thesis work presented in section 5.2.

3.4 AI for games

The "AI for games" dimension investigates the motivation that guides the implementation of AI systems for games. According to Yannakakis and Togelius (2018b), it is possible to identify three key motivations:

1. *playing games*, which concerns the development of intelligent systems capable of playing a game or enhancing the human game experience by acting as non-player characters (NPCs). It includes much of the research on games AI.

2. *generating content*, which refers to the generation of game content autonomously or as a support for the human designer;

3. *player modelling*, which includes all the studies that aim at the analysis (and prediction) of players' experience and behaviour from a cognitive, emotional and behavioural perspective.

Figure 3.5 shows that almost all research using cognitive architectures in games considers the modelling and realisation of agents capable of playing (113 articles out of 118, amounting to the 96% of analysed papers). Twenty-four per cent of the research also analyses player modelling, and only in one case are cognitive architectures considered for creating game content.

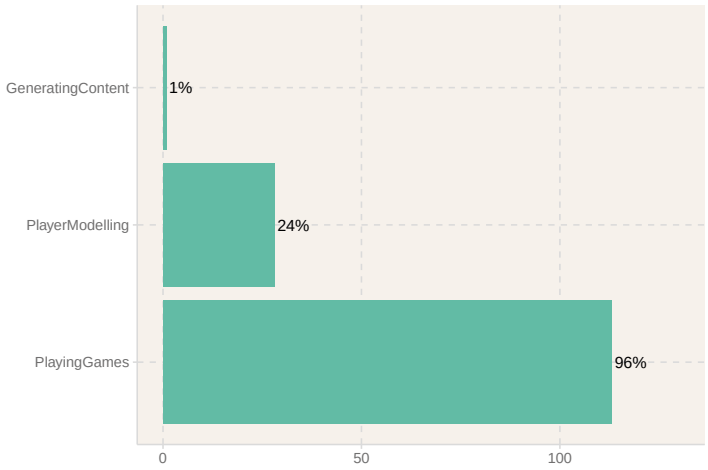

Figure 3.5: Distribution of the rationale for the implementation of AI systems for games in the investigated literature.

3.4.1 Playing games

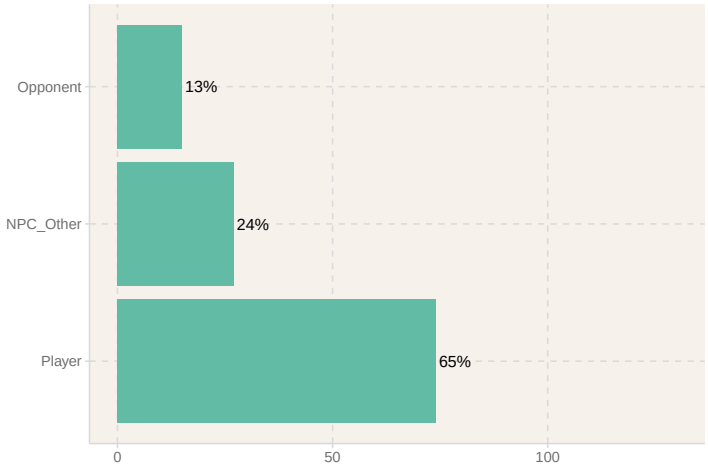

Figure 3.6: Distribution of AI-based character types implemented in the examined literature.

As shown in Figure 3.6, 65% of the 113 articles provide for the creation of playing agents, specifically focusing on the design of agents capable of assuming the player's role. In this case, the primary objective is the creation of agents capable of simulating human-like behaviour based on cognitive models or theories rather than creating agents capable of equalling or improving the performance of a human player. In many cases, this research aims to analyse specific cognitive processes that find a privileged field of exploration and testing in the game contexts.

One of the main triggers for integrating cognitive architectures in the design of

games is to increase their realism. While a lot has been done concerning the graphical rendering of games, the same cannot be said for the realism of the characters the player has to interact with. Therefore, one of the main motivations is to favour the realisation of human-like non-player characters (NPCs).

Specifically, 24 per cent of the analysed papers provide for the creation of NPCs that enrich the game.

Finally, 13% of the investigated research provides for the implementation of agents designed to challenge the human player. Although these systems are theoretically capable of assuming the player role, their primary goal is to enrich the experience of the human agent rather than simulating a player.

It is the case, for example, of first-person shooter games in which non-player characters (NPCs) challenge the opponent. In (Wray, Laird, Nuxoll, Stokes, & Kerfoot, 2004), the authors defined the general requirements for synthetic adversaries definition and developed a general framework for supporting behavioural variability, and implemented portions of this framework using the Soar cognitive architecture.

3.4.2 Player-modelling

In this area, Yannakakis and Togelius (2018b) place all studies that look at modelling the human player from a behavioural, emotional and cognitive perspective. In contrast to player profiling, which examines the static characteristics of the player, player modelling is oriented towards understanding dynamic phenomena that occur during gaming activity.

Within this area, Yannakakis and Togelius (2018b) distinguish two main axes: the goal of the modelling task and the approach used.

Concerning the goal of player modelling, the authors differentiate the study of the player gaming experience from the understanding of player behaviour. The rationale behind this distinction is linked to the data source used to model the player. According to Yannakakis and Togelius (2018b), if we rely exclusively on game analytic analysis, we can only investigate *player-behaviour*. While it is necessary to use data external to the game (e.g. observation systems and their annotations) to analyse how the player *feels during* the game activity.

Regarding the approach used, they highlight the differences between the *model-driven* (top-down) method from the *model-free* (bottom-up) approach. Of course, between these two extremes, possible hybrid approaches also lie at different levels of nuance. And it is in this continuum that we see the potential use of cognitive architectures.

Figure 3.5 shows that twenty-four per cent of the research also analyses player modelling.

Most articles in this area focus on analysing player behaviour, often intending to anticipate following moves.

Very few cases could be reported in which cognitive models are implemented to investigate skills acquisition. Of course, this is the case with the works of Anderson and colleagues previously analysed.

In the context of the turn-taking game "Marble Drop with Surprising Opponent", Ghosh and Verbrugge (2018) proposed a participant profiling system to explore how people make decisions by reasoning about their opponent. According to the identified player types, the authors delineated plausible reasoning strategies by defining computational models in the cognitive architecture PRIMs.

Also of note is the work of Streicher et al. (2021) who, To create adaptive serious games, present a cognitive approach to user modelling that exploits memory activation levels of learned concepts. The central aspect of this work is the dynamic generation of ACT-R models from observations and the technical implementation of a standard activity stream for the observed data based on the xAPI standard.

3.5 Multidimension analysis

In this section, some interaction analyses among the investigated dimensions are reported to complete the picture provided by the literature review.

For example, Table 3.2 shows the relationship between game genre and cognitive skills investigated in the selected studies. From an educational point of view, this picture can provide valuable insights into selecting the right kind of game from the point of view of the skills needed to play games or, on the contrary, the skills trained by the games. In this view, it is sufficient to highlight the enormous differences between strategy games — which require cognitive skills such as planning,

Game Genre	Action	Attention	Emotion	Language	Learning and Memory	Motivation	Perception	Reasoning and Decision Making	Social Function	No Specific Process
Action games	17	13	1	1	19	1	18	19	3	
Cognitive games	7	1	3	2	13		7	15	10	
Games of chance					4			7	2	
Game Theory games	1			1	2			7	8	
Mental tasks					1			2	1	
Puzzle games	3	1			2		2	6	2	
Role-Playing games					2		2	1		
Serious Games			3		2			3		
Sports games	2				1		2	4	1	
Strategy games				4	5		4	3	1	
Other	3	2	1	1	7		5	12	4	1
No Games	6	1	5		5		6	9	1	3
Total	39	18	13	9	63	1	46	88	33	4

Table 3.2: Mental processes analyzed by game genres.

consequence prediction, and problem-solving — compared to action games, which require visual perception, eye-hand coordination and quick reaction skills.

Valuable insights can also be derived from analysis of the relationship between the types of games and the type of cognitive architectures used. In fact, each cognitive architecture is often highly specialised in simulating some distinctive cognitive processes and thus may be more or less appropriate to be employed in game design depending on the specific type of game.

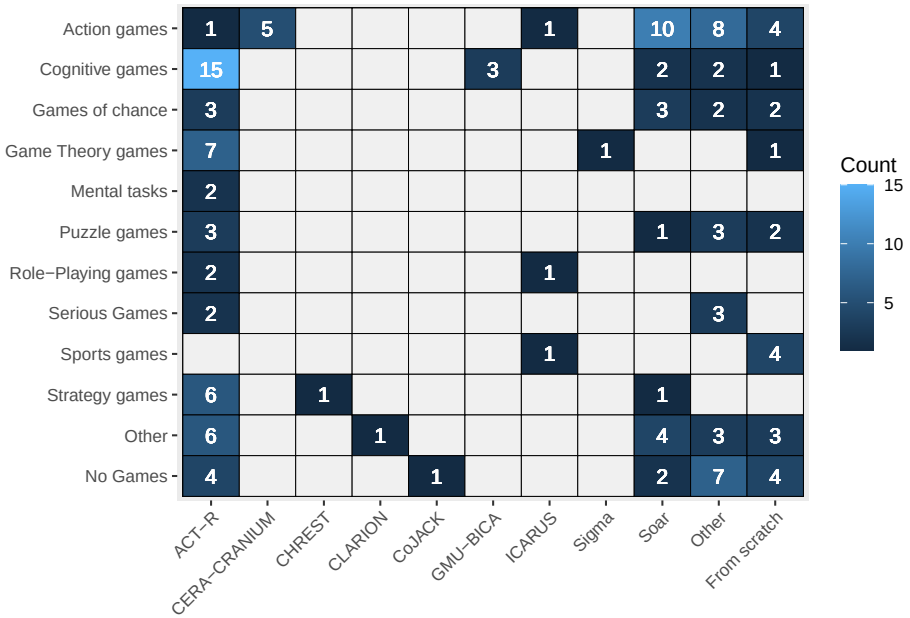

Figure 3.7: Distribution of research papers investigated by CA and games genres.

Figure 3.7 shows a heatmap highlighting the game categories applications of the different cognitive architectures. First, the figure shows that ACT-R and Soar — among the established and widely studied architectures in general — are the most

commonly used in all the game categories. Probably their functional characteristics allow their use in different domains.

However, it is possible to highlight how whereas ACT-R has a substantial prevalence of use in the area of cognitive games, Soar is particularly used in the area of action games. This result is consistent with the specific aims of the research programmes of Anderson and colleagues developed using the ACT-R architecture and of Laird and colleagues and their studies developed within the Soar/Game research programme.

4 Cognition in the "loop": A theoretical framework for a Cognitive-based Serious Games lifecycle

The literature analysis conducted in the previous chapter has highlighted how the application of cognitive architectures (CAs) in games is limited and, above all, restricted to those types of games that refer more or less explicitly to the field of cognitive sciences.

Moreover, analysing the field from a game industry perspective, we can conclude that in the panorama of AI techniques adopted in games, CAs represent a minority compared to more recent AI developments like deep learning (Yannakakis & Togelius, 2018b).

Nevertheless, the field of serious games may be a perfect area in which to realise Newell's programme (Newell, 1973) and also respond to Gray's recent invitation (W. D. Gray, 2017). The rationale that may drive this research programme is the need for a step toward the methodologically grounded demonstration of their educational effectiveness, highlighted by the analysis conducted in section 2.1.1.

According to Mayer (2016), psychology and cognitive science can provide theoretically founded solutions to improve the instructional effectiveness of educational games.

Moreover, using a cognitive approach to evaluate the effectiveness of serious games may meet the need for theoretically-founded assessments approaches as raised by many researchers (Ifenthaler, Eseryel, & Ge, 2012a; Ifenthaler et al., 2012b; Ifenthaler & Kim, 2019; Kim & Ifenthaler, 2019; Kim, Valiente, Ifenthaler, Harpstead, & Rowe, 2022; Loh, Sheng, & Ifenthaler, 2015b, 2015c).

According to Mayer (2019), serious games should be created based on the cog-

nitive principles of acquiring new skills to fulfil the educational goal.

The framework presented in this chapter constitutes the primary theoretical result of this thesis. It aims to provide a guide for enhancing the educational effectiveness of SGs by taking advantage of the formal approach promoted by computational cognitive modelling and specifically by CAs. For the instructional activity as a whole to be successful, its design —including the specification of when and where it takes place — must be carefully thought out. However, considering these factors would have significantly expanded the scope of the research, making it difficult to conduct an in-depth investigation of the subject at hand, which was the design, development and validation of a cognitive-grounded game.

