

MASARYK UNIVERSITY

FACULTY OF ARTS

VIRTUAL SIMULATIONS IN  
PSYCHOLOGY

EVALUATING CURRENT TRENDS OF IMMERSIVE  
VIRTUAL SIMULATIONS USE IN PSYCHOLOGICAL  
RESEARCH AND FOLLOW-UP APPLICATIONS

HABILITATION THESIS

BY VOJTĚCH JUŘÍK

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Faculty of Arts

# Virtual Simulations in Psychology

Evaluating Current Trends of Immersive Virtual  
Simulations Use in Psychological Research and  
Follow-up Applications

Habilitation thesis

Mgr. Vojtěch Juřík, Ph.D.

Brno, 2025

## Declaration

Hereby, I declare that I worked on this work alone and independently, using only sources listed in the reference list. Parts of this work have been upgraded with AI technologies (Grammarly, ChatGPT) regarding language fluency and style.

.....

Mgr. Vojtěch Juřík, Ph.D.



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## Abstract

Immersive virtual reality rapidly advances across disciplines, uncovering new applications in various domains. In psychology, immersive virtual simulations aspire to become integral to research methodologies and practical applications, offering significant potential for creating ecologically valid yet controlled and safe environments for experimentation and practical use.

This work aims to research the concept of human-centered simulation in psychology, resulting in the suggestion and adoption of immersive virtual simulation as a technology advancing psychological research and application. To support this idea, several specific applications of immersive virtual reality, which have been conducted and published within the author's up-to-date research practice, are introduced and critically evaluated. The methods employed involve theoretical analysis and synthesis, which is further narrowed into a critical reassessment of the existing empirical evidence provided by the author of this thesis and his colleagues in the immersive virtual reality field. As a result, original statistical procedures applied in human evacuation spatiotemporal movement analysis are demonstrated to promote potential interconnections between virtual simulations and the machine learning domain. This part of the thesis, stemming from the broad theoretical discussion and empirical evidence, represents a novel finding, showcasing data processing from immersive virtual simulations with potential applications in agent-based modeling.

In summary, this work presents novel findings in several aspects: (1) it creates a theoretical framework for human-centered simulations, including immersive virtual simulations; (2) on a theoretical level considering simulations, it connects current cognitive psychology perspectives with human interactions with the environment; (3) it establishes a basis for using virtual simulations as a foundation for effective, safe, controlled and ecologically valid research and application in psychology; (4) it summarizes and critically comments on several of the author's studies on the use of virtual reality within psychological research and applications to reassess follow-up directions of the research; and finally (5) it demonstrates new research insights in the field of evacuation modeling by linking the field of virtual simulations and agent-based modeling considering the human-in-the-loop principle.

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## Part I – Theoretical Background

## On Simulations

Simulations, a reproduction of a setting and issues typical of some context or situation, significantly enhance human lives by providing advanced tools to predict and analyze a wide range of phenomena in our world. *Simulation* is defined as imitating a real thing or process (Gallagher, 2011; Hees, 1972; Rybing, 2018). Simulations are commonly used for training, evaluating performance, and forecasting future results (Landriscina, 2013). As a versatile tool, they are employed across a wide range of fields, enabling the exploration of scenarios that would otherwise be too costly, impractical, or unethical to investigate directly. Therefore, simulation is used in many different contexts, including modeling natural or human systems, primarily to gain insight into their functioning, often in an attempt to predict the outcome of specific processes. The main applications are testing systems, demonstrations, training skills, and education. In agriculture, simulations forecast crop yields and optimize planting strategies, while in neuroscience, they facilitate a detailed understanding of brain cell activation under various conditions. Environmental science uses simulations to predict the effects of climate change on ecosystems, aiding policymakers in developing informed conservation strategies. Similarly, simulations of cellular processes contribute to drug development and disease treatment in the medical field, allowing for tailored therapies based on personalized models of patients' biology, including psychotherapy. Urban planning also benefits from simulations by enhancing city and building layouts, thereby improving traffic management and disaster

response strategies, such as evacuation processes (Snopková, 2023), as we will see later in this thesis.

Beyond these applications, simulations are integral in fields like economics, sociology, political science, and psychology, where they model natural or human systems to depict the effects of various conditions and factors. These models are particularly valuable when direct observation of the actual system is unavailable or impractical. The challenge in creating these models lies in obtaining accurate information about key characteristics and behaviors and making necessary simplifications and assumptions. Ultimately, simulations serve as a powerful problem-solving tool across disciplines, providing a dynamic environment for analysis, experimentation, and decision-making, especially where complex systems involve nonlinear relationships or unclear dynamics, making predicting outcomes difficult. This wide-ranging utility demonstrates the practical applications of simulations and underscores their critical role in enhancing decision-making and fostering innovation in our rapidly changing and challenging world.

Keeping this in mind, it is crucial to distinguish the dual aspect of simulations, encompassing both *simulation technology* and *simulation science*. The former involves employing simulations to address real-world challenges, as outlined above, while the latter focuses on studying the simulations themselves (Rybing, 2018). Before I address virtual reality as a simulation technology suitable for resolving various issues in psychology research and application, where specific examples are presented in the second part of this thesis, perspectives of

*simulation science* will be discussed in the theoretical part. Specifically, various types of human-centered simulations (i.e., those including a human as an active agent within the simulation) are closely introduced and discussed to set a solid framework for the discipline of psychology.

## Definition of the Simulation

Simulation broadly involves the imitation of real phenomena, states, or processes. The online Merriam-Webster's dictionary defines simulation as "the imitative representation of the functioning of one system or process employing the functioning of another", but also as the "examination of a problem often not subject to direct experimentation by means of a simulating device" (Merriam-Webster, n.d.). The act of simulation, and here, lets us understand simulation in its broader context, thus generally representing key features or processes of a selected physical or abstract system. From the definition, the simulation is a temporally defined imitation of the operation of a specific process or system from the real world (Banks, 1999). According to Banks, simulation involves generating an "artificial" (meaning artificially generated) history of system states with the possibility of analyzing this artificial history. Such analysis aims to conclude the operational characteristics of the real system represented in the simulation. In Banks' conception, simulation is perceived as a methodology for solving real-world problems and describing and analyzing system behavior. Here, the simulation helps us understand connections when we pose a "what if" question regarding a real system while also aiding in the design of real systems because simulations can model both

existing and conceptual systems. According to Banks (1999), it is a pragmatic approach that responds to real needs.

## Simulation and Models

The term *simulation* is sometimes interchanged with the term *model*. From a scientific perspective, models are abstract representations of reality or systems used to describe, explore, or predict a system's behavior, properties, or interactions. Its purpose is usually to determine or predict the system's behavior under different conditions. Therefore, like simulations, models are often created to understand complex phenomena better and develop hypotheses or theories. The model usually serves as a simplified representation of reality. Since scientific models are representations of simplified explanations, they do not aim to account for every situation or detail. Consequently, scientific models often do not perfectly match the 'real world' from which they are derived. It is an abstraction that focuses on the key elements or characteristics of the system under study while neglecting details and complexities that are not essential for the given purpose. This simplification of reality is necessary to create a usable model that is more easily interpretable and allows for analyses and experiments with sufficient efficiency.

Models are an integral part of scientific research and help us understand and interpret complex processes and phenomena in the world around us. According to Shannon (1975), simulation involves designing a model of a real system and experimenting within this model to understand the behavior of the system or to evaluate the effectiveness of different strategies for system

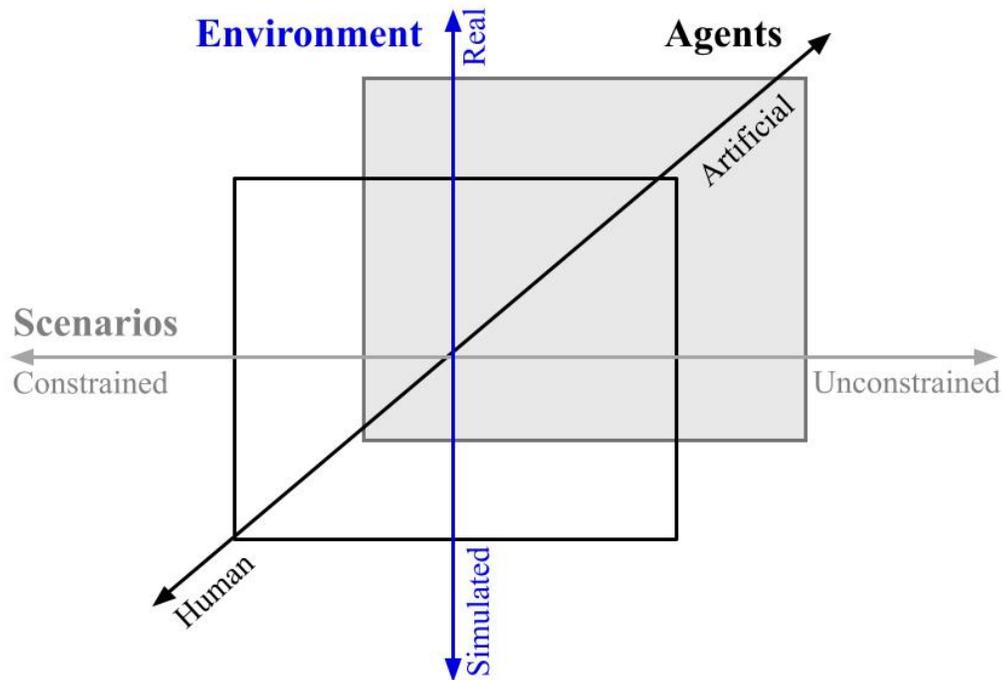
operation. However, most models, including highly performant optimization models, cannot account for the dynamics of the real system. Therefore, Ingalls (2011) corrects that simulation is the process of designing a dynamic model of a real dynamic system to understand the system's behavior or evaluate different strategies (within the constraints of a given criterion or set of criteria) for system operation.

However, we also encounter definitions that clearly distinguish between the terms model and simulation, where models are considered structures within which simulations or experiments can be performed without manipulating the real system (Boyer-Kassem, 2014). Here, the model represents the key characteristics and behavior of the selected system or process, while the simulation represents the evolution of the model's states over time. Thus, simulation can be defined as experimentation using a model.

The terms "simulation" and "model" are sometimes misunderstood in some domains. Common misconceptions include the belief that using a model or simulation means there is strict control and no need for testing in real-world conditions, that a model must always represent people or, for example, traffic scenarios, and that concrete, testable research questions cannot be addressed without both a model or simulation and real-world testing (Janssen et al., 2020). Therefore, Janssen and colleagues (2020) suggested a model (despite primarily being applicable in driving simulation research) where simulations can happen along three dimensions: agents, environments, and scenarios. Figure 1 demonstrates this concept.

**Figure 1**

*Three dimensions of simulation*



*Note.* Adapted from Janssen et al. (2020).

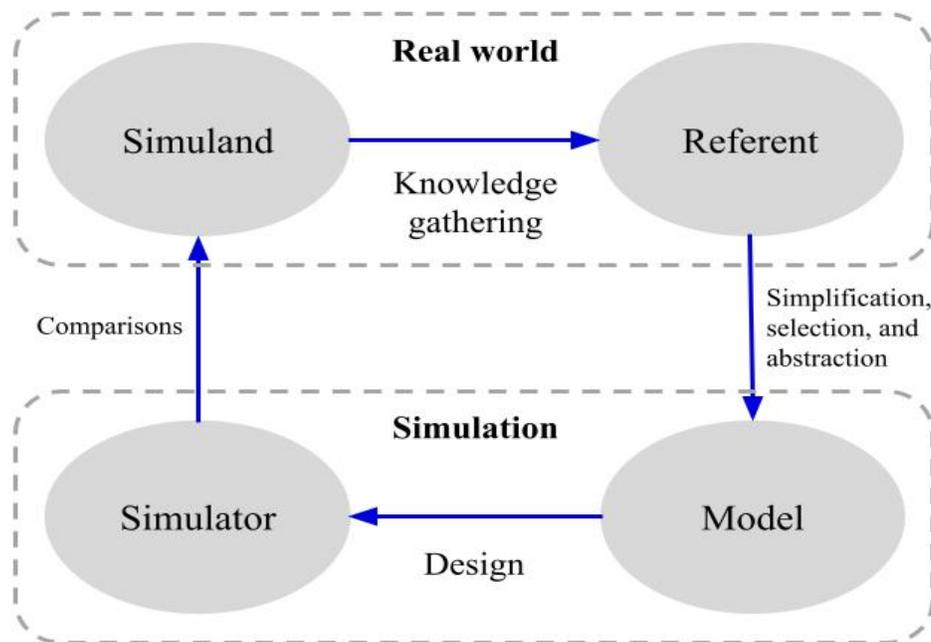
Within each dimension highlighted, various styles and approaches to simulation and modeling exist. These approaches vary in how accurately they replicate the agent's performance, the environment, or the simulation scenario. The framework allows researchers to categorize and contrast their chosen methods and tools against existing studies and pinpoint potential areas where further research could progress.

## Simulation Components

Regarding those mentioned above, it may be challenging to pinpoint a precise definition of simulation, as the existing literature offers many interpretations. This section will break down simulation into four key theoretical components described by Rybing (2018): simulands, referents, models, and simulators. Figure 2 shows the interconnections between these components, and the text will elaborate on these relationships as the discussion of each concept unfolds.

**Figure 2**

*Central concepts of simulation*



*Note.* Adapted from Rybing (2018).

According to Rybing (2018), *simulands* and *referents* are foundational concepts in simulation, representing the real-world entities we aim to simulate—ranging from physical objects like airplanes or patients to processes and phenomena such as patient flows in hospitals or weather patterns—and the knowledge we have about these entities, respectively. This knowledge blends quantitative data, like physics formulas, with qualitative insights, like scientific theories. In simulation theory, a model serves as a simplified, abstract representation of reality, aiding in understanding the simuland and employed across various scientific disciplines to convey and analyze information. Unlike scientific theories, which seek to reflect actual reality in its complexity, models prioritize simplicity, allowing applicability to a wide range of situations at the expense of their correctness. George E. P. Box encapsulates this notion with his renowned aphorism, "All models are wrong, but some are useful." *Simulators*, the apparatuses or software that execute these models to create simulations, can range from hardware and software in computer-based simulations to human groups in role-play scenarios. Defining *simulation*, however, remains complex due to its diverse applications and conceptualizations, which can focus on the simulation's purpose, operational method, or comparative value to traditional experiments, reflecting the broad spectrum of perspectives on simulation in academic and practical contexts.

## Aims of this Thesis

Technological integration has precipitated profound advancements and transformations in the dynamic and continuously evolving discipline of

psychology. On the one hand, various modern technologies are becoming an inertial part of people's lives, and as such, they should be studied; on the other hand, they offer great potential for overcoming various theoretical and methodological issues that have plagued psychology for years. Next to currently widely discussed artificial intelligence, one of the most visible technologies emerging, especially within the last decade, is *virtual reality* (Jerald, 2015), usually called VR. VR has the power to introduce humans into artificial, computer-generated environments providing a unique world of alternative rules and experience (Jerald, 2015). Since such environments are designed to be interactive, they create unprecedented space for conducting *virtual simulations*, a specific type of *human-centered simulations* (as defined by Rybing, 2018), whose purpose and eventual implications may significantly vary from basic experimental research to highly specialized military training. *Virtual simulation*, a standout among technological innovations, has emerged as a pivotal tool, revolutionizing theoretical frameworks and practical applications within the field. In the context of psychological research, *virtual simulations* present a controlled yet highly adaptable environment wherein theoretical models can be rigorously tested, and human behavior can reliably be observed under a spectrum of simulated yet valid conditions (Juřík et al., 2019; Juřík et al., 2021; Loomis et al., 1999; Ugwitz et al., 2019). This methodological approach may deepen our comprehension of intricate psychological phenomena and enhance the practical application of psychological theories to complex real-world scenarios. Spanning various sub-disciplines from cognitive behavioral therapy and social psychology to

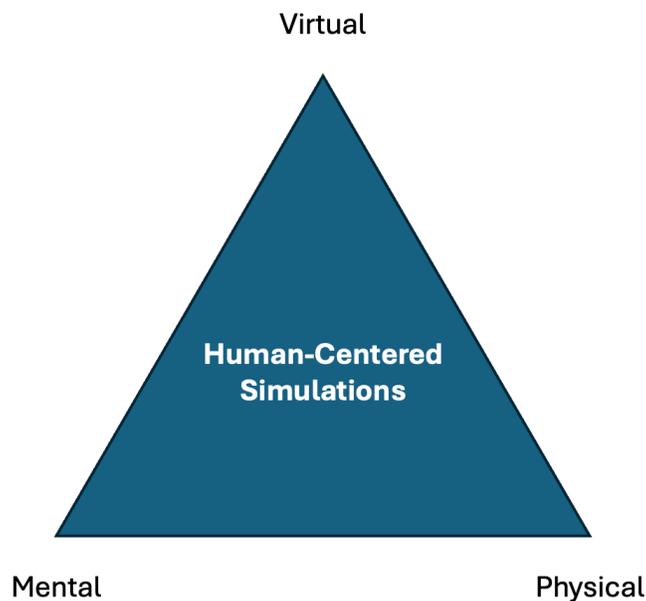
neurological assessments and educational psychology, in this thesis, we promote *virtual simulations* as the forefront of pioneering a new approach to psychological research and practice.

This work explores the theoretical foundations of simulations within psychology, offering new perspectives on mental processes occurring within various contexts that can be labeled as simulations and extending these insights into the realm of virtual simulations. Reflecting the area of psychology, this thesis endeavors to provide an exploration of the multifaceted role of *human-centered simulations*, i.e., those involving human agents, eventually focusing on virtual simulation as a specific subtype of human-centered simulation, offering a detailed overview of its diverse applications, inherent challenges, and its future potential. Since the topic of simulations is widely discussed in various exact disciplines such as mathematical, statistical, or computerized modeling, the central line of this work is to comment on those simulations that are based on actual human activity, i.e., simulations that are outlined in the context of a human as a central part of the simulation, where so-called *mental simulations* (Kappes & Morewedge, 2016; Waytz et al., 2015) and *physical simulations* engaging real human agents conducted in the real-world context are discussed and developed to create a field-relevant research oversight. Concurrently, mentally simulated situations and physical simulations currently represent the very base of the psychological research methodology, usually defined by self-report inquiries as mental simulations of hypothetical situations and psychological experiments as physical simulations (Keys & Wolfe, 1990), which needs to be critically addressed as potentially

problematic regarding the validity of the research conclusions. In these areas, *virtual simulations*, as a specific subtype of physical simulation potentially boosted by the computational capacities of modern computers, are expected to significantly contribute to the psychological field since they have great potential to overcome several unresolved limitations, as discussed below. Three types of simulations central to this work are depicted in Figure 3.

**Figure 3**

*The basic scheme of human-centered simulations is discussed in this thesis.*



The subsequent chapters of this thesis will delve deeply into utilizing *virtual environments* to simulate real-life situations that would otherwise be hard or impossible to present, too hazardous, unethical, or simply impractical to be

recreated physically. For instance, in this thesis, we will discuss VR technologies as tools enabling researchers to safely expose patients to phobic stimuli or events in a meticulously controlled setting, thus facilitating therapeutic processes in a secure environment. Similarly, virtual simulations are instrumental in studying human behavior within high-stakes contexts such as conflict zones, emergency management, or evacuations, circumventing the real-world risks typically associated with such research.

Moreover, this thesis discusses the design, implementation, and rigorous evaluation of *virtual simulations*. Insights are provided into the sophisticated technologies that underpin these environments to make them as realistic and interactive as possible. It examines the foundational psychological principles that govern these simulations, such as the perception of virtual spaces, the cognitive processes required for navigating these environments, and the emotional responses they trigger. Much of the discussion is dedicated to the technological advancements in *virtual simulations* and their implications for diagnostic procedures, therapeutic interventions, and educational strategies within psychology.

Building on this foundation, the thesis critically examines several key research areas central to the author's focus in recent years, particularly concerning the potential of virtual simulations in the psychological domain. Specifically in the domain of replication methodology (Chocholáčková et al., 2023), education (Šikl et al., 2024), virtual reality exposure therapy (Varšová et al., 2024), evacuation behavior (Snopková et al., 2022) and agent-based modeling (Juřík

et al., 2023). The work also introduces novel statistical methodologies applied in human evacuation studies, highlighting the integration of virtual simulations with machine learning.

To summarize, this thesis presents several new contributions:

(1) It establishes a theoretical framework for human-centered simulations, including those involving virtual reality – i.e., virtual simulations.

(2) It connects current cognitive psychology perspectives with environmental interactions on a theoretical level.

(3) It provides a foundation for using virtual simulations as a tool for ecologically valid psychological research and application.

(4) It critically reviews and comments on several of the author's studies involving virtual simulation in psychological research and applications, intending to guide future research directions.

(5) It introduces new perspectives on evacuation modeling by linking virtual simulations with an agent-based modeling approach considering the human-in-the-loop principle.

In summary, this thesis is crafted to serve as an indispensable resource for psychologists, IT specialists, researchers, and practitioners keen to understand and leverage the potential of virtual simulations. It aims to create a context in which the simulation can be understood in terms of psychological science and further lay a foundation for future research and development in the

continually evolving field of psychology, promising contributions to theoretical knowledge and practical applications. In this regard, as virtual technology grows, its applications in psychological practice become increasingly integral and far-reaching. This thesis underscores the successful applications and addresses the ethical considerations and potential limitations of virtual simulation in psychological practice.

# Simulations in the Domain of Psychology

The Latin verb *simulare* forms the very foundation of the central term of this thesis — a simulation. *Simulare* was employed to describe actions such as "to imitate" or "to behave as if", and as discussed above, simulations aim to reproduce a specific setting, process and issues typical of some context or situation. We often use the verb "simulate" for something very human, a mimicking, replicating, or duplicating something using alternative means. However, we also encounter this term with negative associations, like assume, fake, or deceive, emphasizing the representation of abstracted concepts that we presume mimic real phenomena. Nevertheless, the simulations themselves are artificial or unreal (Rybing, 2018). Therefore, although simulations may refer to something untrue or synthetic, from a psychological perspective, they can be seen as a central evolutionary tool of our species, which has helped us ascend to the very top of the food chain. Moreover, that is not all. Simulations have also led us to all continents, delved into the atom's nucleus, and even reached into space. While this might seem like an ambitious claim, our imagination—a distinctly human quality to construct the reality in our minds—enabled our species to anticipate most of the influential discoveries in our history, i.e., to simulate potential states of various systems mentally. Early models of the solar system, various philosophical thought experiments, or the hypothetico-deductive method, which is now commonly used also in psychology, are all examples of simulations that had to be conducted in our minds long before the advent of computers.

The ability of humans to envision possible scenarios in advance and choose the most beneficial one has undoubtedly proven to be evolutionarily advantageous. In the context of this work, we will understand this ability as an example of *mental simulation* (Kappes & Morewedge, 2016; Waytz et al., 2015) because that is precisely what simulation represents from the definition – it is an attempt to reproduce the environment and problems typical of a specific context or situation (Keys & Wolfe, 1990). In this case, our brain becomes a sort of hardware on which the simulation runs. Considering, for instance, dreams, the *mental simulation* may be of a conscious or subconscious nature. Extensive research in cognitive science (Barsalou, 2008; Gibbs, 2006; Goldman, 2006; Johnson-Laird, 1983) supports the notion that mental simulation is a core function of the human brain, enabling the transition from static to dynamic mental representations. This capability allows us to envision potential events resulting from our actions. Adopting psychological terminology regarding mental representations, a *mental simulation* can be classified as an example of *internal simulation* (the opposite of in-the-world-occurring *external simulation*) since it is conducted within one's mind, potentially without engaging any external, real-world processes.

Even though the simulations happening in our heads are significant, they are not the only ones we can consider crucial from a psychological perspective. *Mental simulation* enabled our ancestors to become “masters of creation” (or, less euphemistically, to become the ultimate predators). Still, the primary focus of this thesis is not to delve into the history of our species to pinpoint instances where the exceptional and seemingly unique ability to foresee potential

scenarios and select the most advantageous outcomes (Gilbert, 2006) has proven to be evolutionarily beneficial. Simulation is not demonstrated solely in the context of the human mind, and *external simulation* types need to be mentioned. Although the classification of various simulation types is not easy, regarding this thesis, we need to address simulations based on physical background. Such a method that replaces actual/real environments with artificial ones is extensively employed across various sectors, such as driving, piloting, education, professional assessment, or military training, and can be labeled as *physical simulation* (Keys & Wolfe, 1990). Since direct participation in specific situations may not be feasible in many contexts (military issues, space pioneering), physical replicas of these environments are created for simulation purposes. Whether it is imagining or planning a process, i.e., the above outlined *mental simulations*, or then more environmentally anchored ones, such as military training, flight simulations, or the assessment and development centers, which we can refer to as the above-mentioned *physical simulations*, for the simulations in this thesis the central part is a human actor participating in the simulation. Physical simulation involving human actors can be referred to as a *human-centered simulation* (Rybing, 2018). For *human-centered simulations*, the human will always remain the central actor. A specific type of *human-centered*, live simulation entails real individuals operating equipment to recreate particular scenarios, such as military war games or comprehensive emergency medicine drills using actors, without any computational extension or connection. In these situations, participants are engaged in simulations of real-world activities in a controlled setting. These may be scripted or semi-

scripted but always involve real human interactions and decisions, typically without computer control or augmentation. According to Rybing (2018), they include scenarios where humans play a crucial role, either by actively participating as part of the simulation (such as in role-playing exercises) or by interacting with the simulation (for instance, using a medical mannequin). Unlike traditional simulation research, where human involvement has often been considered merely a source of input to the system (Rothrock & Narayanan, 2011), human-centered simulations position humans as integral components of the simulation process. Related concepts in the simulation literature include human-in-the-loop and interactive simulations (Narayanan & Kidambi, 2011), where human operators have direct control over simulation functions. However, a key distinction is that human-in-the-loop simulations typically emphasize computer-based interactions, whereas human-centered simulations do not necessarily do so.

*Human-centered simulation* describes any simulation involving humans and their behavior and cognitive processes, serving the simulation's function and purpose, such as simulation-based training. According to Rybing (2018), a key challenge in these simulations is accurately capturing and replicating the cognitive processes and activities of the real-world task they are meant to emulate. While traditional views in simulation research often consider cognition as internal, isolated computational activities within individuals, recent cognitive theories highlight the significant roles of the external environment, tool usage, and social and cultural influences, emphasizing, for example, extended mind or embodied cognition paradigm (Clark & Chalmers,

1998; Morse et al., 2009). Thus, there is a growing need for research that applies these modern views to understand human-centered simulations better, reinterpret their theoretical frameworks, and guide their design, modeling, and evaluation. Emerging technologies may represent an excellent opportunity for further research and development.

The level of available technology defines the possibilities of simulations being conducted. Computers have led to a significant boom in the field of simulations over the past half-century. Computers represent a tool on which simulations can be performed with high efficiency. However, we also consider other similar tools for simulation. Indeed, the human brain comes to mind, which, as a potential simulator, resonated at the beginning of this chapter. As a less intuitive example of a simulator, we could also consider, for instance, a music box and, with a small amount of exaggeration, even a pianist playing a musical score. Similarly, it is a platform (piano and pianist) into which informational inputs (musical score) are placed, and the simulation (music) is reproduced. Of course, such an analogy is somewhat exaggerated within a scientific discussion; nevertheless, the box-produced music (as an example of physical simulation) enriches the understanding of the fundamental significance of the concepts. A music box can hardly be compared to a computer today. However, it essentially operates on the same principle of ones and zeros (a specific tone playing and not playing), and we agree that current computers surpass other simulators in many respects. Since these cutting-edge technologies still open new potentials for psychological science, the connection of the *human-centered simulations* fundamentally rooted in human acting to computational paradigm

cannot be wholly omitted. *The* high efficiency of computers makes them a unique tool for simulating complex systems and *computational simulations*, which are still increasingly represented within various research and application domains.