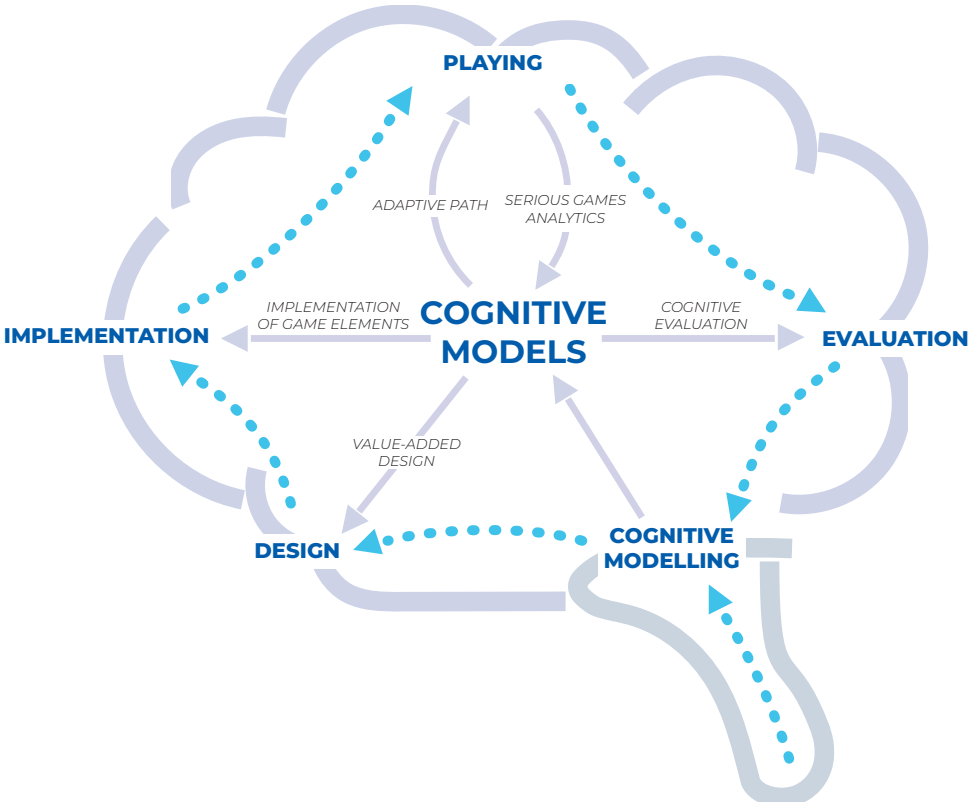

Figure 4.1: Cognition in the "loop": A theoretical framework for a Cognitive-based Serious Games lifecycle.

The rationale behind the definition of the proposed model is that serious game development should follow a cyclical pattern, where cognitive-grounded phases drive the game's evolution according to the empirical analysis of its learning effects.

As shown in Figure 4.1, the model foresees five phases: cognitive modelling,

design, implementation, playing, and evaluation.

In this perspective, cognitive models and CAs act as a cross-cutting *methodologically sound, theoretically grounded, and educationally relevant* approach across all the phases of a serious game's life-cycle.

The application of the proposed framework during the different phases provides a common theoretical background that links together the definition of the game used by the players to train specific competencies, the mechanisms of analysis of the collected pieces of evidence and their subsequent interpretation.

The need to compare the expected results with the findings from field trials is, of course, valid for every type of game; however, this need is even more urgent for serious games that often represent a tool for educational research rather than the realisation of a commercial product. Considering that the cognitive dimension is crucial to conceive effective serious games, it was necessary to determine where integrating the cognitive modelling phase during the development of a serious game. The decision to consider cognitive modelling as the cycle's starting point is suggested by the meaningful roles the cognitive models could assume in the other stages of the serious game lifecycle, as explained in the following sections.

The framework can provide guidance to:

- define an original serious game;
- assess an existing game from an educational point of view.

In the latter case, every type of game could be the object of analysis and used as-it-is or as a starting point for re-design the game (e.g., existing serious game or COTS[1] game).

In the following sections, each phase will be analysed in detail to provide guidelines for cognitive modelling and the practical use of CAs.

4.1 Cognitive Modelling

Cognitive Modelling represents a fundamental phase of the cyclic process described by the framework. In the proposed framework, cognitive modelling refers to the

[1]COTS is the acronym for Commercial Off-the-Shelf and indicates software product available for purchase or lease to the general public.

crucial phase in which the computational cognitive model for the targeted process is designed and implemented.

Educational games should have clearly targeted goals, and the cognitive processing required in the game should correspond closely to the learning objectives (Mayer, 2016). For that reason, the first step in this phase is to explore the connections between the desired high-level educational outcomes and the underlying cognitive processes. It is essential to keep in mind that games often engage several cognitive skills. A proposal comes from Mayer (2019), who suggests focusing on a single cognitive skill to clarify the educational goals of the entire research design.

The initial choice of whether or not to start from an existing game drives the identification of the target cognitive skill. In the former case, the core skill that is repeatedly exercised within the game has to be identified. In the latter case, this step must result in a clear choice of the cognitive processes to be trained in the game.

After identifying the cognitive skill to be worked on, is necessary to define the computational models.

It is generally convenient to start with the cognitive modelling of a player agent. The definition of a cognitively credible player model is the reference on which all other steps of the framework are based. This is the task in which CAs play their role.

CAs support modelling by guiding the creation of cognitively plausible models. Of course, each architecture, developing a specific cognitive theory, constrains this phase differently (see section 2.2).

Furthermore, at this stage, the re-use or ex-novo realisation of cognitive models referring to specific theories, such as the "Cognitive Load" theory (Sweller, 1988), may be necessary to construct a cognitive model based on additional assumptions not provided by the basic implementation of the chosen cognitive architecture.

For example, according to the theory at the base of ACT-R, Taatgen et al. (2005) propose the following five different approaches to modelling:

- Instance learning;
- Competing Strategies;

- Individual Differences;
- Perceptual and Motor Processes;
- Specialization of Task-Independent Cognitive Strategies.

In the *instance learning* approach, the cognitive model is defined to use past experiences in decision-making. In ACT-R the main components used in this approach are the declarative memory and partial matching mechanism, together with the activation mechanism of knowledge chunks.

The *competing strategies* approach involves testing multiple ways to solve a problem. Within the ACT-R model, the utility learning mechanism ensures that the most successful strategy, with the lowest costs, is used more frequently than others.

Where it is possible to evaluate the effectiveness of different strategies it is possible to adopt the *competing strategies* approach. This is the case of games, where the game score is a natural measure of performance. The utility mechanism that is part of the ACT-R's procedural memory management, is a viable way to implement this approach.

Sometimes, CAs offer mechanisms to adapt models' functioning to specific individuals' behaviour (i.e., *individual differences* approach). For example, ACT-R provides the modeller with a series of parameters that regulate the general functioning of its modules. A classic example is the use of the W parameter that regulates the functioning of the spreading activation mechanism.

One of the most frequently used features in the cognitive modelling of players is the interaction with perception and motor process systems offered by CAs.

In CAs in which these systems are realised to satisfy time constraints, it is feasible to define models that attempt to emulate human behaviour by respecting the timing of actions as if they were performed by human players.

In chapter 3, several case studies using this modelling approach are discussed.

Finally, the *specialization of task-independent cognitive strategies* approach is used to test the ability of a model to adapt his behaviour to a specific task (a game in this case). To this aim, it is possible to start from a general model and use the learning capabilities offered by the specific cognitive architecture to create a new cognitive model. This is the case with the production compilation mechanism offered by

ACT-R or the impasse resolution mechanism offered by Soar.

In addition to the modelling approaches proposed using a specific cognitive architecture, it is also possible to mention examples of more general approaches. An example is the Goals, Operators, Methods and Selection rules (GOMS) method (John & Vera, 1992) or its derivations such as SGOMS (R. West, Ward, Dudzik, Nagy, & Karimi, 2018) that have been employed to predict the course of the highly interactive behaviour that characterized games. The adoption of such a method generally precedes the implementation of the model in a specific cognitive architecture.

4.2 Design

As highlighted in section 2.1.2, various approaches are available in the literature to guide the design of a serious game. Educational objectives are obviously the central element in the analysis of existing games and a primary component to be considered during the conception of new games.

However, to the best of our knowledge, derived from the systematic literature review conducted so far, no model offers a formal definition of educational objective, and, in particular, none of the models mentioned analyses this dimension from a cognitive point of view.

The cognitive models resulting from the previous phase provide the designer with an essential input for the definition of game dynamics.

According to Mayer (2019), if we look at the gameplay activity from an educational perspective, it is possible to identify three different cognitive processes involving a player: *essential*, *generative*, and *extraneous processing*. *Essential processing* represents the core mental process needed to identify and select the essential information necessary to understand the content domain, and that serves as an input for the *generative process* that fosters full awareness and comprehension.

All mental processes used while playing that are not inherent to the learning goals are called *extraneous*. The goal is to foster essential and generative processing while trying to minimize extraneous processing.

The cognitive models inform the designer about the cognitive processes activated during the gameplay providing essential input for selecting and defining the

game elements that determine the game dynamics.

The following table exploits the classification of game elements provided by Järvinen (2008) and summarises how cognitive awareness can intervene in defining each of them.

Game element	Description	Cognitive-based design	Goals
components	the objects the player possesses and manipulates during the game	characteristics, type and number of objects to be manipulated by the player	specialisation of the cognitive effort required by the game
environment	represents the play space that constrains (physically or virtually) the dynamics of the game	structure, size and scale relationships of the play space	specialisation of the cognitive effort required by the game especially in terms of visuo-spatial skills
rule set	represents a primary design element that determines game dynamics	rules embedded in the game elements, goal rules (scores, win and loss conditions) and procedures (rules that are activated under certain conditions)	specialisation of the cognitive effort
game mechanics	represent what the player can do within the game. They are a strongly characterising element of the game itself and, as pointed out in the section 2.1.2, represent the main element on which various design frameworks are developed	types and numbers of game mechanics	specialisation of the cognitive effort
information	information that the game can provide to the player[2]	amount of information provided, level of explicit or non-explicit information	developing the player's analytical and critical thinking skills
theme	the theme contextualises the game by providing a pattern of meanings to its elements	setting, motivational element, metaphors	to modulate the impact of prior knowledge in gameplay
interface	represents the way the player operates in the game. The interface determines the game mechanics available to the users	input device	exploiting the knowledge of perception systems and motor systems constraints reproduced by CAs
player	refers to the different aspects of the player that can influence game design	points of adaptability	ensuring the adaptivity of the gaming and learning experiences to player's competencies levels and skills
contexts	it represents where the game takes place and naturally influences the game activity	place and timing of gaming experience	the analysis of the mental processes involved in the game could provide insights into the optimisation of the organisation of the game activity in terms of time and space

Table 4.1: An overview of how cognitive modelling can influence the main design elements of a serious game.

According to the value-added research proposed by Mayer (2016), the results of this analysis can lead subsequent iterations of the framework towards a re-design of the game allowing a greater stimulation of a specific cognitive process.

In addition, by highlighting the cognitive processes that the game prompts at the beginning of the cycle, it is possible to identify both the assessment tools and to

figure out the transfer learning potential of the games.

4.3 Implementation

One of the primary uses of CAs in gaming already examined in the literature (see chapter 3) is undoubtedly the use of CAs for the implementation of non-player characters that are able to reproduce human-like behaviour and increase the realism of games.

However, although CAs have gained interest among academics and researchers, their use in this context has been limited by various factors.

A major limitation to the application of CAs is the technological challenges they introduce, as highlighted in (Dignum, Bradshaw, Silverman, & van Doesburg, 2009). Currently, it is difficult to integrate CAs into popular platforms for game creation, such as Unity and Unreal. Both game engines and CAs require significant computational power to meet the responsiveness requirement of various types of games.

Some solutions to overcome these issues involve developing a communication middleware to link a proxy version of the game agent with a more advanced, remote agent relying on CAs (Gemrot et al., 2009; J. E. Laird, 2001b; van Lent et al., 1999; van Oijen, 2014). These proposals aim to connect game environments with any cognitive architecture without requiring a specialized integration module.

Despite the fact that the proposed solutions may have high quality, their applicability has been limited due to the amount of effort needed for design and development, as well as some technical limitations such as the inability to use algorithms that are already integrated into game development environments.

Experimental results from cognitive science (CS) indicate that it may be possible to achieve a simplification at a cognitive level, by modelling cognitive processes exploiting heuristics conforming to the input-output functions of CAs. This can be obtained by efficiently developing the information processing dynamics of these systems.

In this way, it would be possible to allow designers to build agents using a well-founded cognitive model, while at the same time enabling developers to create simplified agents easily implementable into gaming platforms (such as Unity and

Unreal), but still able to 'simulate' complex behaviour.

According to the definition given by Gigerenzer, Todd, and Group (2000), heuristics are mental shortcuts that require minimal time, knowledge, and computation to make effective decisions in specific environments. These shortcuts are designed to adapt to the situation at hand.

These shortcuts, based on practical rules derived from past experiences and knowledge, provide direction for our daily actions that require immediate attention and rely on limited knowledge. According to Kahneman (2011), they can be considered as paths of reasoning or mental events that happen automatically and involve both innate (e.g. recognizing objects, orienting attention, perceiving the world) and learned skills (e.g. reading and/or understanding the shades of a situation). They manifest as various automatic activities such as reading, understanding simple sentences, perceiving distance, driving, and more.