*Computational simulation* utilizes computer technologies to model and reproduce the behavior, processes, or events of the real world; nowadays, it is a crucial domain since the twenty-first century is addressed as the age of *computer simulation* (Winsberg, 2010). This simulation allows for examining system or process behavior under different conditions, testing their properties, predicting their future development, or conducting experiments that would otherwise be difficult, impossible, or dangerous in a real environment. *Computer-based* and *mathematical simulations*, therefore, represent a fascinating and intensively studied area, the principles of which, however, can thrive perfectly well without humans as the central living actors of the simulation. That is why they are abstractly labeled as *constructive simulations* (Rybing, 2018). *Constructive simulations* operate autonomously, simulating all the systems, equipment, and interactions without real-time human influence, aside from setting initial conditions and parameters. Common types include discrete event simulations, agent-based modeling, or Monte Carlo simulations (Banks, 2010; Sokolowski, 2010), which can be used to model phenomena like the orbital movements of planets or the below-discussed process of evacuation from the building (Johnson, 2005; Juřík et al., 2023). Even though the area of *computational simulations* cannot be deeply elaborated in the framework of this

psychological work, computational advances allowed for the creation of more sophisticated simulation tools, which will be addressed below.

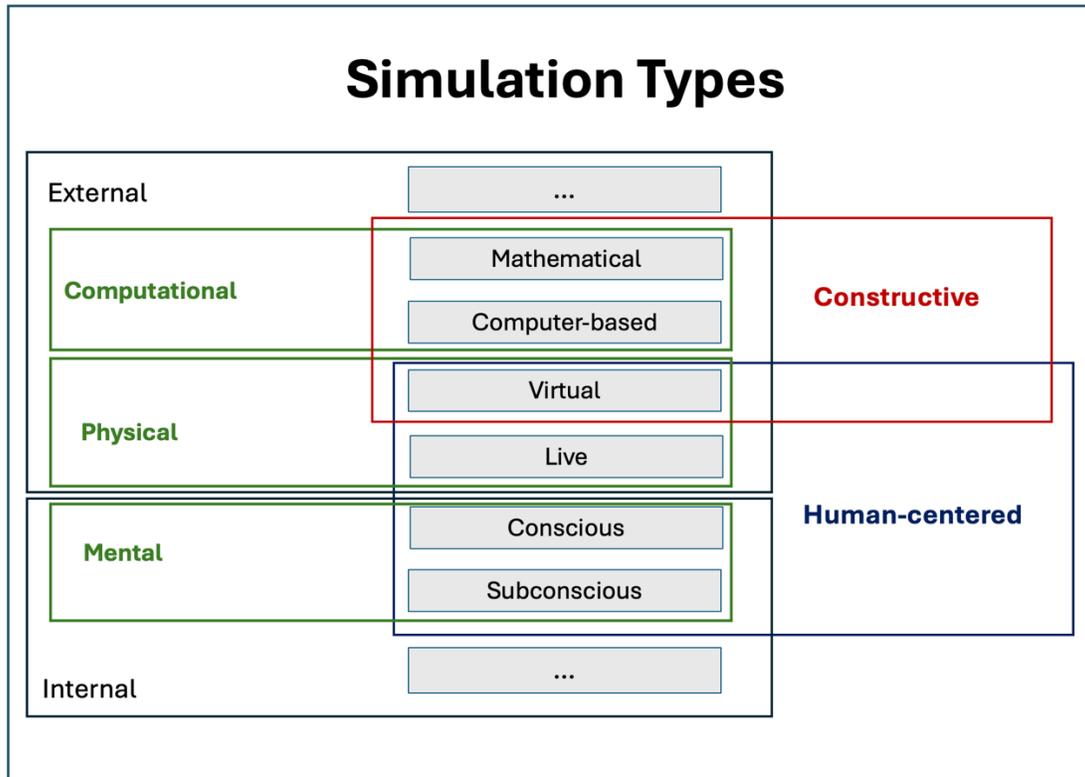
There are features from the computational approach; however, that need to be considered since they create a vital framework for the main scope of this thesis. Specifically, it is the technology designed to immerse humans in other, alternative, artificially created worlds, which have been with us only in the last few years, at most decades, unlike, for example, our mental simulation abilities. These technologies provide us with a credible reproduction of reality, that is, introducing a person into a realistic, immersive alternative reality, which today bears the somewhat oxymoronic term virtual reality (Jerald, 2015; Mendelová, 2019). As a researcher, I have been studying various aspects of virtual reality technologies for almost 10 years, which has led me to write these insights on virtual simulations as a powerful tool for psychological research and application. In my dissertation thesis (Juřík, 2020), I have focused on the visualization aspects of visually presented models of geographical environments as a fundamental form of a virtual environment. Since then, technologies have advanced, so in this work, I will discuss research and application aspects of immersive virtual reality (IVR) (Jerald, 2015), in which a person can become directly involved from a first-person perspective and can interact realistically with the displayed content through sophisticated user interfaces. It can be, therefore, labeled as a *virtual simulation*. While maintaining the key role of human operators, virtual environments, usually generated by a computer, may implement or contain various computational aspects, such as presenting specific scenarios based on mathematical or agent simulations. In

this matter, some specific designs of *virtual simulations* can be seen as an example of *constructive simulations*. *Virtual simulations*, on the other hand, are usually created to involve real people engaging with simulated environments and tools, making them one of the most prevalent forms of *human-centered simulation*. This category encompasses a variety of simulators, including vehicle cockpit simulators, augmented reality technologies, educational and training technologies, and different forms of VR role-playing simulations.

Since the literature offers various classification schemes for simulations (see Gaba, 2004, for example), regarding the purpose of this thesis, I suggest a scheme (see Figure 4) based on the above-discussed topics. Mental and physical simulations will be discussed in more detail below since they represent the human-centered simulation types relevant to psychology and, therefore, this thesis. The suggested scheme primarily aims to classify virtual simulations as an example of physical simulation created based on human-centered and constructive simulations. This fusion is closely discussed in the section on virtual simulations.

**Figure 4**

*The typology of simulations relevant in the framework of psychological research*



*Note.* In this scheme, virtual simulations represent a specific simulation subtype that engages human user/operator on the one hand and constructive computer-generated processes such as virtual agents on the other.

Virtual simulations can be seen as a combination of human-centered and constructive simulations due to the intricate way they integrate elements from both types to create immersive and interactive environments. In the virtual simulation, a real user (human) can be immersed and interact with the environment. In contrast, virtual content can be enriched with elements of

constructive simulations such as agent-based avatars, which can – based on a specific computational model - simulate a specific situation (e.g., evacuation from the building), as discussed later in this thesis. Virtual simulation is where constructive and human-centered simulation meets to mesh real human experience with computer-generated situations, as depicted in Figure 4.

Human-centered simulations focus on replicating human experiences and behaviors, often requiring detailed psychological and physiological models to simulate human responses accurately. This is crucial in virtual simulations, where user experience and interaction play a significant role. For instance, the simulation must consider the user's cognitive load, emotional state, and physical interactions in virtual reality training programs to create a practical and realistic training environment. On the other hand, constructive simulations emphasize the building and modeling of complex systems and processes, often independent of direct human interaction. These simulations are used to understand and predict systems' behavior through algorithms, mathematical models, and data analysis. In virtual simulations, constructive elements are evident in the underlying computational models that drive the virtual environment's behavior. The synergy between human-centered and constructive simulations in virtual simulations is evident in applications such as virtual training for pilots or surgeons. These applications require accurate physical modeling of aircraft or surgical tools (constructive simulation) and replication of the human experience, such as a pilot's stress and decision-making processes in an emergency (human-centered simulation). By

combining these two types, virtual simulations offer a holistic, immersive training experience that is physically and psychologically realistic.

In summary, virtual simulations exemplify the fusion of human-centered and constructive simulations by integrating detailed human experience modeling with robust system and process simulations. This combination ensures that virtual simulations are interactive and realistic, making them invaluable tools in psychology, training, and beyond. As mentioned above, virtual simulation can be framed as a *hybrid simulation* (Andrews et al., 1998), combining elements from two or more of the aforementioned types and enriching the simulation approach by integrating diverse simulation styles.

## Mental Simulations

Let us more closely consider the idea resonating in the previous chapter: the human mind is essentially one big simulator that helped our species dominate the world. In line with some foundational theories of human mind evolution (Hills, 2018), let us assume that the human mind, like other organisms, is primarily oriented towards seeking resources that help sustain us and ideally – when circumstances allow it – our future generations. An essential aspect is also the significant focus of the human mind on ways that lead to the next generations, i.e., reproduction. In this regard, the mind can be viewed as a search algorithm that seeks elements important for environmental survival – food, shelter, and mates. In psychology, the idea of selective perception, which is somewhat influenced by our current psychological states in combination with the surrounding environment, is not new; one only needs to recall Ulric Neisser's traditional work (1976) and his principles of anticipatory schemata, which, in describing the principles of the human mind's functioning, represent bidirectionally modifiable organism-environment structures, which is constantly changing state then influences strategies and processes of searching for elements in the environment. According to Neisser, individuals form mental representations of the world, which are used to anticipate and interpret sensory input. These mental representations are constantly updated based on new sensory information, creating a cyclical process of perception and action. Mental representations are internal and subjective; therefore, they are also highly variable models of the external world stored in our minds, which tend

to be more than just ordinary memories. They are internal cognitive symbols or codes representing external reality or concepts. They include images, symbols, or propositions the mind uses to store and manipulate information, forming the basic units of thought that enable sensory processing, memory recall, and idea generation. These representations are the building blocks of cognition, underpinning perception, memory, and language. For example, most people have an internal mental representation of a television remote control as a plastic box with buttons, usually used to switch television channels. When someone sees such a thing, they will probably immediately know how to use it. Eysenck and Keane (2008) categorized representations where internal mental representations can be divided into propositional and analogical representations. Propositional representation manifests in a form similar to language and carries meaning, regardless of the specific modality (the remote control changes channels on the television or radio).

In contrast, analogical representation is a visual, auditory, or motion image (e.g., the remote controller is a black box with buttons). Mental representations create subjective, more or less abstract models of various aspects of reality and enable the psyche to think without overloading working memory. Their function is to abstract incoming information and process it efficiently, thus promoting thought fluidity. While mental representations are the individual pieces of information encoded by the mind, mental models are the complex structures that organize and use these pieces to simulate and understand real-world phenomena. Their connection is essential for the mind's ability to process, organize, and apply information effectively.

In summary, mental representations are the essential elements of thought-encoding information. In contrast, mental models are structured simulations that use these representations to replicate and predict real-world phenomena, as discussed in the first chapter of this work. Both are essential for understanding how the mind processes, organizes and navigates information. As a result, *mental simulation* allows us to project ourselves into alternative versions of the future. This self-projection is characterized by its non-exact, random nature, seeking solutions for unknown elements—a kind of intuition. In contrast, constructive simulations (discussed above) provide specific parameters and aim to solve particular problems, sometimes yielding unexpected results.

## Mental Models as Simulations

As seen in the previous chapters, the term model is often presented using the word *simulation*. Mental models are complex, structured representations we use to understand and interact with the world. They simulate real-world processes, allowing individuals to predict outcomes and reason about causal relationships. Dynamic and manipulable mental models help us understand mechanical systems, social interactions, or problem-solving by running mental simulations, enabling us to predict future events, understand others' intentions and emotions, and generate new ideas. They integrate various mental representations to understand events and systems and predict events worldwide coherently. According to Landriscina (2013), Heinrich Hertz and Kenneth Craik were early proponents, suggesting that our thoughts simulate

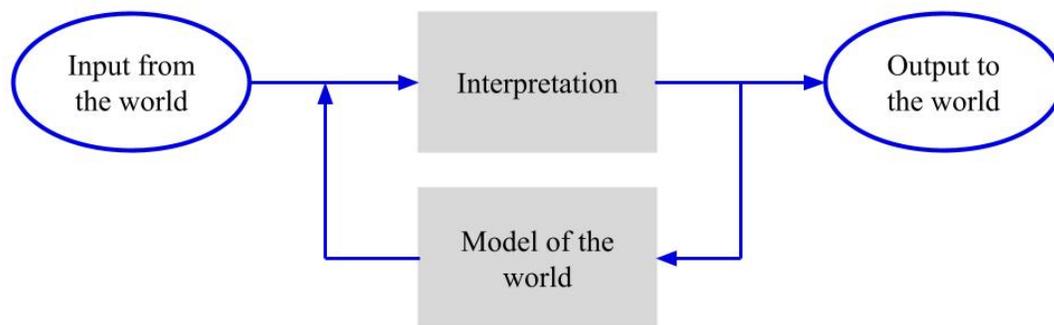
external reality through internal images or models. The concept gained prominence with Shepard and Metzler's experiments on mental rotation, highlighting mental representation's visual and spatial aspects. In 1983, Gentner, Stevens, and Johnson-Laird advanced the field with differing approaches. Gentner and Stevens (1983) focused on mental models as knowledge structures for understanding specific domains, while Johnson-Laird (1983) viewed them as structural analogs of the world, supporting speech comprehension and logical reasoning. Johnson-Laird's theory parallels Charles Sanders Peirce's semiotics, emphasizing multimodal representations. The distinction between mental images and models and their relation to schemas was explored by various psychologists. Piaget and later researchers integrated schemas into cognitive development and learning theories, influencing educational psychology. Despite various interpretations, schemas now broadly represent complex knowledge structures, with mental models addressing specific aspects of cognition.

As discussed by Landriscina (2013), the concept of mental models often connoted them as static structures akin to physical models or pictures. However, according to various researchers, mental models are dynamic and capable of representing causal or temporal relationships among events through mental simulations. As discussed above, this idea traces back to 1940' ( Craik, 1943) and was further supported by Gentner and Johnson-Laird, who emphasized the ability to "run" these models internally to predict outcomes. Rumelhart and colleagues (1986) described mental models within the *parallel distributed processing* (PDP) paradigm, where an interpretative system interacts

with a world model to predict and simulate future events. This approach describes the cognitive system as comprising two processing units: an interpretative system that receives input from the world and generates actions and a world model that uses these actions to predict environmental changes. For an illustration, see Figure 5. The PDP paradigm suggests that even without real-world events, we can use mental models to simulate actions internally, predicting and evaluating potential outcomes. This cybernetic model represents an internal control system where these units interact through a feedback loop, enabling internal simulations and decision-making. This cybernetic approach highlights the evolutionary advantage of mental simulation, such as prehistoric humans simulating hunting strategies.

**Figure 5**

*Rumelhart's (1986) scheme of the PDP model*



*Note.* Adapted from Landriscina (2013).

For some species, attention is focused on more sophisticated aspects than just satisfying basic needs, including forming alliances, efficient ways of revenge, or achieving long-term goals. From those primitive aspects to (not only in our species) rather complex elements such as social reality, this selective attention of our minds usually does not miss what is relevant to survival. However, while the brains of most animal species have gradually adapted in a way that allows them to effectively explore the physical environment (e.g., excellent sense of smell and spatial orientation in dogs, night vision in cats, etc.), the human brain has evolved to be able to store the environment and its elements in memory, later imagine them, and in these imaginations, further search without the need to be physically present in a specific situation. Simply put, we can summarize that the human brain has evolved to search the world through *mental simulations* (Pezzulo et al., 2014). The brain can simulate future realities based on its ability to represent and store a mental model of the world. Mental simulation is a core function of the human brain, which is addressed as enabling the transition from static to dynamic mental representations (Kappes & Morewedge, 2016). This capability allows us to envision potential events resulting from our actions. According to Kappes and Morewedge (2016), mental simulation is a substitute for real experience because it has effects similar to those of perception, cognition, motivation, and action compared to physical experiences. Also, other researchers highlight the role of mental simulations in self-regulation and as substitutes for real experiences.

In contrast, mental simulations involve creating detailed mental images or narratives of one or more specific events, mimicking real experiences (for

instance, see Taylor et al., 1998). Unlike semantic representations, which are abstract and general, mental simulations focus on vivid and specific depictions of actual or imagined scenarios (Szpunar et al., 2014). People can imagine possible future scenarios and realities without the need to be present *in situ*.

According to Kappes and Morewedge (2016), mental simulations of past, future, and counterfactual events exhibit numerous similarities. They follow similar developmental patterns (Suddendorf & Busby, 2005), respond similarly to experimental interventions (Morewedge, 2013; Morewedge et al., 2005; Nussbaum et al., 2006), and depend on a shared "core network" of brain regions. This core network includes the medial prefrontal cortex, medial temporal lobe, posterior cingulate cortex, and inferior parietal lobule (Schacter et al., 2008). Extensive research in cognitive science (Barsalou, 2008; Gibbs, 2006; Goldman, 2006; Johnson-Laird, 1983) supports the notion that mental simulation is a core function of the human brain, enabling the transition from static to dynamic mental representations. This capability allows us to envision potential events resulting from our actions. The neural and conceptual systems involved in mental simulation closely overlap with the sensory-motor systems active during the real behavior. Research using fMRI and TMS indicates that mentally simulating motor actions mirror the pre-execution stages of those actions (Jeannerod, 2001). Mental simulations consistently engage the same brain regions as actual motor actions, including the supplementary motor area (SMA), premotor cortex (PMC), and primary motor cortex (Munzert et al., 2009). Additionally, sensorimotor simulations incorporate fundamental conceptual information (Barsalou, 2003; 2008). This information is context-

dependent and grounded in the sensory modalities through which it was initially acquired. For example, the concept of an elephant's size is inherently linked to the visual representations associated with learning this information. Therefore, activating similar systems and processes during mental simulations and corresponding actions suggests that mental simulations can sometimes substitute for actual experiences (Kappes & Morewedge, 2016). Moreover, the mental simulation system is intricately connected to the linguistic system, highlighting its significant implications for learning.

*Mental simulation* is a process of self-projection into alternative temporal, spatial, social, or other hypothetical realities. Mental crossing of the "here and now" occurs here to psychologically occupy a different time and space (whether past or future), the subjective experience of another person, or a hypothetical reality (Waytz et al., 2015). According to Landriscina (2013), mental simulation is a key mechanism underlying the theory of mind (ToM). It allows individuals to attribute mental states such as beliefs and desires to themselves and others, facilitating the understanding and predicting thoughts, intentions, and emotions. Two primary theories explain this cognitive ability: the "theory-theory" (TT) and "simulation theory" (ST). The "theory-theory" perspective views ToM as a form of naive theory or "folk psychology," constructed with posits and rules similar to scientific theories (Stich & Nichols, 1992). Children are thought to develop ToM through empirical methods akin to scientific inquiry (Gopnik & Wellman, 1994) or by activating innate modules during biological maturation (Leslie, 2000). Conversely, "simulation theory" (ST) posits that individuals use mental resources to simulate the psychological

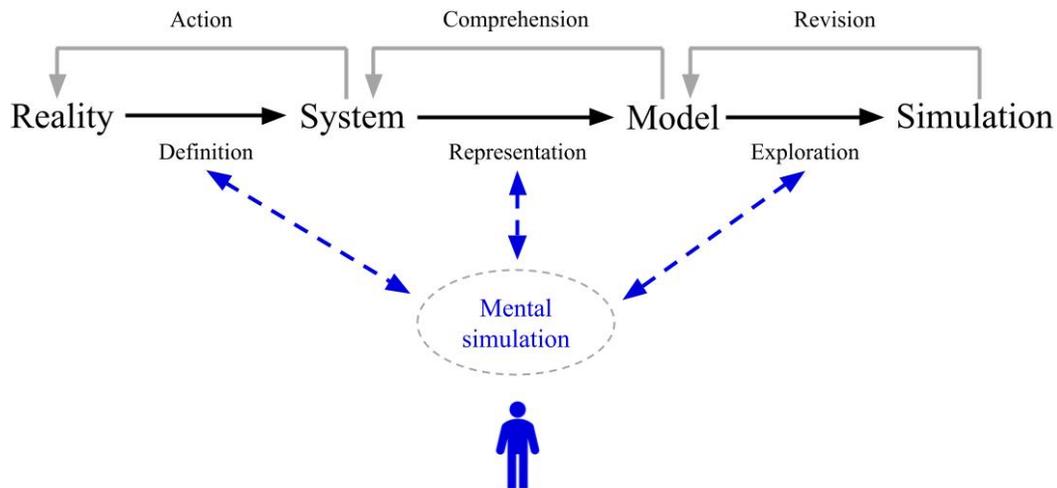
causes of others' behavior without relying on a structured theory (Gordon, 1995). Two approaches within ST explain this process: the role-taking approach, where people imagine themselves in another's situation to simulate their thoughts and feelings (Gordon, 1995), and the introspection approach, where individuals use their own beliefs and desires to simulate and infer others' mental states (Goldman, 2006). However, this process can lead to "egocentric biases," where one's own experiences distort the accuracy of mind reading. ST has gained support by discovering mirror neurons, which activate when performing an action and observing the same action in others (Rizzolati et al., 2006). These neurons help understand others' goals and intentions, forming a neurological basis for simulation (Gallese & Goldman, 1998). Goldman (2006) distinguished between "low-level" mental reading, which involves automatic responses like mimicking facial expressions, and "high-level" mental reading, which involves more complex reasoning and conscious effort.

#### *Example of Learning Models Based on Mental Simulation*

According to Landriscina & Seel (2013), fundamental cognitive processes such as learning can be described and understood through the concept of mental simulation through his Epistemic Cycle (see Figure 6), where the specific relationship between "model" and "simulation" as terms discussed above is employed.

**Figure 6**

*The Epistemic Cycle according to Landriscina*



*Note.* Adapted from Landriscina (2013).

The Epistemic Cycle is a model that explains how students acquire knowledge through simulation in an educational context, focusing on the interaction between four key concepts: Reality, System, Model, and Simulation. These concepts can manifest as physical objects or conceptual tools, forming a cycle that includes three feedback loops: Reality-System, System-Model, and Model-Simulation.

The cycle begins with transitioning from “Reality” to “System,” where a specific part of the world is defined as a system, establishing a conceptual boundary. This is akin to visual perception distinguishing between figure and ground, enabling us to focus on particular elements within a complex environment.

Next, the “System” to “Model” loop involves representing the defined system through increasingly sophisticated models. These models serve as tools to further understand and simulate the system, allowing different strategies to be employed depending on the aspects of the system being studied.

In the “Model” to “Simulation” phase, dynamic models are used to simulate system behaviors that might be unpredictable through simple observation. Simulations can extend the observation interval, providing insights into the system's past and future behaviors.

The cycle then moves from “Simulation” to “Model,” where the results of simulations are critically analyzed. This analysis often leads to modifications of the original model, improving its accuracy and reliability, much like the process of hypothesis testing in scientific inquiry.

In the “Model” to “System” loop, refined models enhance understanding of the original system, often leading to new perspectives and additional cycles of modeling and simulation. This iterative process deepens comprehension of the system's structure and function.

Finally, the cycle completes with the “System” to “Reality” phase, where the new understanding gained from the model is applied back to reality. This application may reveal new aspects of reality, prompting further cycles of exploration and refinement. The Epistemic Cycle underscores the iterative and reflective nature of learning through modeling and simulation, highlighting how this process advances understanding of specific systems and deepens the

relationship between the observer and the observed reality. Through this cyclical approach, knowledge acquisition becomes a continuous exploration, evaluation, and application process. In this regard, interactive virtual simulations represent an important opportunity.

## Predictive Processing in the Context of Mental Simulation

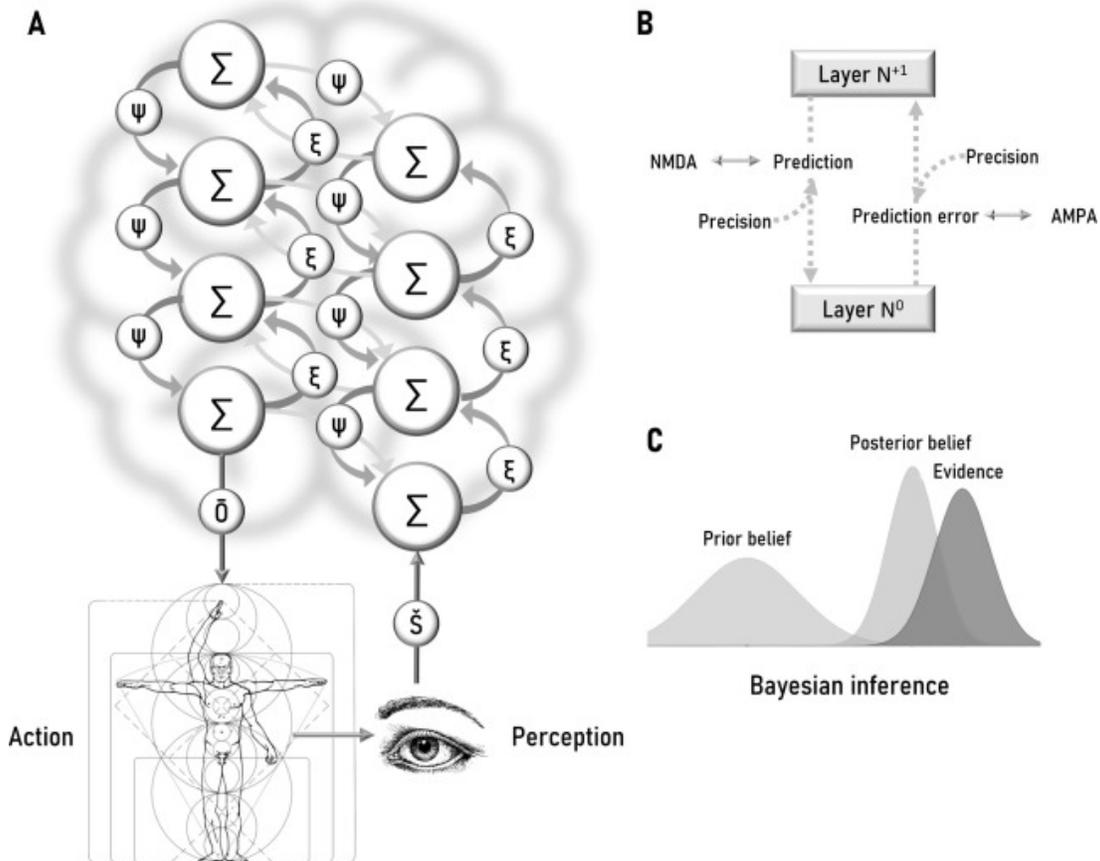
Current influential theories on human cognition emphasize the brain's role in processing, predicting, and responding to information, highlighting its dynamic and context-dependent nature. Dual-Process Theories (Grayot, 2020) propose that cognition operates through two systems: a fast, intuitive System 1 and a slow, analytical System 2. Embodied Cognition (Farina, 2021; Varela et al., 2017) underscores the idea that cognitive processes are deeply rooted in the body's interactions with the environment. Connectionism and Neural Networks model cognition through interactions between simple units, akin to neural processes in the brain. The Extended Mind Theory (Clark & Chalmers, 1998; Gallagher, 2018) argues that cognition can extend beyond the brain to include external tools and environments, while the Bayesian Brain Hypothesis posits that the brain uses probabilistic reasoning to update its beliefs based on new data. These theories reflect the intricate interplay between the brain, body, and environment in shaping human cognition. Among them, it is especially dynamically developing predictive processing theory (Clark, 2015), which sees human cognition as a specific type of mental simulation.