Cognitive heuristics are rapid, unconscious and automatic methods of reasoning that alleviate the load on the working memory. These heuristics define the specific ways of gathering and analyzing information used in certain decision-making procedures, and they can be computationally instantiated.

4.4 Playing and Evaluation

In this section, we analyse the *playing* and *evaluation* phases. The two phases required a joint analysis since they are closely interrelated.

Playing is the phase in which the gaming experience is concretely realised. In this phase, the player is confronted with a complex system in which rules, mechanics, and the different elements designed and implemented in the previous phases determine the game's dynamics. The *evaluation* phase represents the context in which the results of the game experience are analysed. Generally, in a classical approach, it is performed after the game phase.

However, especially in education, anticipating the assessment during the gameplay allows a dynamic modulation on the learning path by adapting it to the student's specific needs. Such a dynamic adaptation is crucial to maximise the educational effectiveness of the game.

4.4.1 Assessment approaches in Serious Games

A crucial purpose of any educational practice is to verify whether and in what terms students learn. Research in the field of educational assessment aims to determine the level of student learning and to provide insight into the effectiveness of educational practices for all the actors involved, primarily students and teachers.

The need to verify the effectiveness of educational paths based on the use of serious games emerged early on in the relevant field of research. In this context, three main approaches can be identified. The first has been pinpointed as *game scoring* by Kim and Ifenthaler (2019) and *assessment inside the game* by Mislevy et al. (2016). It is the assessment carried out to measure the player's performance against the explicit objectives of the game. The second approach is based on assessment tools outside the game experience (e.g., pre/post tests, interviews and focus groups). Finally, the third case, defined as *embedded assessment*, refers to the analysis of data directly collected within the experiential context defined by the games themselves.

Generally speaking, the *game scoring* approach is functional for defining the game dynamics and thus not expressly designed to assess the student's learning level.

Concerning the objective of assessing the students' learning, even today, the external approach is the most frequently used in the literature. However, the typical ways in which the external approach is implemented, especially the timing that places it outside the game experience, do not allow for a formative use of the assessment and therefore make it suitable exclusively for a summative assessment of the student (Wiliam & Black, 1996). Furthermore, the external approach does not allow the tracking of players' actions to be exploited for evaluation purposes, which are intrinsic to the digital nature of games.

It follows that embedded assessment is the most suitable of the three approaches for responding both to the need for real-time formative assessment of the student's journey and for an objective evaluation of the student exploiting the evidence gathered during the game experience.

For this reason, this approach is analyzed in more detail by discussing how it enables the design of an adaptive game.

4.4.2 Adaptivity of the gaming experience

The possibilities of adapting a game according to the characteristics of an individual are manifold and depend on the time in which the adaptation should take place and by who makes the adaptation. Regarding the first point, adaptation may be realised statically outside the game experience or dynamically during the game activity. In contrast, the person responsible for adapting the game may typically be the designer or the game environment itself.

According to Streicher and Smeddinck (2016), the adaptation realised outside the gaming experience is usually called personalisation when addressed to the needs of a single user, or customization when addressed to the needs of a group of users. Dynamic adaptation is called adaptivity and is realised during the game activity, typically through the analysis of the player's behaviour.

The choice of the timing of adaptation is linked to the figure in charge of this adaptation. In the case of a static adaptation, the designer usually deals with the customization or personalization of the game. In contrast, the game system itself usually generates adaptations during gameplay. Moreover, the choice of adopting a static or dynamic adaptation is naturally closely linked to the choices made in the design phase that enable or disable the game's adaptability.

On this subject, several authors (Lopes & Bidarra, 2011a; Streicher & Smeddinck, 2016) offer overviews of the techniques suitable for the realisation of an adaptable game, among which parameterization is one of the most prominent.

In the context of this thesis work, we are interested in analysing the dynamic adaptivity of games because it represents the most effective method to support the effectiveness of the learning pathway (Hattie, 2012). In fact, according to various psychological and educational theories, the adaptability of the learning pathway concerning the individual's competencies maximises the effectiveness of any teaching practice. The goal is to maintain the level of competence required by the game slightly more difficult than the learner's current level of competence, thus operating in what Vygotsky (1978) define as the *zone of proximal development (ZPD)*, and Csikszentmihalyi (2014) names *state of flow*.

Among the possible approaches to realise in-game adaptivity, Streicher and Smeddinck (2016) mentions the *Dynamic Difficulty Adjustment (DDA)* and the game

mechanics or content adaptation. Lopes and Bidarra (2011b) offer an overview of game elements that can be adapted.

4.4.3 Towards cognitive-based Serious Games Analytics

Starting from what has been done in the field of Learning Analytics (Ifenthaler, 2015), research on so-called Serious Game Analytics (SGA) (Loh, Sheng, & Ifenthaler, 2015a) has also been conducted in the serious games sector for several years. Specifically, the label SGA refers to the collection and subsequent analysis of the actions and behaviours performed by players during gaming activities.

In terms of the data type, SGA make it possible to track any action performed by the player at a level of detail appropriate to the educational objectives. Some examples of data that can be tracked in a non-invasive manner during the game activity are the time needed to complete a session or a game activity, the errors made and their typology, the access to information content available in the game, the sequence of actions performed by the player to complete a specific task. The large amount of data that can be collected in these environments (often referred to as "high frequency" interactions) also contributes to the reduction of uncertainty in evaluation results that is inherent to any measurement process (Committee on the Foundations of Assessment, Board on Testing and Assessment, Center for Education, Division of Behavioral and Social Sciences and Education, & National Research Council, 2001).

Concerning analysis techniques, SGA algorithms aim to derive from the raw data stream what Shute (2011) calls *stream of evidence*. The SGA algorithms most prevalent in literature are those employing numerical techniques to construct metrics capable of summarising learner behaviour. Schrader, McCreery, Carroll, Head, and Laferriere (2019) provides an overview of some of the most widely used techniques, for instance, neural networks, Bayesian/Markow networks or Path analysis.

However, despite the enormous research interest, ten years after their previous work (Ifenthaler et al., 2012a, 2012b) in which the authors emphasised that research in the field of game-based learning assessment was in its infancy, they still argue that "many promises of game-based learning and assessment have not been fully

accomplished in the actual education system" (Kim & Ifenthaler, 2019).

A critical insight is provided by Kim and Ifenthaler (2019), who argue that current SGA analysis approaches rarely provide a cognitive interpretation of the analysis results.

In this direction, we can read the significant efforts to analyse SGA according to an Evidence-Centred Design (ECD) approach (Behrens, Mislevy, DiCerbo, & Levy, 2010; Mislevy, 2018; Mislevy, Almond, & Lukas, 2003; Mislevy et al., 2016). Shute, Ventura, Bauer, and Zapata-Rivera (2009) tried to achieve such an objective. They describe an approach called stealth assessment where in-game behavioural indicators are identified to make inferences about the player's underlying skills like creative problem-solving.

The cognitive-grounded analysis of the user's interactions collected during the gameplay would represent a promising research paradigm both for the computational cognitive sciences as well as for serious game scientists. Assessing and reporting on the mental processes involved in solving and reasoning about a problem is a key goal of cognitive-grounded analysis (Leighton & Gierl, 2007). However, according to Kim and Ifenthaler (2019), research advances are needed to support the formalisation of evaluation models whose results are interpretable also from a design perspective.

Computational cognitive models, a result of the cognitive modelling phase, may be an adequate response to the need for a cognitive reading of SGA that can provide an interpretation valid as an input to the design phase. In fact, compared to ECD approaches, cognitive models are not limited to the definition of a psychometric model capable of linking observed variables and latent variables representing students' abilities according to a more or less complex mathematical structure [3]. Instead, the approach proposed in this framework links the observed variables and students' abilities through a computational model of mental processes, whose cognitive validity is also guaranteed by the constraints imposed by the specific cognitive architecture in which these models are defined.

In this sense, the proposed approach is perhaps the one that is most consistent with the idea of an educational assessment as a process. According to this per-

[3] For a comprehensive discussion of the ECD approach please refer to (Mislevy et al., 2016).

spective, a measurement instrument is also a tool for the cognitive investigation of the complex process that links what we call abilities with observable behaviour (Committee on the Foundations of Assessment et al., 2001; Pellegrino, 2002).

Moreover, starting from a cognitive model of the player, it will be possible to improve also the research on the adaptivity of the "game content" to the specific needs of the player.

In this field, the contribution of CAs can be significant, as demonstrated by their use in the construction of intelligent tutoring systems (Lopes & Bidarra, 2011a). One demonstration of the CAs' potential is the application of ACT-R for creating an intelligent tutoring system widely used in the educational context of the United States (J. R. Anderson & Gluck, 2001; S. Ritter, Anderson, Koedinger, & Corbett, 2007). With similar objectives, Ghosh and Verbrugge (2018) offer an example of PRIM cognitive architecture application. In support of this approach, a recent paper (Streicher et al., 2021) employs the fundamental processes of the ACT-R cognitive architecture to track the memorisation path and subsequent maintenance of activation levels of knowledge chunks promoted by a serious game, demonstrating the effectiveness of the system in highlighting the needs of the learner and adapting the game dynamics accordingly.

5 Case studies

In this chapter, we will explore two case studies that illustrate the use of the framework presented in chapter 4.

By examining these case studies, we will show how the proposed framework can guide the design, development and evaluation of a serious game according to a cognitive-based approach.

We explore two case studies concerning two different areas. The first case study focuses on the use of a popular game, Tetris™, to train a specific visuospatial skill called mental rotation. Although some studies have reported positive effects of Tetris on mental rotation training, others have reported contrasting results. To better understand how Tetris affects mental rotation training and investigate the reason for such contrasting results, we analyse the game through the lens of a cognitive model. In particular, we will show how the cognitive model helps to understand how game dynamics activate the mental rotation cognitive process and how the game mechanics can be structured to redesign a version of Tetris that maximises training effectiveness.

The second case study examines the design of a persuasive game that uses cognitive models to understand how persuasive techniques affect the player. We show how the game designer can model the player's mental image using cognitive models and how this model can be used to adapt the game's interaction to make it more persuasive.

5.1 Enhanching Tetris to train mental rotation ability

The aim of this case study is to improve the effectiveness of Tetris™ as a training tool for mental rotation skills.

Tetris is a well-known puzzle game, created in 1984 by Russian game designer

Alexey Pajitnov. Tetris players have to manipulate falling shapes, called *zoids*[1] to fill horizontal lines without any gaps, preventing the stacking up of the blocks to the top of the screen. The zoids can be moved left or right and rotated in either direction to be placed in the desired location. In the game, the player places the zoids one at a time. Each time a full horizontal line is completed, that line disappears and the player is awarded some points. Moreover, when a line is "cleared", the blocks above it drop down, creating more space at the top of the board for the player's next moves. The game ends when the stack of blocks that have not been cleared reaches the top of the playing field. In the game, it is necessary to handle dynamic situations; the player must react quickly to properly fit the zoids into the available space. Moreover, the game's difficulty increases as the player progresses since the speed with which blocks fall increases. In its original form, Tetris consists of a game board comprising 20 rows and 10 columns, as depicted in Figure 5.1. Seven types of zoids are used in the game, all consisting of four interconnected blocks. It is worth noting that each block is linked to at least one other block in one of the four cardinal directions, as shown in Figure 5.2.

Tetris has been extensively studied and analyzed in numerous scientific works, with over seven hundred research articles about it currently indexed on Scopus. The reason why this game has garnered such attention is that it requires a combination of spatial awareness, hand-eye coordination, quick decision-making, and the use of different skills, such as strategic thinking, visuospatial and motor skills. It has been investigated for a variety of purposes, including enhancing spatial skills through training (Milani, Grumi, & Blasio, 2019), examining cognitive abilities such as cognitive workload (Trithart, 2000), as a tool to investigate mental processes related to pragmatic and epistemic actions (Kirsh & Maglio, 1994), and as a workspace for training and testing neural models or other AI algorithms capable of replicating or competing with human performance (Lora Ariza, Sánchez-Ruiz, & González-Calero, 2017; Schrum, 2018).

According to Pilegard and Mayer (2018), different visuo-spatial abilities are elicited by Tetris. Nevertheless, according to the suggestion of Mayer (2019), we choose to focus on a single skill: mental rotation. First, it emerges as one of the

[1] Another common name for a zoid, is the term "tetromino", which indicates a geometric object of four squares connected orthogonally.

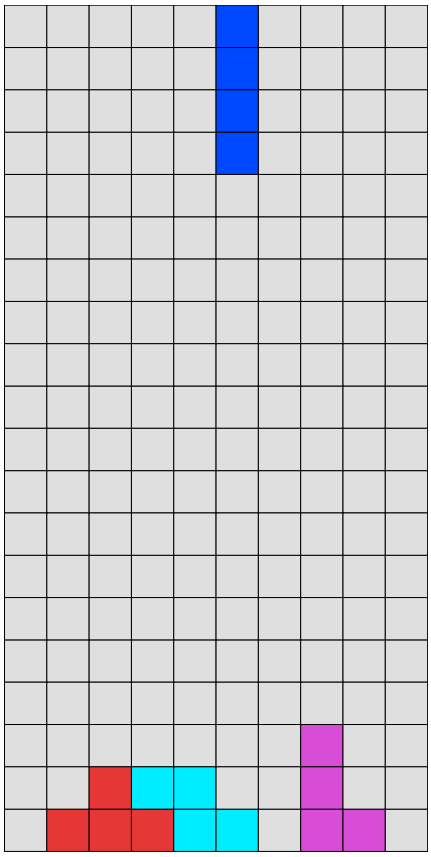

Figure 5.1: An example of Tetris gameplay.