The perspective of predictive processing (Clark, 2018; Hohwy, 2020), deeply rooted in the Bayesian Brain hypothesis (Hipólito & Kirchhoff, 2023), has

increasingly become a dominant framework in cognitive neuroscience (Lee et al., 2021). This framework posits that the brain functions as a prediction machine, constantly generating and refining internal models to predict sensory inputs and guide behavior. At the core of predictive processing (PP) is the idea that perception and cognition are fundamentally inferential processes, where the brain actively constructs interpretations of the world based on prior knowledge and sensory data. This process can be understood as a form of simulation, where the brain creates a dynamic, real-time model of the environment to navigate and respond to various stimuli, see Figure 7. Bottemanne (2025) illustrates hierarchical predictive processing in the brain, where the brain encodes a hierarchy of beliefs to generate predictions about the sensory consequences of actions ( Figure 7 - A). These predictions are continuously updated by prediction errors and discrepancies between expected and actual sensory input. This process influences both goal-directed actions and sensory signal processing, creating a feedback loop where behavior impacts sensory perception, and sensory signals, in turn, update the brain's beliefs about the environment, guiding future behavior (Clark, 2018). The mechanism is underpinned by neural network architecture (Figure 7 - B), with NMDA receptors involved in top-down predictions and AMPA receptors in bottom-up prediction errors. Bayesian inference (Figure - 7 C), a method of processing information under uncertainty, plays a key role in updating beliefs by integrating prior beliefs with new sensory evidence, ultimately leading to an optimal understanding of the environment.

**Figure 7**

*The hierarchical predictive processing in Bayesian brain theory*



*Note.* Adopted from Bottemanne (2025) with permission from Elsevier.

The Bayesian Brain hypothesis serves as the foundation for understanding predictive processing (Hipólito & Kirchhoff, 2023). Bayes' theorem, a fundamental principle of probability theory, underpins this hypothesis by providing a mathematical framework for updating the probability of a hypothesis based on new evidence. In the context of brain function, this translates into a continuous process where the brain updates its internal model

of the world as it receives new sensory inputs. This model is probabilistic, meaning that the brain does not just react to stimuli; it predicts them and adjusts its expectations based on the accuracy of these predictions (Knill & Pouget, 2004). According to this view, perception is not a passive reception of sensory data but an active inferential process. The brain receives noisy and often ambiguous sensory inputs and uses prior experiences to generate the most likely interpretation of these inputs. For example, when seeing an object in low light, the brain does not simply perceive it based on the limited visual data available; it infers what the object is likely to be based on prior knowledge and contextual clues. This inferential process is central to how we navigate the world, allowing us to make sense of incomplete or unclear information.

A crucial aspect of predictive processing is the brain's use of predictions and prediction errors (Clark, 2018). The brain generates predictions about what it expects to encounter in the environment. When sensory data is received, the brain compares it to its predictions. The difference between the predicted and actual data, known as the prediction error, is then used to update the brain's model of the world. This process of minimizing prediction errors allows the brain to refine its predictions over time, leading to more accurate and efficient processing of sensory information. This predictive mechanism operates hierarchically within the brain. Higher levels of the brain's processing hierarchy, such as the cortex, generate broad, abstract predictions about the environment, while lower levels, such as sensory areas, deal with more specific, detailed predictions. The interaction between these levels allows the brain to integrate detailed sensory information with more general expectations,

creating a coherent representation of the world. This hierarchical processing enables the brain to function efficiently, focusing on relevant details while maintaining a broad understanding of the environment. The Bayesian Brain hypothesis and predictive processing theory have profound implications for understanding neural mechanisms. These frameworks provide insights into how the brain manages uncertainty, learns from experience, and makes decisions (Colombo & Seriès, 2012). For instance, Bayesian models have been used to study neural activity patterns, explaining how the brain might implement Bayesian inference at the neural level. Specific brain regions, particularly those in the cortex, have been identified as heavily involved in these processes, highlighting the brain's reliance on probabilistic reasoning to navigate an uncertain world. The influence of Bayesian inference extends beyond neuroscience, impacting fields such as artificial intelligence (AI) and machine learning (ML). The principles of Bayesian inference have been instrumental in developing algorithms that mimic the brain's approach to processing and integrating information under uncertainty. These algorithms are beneficial in AI applications that require the system to make predictions based on incomplete or ambiguous data, much like the human brain.

Despite its strengths, the Bayesian Brain hypothesis and predictive processing theory face several challenges (Piekarski, 2021). One of the main criticisms is the complexity of implementing Bayesian inference in the brain. The vast number of calculations required to update probabilistic models continuously poses a significant challenge, raising questions about how the brain achieves such complex computations efficiently. While some aspects of the hypothesis

have strong empirical support, other areas remain difficult to validate, leaving room for further research to explore how these processes are realized at the neural level.

### *Predictive Processing as Simulation*

Predictive processing can be viewed as a form of *biological simulation*, focusing on how the brain functions similarly to simulations used in scientific and engineering disciplines. The brain's internal models act like simulations, creating representations of the environment to predict outcomes and guide decision-making. These models allow the brain to anticipate sensory inputs and respond effectively, emphasizing its role as an active modeler of the world. The brain continuously generates and updates these internal models based on sensory inputs and prior knowledge, simulating the environment to predict future events. This dynamic process ensures that the brain's predictions stay accurate and relevant, adapting as new information is acquired. Predicting and updating are central to predictive processing, where the brain generates predictions about sensory input and adjusts them based on actual data received. This iterative feedback loop is akin to how simulations operate—predicting outcomes and refining models when discrepancies arise. A key mechanism in this process is error minimization, where the brain strives to reduce the difference between its predictions and actual sensory input, similar to improving a simulation's accuracy. Hierarchical prediction, a common feature in predictive processing and simulations, enables the brain to manage

complexity by integrating information across multiple levels, ensuring coherent and accurate predictions.

Uncertainty and variability are intrinsic to both predictive processing and simulations. The brain manages uncertainty by assigning weights to predictions and sensory inputs based on their expected reliability. More reliable predictions are prioritized, while less specific inputs are downplayed. This probabilistic approach allows the brain to make informed decisions despite incomplete or ambiguous information. Similarly, simulations incorporate probabilistic methods to account for variability and uncertainty in real-world systems, enhancing their accuracy and resilience. By embracing uncertainty, predictive processing and simulations can function effectively in dynamic and unpredictable environments. Another critical parallel may be seen in both systems' adaptive and dynamic nature. The brain's internal models are continuously updated in response to new information and changing environments, ensuring its predictions remain accurate over time. This adaptability is mirrored in simulations, where models are refined and adjusted as new data becomes available, maintaining their relevance and accuracy. This dynamic nature is essential for both the brain and simulations to stay responsive in evolving conditions. Predictive processing offers insights into complex cognitive functions, such as perception, action, and decision-making, by simulating how the brain processes sensory input and guides behavior. Similarly, simulations are invaluable in studying complex systems across various domains, from weather forecasting to economics, providing insights and guiding decision-making.

In conclusion, predictive processing represents a sophisticated form of biological simulation where the brain continuously generates, tests, and updates internal models to predict and interpret sensory input. This perspective highlights the brain's role as an active predictor and modeler, engaged in a real-time simulation of its environment. By drawing parallels between predictive processing and simulations, we understand how the brain navigates and makes sense of the world, underscoring the profound interconnectedness of cognitive processes and computational modeling.

## Mental Simulations Beyond Consciousness

The traditional philosophical discussion on what reality is remains vivid even nowadays. In his 1978 essay, Philip K. Dick asserts that reality is that which persists even when you cease to believe in it, which is a notion that transcends the framework of interpretation of reality from a phenomenological standpoint. It is true, however, that next to language and culture, modern humans cannot only imagine realistic scenarios based on what we already know but also fantastical, counterintuitive, alternative ones, where we can also simulate potential scenarios, processes, and outcomes. These alternative realities not only appear to exist in our minds, but they probably directly influence the evolution of our species. How close, then, is the idea of a dancing mammoth on the cave walls to the hardly imaginable concepts of relativity or quantum superposition—phenomena in reality that are hardly observable but without which today's physics, and indeed the whole current understanding of the universe, could not exist? Perhaps that is why the wealthiest form of this ability

for simulation seems to be entirely human (Gilbert, 2006), with some theorists speculating that simulation is the ability that enables humans to participate in complex cultures by navigating past, future, and social worlds (Baumeister & Masicampo, 2010).

In scientific discourse, various assertions liken the human brain to a biological computer (see also chapter on similarities between predictive processing and simulation), with consciousness functioning as the software it runs. This analogy draws on the ideas of Stuart Hameroff and Roger Penrose. The brain actively engages with the external world, forming synapses, which are connections between nerve cells. When a person is at rest, the brain autonomously generates synapses, a process that can be seen as a form of simulation because it replicates aspects of the external environment. This running simulation can be automatic, non-voluntary, or even unconscious.

In this manner, dreaming can be considered a specific type of simulation (mental, subconscious). In dreams, the brain constructs a reality that can be vivid and immersive, simulating various experiences, including sensory perceptions, emotions, and complex narratives. From this perspective, the purpose of dreaming may involve mental rehearsal since dreams can simulate scenarios that might occur in waking life, which may help with emotional regulation or problem-solving. This can be seen as the brain practicing or rehearsing responses to different situations. Potential evolutionary function supposes that dreaming could have developed as a mechanism to simulate threatening events so that individuals could rehearse strategies for coping with

these threats, enhancing survival skills without the risks of real-world trial and error (Mathes & Schredl, 2016; Zadra et al., 2006). Therefore, dreaming can be seen as a neural simulation because dreaming involves activating specific brain regions in a way that mimics waking perception and cognition. This simulation can help consolidate memories and learning as the brain re-enacts or reviews experiences or information acquired during wakefulness. Also, dreams often simulate emotional situations that might be too intense or impractical to process while awake, allowing an individual to work through emotions in a safe, simulated environment. Overall, while dreams do not involve external devices or conscious design like many other types of simulations, they function in a way that is internally generated by the brain, providing a fascinating, natural example of how simulation operates within our cognitive and psychological systems.

As suggested above, mental simulations, which span from conscious efforts to subconscious processes, play a pivotal role in shaping our behavior, creativity, problem-solving capabilities, and emotional regulation. At the conscious level, individuals engage in visualization, strategic planning, and active daydreaming. Visualization is prominent in sports psychology, where athletes mentally rehearse successful performances, enhancing performance. Strategic planning involves mentally simulating future scenarios to better prepare for potential outcomes or to facilitate decision-making. Active daydreaming allows individuals to consciously steer their thoughts toward specific topics or desired outcomes, making it a valuable tool for creative problem-solving. On the subconscious side, mental simulations occur without intentional initiation

or conscious awareness. This includes dreaming during sleep, where the brain weaves complex narratives from subconscious material, providing insights into our deeper emotional states. Passive daydreaming happens when the mind drifts aimlessly, often leading to spontaneous and unstructured thoughts that can unexpectedly contribute to creative ideas or emotional insight. Intuitive thinking, another subconscious process, involves insights and thoughts that arise without direct control, offering solutions or ideas that might not be accessible through deliberate thought. Additionally, hybrid states blend conscious and subconscious elements, such as the hypnagogic and hypnopompic states encountered at the sleep thresholds (Foffani, 2024). In these transitional moments, individuals might experience vivid, dream-like scenarios with partial awareness, merging the deliberate aspects of consciousness with the spontaneous generation of subconscious content.

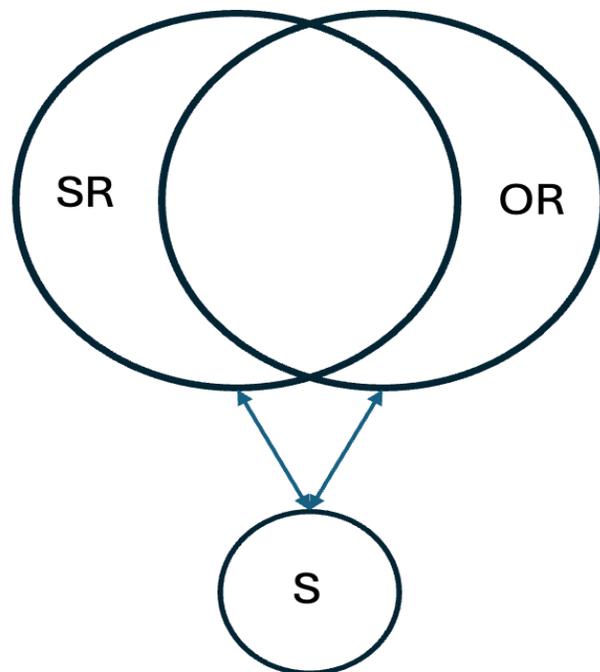
### Critical Reflection on the Significance of Mental Simulations

Regarding mental simulations, it is necessary to mention the inaccuracies that arise when our brain re-creates reality since there are many biases and shifts. As discussed by Kappes and Morewedge (2016), the influence of simulations on expectations is mainly due to their accessibility and/or availability. Simulated events, like real ones, are more likely to be remembered when making judgments, as people consider what readily comes to mind more probable (e.g., Hoch, 1984; Kahneman & Tversky, 1982; Tversky & Kahneman, 1973). For instance, vivid demonstrations—recent, unusual, or spread through word of mouth—powerfully shape expectations (Dickson, 1982). Similarly,

vivid mental simulations have a significant impact (Bone & Ellen, 1992; Brown et al., 2002; MacInnis & Price, 1987; Sherman et al., 1985). Mental models or representations are not exact copies of the world (Shepard, 2001). Regarding this, our mental simulations (representations of reality), even though they overlap with objective reality, are always shaped by our inner states – see Figure 8.

**Figure 8**

*Subjective shift in representation of perceived reality*



*Note.* A person/subject (S) partially forms their representation of subjective reality (SR) based on objective reality (OR) with a necessary representation shift.

Mental simulations, while powerful in many ways, are not the ultimate way to predict the world due to several inherent limitations. Cognitive biases such as confirmation bias, the availability heuristic, and anchoring can distort the accuracy of these simulations, leading to predictions that reflect personal beliefs or past experiences rather than objective reality. Moreover, the human brain has limited processing capacity. Complex systems and large-scale scenarios often require more cognitive resources than our brains can manage. Regarding this, Gerd Gigerenzer (2011) offered a theory on heuristics that perceives human decision-making as often reliable on simple, efficient rules of thumb—called heuristics—that are fast, frugal, and surprisingly effective in many real-world situations. Gigerenzer argues that contrary to the traditional view that sees human reasoning as biased and prone to errors when deviating from rational models, these heuristics are adaptive tools that the mind uses to make decisions under conditions of uncertainty. He emphasizes that heuristics do not aim for perfect accuracy but provide satisfactory solutions quickly and with minimal cognitive effort, making them well-suited for complex and time-constrained environments. Gigerenzer's work suggests that these simple strategies can be more successful than complex, information-heavy methods, especially when dealing with real-world problems. Heuristics are essential for navigating the complexity of the world. They allow us to make quick judgments without needing to process every detail of a situation. However, these shortcuts are based on patterns the brain has recognized from past experiences, which may not always align with current or future realities. For instance, the availability heuristic leads us to judge the likelihood of an event

based on how easily examples come to mind. This can result in an overestimation of risks that are more memorable but statistically rare, such as the fear of flying after hearing about a terrorist attack. The concept of ecological rationality emphasizes that our cognitive tools are adapted to the environments in which they evolved (Cosmides & Tooby, 2006). However, this adaptation does not imply perfect accuracy. A heuristic that works well in one context might fail in another. For example, a hunter-gatherer's ability to judge the speed and trajectory of a moving object is highly adapted to their environment. However, it might not translate well to modern contexts, such as driving in complex traffic (Gigerenzer, 2011). The heuristic is functional but not a flawless representation of reality (Hutchinson & Gigerenzer, 2005). Consequently, while effective, mental simulations tend to oversimplify some situations, missing critical variables and interactions.

The distinction between correspondence and coherence is crucial in the study of rationality. Correspondence refers to the alignment of mental models with the actual world, while coherence involves the internal consistency of beliefs and logical reasoning (Hammond, 2007). Ecological rationality often prioritizes correspondence — achieving practical goals in real-world scenarios — over strict adherence to logical coherence. However, the brain's reliance on functional heuristics means these mental simulations may not correspond perfectly to the world's complexities, leading to systematic errors. The inaccuracies in human mental simulation stem from the brain's need to balance speed and efficiency with accuracy. While our mental models are highly functional, they are not veridical—they do not provide an exact copy of the

world (Shepard, 2001). This means that while we can navigate our environments effectively, we are prone to biases and errors, especially when faced with situations that fall outside the patterns our brains have learned to recognize.

Another significant limitation is the reliance on the information available to an individual. The resulting predictions will be flawed if this information is incomplete, outdated, or inaccurate. The brain often compensates by filling gaps with assumptions, which may not always be correct. Mental simulations are inherently subjective. Two individuals with different experiences, knowledge, and perspectives might generate different predictions for the same scenario, leading to inconsistencies and variability. Emotions also play a role, as they can influence mental simulations and lead to overestimations or underestimations of risks and outcomes.

Furthermore, many real-world phenomena are governed by complex, non-linear interactions that are difficult to accurately simulate mentally. Predicting weather patterns, stock market movements, or the spread of diseases involves intricate dynamics better handled by computational models. While humans can learn from experience, this process is slow and often error-prone compared to machine learning algorithms. Machines can process vast amounts of data and adapt quickly to new patterns and changes, offering a significant advantage in predictive accuracy. Mental simulations also lack quantitative precision. They provide general insights and directions but lack the precision and accuracy of mathematical models in physics, engineering, and economics.

Additionally, the quality of a mental simulation heavily depends on the individual's expertise and knowledge in the relevant domain. An expert might generate accurate simulations within their expertise but may not be as effective in another field. Lastly, communicating and sharing mental simulations with others can be challenging. The nuances and details of one's mental model might be lost or misunderstood, leading to miscommunication and errors in collaborative predictions. Regarding this, our internal simulations need extensions into the external world, such as the physical simulations discussed below.

Anyway, the human brain can quite effectively conceive the world around it, create its mental model, store it in memory, and if necessary, continue working with it (e.g., incorporating additional information coming from the environment); it is also possible to perform simulations of possible future scenarios in such a model, which may occur in the world around us. Thanks to this, our ancestors (and the rest of us) can imagine a journey across a scorching savanna to a wounded animal and realize it would be appropriate to hide a water supply along this route, perhaps in an ostrich egg. From the current psychological perspective, we acknowledge that individuals use different strategies to manage anxiety before significant tasks. Let us consider defensive pessimists or individuals on the autism spectrum mentally simulating possible scenarios. Defensive pessimists manage anxiety by imagining various outcomes and planning responses, creating a sense of preparedness. Similarly, individuals on the autism spectrum often cope with uncertainty in complex tasks by mentally rehearsing scenarios and their reactions. This structured

approach to managing anxiety through mental preparation and control highlights the human reliance on mental simulation as a strategy for handling the environment.

However, we can also repeatedly and involuntarily replay traumatic experiences in our minds, such as witnessing a car accident. By searching in such a model, which, besides the cognitive component, is additionally enriched by significant emotional feedback, we can create more straightforward narratives that help us direct our actions not only prospectively but also seek justification for past events and imagine how things would have unfolded if we had behaved differently. Who among us has never repeatedly replayed in their head the first date (no matter how it ended) with the same intense stomachache? Similarly intense, our minds can also simulate job interviews or school exams to imagine how everything would happen if we did things slightly differently. Such retrospective simulation can have several rational causes and ideally result in learning support, for example, by the process of cognitive elaboration, i.e., deeper cognitive processing of information involving analysis, understanding, and creating relationships between thoughts and concepts, which can lead, for example, to specific lessons on what to do or not to do next time in a similar situation.

On the other hand, it is necessary to mention another psychologically relevant aspect of the potential negative consequences of this brain skill. In psychology and psychotherapy, we often encounter the term "rumination" or "ruminative thinking" (Nolen-Hoeksema, 1991) to describe the tendency to constantly think

or dwell on negative thoughts and memories, e.g., about traumatic events. Ruminative thinking can be part of post-traumatic stress disorder (PTSD) or other psychological reactions to trauma. It is the opposite of processing traumatic events, where an individual has trouble interrupting the thought cycle associated with the trauma, and it keeps replaying like an unpleasant and unstoppable simulation. Even here, our “brain-the-simulator” allows us to return to the event and analyze it, but at the same time, repeatedly experience negative feelings associated with the trauma. In the past, such unwanted replays may have had practical significance and helped our ancestors better remember, analyze, and prepare for similar dangerous situations in the future. However, while such a mechanism may have been adaptive in the past, where threats were immediate and mainly of a physical nature, in today's world, such adaptation becomes problematic, if not maladaptive. Repeatedly reliving traumatic memories can contribute to the development of the frequently discussed post-traumatic stress disorder referred to by the acronym PTSD (post-traumatic stress disorder; Brady, 1997), where an individual experiences intrusive thoughts, memory flashbacks, and heightened emotional reactivity as a reaction to trauma and associated stimuli. The evolutionary advantage of this adaptation thus remains questionable today. Such negative simulation, however, can be treated by another psychologically controlled simulation. In this manner, a virtual simulation takes place since they can realistically expose the content to the client in a safe, controlled, and expert-mediated context. Next to PTSD, it applies to anxiety disorders such as phobias, as we will demonstrate below (Juřík et al., 2024a; Varšová et al., 2024). Regarding this, VR-based

psychotherapeutic simulations such as virtual reality exposure therapy may significantly advance the treatment of various psychological diseases.

Mental simulation is a crucial cognitive process in the psychology domain, for instance, in self-report-based psychological testing. When respondents are asked questions like "How do you usually feel when your loved ones appreciate you?" they are prompted to simulate a specific scenario mentally. This involves placing themselves in a given context, attempting to relive or imagine the experience, reflecting on the associated emotions, and then formulating a response. The effectiveness of mental simulation in such tests hinges on the accessibility, accuracy, and vividness with which individuals can recreate these scenarios in their minds. Meta-cognitive processes should also be taken into account. While mental simulation in self-report-based psychological testing can provide valuable insights, its validity is not without limitations. One key issue is the reliance on an individual's ability to accurately recall or imagine scenarios, which can be influenced by various cognitive biases, such as memory distortion or the tendency to respond in socially desirable ways.

Additionally, hypothetical scenarios may not fully capture real-life situations' complexity or emotional intensity, leading to responses that may not accurately reflect how a person would genuinely feel or behave. Furthermore, respondents' emotional and cognitive states during testing can affect their ability to engage in effective mental simulation, potentially skewing results. This variability challenges the consistency and reliability of such methods,

suggesting that while mental simulation can be helpful, it should be complemented with other assessment techniques to ensure a more robust and valid evaluation of psychological constructs.

In summary, human mental simulations are powerful tools that allow us to make quick, adaptive decisions. Despite the crucial evolutionary significance and essential role in our everyday life for individual decision-making and problem-solving, they possess limitations regarding environmental correspondence (Hammond, 2007) and heuristics. Their reliance on heuristics and other mechanisms shaped by past environments is not always accurate. To gain better predictions about the world, understanding these mental processes' limitations and potential biases is crucial for improving decision-making and navigating the complexities of modern life (Simon, 1992). Therefore, they should be supplemented by other methods that are more systematic and objective.

## Physical simulations

As discussed above, mental simulations are not the ultimate tool for reliably predicting the world. If they were, most human activities could be quietly simulated in our heads, eliminating the need for any physical activity taken outside in the dangerous world. However, the amount of available information necessary for accurate simulations is often limited, and additional cognitive limitations considerably lower the quality of any potential mental simulation. Consequently, we sometimes engage in real-world actions and experiments to gather information and test our internal hypotheses to meet the world's expectations better.

The real world can be considered a plane for *physical simulations*, which are rooted in our environment. *Physical simulation* is the process that utilizes physical principles and real objects to imitate a particular system, phenomenon, or process. This technique, which substitutes a real environment with a fake one, is widely used in various fields, including driving simulators (Mokhtar, 2008), nursing education (Rooney & Nyström, 2018), queuing processes (Paidy, 1982), and many other fields, and as such the presence of a human operator is expected. According to the abovementioned simulations typology (Figure 4), physical simulations can also be labeled human-centered simulations when involving humans. Unlike virtual simulation, which occurs in the digital environment of a computer, physical simulation works with real physical objects and environments. Physical simulation may involve creating models and prototypes, experimenting with various materials, testing the functionality

and behavior of real devices and systems, or simulating natural phenomena. Physical simulation involves using physical objects as substitutes for real equipment or systems. These objects are often selected because they are smaller or more cost-effective than the simulated items. This method is often used in industry, research and development, engineering, architecture, medicine, and other fields to test and validate various designs and concepts before their actual deployment or production. Physical simulation allows one to examine and understand the behavior and interactions among objects in the real environment.

Regarding the physical nature of this type of simulation, compared to mental simulations, physical ones may play a central role when gaining a specific skill or bodily based experience, primarily reflecting embodied cognition and grounded cognition frameworks (Barsalou, 2008; Barsalou et al., 2003; Varela et al., 2017). These theories argue that cognition arises from the interaction between the brain, body, and environment, challenging traditional views that separate mind and body. Lawrence Barsalou suggests that simulation re-enacts perceptual, motor, and introspective states stored in multimodal representations, enabling the grounding of abstract and conceptual knowledge. While traditional cognitive science relies on formal logic and computational models, theories, like embodied and grounded cognition, emphasize the body's and environment's role in shaping cognitive functions. This notion is also considered in the case of mental simulations while gaining various cognitive abilities, offering a dynamic and flexible way to understand and predict others' behavior. Here, mental simulation provides a compelling

explanation for how abstract and conceptual knowledge is grounded in sensory and motor experiences, ultimately influencing how we perceive, understand, and interact with the world around us.

On the other hand, the human-centered physical simulation, where the human actor interacts with a specific setting of conditions, considerably promotes the role of embodiment. The relived simulation, which the organism encodes and recalls in a similar future context, represents a valid bodily-based experience accompanied by a vivid emotional and cognitive context. Physical simulations enhance realism, effectiveness, and user engagement. It provides users with a physical or virtual representation of their bodies, increasing immersion and making the simulation more believable. This realism is essential for natural behavior within the simulation, leading to more accurate outcomes. Integrating sensorimotor feedback, where the body's movements and sensory experiences are reflected in the simulated environment, is vital for tasks requiring coordination and interaction with physical objects.

Additionally, it fosters emotional and cognitive engagement, making simulations particularly effective for training in high-stress environments. By allowing for personalization and adaptation, embodiment ensures that simulations are more effective and inclusive, especially in rehabilitation and therapeutic contexts (Riva et al., 2019). Ultimately, a strong sense of embodiment in simulation leads to a better transfer of skills and knowledge to real-world applications (Johnson-Glenberg et al., 2016), making it a key factor in the success of real-world tasks.