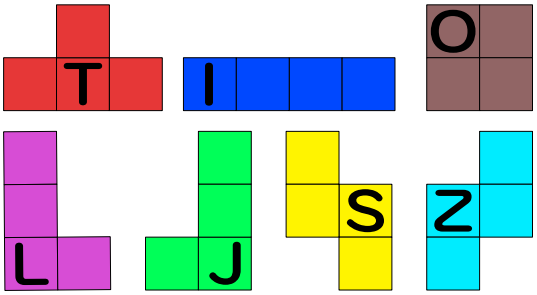

Figure 5.2: Original Tetris zoid types.

essential cognitive processes used in the game, and, above all, it seems to be an essential building block for spatial reasoning tasks in general.

The relation between Tetris and mental rotation skill has been studied in several works (Boot, Kramer, Simons, Fabiani, & Gratton, 2008; J. Goldstein et al., 1997), either as a measure of players' effectiveness in the game or as a skill to be improved. However, with regard to the effectiveness of Tetris as a tool for training this skill, the literature presents contrasting results(Pilegard & Mayer, 2018). Similar results

could be linked to an imperfect understanding of the ways in which mental rotation ability comes into play during Tetris gameplay.

It is precisely in situations like these that the proposed framework (see chapter 4) can play a crucial role in improving the learning processes by investigating the reasons why a game may or may not be effective in training a specific skill.

Starting from the definition of a cognitive computational model able to explain how a certain cognitive process is activated and exploited by the player during the game activity, it is possible to identify the conditions that allow maximizing the training effectiveness of a certain game, both with respect to the educational setting and to the nature of the game itself. In the case of Tetris, the ability we will focus on is precisely that of mental rotation.

This is the approach that we followed in our work and that will be discussed following. In particular, we will describe the cognitive modelling phase in which we provide a detailed description of mental rotation ability and describe the computational model.

Subsequently, we will discuss the lesson learned through the cognitive analysis of the game and how we exploit these considerations to define a modified version of the game capable of improving its effectiveness as a mental rotation training tool.

5.1.1 Cognitive modelling of Tetris gameplay

According to the framework proposed in chapter 4, the first stage involves a cognitive modelling phase aimed at understanding the role of mental rotation ability in the game.

Although many researchers have shown interest in the topic, according to the information available at the time, there had not yet been a "formal cognitive task analysis of Tetris playing" (Pilegard & Mayer, 2018) at the beginning of the study.

In the study by Gentile and Lieto (2022), we, therefore, introduced an agent that integrates mental rotation ability into an ACT-R cognitive computational model. The purpose was to examine how and in what circumstances the mental rotation is activated during the game.

For the purpose of this work, we employed the cognitive architecture ACT-R with the extensions provided by Peebles (2019) (see section 2.2.1. Peebles (2019) en-

hanced ACT-R with specific chunk types and imagery operations like translation, scaling, zooming, reflection, rotation and composition functions (such as intersection, union and subtraction) for the representation and manipulation of imaginary objects. Before illustrating the definition of the cognitive model, the following is a brief description of the mental rotation skill that is to be modelled.

Mental Rotation

In 1971, Shepard and Metzler (1971) introduced the term "mental rotation" to describe a cognitive process that involves the mental visualization and rotation of objects. This process has since been recognised as a specific visuospatial ability (Metzler & Shepard, 1974; Shepard & Metzler, 1971), consisting in mentally representing, manipulating and rotating objects in a 2D/3D space (Burnett & Lane, 1980). According to the empirical evidence, the mental rotation could be performed either in a *holistic* way, as a whole unit, as well as *piece-by-piece* (Battista et al., 1989; Clements & Battista, 1992; Olkun, 2003).

The process of mental rotation is commonly described as tasks that involve comparing shapes shown at the same moment or separately in consecutive phases. The individual must determine if the two figures (for example, two objects or two images) match after a simple rotation operation or if other operations like manipulation or reflection are needed to make the two figures overlap (Shepard & Metzler, 1971).

During the experiment conducted by Shepard and Metzler (1971), participants had to analyse a set of pairs of three-dimensional objects. The first object served as the reference, while the second object was a slightly modified version of the reference object. Typically, the second object was rotated around its centre. Figure 5.3, provides an illustration of this task, taken from the original experiment (Shepard & Metzler, 1971).

Vandenberg and Kuse (1978) proposed a two-dimensional version of the same test conceived for children, where flat images of animals are used for comparison instead of complex 3D objects. In this version, while the matching images are rotated versions of the reference image (at different degrees of rotation), to create the non-matching cases, the target images are presented in a rotated and mirrored

form.

The complexity of the mental rotation process was explained by Cooper and Shepard (1973), who proposed a decomposition into four steps:

- creating a visual representation of the stimuli;
- rotating an object in relation to another one;
- comparing two objects to determine if they are similar or different;
- producing a response [(Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008)]

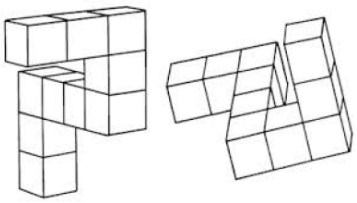

Figure 5.3: An example of the stimuli employed by Shepard and Metzler (1971).

Numerous studies have shown that the ability to mentally rotate objects is a strong antecedent of mathematical ability and performance in the subject, as stated in numerous studies (Cheng & Mix, 2013; Holmes, Adams, & Hamilton, 2008; Kozhevnikov, Kosslyn, & Shephard, 2005; Verdine et al., 2013). Mental rotation is also used as a predictor of spatial reasoning ability, which is important in fields like STEM and critical thinking (Carpenter, Just, Keller, Eddy, & Thulborn, 1999). Additionally, Città et al. (2019) have linked mental rotation ability to advanced high-order cognitive processes associated with computational thinking.

The process of mental rotation has been examined in computational cognitive science research. Peebles (2019) conducted a study where two computational models were created by using the ACT-R cognitive architecture in order to compare piece-by-piece and holistic strategies. The findings indicate that the models are reliable in terms of the rotation times obtained from a study that involved human subjects.

The cognitive model of playing Tetris

Specific theoretical assumptions were assumed to create a computational cognitive model for a virtual agent that can play Tetris using mental rotation.

The first assumption regards the process of attention. We have assumed that the player focuses on a portion of the board while looking for the position in which to place the zoid. Henceforth, in the rest of this thesis, we'll refer to the portion of the board that the player focuses on during the first part of the task as the *attention area*.

The second assumption is that the player, based on the shapes of the descending zoids (*target zoids*), mentally locates a set of imaginary zoids (*solutions*) in the blank spaces.

Finally, the third assumption is that the user generates the solutions through a subitizing process[2] in order to reproduce the characteristic features of the *target zoid*.

This last assumption stems from the simple observation that all the zoids are made up of four cells. The table 5.1 shows for each zoid an abstract description of its shape (feature) that synthesises the rules used for generating solutions.

Zoid	**Features description**
I	4 aligned blocks
O	a 2x2 blocks square
T	3 aligned blocks plus one in the middle of the parallel line
S / Z	2 offset lines made by two aligned blocks
J / L	3 aligned blocks with one at the beginning or at the end of the parallel line

Table 5.1: Summary of the zoids features used in the solution generation process.

An indirect but important side-effect of the last hypothesis is that producing solutions involves some degree of error. To put it differently, we suggest that for certain types of zoids the solutions generated may not match the target zoid.

Figure 5.4 highlights the zoids that demand the activation of the mental rotation process, according to the zoids features reported in Table 5.1.

Therefore, assuming that one of the four zoids (L, J, S, or Z) needs to be po-

[2] i.e. the capability to fast and accurately enumerate small groups of four or fewer objects (Mandler & Shebo, 1982)

sitioned, it is possible that the resulting solutions may produce a zoid that, while respecting most of the features of the target zoid, does not exactly correspond to it.

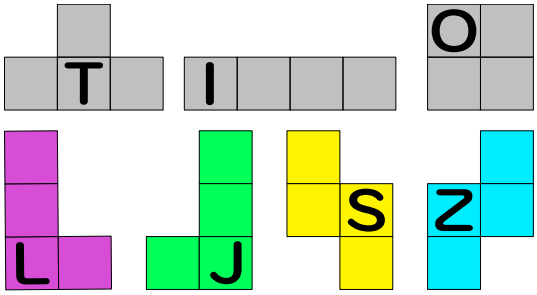

Figure 5.4: The list of zoids in Tetris.

To provide a clearer depiction of the scenario, suppose a S-shaped zoid appears in a 4x4 region with the configuration shown in Figure 5.5. The yellow zoid is the one to be positioned, while the 4x4 square refers to the area where it will be placed. However, not all locations in this region can be accessed because certain spots have already been occupied by other zoids placed earlier (depicted in magenta).

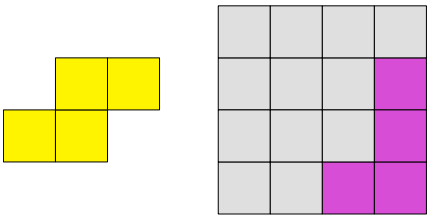

Figure 5.5: An illustrative scenario of Tetris.

Using the same scenario, Figure 5.6 presents some potential solutions produced according to the features of the zoid S. It's worth noting that not all of the solutions match the original zoid S. As shown in Figure 5.6 the last two solutions are examples of wrong generated zoid, the Z, that is the mirrored version of the S zoid.

According to the definition of the mental rotation process proposed by Shepard and Metzler (1971), after identifying a possible solution, it's necessary to mentally rotate it to determine if it matches the initial zoid unless it's been rotated or mirrored.

Based on the aforementioned assumptions, the cognitive model depicted in Figure 5.7 was formalised. The model consists of an initial stage where the zoid target is identified, resulting in the generation of a corresponding imaginal chunk. For

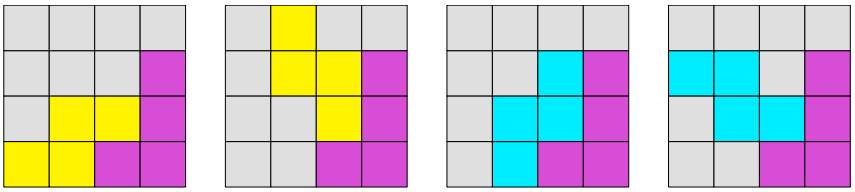

Figure 5.6: Examples of solutions created according to the zoid features.

this purpose, the ACT-R's visual attention and perception models are employed, whereby a group of perceived visicon characteristics representing the zoid are added to the iconic memory. In particular, the model initiates a search operation in the visual location buffer to locate the zoid. Once identified, the zoid is then searched in the visual buffer and when retrieved it is duplicated in the imaginal buffer.

Afterward, the model proceeds to analyze the board and extract potential attention areas. To identify these areas, the top portion of the board is divided into blocks with dimensions of n x m, where n and m represent the number of rows and columns in the attention area. These parametric dimensions can be modified to explore various configurations. The algorithm looks for blocks of size n x m that touch either the last row or a complete row on the board. To do this, it moves the upper left corner of the search area from the first column to the $cols - m$ column (where $cols$ is the number of columns on the board). The identified areas are then sorted by using a heuristic. The implemented heuristic sorts the areas based on the percentage of free squares within the attention area, giving preference to areas with the highest amount of free blocks.

After selecting an area, the model proceeds to the next step of exploring every potential solution within the attention area. By "solution", we refer to a hypothetical position for a mentally imagined zoid within the empty spaces of the attention area, as previously explained.