*Physical simulation*, which can replicate purely physical processes, also includes a subcategory known as *behavioral simulations*. These focus on the behavior of organisms within environments, aiming to recreate settings and challenges typical of specific contexts or situations. In this context, individuals or groups of individual organisms are immersed into a simulated, life-like context for a specified time. *Social and behavioral simulation* is an emerging field at the intersection of computational social science and simulation modeling and analysis. Modeling how individual and heterogeneous agents "behave" by converting sensory inputs to decisions, emotions, or actions is the essence of behavioral simulation. For example, Stumpf and Dunbar (1990) already addressed the possibilities of business simulations, represented as large-scale behavioral simulations distinguished from computer simulations. The essence of social simulation, analogously, is modeling how these agents "interact" with each other and behave collectively as a group as a function of their behavioral imperatives. When techniques from these two fields are combined, social and behavioral simulation connects individual behaviors at the micro-level to system-level behaviors at the macro-level, allowing the study of dynamic social behavior. This modeling can lead to new insights into social systems' causal mechanisms. Until now, social and behavioral simulation has consisted mainly of innovative applications of simulation to illustrate social or group behavior. More recently, the ability of agent-based modeling, system dynamics, network analysis, and associated techniques to study these micro-macro interactions is unparalleled. This brings us to the interconnection of physical simulation with computers. Physical simulations are often paired with computer simulations

to enhance the teaching of physical experiments (Jun-chao, 2008). However, physical simulations are distinct from computer simulations, which aim to replicate the individual and collective behaviors typically observed in real-world environments. Interactive, physically based simulation, which allows user influence, is a key development area, particularly in computer games and virtual environments (Weber, 2015), as discussed below. The field is ripe for methodological and theoretical advancements.

### *Human-in-the-Loop*

*Interactive simulation*, a specialized type of physical simulation, includes human operators and is often called *human-in-the-loop simulation* (HITL; Karwowski, 2006; Wu et al., 2022). HITL simulation incorporates human operators into the simulation process conducted in various conditions, including constructive ones. Examples include flight, sailing, and driving simulators, where human interaction is integral to the simulation process. HITL simulations are often used when humans' decisions and actions are essential to the functioning of the simulation itself. HITL is a key principle in artificial intelligence (AI), machine learning, and control systems, where human input enhances automated processes, ensuring better performance, reliability, and adherence to ethical standards (Chen et al., 2023; Kumar et al., 2024). HITL integrates human intervention at various stages, including data input, decision-making, and feedback. The goal is to combine human cognitive strengths with the efficiency of automated systems. It improves data quality, algorithmic assurance, and system transparency (Wilchek et al., 2023). This is common in

flight or driving simulators, where the simulation responds to human inputs in real time. HITL simulations involve human interaction with simulation components and are crucial for training, entertainment, and research purposes (Folds, 2015). These simulations can be used in various applications, such as virtual reality-based training (Nilsson, 2015) and driving experiments (Driggs-Campbell, 2014). Integrating human expertise can enhance decision-making processes, address ethical concerns, and facilitate safe exploration in autonomous systems (Chen et al., 2023). They are also valuable for informing models of cognitive processes (Rothrock, 2011) and improving autonomous surveillance using uncrewed vehicles, where human drivers can intervene in critical situations to ensure safety. The effectiveness of human integration in simulation processes has been highlighted, particularly in the design process.

Furthermore, the co-simulation of cyber-physical systems with a human-machine interface has been proposed to investigate human interaction during system development (Pedersen, 2017). In robotics, HITL enables robots to learn complex tasks by mimicking human actions through a process known as learning from demonstration. In healthcare, HITL systems assist in diagnostics by combining AI's pattern recognition with human expertise, leading to more accurate outcomes. HITL helps monitor automated trading systems in finance, allowing human traders to oversee and correct algorithmic decisions during volatile market conditions. HITL offers several benefits, such as remedying AI biases, embedding ethical considerations, and adapting to unforeseen scenarios. However, it also presents challenges, including potential operator fatigue and the complexity of integrating human input with automated

systems. HITL approaches are particularly beneficial in complex, uncertain environments where complete automation may not be optimal (Sreeram & Nof, 2021). Challenges in designing effective HITL systems include methodological, technical, and ethical considerations (Kumar et al., 2024). The future of HITL involves enhancing human-AI collaboration through advanced interfaces, hybrid intelligence systems, and explainable AI, aiming to create intelligent systems that are safe, reliable, and aligned with human values, where the virtual reality discussed below has its place. Ongoing research focuses on improving human-agent interaction, explainability, and the development of society-in-the-loop frameworks (Rahwan, 2017; Retzlaff et al., 2024).

## Physical Simulation Use

When thinking creatively, we can quickly identify numerous practical examples from everyday life where physical simulation serves as preparation for future activities. For instance, children often engage in play that mirrors real-world scenarios, such as caring for others, solving problems, or collaborating in groups. Similarly, traditional practices like hunting rituals among Indigenous peoples serve as a form of rehearsal or training for critical survival skills and community bonding. These examples highlight how simulation, whether through play or ritual, functions as a fundamental way to develop essential skills and adapt to challenges in humans. A range of studies have explored *human-centered physical simulations* from a psychological perspective. Sinclair (2014) and Correa (2016) emphasize integrating psychological and socio-psychological factors in crowd and traffic simulations.

Lambert (1989) and Feldman (1989) have developed computerized case simulations and binary choice experiment simulations to aid in behavior therapy training and hypothesis-testing models. Ward (2011) has reviewed human simulations in behavior analysis, highlighting their potential to facilitate research in complex human behavior. Lastly, Miles (2014) has explored the impact of spatial visual perspective on the real-time behavioral correlates of simulated events. These studies collectively underscore the value of behavioral simulations in understanding and predicting human behavior. Simulation is widely used in education as a cost-effective and safe alternative to real-world equipment, especially when direct access is complicated, expensive, or dangerous (Juřík et al., 2019; Šašinka et al., 2021; Šikl et al., 2024). Learners engage in immersive virtual environments that replicate real-life scenarios, allowing for mistakes and valuable insights, particularly in training for safety-sensitive systems. Educational simulations, including "microworlds," popularized by Seymour Papert (1980), focus on specific tasks or abstract concepts, such as the Logo programming environment. Simulation is also increasingly used in project management and social sciences, providing role-playing and negotiation experiences in disciplines like anthropology, economics, and political science. Additionally, social simulations are employed in staff training for aid and development agencies, and military training heavily relies on simulation for aircraft, armored vehicles, and firearms. Virtual ranges are becoming standard, offering realistic and practical training for armed professionals.

### *Analog Missions*

Analog or simulated missions are designed to replicate specific scenarios and environments to study or train human behavior and performance under controlled conditions (Reagan et al., 2012). This approach has a long-standing tradition in space research, where the isolation and extremity of space conditions necessitate thorough testing of human responses. The concept of analog missions leverages environments that mimic the challenges of space exploration, thus providing valuable insights into the psychological and physiological impacts on crew members. Research into human behavior in isolated, confined, and extreme (ICE) environments has a rich history, traditionally associated with space exploration. Despite the lack of a domestic space program in the Czech Republic, research on human responses in extreme conditions has been actively pursued since 1970'. This is evidenced by over forty years of psychological space research and recent projects involving Czech researchers, such as the MARS 500 mission. Internationally, the history of analog missions extends even further (e.g., Léveillé, 2009; Rader & Reagan, 2013).

Analog research builds upon knowledge from various analogous environments, including polar expeditions, submarine crews, and other simulated missions. These simulated environments vary widely in format: they may be located within research institution buildings, in deserts or volcanic regions, polar regions, or underground settings. Among these, underwater environments offer significant potential for realistic physical simulations. They

provide ecologically valid simulation conditions by inducing isolation and equivalent levels of contextual stress, which are challenging to replicate in "dry" habitats. Underwater environments are particularly effective for simulating the experience of isolation and stress akin to space missions. The awareness of being in a hostile environment and the inability to quickly exit the habitat in case of discomfort mirrors the psychological pressures of space travel, especially. While numerous projects examine human behavior in ICE environments (e.g., Häuplik-Meusburger & Bishop, 2021), most studies have monitored crew responses without the opportunity for effective comparison in controlled environments with different stress factors. In this context, underwater simulators allow for the manipulation of depth, providing a research advantage by enabling experimental manipulation of independent variables—precisely, the actual stress level. This capability enhances the ability to isolate and study the effects of stressors in a controlled setting, thus advancing the understanding of human responses in extreme environments.

### *Assessment Centers*

Assessment centers are a good example of physical simulation in psychology and human resource management. They evaluate candidates' skills, competencies, and potential through structured exercises and tasks that closely mimic real job scenarios – a simulation. Assessment centers (ACs) have long been a cornerstone in human resource management. ACs are particularly valuable in assessing leadership, management, and other key positions, where a comprehensive evaluation of a candidate's abilities is essential for making

informed hiring decisions. The origins of ACs can be traced back to World War II, when they were first used for selecting military officers in the German army. These early applications focused on evaluating candidates through simulations of real-life scenarios that required them to demonstrate their decision-making, problem-solving, and leadership skills under pressure. The success of these early ACs led to their adoption in the business world, with companies like AT&T creating the first private sector assessment center in the 1950s. This approach was soon followed by major corporations such as Sears, Standard Oil, and IBM, which recognized the value of ACs in selecting and developing their workforce. ACs typically involve a variety of job simulation exercises designed to assess different aspects of a candidate's performance. These simulations include in-basket exercises, where candidates are presented with a simulated inbox full of emails and memos that they must prioritize and address within a set timeframe. This exercise mirrors the daily tasks of managerial roles and provides valuable insights into candidates' decision-making and time-management skills. Role-playing scenarios are another common component of ACs, where candidates must engage in situations such as handling a demanding customer or mediating a team conflict. These scenarios assess a candidate's interpersonal skills, emotional intelligence, and problem-solving abilities. Group discussions and case studies are also integral to the AC process. These exercises evaluate teamwork, leadership, communication, and analytical skills by requiring candidates to collaborate with others to solve complex problems or discuss strategic issues. The structured nature of these exercises allows for consistent observation and

evaluation across candidates, ensuring that the assessment process is fair and objective.

Despite their widespread use and apparent success in predicting job performance, ACs have been the subject of ongoing debate and scrutiny, particularly regarding their construct validity—the degree to which they measure what they intend to measure. For example, early concerns about the validity of ACs were raised by Schein (1969), who argued that the effectiveness of performance diagnostics in ACs could vary significantly depending on the position being assessed. For example, while ACs may be highly effective in selecting pilots or clerks, their ability to evaluate accurately managerial potential has been questioned. Further research has continued to explore these concerns. Klimoski and Brickner (1987) highlighted the uncertainty surrounding why ACs are considered good predictors of job success. This skepticism was reinforced by Sackett and Harris (1988), who questioned the construct validity of ACs, leading to a broader inquiry into what exactly is being measured in these assessments. A meta-analysis by Fleenor (1996) consolidated findings from several studies, including those by Joyce et al. (1994), Silverman et al. (1986), Sackett and Dreher (1982), and Turnage and Muchinski (1982), concluding that ACs may not measure general managerial skills as effectively as previously thought, but rather assess situation-specific performance. Fleenor (1996) also provided recommendations for improving the design of ACs to reduce errors and increase their predictive validity. These validity concerns have contributed to a decline in the use of ACs in some regions, where HR professionals are increasingly reverting to traditional

interviews or behavioral interviews or placing greater emphasis on obtaining references. However, ACs remain popular, particularly for roles where the ability to simulate real job scenarios is crucial for making informed hiring decisions.

Regarding this, solutions built on emerging technologies such as virtual reality are discussed. Virtual Assessment Centers (VACs) have emerged as a digital alternative to traditional in-person assessment centers, driven by the increasing digitalization of professional life and the growing trend of remote work (Ariesthiawati, 2022). VACs allow candidates to participate in assessments from different locations at their convenience, offering flexibility and accessibility. They replicate many simulation exercises used in traditional ACs, such as role-playing scenarios and group discussions. However, these activities are conducted in a virtual environment accessed through an online portal. Candidates are often assigned identification numbers to protect their privacy and ensure objectivity, with assessments evaluated anonymously by trained assessors. The primary advantages of VACs include cost-effectiveness, as they eliminate the need for physical space and reduce logistical challenges, and efficiency, as technology facilitates the automatic scoring of tasks and easy access to data. However, VACs also face challenges, particularly in replicating the nuances of face-to-face interactions, which are crucial for assessing competencies like teamwork and leadership.

Additionally, the reliance on technology may introduce bias, especially for roles where computer skills are not essential. VACs are expected to

complement, rather than replace, traditional ACs. They can serve as preliminary screening tools to identify candidates with the necessary skills before a more in-depth evaluation through traditional methods. As technology advances, innovations such as neurolinguistics and eye-tracking cameras may enhance VACs and traditional ACs, leading to more precise and accurate assessments. The future of assessment centers likely lies in balancing traditional and virtual methods to create a comprehensive approach to talent evaluation.

### Psychological Experiments as Physical Simulations

In the context of psychological science, the example of simulation from this definition is also the scientific experiment – a methodically organized procedure carried out to test a hypothesis, demonstrate a known fact, evaluate the efficacy of an intervention, or discover a new effect. For example, behavioral simulations aim to mimic a specific context or situation by placing a group of individuals within a realistic, simulated environment for a designated period. This approach allows them to experience and interact with typical issues and settings relevant to the explored context. According to Keys & Wolfe (1990), “a simulated experimental environment is a simplified and continued situation that contains enough verisimilitude or illusion of reality to induce real world-like responses by those participating in the exercise” (p. 308). A typical example of physical behavioral simulation could be considered the famous experiment "Mouse Utopia" conducted and published by biologist John Calhoun (1962). This study of rodent colonies is well known in the media,

as it sparked considerable public outcry upon the publication of results, primarily due to its dystopian implications. In 1968, Calhoun established a colony of rodents that had all their basic life needs met and survived under more than favorable conditions in the basement of the Maryland National Institute of Mental Health. The habitable structure for rodents provided its tenants (in this iteration, laboratory mice) with all comforts and safety, sufficient food and water resources, comfortable temperature, and ventilation.