The process of generating solutions involves a subitization method that involves triggering 4-connected blocks. The algorithm generates all feasible 4-connected configurations and then filters them based on their compatibility with the salient characteristics of the target zoid. Once generated, the solutions are sorted using a second heuristic that considers the empty connected components in the attention area and the percentage of rows occupied, starting from the lower rows of the

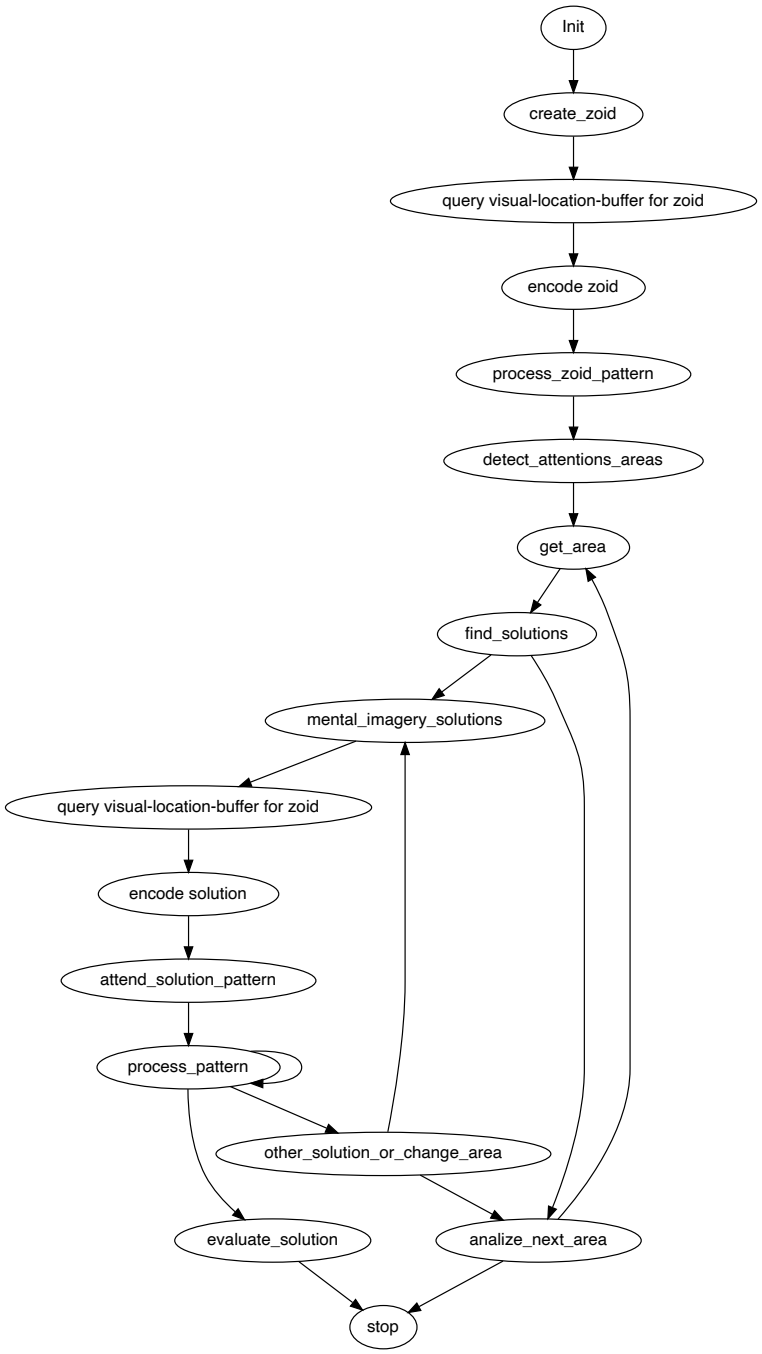

Figure 5.7: The Tetris cognitive model.

area. Then, the model creates a visual chunk representing it, by using the same steps described earlier for generating the target zoid chunk. Once both chunks are identified, the mental rotation process begins to determine the angle of disparity

between the target zoid and the hypothetical solution being analyzed. If the angle is higher than a specific threshold, the model performs the rotation.

The holistic computational model developed by Peebles (2019), served as a basis for defining the mental rotation phase in our model. Nevertheless, our model has several differences when compared to Peebles' model, as presented in (Peebles, 2019). Specifically, our model has a two-phase approach for recognizing the two figures to be compared. The target zoid recognition is performed just once outside the cycles at the beginning of the process, whereas the recognition of the second object is done for each tested solution as the model explores different areas of attention and solutions in each area. Moreover, our model also employs a 90-degree rotation step.

The rotation process will stop if either an angular configuration is discovered where the two images match or if all possible rotations have been attempted. If the figures are not matching, the algorithm will proceed to assess the next solution in the attention area only if the number of solutions tested in that area is lower than the *MAX_solutions* parameter. Otherwise, if the algorithm has already tested the maximum number of solutions in the area, it will move on to analyze the next area of attention. This process will continue until the maximum number of areas that can be explored, as determined by the *MAX_areas* parameter, has been reached. If the algorithm detects a rotation that causes the two shapes to match, it will stop running and assess the identified solution. Specifically, the algorithm will measure the difference between the current solution and the one previously identified by a human user for the same task.

It is important to highlight that the model enables the testing of different experimental hypotheses, and it is distinguished by two heuristics. The first heuristic is used to order the areas of attention, while the second is used to order the imagined solutions. Additionally, the model includes various parameters, among which are two that determine the size of the area of attention. Two other crucial parameters are the maximum number of solutions that can be tested in a single area of attention and the maximum number of areas that can be analyzed.

5.1.2 Towards a new version of Tetris

The cognitive model defined in the previous section represents the starting phase of the cyclical process defined by the framework.

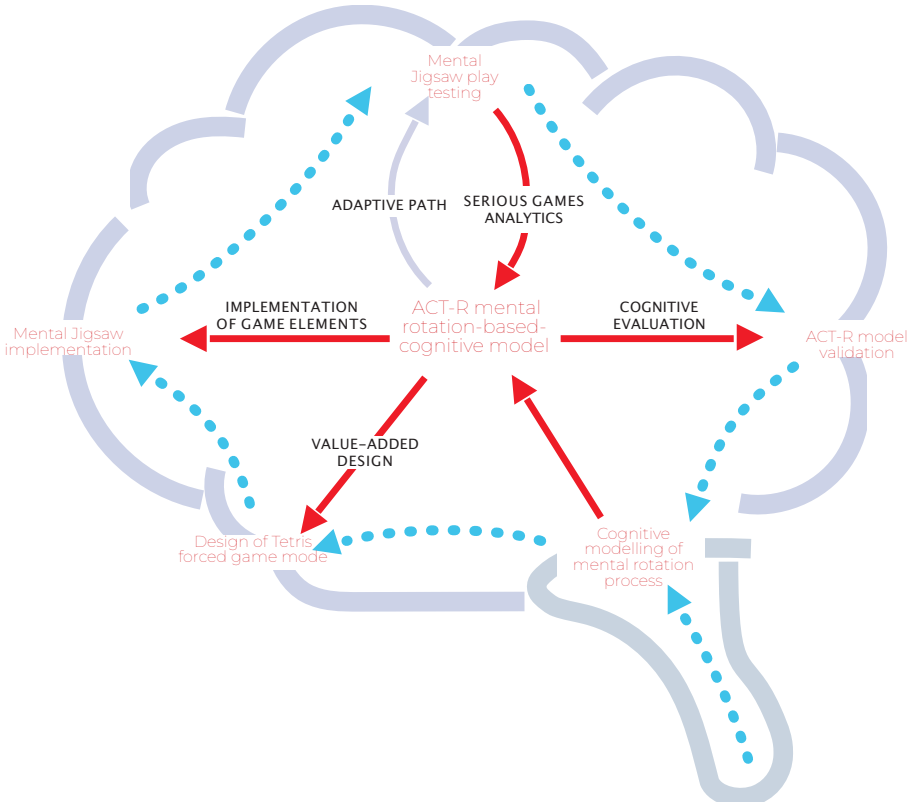

Figure 5.8: The first iteration of framework application in the Tetris case study.

The first iteration of the framework cycle (see Figure 5.8) was devised to formalise a first version of an agent able to explain the cognitive processes underlying the game activity in the TetrisTM, and in particular, the activation of the mental rotation cognitive process in the gameplay.

During the design and implementation phases, an ad-hoc version of Tetris called Mental Jigsaw was realized (the complete description of the game is reported in Appendix A.1). Mental Jigsaw has been tailored to meet our research requirements. In particular, during the first iteration, the aim of the game was to collect the learning analytics produced by human players. The model was validated by comparing the collected results with the data produced by the proposed cognitive model. Gentile and Lieto (2022) report the validation process.

During the first validation of the cognitive model, the game provided two dif-

ferent game modalities: the classic and the forced. In the forced modality, the user can't rotate the zoid before it passes a certain zone delimited by a line on the board. The idea behind this choice was to provide a game modality that forces the player to activate the mental rotation process by preventing what Kirsh and Maglio (1994) called epistemic rotational actions. The two modes are illustrated in Figure 5.9.

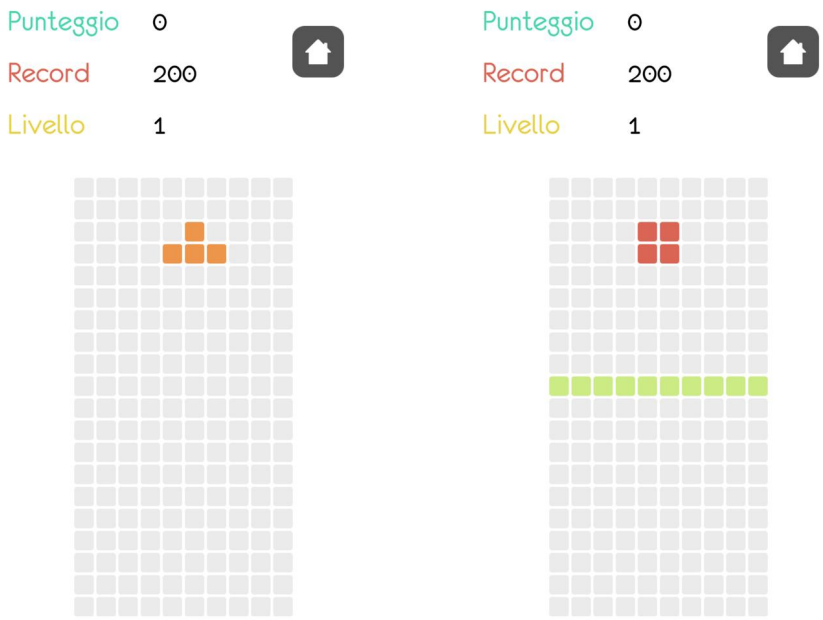

Figure 5.9: Classical and Forced game modes in Mental Jigsaw.

As stated in Gentile and Lieto (2022), the proposed computational model was validated on a significant amount of tasks. The results confirm the validity of the assumptions underlying the definition of the cognitive model, and in particular that in order to force the activation of the mental rotation process, it is necessary to operate on the game dynamics.

The key finding indicates that mental rotation is only triggered for zoid types with two similar versions, one being a reflection of the other. Our model suggests that mental rotation is necessary to prevent errors in the S/Z and J/L pairs, and is not involved in any other pairs. The study's results support the previous observations made by Kirsh and Maglio (1994) regarding human players' tendency to use rotation as an epistemic action to minimize cognitive load when solving a task under specific conditions. Our study shows that the model's significance in the forced game condition validates this hypothesis.

These results present intriguing opportunities to reconsider game activities to enhance their educational usefulness. Increasing the opportunities for the activation of the mental rotation process, therefore, represents a way for improving the effectiveness of the game as a training tool.

The study by Gentile and Lieto (2022), demonstrated that introducing the forced rotation mode by preventing the player from using rotations as epistemic actions would seem to succeed in forcing the mental rotation process in the player.

From this evidence, a second cycle of framework iteration (see Figure 5.10) has been started to how to increase the frequency of mental rotation activation by designing a new game mode.

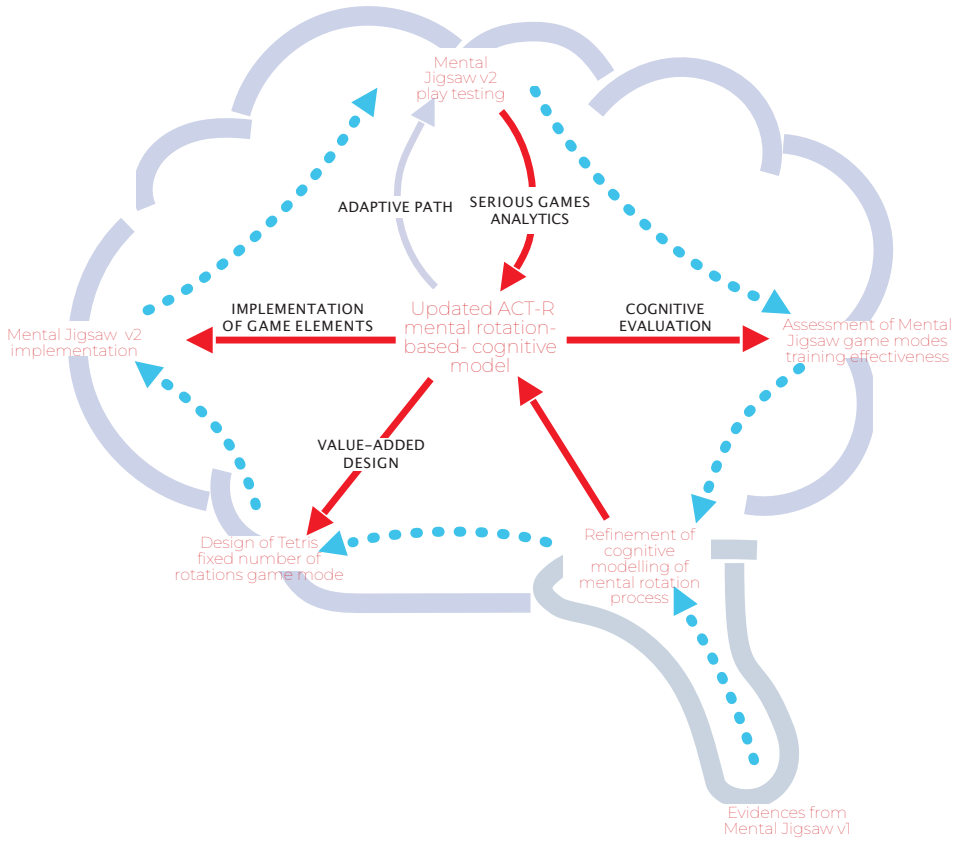

Figure 5.10: The second framework iteration in the Tetris case study.

In particular, it would appear from early simulation studies that further improvement could come from using a third mode in which, instead of blocking the possibility of rotation on a time basis, the total number of maximum rotations allowed for the individual piece is reduced. Specifically, by limiting to only two ro-

tations, the player is forced to mentally identify the final rotation configuration because any incorrect epistemic rotation operation could make it impossible to reach the optimal configuration. With a maximum of two rotations, the player must also decide the direction of rotation in order to arrive at the final configuration. To illustrate this, let us think of reaching 270° rotation. If the player would start rotating clockwise, this configuration would not be attainable with only two rotation operations; three would be needed. In this case, he would be forced to activate counterclockwise rotation.

The last step of this second cycle will be aimed to assess the efficiency of various game modes created through cognitive models for enhancing visuospatial abilities.

5.2 Towards cognitive-inspired persuasive games

The second case study regards the use of the proposed framework for the design and implementation of a persuasive game. Persuasive games (PGs) are games intentional design for promoting a behaviour change, or shaping and reinforcing a desired behaviour (Fogg, 2003; Ndulue, Oyebode, & Orji, 2020)

The modern theory of PGs was laid out by Bogost in his book "Persuasive Games" (Bogost, 2007). He argues that games are a form of procedural rhetoric, allowing users to experience persuasive messages through active participation.

In the last years, research in the field of PGs has shown a continuous increase in the development and application of persuasive games across various domains. Recently, Ndulue and Orji (2022) provide a systematic review of 130 PGs published since 2001. The authors found that most PGs focus on PCs and mobile platforms rather than game consoles. Nevertheless, there is a lack of studies comparing the effectiveness of the different delivery modalities. Moreover, the review highlights that in a few cases, longitudinal studies are carried out and that the majority of the evaluations of the PGs were realized within a short period, most likely for economic sustainability purposes. While PGs have been shown to be effective in the short term, long-term studies are needed to draw firm conclusions about their impact on behaviour.

The definition of frameworks for the design and implementation of this type of game is one of the most prominent research themes, which contributes to the pro-

liferation of research studies in this field. According to Ferrara (2013), to conceive an effective PG designers must take into account the following five criteria:

- defining a core message;
- linking the message to the strategy;
- enabling self-directed discovery;
- offering meaningful choices;
- keeping it real.

First, it is crucial to design a PG around a clear and concise statement of what you want players to do or believe. Moreover, it is crucial to embed the persuasive argument in the game by allowing the user to experience the message by implementing the strategy. Of course, it is important to give meaningful options to the users, which means making sure that even choices that are inconsistent with the intended message still give the player an advantage in some terms. To put it differently, a game in which the winning strategy is exclusively that of correct behaviour risks not being meaningful from a persuasive point of view. For this reason, it is important to be true to the complexity that is often inherent in the themes under consideration.

The analysis of the literature shows that various persuasive strategies and techniques could be implemented to foster persuasion in the games and achieve the intended behaviour change.

Having an insight into the theoretical possibilities to support these processes is important because, of course, there is no one persuasive strategy that fits every situation and every individual. The inclusion of behavioural theories assists researchers in understanding how to develop persuasive interventions based on the determinants that affect the behaviour of individuals of different personality types. Previous research has shown a variety of frameworks and models that specify persuasive strategies that could be employed in PG design. Persuasive Systems Design (PSD) (Oinas-Kukkonen & Harjumaa, 2009), the Fogg Behavioural Model (Fogg, 2003), the principles of persuasion proposed by Cialdini (2001), and the Behaviour Change Technique (BCT) Taxonomy (Michie et al., 2013) are among the most applied frameworks.

For the development of this case study, we relied on two different but interconnected theories coming from cognitive psychology, namely the Elaboration Likelihood Model (ELM) theory elaborated by Petty and Cacioppo (1986), and the dual process theory of reasoning elaborated by Kahneman (2011).

The ELM theory asserts that messages are processed through two distinct paths or routes: a peripheral route, where the processing relies on limited attention on surface-level elements (more likely triggering automatic and fast cognitive mechanisms not undergoing any deliberative control), and a central route, which involves more controlled, logical, and deliberate processing of information.

Similarly, dual process theories of reasoning propose that decision-making is governed by two cognitive systems known as system(s) 1 and system(s) 2, which interact with each other. System 1 (S1) operates using automatic, rapid and associative reasoning processes. It is phylogenetically older and performs tasks in a fast and parallel manner. In contrast, System 2 (S2) is evolutionarily newer and relies on controlled, conscious, sequential processes and logic-based rules. As a result, S2 processes are slower and require more cognitive effort compared to S1.

Our working hypothesis, based on these theories, was that persuasive strategies should activate heuristic-driven and fast processes (i.e., type 1) via the peripheral route of the ELM. Therefore, we have chosen persuasive strategies based on well-known rhetorical arguments and framing techniques.

These persuasive tactics are based on commonly known reasoning shortcuts and exploit the peripheral route (O'Keefe, 2013; Petty, Barden, & Wheeler, 2009; Petty & Briñol, 2011); they are thought to be processed automatically and bypass some forms of cognitive control that are used in the central route of information processing. Specifically, this study focuses on rhetorical arguments that use inferential schemas that may be informally invalid but appear plausible and psychologically persuasive (Lieto & Vernero, 2013, 2014). These types of arguments should not be considered irrational, as they can have heuristic value according to ecological approaches to rationality and cognition (Walton, 1998).

5.2.1 Cognitive modelling of a Persuasive Dialogue Game

In this section, we discuss the fundamental principles for the formalisation of the cognitive model for a persuasive agent acting in the game, presented in the research conducted in Augello et al. (2021). The model has been defined by exploiting ACT-R, and in particular its spreading activation mechanisms, which aid in the retrieval and activation of the rules that govern the interaction between a user and the persuasive agent (Lieto, 2021). This mechanism, relying on a narrative structure and an internal model of needs-actions, allows for the creation of non-deterministic behaviour. The utilization of these mechanisms enables us to design a flexible decision-making strategy that we incorporated into our agent.

Furthermore, by utilizing the underlying information processing mechanisms of the ACT-R architecture, we were able to anchor and constrain the model in a cognitively well-founded framework. Although this was not directly used for measuring human performance, it allowed us to reuse an already established framework for incorporating intelligent abilities and modules. This enabled the agent to independently manage its decision-making in a non-sequential narrative flow.

Our model draws inspiration from the *theory of planned behavior* (Ajzen, 1985). This theory suggests that the agent must gather information about the user's beliefs and attitudes to determine their intention and subsequently assess the appropriate persuasive strategy. As needed, the agent should employ argumentative examples to alter or reinforce the listener's intention.

The agent aims to achieve its persuasive goal by planning a series of related scenes based on its specific needs. The agent selects dialogue acts to carry out these scenes. This selection is done through an approach called the *Information State* (Traum & Larsson, 2003). The agent evaluates and updates information about the dialogue participants and the dialogue's state over time.

The *Information State* keeps track of various elements, including the user's knowledge level and intentions regarding the conversation's main and subtopics. The current needs of the agent, the current scene (identifying a specific topic or conversational phase), and the previous scene are also monitored.

The participants' actions and a set of updating rules are used to update the *Information State*, which takes into account the effects of the interlocutors' actions.

As a result, the agent's behaviour is affected by the conversation's context and the information needs that arise from the information state. This enables the agent to maintain a balance between conversational norms and its personality. Figure 5.11 outlines the reasoning process of the agent.

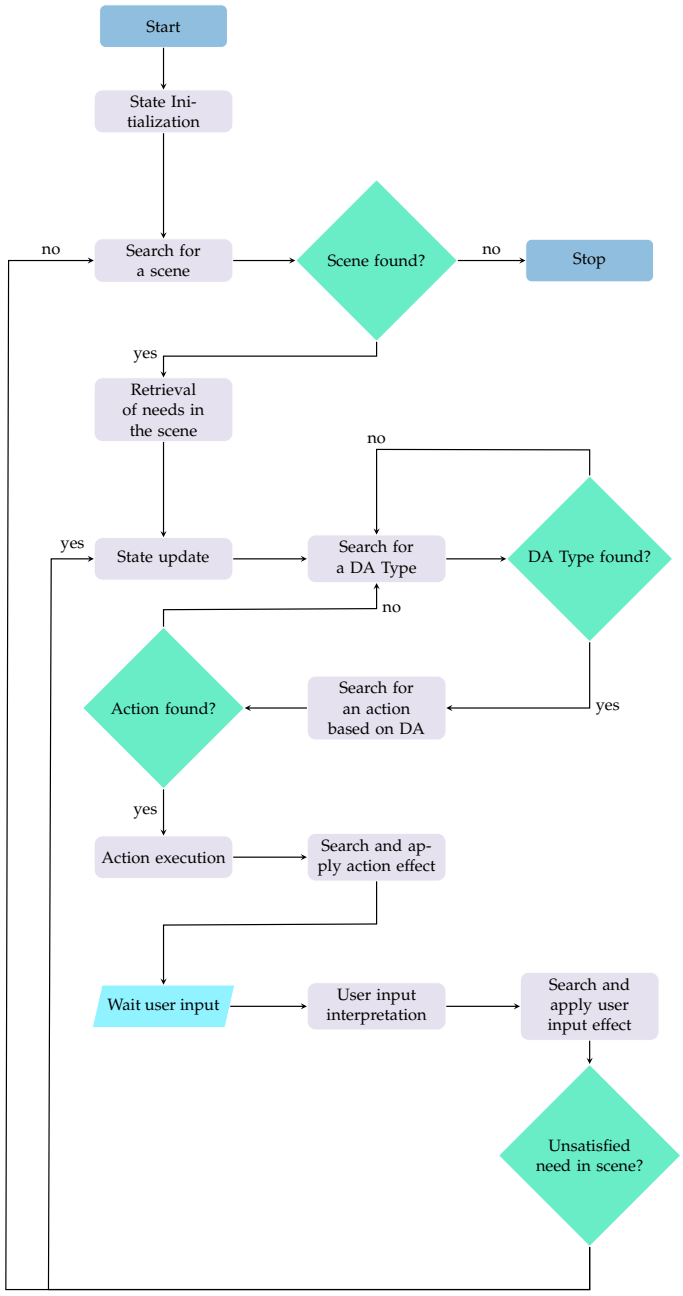

Figure 5.11: Flow of the agent's reasoning process.

Figure 5.12 illustrates how the agent utilizes various modules of ACT-R to handle conversational practice.

The agent analyses the input and produces an output by using respectively the Aural and Speech modules and their respective buffers and by interacting with the user through a graphical user interface (GUI) interface. The agent exploits two ACT-R types of memory: declarative and procedural. The first manages the creation and storage of *chunks*, which, as previously discussed, are atomic pieces of knowledge. The latter manages knowledge about conversational practices and the personality of the character, including ethical profiles and needs. The imaginal module and its buffer are used by the agent as a short-term memory to manage all elaborations. The procedural module processes and interprets user input and is responsible for planning conversations by elaborating rules according to the Information State. It also updates the Information State.

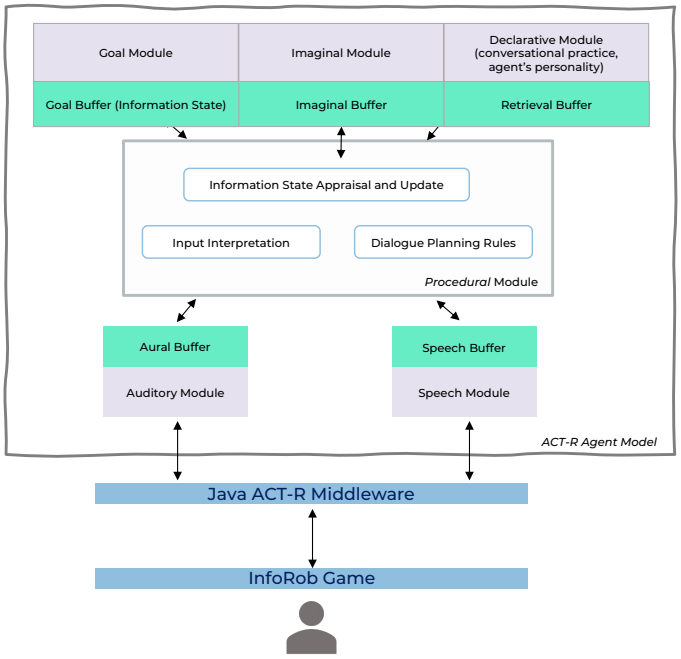

Figure 5.12: ACT-R based Architecture of the persuasive agent.

Needs and Dialogue Acts deserve a more detailed description as they represent the main chunks of information characterizing the Information State.

Needs

The model, by taking inspiration from the concept of motivated cognition (Bach, 2009), includes a motivational component consisting of a set of needs. The *needs*

drive the agent's dialogue acts when they are not met, with the aim of reducing the gap between their expected and current value. The emergence of the agent's needs is triggered by different phases of the dialogue, and these needs can be satisfied by performing various dialogue acts. These acts correspond to different scenes in the dialogue.

We have considered four types of needs: social, cognitive, narrative and argumentative. The social needs represent the agent's desire to interact with others and fulfil social responsibilities. Specifically, we have identified a*social affiliation need* within this category, which arises at the beginning of each conversation when the agent must greet the user and introduce itself. Once this need is met, cognitive needs arise as the agent must gather information about the user. When the agent detects that the user's intent is weak, a *argumentation need* is triggered leading the agent to exploit persuasive arguments that can increase the intent value. Additionally, the agent also has a *climax need* to maintain the user's engagement by following a narrative structure that leads to a climax-based situation, as explained in section 5.2.1.

In addition, we have recognized an additional requirement that pertains to the ethical behaviour of the agent while engaging in a conversation. This requirement is influenced by Virtue Ethics and Virtue Argumentation Theory (VAT) as described in(Aberdein, 2010).

The VAT framework proposes an approach to argumentation that emphasizes the virtues of the arguer, including his/her attitudes and conduct (Gascón, 2016) [3].

We refer to this requirement as *open mindedness* need, since it reflects the agent's willingness to have an open mind toward the user's perspective, even if including ideas and opinions that may differ from its own. This need is an indicator of the agent's ethical readiness, and unlike the other needs, it may only arise during di-

[3]Gascón (Gascón, 2018) proposes two categories of virtues that pertain to argumentation: reliabilist virtues and responsibilist virtues. Reliabilist virtues are related to the arguer's skills, while responsibilist virtues are related to their attitude, character, behavior, and habits. In this perspective, a good arguer beside being able to present persuasive arguments should also possess traits such as open mindedness, willing to subject their beliefs to rational criticism, and respectful of other perspectives. These virtues are part of an argumentative ethical system that provides a conceptual framework for studying argumentation as a social practice instead of a fixed set of rules (Aberdein, 2010). Open-mindedness is considered the "critical virtue" of the arguer within this system, according to the Aristotelian viewpoint(Kwong, 2016). It is considered as the ability to listen attentively, take other people's opinions seriously, and be willing to adopt them if necessary (Cohen, 2009)

alogue if the agent has been configured with this ethical profile at the outset and may only emerge in a situation characterised by a conflict of opinions.

Dialogue Acts

In this section, we describe the dialogue acts that can be used by the agent to pursue its needs. The dialogue acts represent the communicative functions associated with each action in a dialogue between the agent and the user. They have been named and defined according to the ISO 24617-2 standard for dialogue annotation (Bunt, 2019). The choice of each act depends on the current needs of the agent. For example, if the *argumentation need* is high and therefore the agent needs to argue a topic, it will activate one of the persuasive arguments presented and use the corresponding dialogue act. Similarly, some acts allow the agent to fulfil its *social affiliation need*. For example, by choosing at the beginning of the dialogue an act that combines "Initial Greeting" and "Initial Self-Introduction" communicative functions to perform a socially compliant self-introduction to the interlocutor. Similarly, it will choose a "Goodbye" communicative act at the end of the dialogue.

Some acts serve a general purpose, like giving information to the users (*informative acts*) or requesting information from them (*question acts*). The *informative acts* have been categorized in more detail. An *inform* act has been introduced to allow the agent to provide information about a topic when the user's knowledge about a topic is low. This could involve providing basic facts, definitions, or explanations to help the user understand the topic better. The goal of this act is to increase the user's knowledge and understanding of the topic.

A *reinforce* act allows the agent to provide additional information about a topic when the user's knowledge about the topic is moderate. In this case, the user may already have some familiarity with the topic, but the agent provides additional information to help reinforce their understanding.

Finally, an *argument* act, can be exploited by the agent to argue or present a particular point of view with regard to a topic when the user's intention towards that topic is low. This could involve presenting reasons, evidence, or examples to support a particular opinion, or engaging in a debate with the user to persuade them to adopt a particular viewpoint. The goal of this act is to influence the user's

perception of the topic and shape their attitudes towards it. These dialogue acts, implemented to satisfy *the argumentation need*, can rely on different persuasive techniques (e.g. ad verecundiam, framing, or ad populum).

Overall, these three types of dialogue acts reflect different strategies that agents might use to engage in effective communication with users, depending on the user's level of knowledge and their intention towards the topic.

To strengthen the persuasive effect of the conversation, the agent can create a *climax* to present potential alternatives to the listener during a crucial moment. It employs a role-playing technique to achieve this goal, encouraging the listener to imagine themselves as someone facing a particular condition that makes it difficult to follow certain rules. *Exception* and *substitution* actions are introduced to fulfil a *climax need* leading to presentation and management of conflicting scenarios.

The former refers to how an agent can use a particular method to assign a role to the listener, which will make an exception for an argument put forth by the agent, denoted as $arg1$. By doing so, the agent creates a circumstance denoted as $cond$, in which the argument made by $arg1$ is not applicable.

The latter is exploited by the agent to handle a situation of conflict by substituting the argument $arg1$ with an alternative argument, $arg2$, which is compatible with the user's condition, $cond$. This alternative argument provides a possible solution to the argument, taking into consideration the user's condition. However, the agent will only consider this alternative if it has an ethical profile that is open-minded, as defined previously.

5.2.2 The COVID19 scenario

The ACT-R cognitive model has been defined as the basis for a persuasive dialogue game.

In particular, the model allowed the definition of an agent able to dynamically manage the dialogue practices dealing with narrative and persuasive strategies about the controversial topic of COVID-19 (Augello et al., 2021).

The objective of the conversational game was to assess how persuasive and narrative techniques, applied in diverse ethical contexts, can aid in promoting compliance with COVID-19 regulations and increasing people's readiness to receive the

vaccine. Figure 5.13 shows a screenshot of the game environment[4].

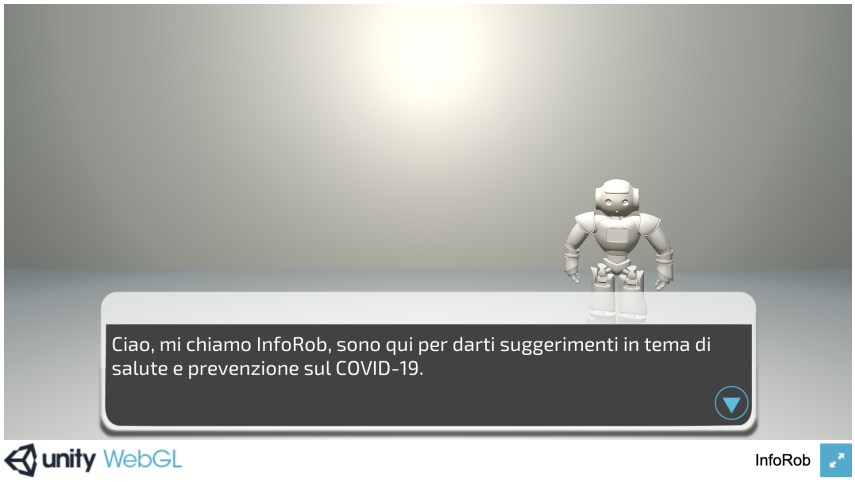

Figure 5.13: A screenshot of the InfoRob system.

We selected specific topics that could be used in COVID-19 conversation, such as contagion, washing of hands, mask usage and social distancing. Additionally, we included introductive and conclusive scenes.

The ACT-R model relies on the needs emerging during the conversation, which prompt the agent to follow a particular flow of reasoning, which is illustrated in Figure 5.11. The conversation progresses based on the user's choices and the agent's ethical profile. Figure 5.15 provides a comprehensive example of a dialogue that evolves from a set of unmet needs that arise during the interaction and the corresponding actions of the agent. As discussed in Section 5.2.1, the agent will choose a dialogue act based on its needs.

Such a *needs-driven* model drives and assesses the exploitation of persuasive methods stored in the agent's procedural memory. The range of persuasive techniques examined in this model includes storytelling, framing techniques, and arguments based on rhetoric.

Figure 5.14 shows the application of the proposed framework to this case study. In Augello et al. (2021), the exploratory evaluation of the system is reported. The study's results confirmed that using a storytelling strategy in the dialogue enforces the persuasive strength of the dialogue. Nevertheless, adopting ethical principles during the dialogue increases persuasion effectiveness.

[4]The screenshot shows the agent greeting the user: "Hello, my name is InfoRob, and I am here to give you suggestions concerning health and prevention issues on the topic of COVID-19".

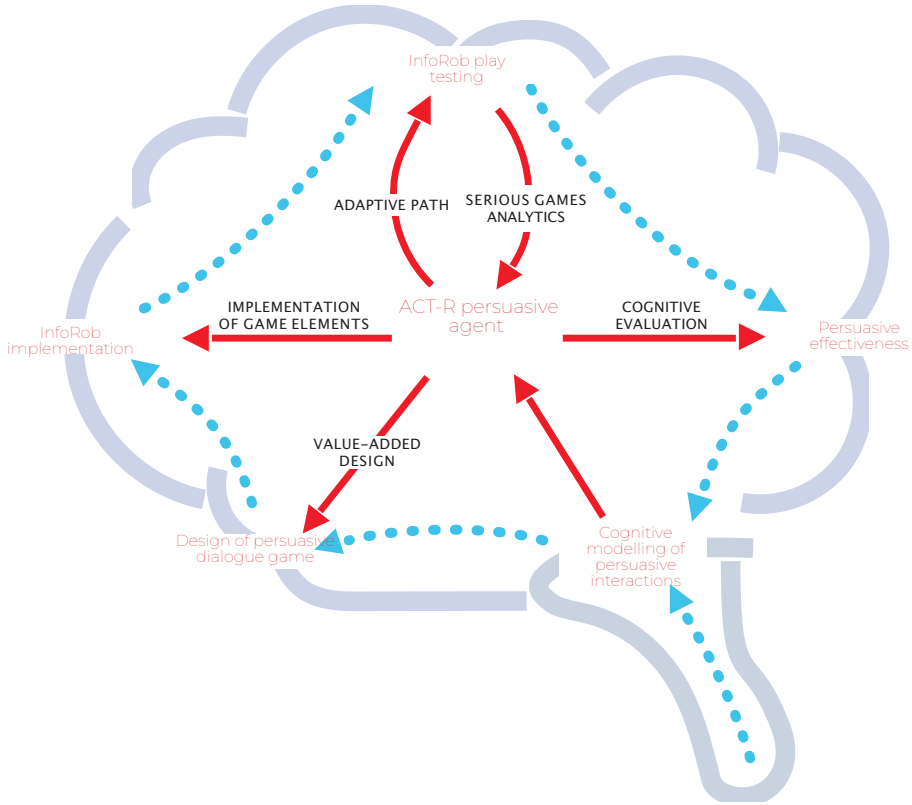

Figure 5.14: Framework application in the Persuasive Dialogue Game case study.

To the best of our knowledge, this represents the first attempt at building a persuasive agent able to integrate a mix of explicitly grounded cognitive assumptions about dialogue management, storytelling and persuasive techniques as well as ethical attitudes.

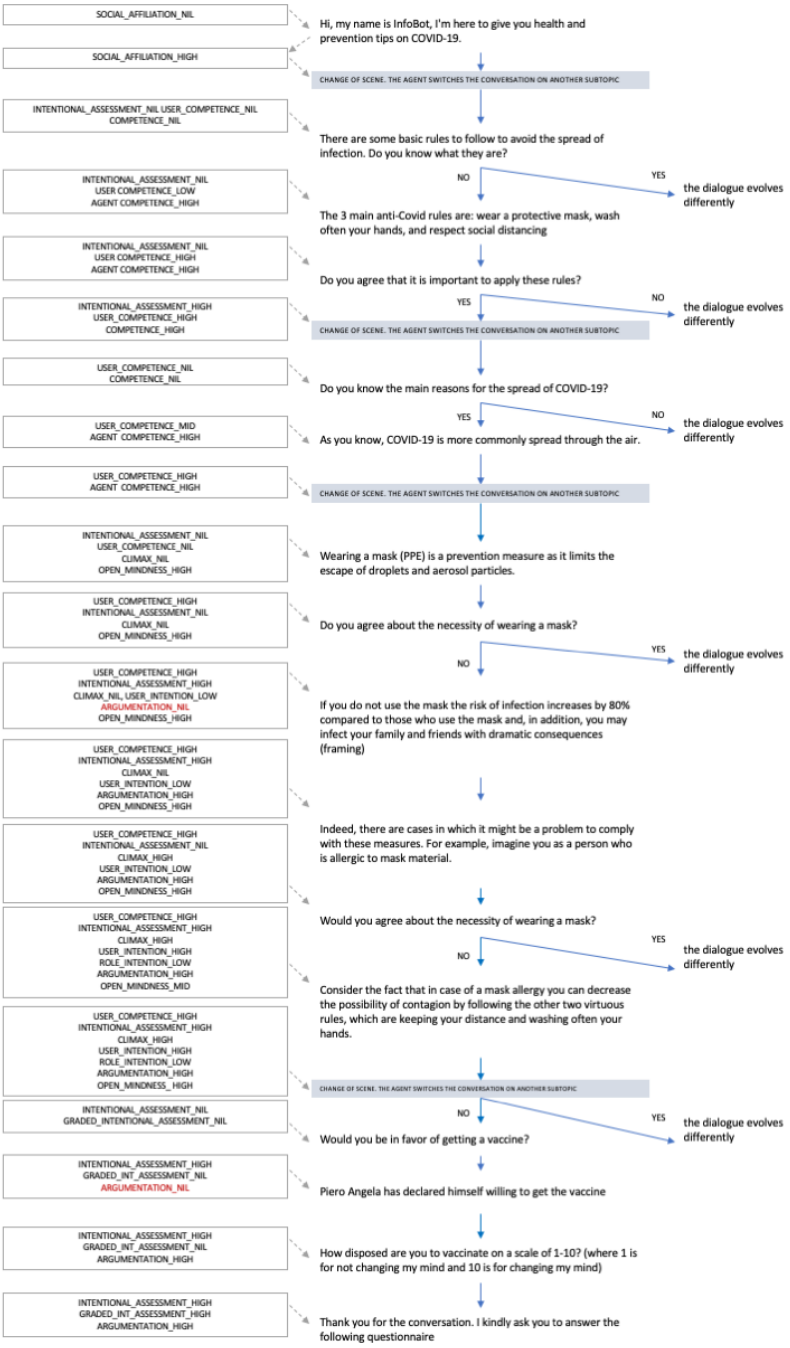

Figure 5.15: An example of a persuasive dialogue evolution.

6 Conclusions

This dissertation summarises a research path aimed at contributing to SG research by employing CAs, a well-known and extensively studied area of AI that deals with analysing and modelling cognitive processes.

To provide the reader with a comprehensive overview of the topic addressed in the thesis, the SG and the CA research areas are first analysed separately in chapter 2, and then jointly in chapter 3.

The conflicting evidence about the effectiveness of game-based learning activities and the difficulty in identifying well-founded theoretical design frameworks confirmed the lack of maturity of SG research.

The initial idea of this research of using CAs and the computational cognitive models that can be realised with them to enhance both the design process and the assessment finds confirmation in the pragmatic approaches proposed by several authors (Kim & Ifenthaler, 2019; Mayer, 2019). In particular, the literature highlights the need for embedded assessment tools in games that can evaluate the effectiveness of games on a cognitive basis also providing results that can also be interpreted from a design perspective.

The joint analysis in chapter 3 represents a fundamental step in constructing a solid and theoretical framework well-founded framework. The systematic analysis of the use of CAs in the broad field of games reveals a fragmented area in which the adoption of CAs seems to be limited to research in the cognitive sciences sector. The literature on this topic outlines a picture in which research has mainly moved to respond to the research programme launched by Newell (1973) and subsequently raised by other authors such as W. D. Gray (2017). The vast majority of work in this area focuses exclusively on using games as a testing ground to validate hypotheses and theories regarding specific cognitive processes. Specifically, the research field is polarised towards the two architectures described in section

2.2, ACT-R and Soar. ACT-R is mainly used in the context of the so-defined cognitive games, which are often nothing more than a simple digital transposition of mental tasks defined in the cognitive sciences field. On the other hand, case studies that use Soar refer to types of action games involving dynamic real-time interactions and spatial exploration, thus moving within the research thread outlined by Newell (1973). The works in which CAs are used as support tools for game implementation are residual, especially when compared with the enormous interest that other AI technologies, such as those related to machine learning and deep learning, are registering. Finally, in very few cases, CAs are exploited to support the game design process.

Nevertheless, the initial motivations for this research path remain valid. The difficulties of integrating CA into the systems used for game development (i.e., game engines such as Unity3D or Unreal) appear less relevant in the field of SGs, where the greater complexity of CA adoption is balanced by the potential benefit that their use could provide.

Through the analysis of the limits of research in the field of SGs, and the simultaneous systematic exploration of the uses of CA in the broad field of games found in the literature, we have thus arrived at the formalization of a methodology aimed at guiding designers, researchers, and experts in the SG sector in the design, implementation, and evaluation of SGs through a well-founded theoretical approach guided by the exploration of cognitive processes.

Chapter 4 presents this theoretical framework in detail by proposing a cyclical design, implementation, testing and evaluation process of cognitive-grounded games. For each of the different phases under this approach, the framework illustrates a practical use of the cognitive models resulting from the cognitive modelling phase. The introduction of this phase as the starting point of the process formalises the moment of choosing the cognitive objectives and implementing the computational models that enable their identification and elicitation in the game activities. It represents the essential stage in designing, implementing and evaluating a serious game.

The case studies presented in chapter 5 represent a first attempt at empirically validating the proposed framework in two very different areas.

In the first case study, the framework was used to implement a version of Tetris, aimed at improving the game's effectiveness in training the visual-spatial ability of mental rotation. In the second case, the framework was used to guide the design of a new persuasive serious game. This case study assessed the advantages of CAs in the implementation of NPCs whose human-like behaviour is generated based on specific cognitive theories.

For the sake of completeness, I would like to highlight that the assessment of the effectiveness of new Tetris gameplay modes, designed by means of the framework, is ongoing and involves experimenting with approximately 160 students from a lower secondary school. Once the training potential of the different modes has been verified, a new version of the cognitive model will be defined as the basis for creating a new game mode capable of integrating all the different versions into an adaptive path. Indeed, it remains essential to ensure a progressive development that considers the individual player's needs and produces a pleasant and non-frustrating gaming experience.

The results of the second case study will instead be used for implementing a serious game with a goal other than persuasion, namely the training of argumentation skills.

Other opportunities to empirically validating the proposed framework involve applying it to enhance the assessment of other Serious Games developed within the scope of my work at the National Research Council of Italy, among which the case study of uManager (Gentile et al., 2016; Gentile, Città, et al., 2019) is noteworthy. In the uManager case, we are adopting the proposed framework to analyse decision-making and problem-solving processes in the context of entrepreneurial education.

However, full validation of the proposed model necessarily requires sharing and comparison with the research community it addresses. Specifically, as extensively stated in the course of the thesis, the invitation is addressed not only to researchers in the field of educational games but also to those experts in the computational cognitive sciences who see games as a possible field of experimentation.

By initiating the process of validating the proposed framework employing qualitative analysis techniques (e.g. Delphi method, focus groups, or nominal group technique), the aim is to contribute to the creation of an open space for discussion

among experts in the field, which will provide a solid scientific basis for a research area - that of educational games - that is still not fully mature.

It is hoped that the ideas put forward in this thesis will go a long way towards establishing a solid research foundation for the Serious Games field.

A Appendix

A.1 Mental Jigsaw

Mental Jigsaw is a mobile application, available for download on major app stores[1]. A screenshot of the app can be seen in Figure A.1. The Unity3D game engine was utilized to create a mobile game. Thus, touch interaction was employed to execute the translation, rotation, and drop game mechanics. The user can move the *zoid* by dragging it. The rotation can be achieved by tapping on the screen to the right or left of it, resulting in clockwise or anticlockwise rotation, respectively. Lastly, a drop is triggered by tapping the bottom of the screen.

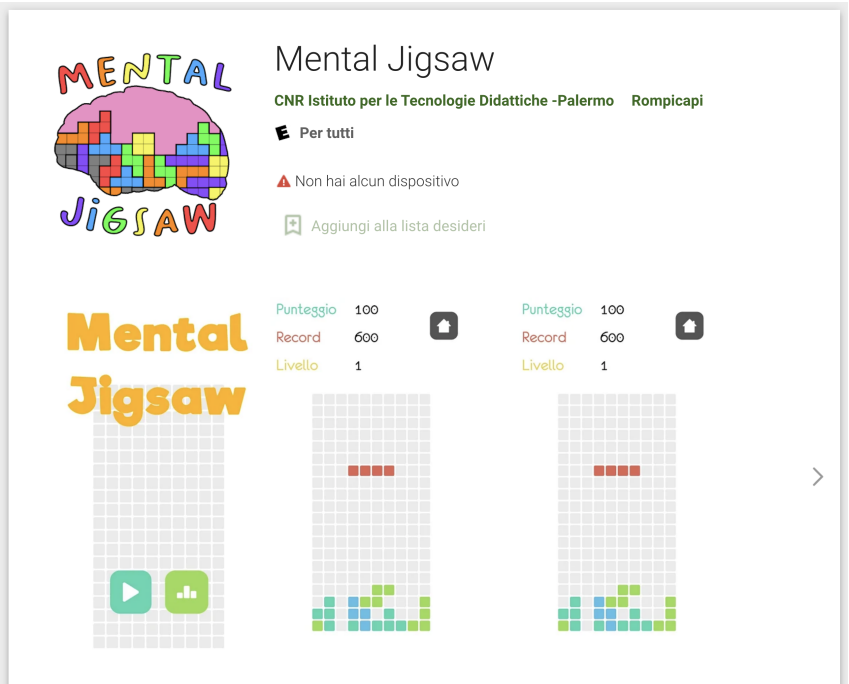

Figure A.1: The MentalJigsaw web pages on Google Play Store.

[1]Google Play Store - https://play.google.com/store/apps/details?id=it.cnr.itd.pa.MentalJigsaw&hl=it&gl=US
Apple Store - https://apps.apple.com/us/app/mental-jigsaw/id1524501681

The game was developed following the suggestions provided by W. D. Gray (2017). One notable feature is its server-side backend, which enables the management of key game parameters such as drop speed and level progression rules. Additionally, the game stores every user's actions as learning analytics. Every action is anonymously recorded along with its timestamp with a unique identifier for linking the data to the corresponding player.

Another unique feature of Mental Jigsaw is its ability to adjust the game dynamics in real-time to constrain human behaviour. This possibility was included in accordance with the value-added research approach proposed by Mayer (2019).

For this purpose, Mental Jigsaw has been adapted to become a training tool and has been equipped with the tools to assess mental rotation ability.

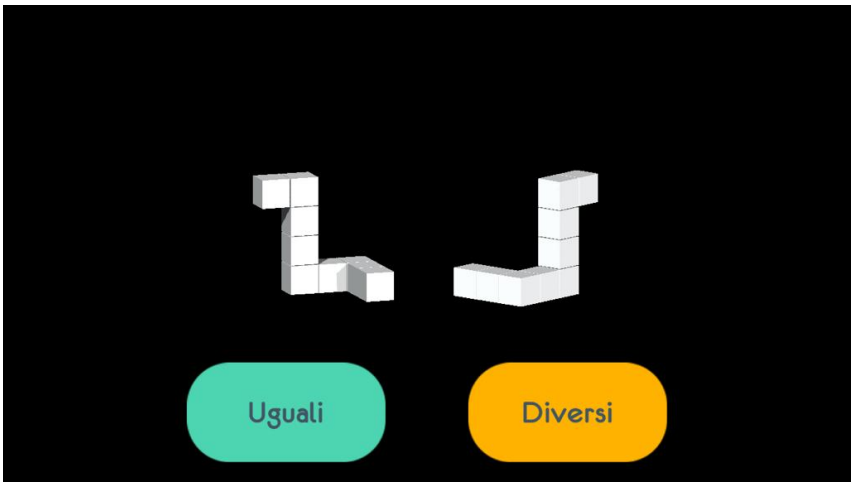

Figure A.2: The mental rotation test in Mental Jigsaw.

According to a server-side setting, the app prompts players to participate in the research by completing the mental rotation test if they are willing to do so. We utilized the mental rotation stimuli suggested by Ganis and Kievit (2015) to carry out the Mental Jigsaw test. Ganis and Kievit (2015) created 384 stimuli with varied angular differences, using a pool of 48 three-dimensional objects and minimizing self-occlusion at all angle. Figure A.2 depicts an example stimulus presented to the user. The stimuli, as in (Shepard & Metzler, 1971) study, typically consist of a pair of three-dimensional objects, with the baseline object on the left and the target object on the right.

A.2 InfoRob

The ACT-R model presented in section 5.2 has been implemented in a system we named InfoRob, which is accessible through the GUI interface shown in Figure 5.13. The system integrates the ACT-R cognitive architecture and the Unity3d engine. The behaviour of the virtual agent is controlled via the ACT-R model presented in section 5.2.1.

The agent was implemented by connecting the Unity 3D engine with ACT-R. To this end, we implemented communication middleware through a WebSocket, which is responsible for starting and monitoring the conversation and managing the logging. The WebSocket has been realized in Java language and exploits a Java porting of ACT-R's Python interface. The ACT-R model used for this work is available at `https://github.com/manuelgentile/inforob`.

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