The entire space was divided into 256 separate habitats, so each mouse had its own space. This resembles the earlier definition of creating a physical model representing the system's or process's fundamental aspects. Calhoun aimed to place eight rodent individuals here and observe how the colony's growth would develop. Today, we already suspect that, like a diligent student of the Bible, his main concern was the dystopian sensation. For this reason, he had already tried this experiment twenty-four times before, mostly with uninteresting (or at least not shocking) conclusions (see, e.g., Ramsden & Adams, 2009). But back to the simulation. In our terminology, the biologist decided to conduct a physical simulation of the system based on input parameters, continuously observing the development of this system and subjecting the collected data to analysis. A scientific experiment can, therefore, be an example of physical simulation. Moreover, how did the simulation of the mouse utopia turn out? Although, at first glance, it seemed that the mouse population thrived and grew in this simulated paradise, undesirable phenomena gradually appeared. Available results inform us that with the increasing population, social problems emerged, such as aggression among

individuals, changes in behavior, or decreased ability to care for offspring. Dominant alpha males began to resign from their roles, leading to chaos and degeneration of the social structure. The experiment showed that negative social phenomena such as stress, behavioral degradation, and reduced reproductive success can occur even in an environment of apparent abundance and prosperity. The results of the study caused a sensation. And a stormy response. After all, it is all about us, about people! The purpose of the simulation is fulfilled; the real effects of alternative conditions and procedures were depicted by imitating a real-world situation in a controlled, interactive environment. Let us set aside the dystopian undertone of this experiment, which still raises concerns about the future of humanity in both past and present societies because this study is still interpreted in precisely this spirit – as an unflattering prognosis for the future of our species. Let it be our consolation that this experiment was not the first one conducted by Calhoun. However, it was the twenty-fifth experimental device of this type and the third animal species on which the simulation was performed. The previous 24 simulations thus yielded results that would draw some attention regarding the outlook for our species in the future. Moreover, most scientific interpretations emphasize that the conclusions of the experiment conducted on mice related to humans will be at least unreliable (Ramsden, 2011).

In human-centered famous experiments, let us remind Phillip Zimbardo (1972), Stanley Milgram (1963), and Mazufer Sherrif (1956) all these are examples of famous scientists who created *physical simulation* contexts to observe how

humans would perform. There is no need for an in-depth introduction to these famous experiments.

## Critical Reflection on the Significance of Physical Simulations

Physical simulations, while valuable, present significant logistical challenges. They demand considerable time and resources and are inherently tied to the physical world, where conditions cannot be easily or dynamically altered. Human cognition is basically of an interactive nature, and as such, it cannot be effectively observed in a static condition (Cañas, 2021; Dreyfus, 1980; Juřík et al., 2018). Further, when simulations require the cooperation of multiple participants, physical meetings are necessary, which ties the process to specific locations and complicates scheduling. Additionally, physical simulations, such as experiments usually created in laboratory conditions, often suffer from issues related to ecological validity—the extent to which the findings can be generalized to real-world settings. One of the key figures who criticized experimental research for its limitations in identifying dynamic cognitive processes is Hubert Dreyfus (1980). From the strong positions of philosophy, Dreyfus argued that traditional experimental methods, particularly those rooted in cognitive science and artificial intelligence perspectives, fail to capture human cognition's fluid, context-dependent nature. He believed these methods often oversimplify cognitive processes by treating them as static and isolated rather than dynamic and intertwined with the real-world environment. Another prominent critique comes from the perspective of embodied cognition, where scholars like Francisco Varela and his colleagues (Varela et al., 2017),

alongside Dreyfus, argued that cognition is not just computational but deeply embedded in the sensorimotor experiences of the body. They emphasized that experimental research often neglects cognition's dynamic and situated nature, constantly shaped by environmental interactions. These critiques highlight the need for approaches that consider the complexity and dynamism of cognitive processes beyond what traditional experimental research often addresses. These limitations suggest virtual reality as an alternative (Juřík et al., 2018; Juřík et al., 2019; Loomis et al., 1999). VR offers a flexible and dynamic environment where conditions can be easily modified, and participants can interact regardless of their physical location, making it a powerful tool for overcoming the constraints of traditional behavioral simulations.

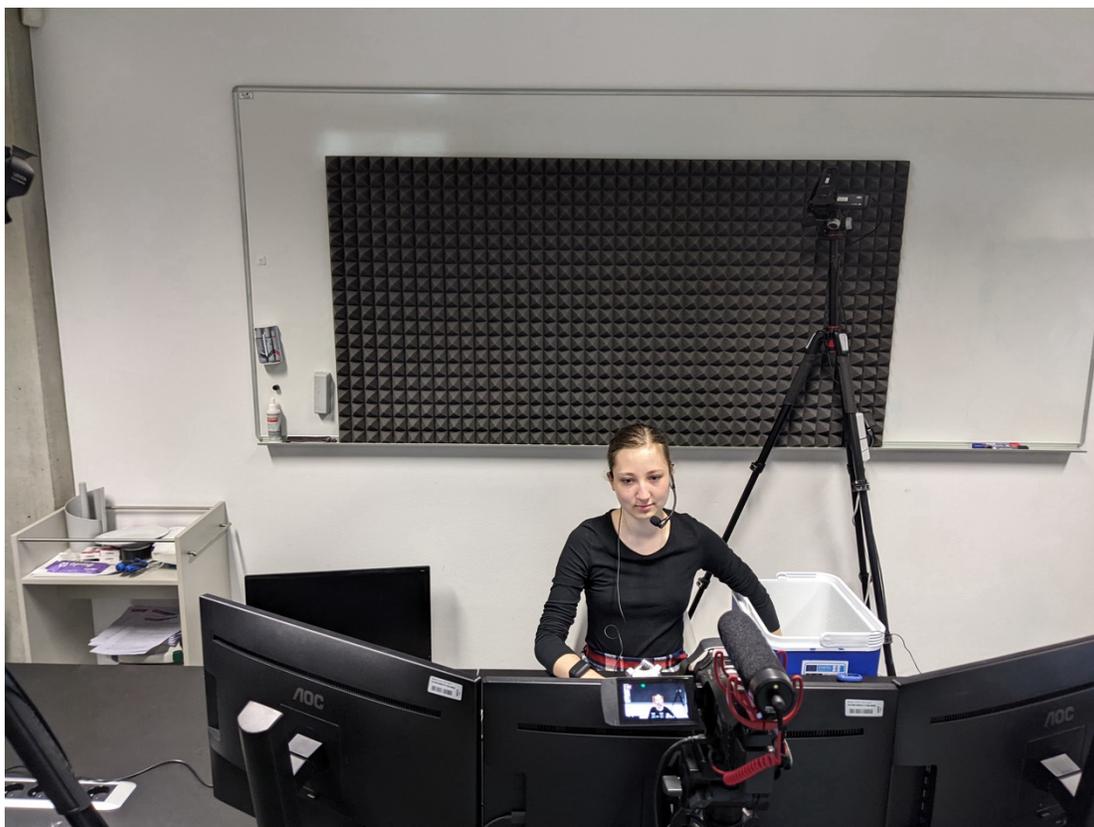
#### *Studying the Interactive Nature of Human Behavior Via Simulation*

The above-mentioned notion of safety and control in virtual simulations potentially addresses a paradox of scientific research, which lies in the longstanding compromise arising from the pursuit of precise and objective measurement of human behavior or cognition, often referred to as the Gordian knot of psychological experimental research (Kothgassner & Felnhofner, 2020; Děcký et al., 2024). Researchers aiming to ensure strong internal validity frequently design experiments that significantly limit external influences, thereby sacrificing some degree of ecological validity (Juřík et al., 2018; Parsons, 2015). Ecological validity refers to the assumption that study results should be applicable in real-world settings, reflecting the phenomena' natural occurrences. In practice, attempting to transfer results from a strictly controlled

laboratory experiment (see an example of the experimental setting in Figure 9), even if conducted with a high degree of methodological expertise, often fails when applied to real-world situations.

**Figure 9**

*Example of laboratory experimental setting measuring stress in speech*



*Note.* Photo by Jan Peřán, used with the author's permission.

However, attempts to transfer findings from controlled laboratory experiments to real-world situations often fail because the experimental context does not

fully replicate the complexities of real-life environments. This issue is encapsulated in the "real-world versus laboratory dilemma," as discussed by Hammond and Stewart (2001). This philosophical problem, rooted in the early days of modern science (Campbell, 1957; Campbell & Stanley, 1967) and further elaborated by thinkers like Dreyfus (1980), gains practical significance in applied fields that rely on scientific research outcomes. Disciplines such as traffic psychology (Juřík et al., 2021), crisis management (Molka-Danielsen et al., 2018), and others that involve human factors often grapple with this dilemma. For instance, psychological tests used in traffic psychology may assess an individual's competencies or skills without placing them in real driving conditions. This practice raises concerns about whether these assessments can accurately predict behavior in everyday life, where social paradigms and environmental factors differ significantly from those in a controlled laboratory setting. The paradoxical nature of this problem was already apparent in the 1940s when cognitive research was in its infancy. Egon Brunswik, a foundational thinker and statistician, criticized the direction of psychological research at the time, describing it as overly focused on "narrowly defined problems of artificially isolated proximal or peripheral mediating techniques, which are in no way representative of broader life patterns" (Brunswik, 1943, p. 262). Brunswik argued that the aspects of human psychology being studied were disconnected from real-life contexts. He posited that we do not perceive the world directly; our perception is mediated through our senses, which connect to the brain—a powerful simulation tool. The brain's representation of the world is a distorted reflection of reality, not

an exact copy as discussed above (Bone & Ellen, 1992; Brown et al., 2002; Dickson, 1982; Hoch, 1984; MacInnis & Price, 1987; Shepard, 2001; Sherman et al., 1985). For example, the world may appear vastly different to a depressed individual compared to an optimist or to someone with schizophrenia. Each brain creates its version of reality, corresponding to the objective world but never fully coherent. Brunswik introduced the concept of proximal cues, the sensory inputs that mediate our awareness of distal phenomena (i.e., the external world). When a distal phenomenon becomes apparent, it offers a range of potential interactions the observer can engage in to gain better awareness or utilize. These interactions are shaped by the nature of the distal phenomenon itself and by various factors related to the availability and perception of its properties. Gibson's principle of affordance (e.g., Greeno, 1994) complements Brunswik's theory by describing objects in terms of their perceived suitability for use by the observer. Affordance refers to the potential interactions an object offers, which vary depending on the object's state, the context in which it occurs, and the observer's history, experiences, and abilities. The observer's interactions with proximal cues directly influence subsequent interactions, which can vary based on their choices. As these interactions unfold, the nature of the proximal cues can change, with some information becoming clearer or taking on new meanings, thus providing the observer with a fresh perspective on the distal phenomenon. This interaction between proximal cues and the observer's characteristics (such as experiences, abilities, and dispositions) may be labeled "interactional affordance." Despite Brunswik's foresight, this critical perspective gained traction in psychology

much later. Ulric Neisser, the father of cognitive psychology, reflected critically on the artificial nature of stimuli used in laboratory experiments (Neisser, 1976). Despite being highly sophisticated, he argued that these stimuli were abstract, disjointed, and only marginally relevant to real-world phenomena. Neisser emphasized that human cognition evolved in response to specific environmental principles, shaped by spatiotemporal aspects and natural laws, and is thus ecologically reactive (Hammond & Stewart, 2001). He contended that humans should not be understood merely as passive recipients of external inputs, as is often the case in laboratory research, but rather as active agents interacting with their environment. This interaction involves various aspects, including individual expectations, motives, and goals. The embodied cognition approach further emphasizes these assumptions about perception and cognition's interactive and motor aspects (Barsalou, 2008; Barsalou et al., 2003; Varela et al., 2017). Information processed in the context of physical activity or interaction is of a different quality than information merely visually conveyed and passively received (Meteyard et al., 2012). Neisser's perception cycle highlights the sensorimotor nature of cognition as dynamic, time-varying, and context-dependent. Similar to Brunswik's theory, perception is considered a cyclical activity based on the proactive motor action of the observer. This cyclical process provides more proximal cues, which can lead to better information saturation and more appropriate decision-making. While thinkers like Neisser and Norman (1999) significantly shaped our understanding of cognitive and information processing, much empirical research in psychology focuses on mental phenomena as static and isolated, better fitting the

requirements for high experimental control. Despite efforts to incorporate ecological validity into laboratory research, there is often a lack of clarity on how to achieve it (Holleman et al., 2020). However, recent technological advancements, particularly in virtual reality, offer a potential solution by creating realistic simulations of the real world within a research laboratory. Virtual reality tools can immerse individuals in artificially created yet realistic environments, providing sensory immersion and extensive measurement opportunities. This approach could bridge the gap between the laboratory's controlled conditions and the outside world's complex realities, offering new possibilities for ecologically valid research outcomes.

## Virtual Simulations

Throughout human history, emerging technologies have played a crucial role in bridging the existing instrumental and economic gaps. This dynamic has been evident across various eras, showcasing how innovation fosters progress and equalizes opportunities. Let us consider the Industrial Revolution, which marked a significant leap in bridging technological and economic divides. Innovations like the steam engine, mechanized looms, and the assembly line revolutionized production processes, leading to mass production and reduced costs. Similarly, the advent of information technology once again demonstrated the power of emerging technologies to bridge these gaps. The development of computers, the internet, and telecommunications revolutionized how information is processed, stored, and shared. These advancements democratized information, education, and communication access, reducing knowledge and economic opportunity disparities. Moreover, by that time, it also revolutionized perception and understanding of human cognition by adopting human-computer metaphors.

As discussed above, for making reliable predictions about the world around us, our mental simulations may not be precise enough, and physical simulations possess ecological validity limitations and may be logistically challenging and costly. Humanity can overcome disparities and build a more equitable and prosperous future by continually embracing and advancing new technologies. In this manner, one of the frequently discussed technologies is represented by virtual reality and, consequently, *virtual simulations*. *Virtual*

*simulation*, this dynamically emerging topic, still lacks precise terminology and definition. The older definitions consider *virtual simulation* as the recreation of reality depicted on a computer screen; more lately, it is seen as simulation involving real people operating simulated systems, often integrated with haptic devices, usually used for on-screen procedural training (McGovern, 1994; Robles-De La Torre, 2011). Tarver (2022) sees it as a learning tool that uses specific HW and SW technologies for simulation-based training within a digital domain. Another definition characterizes it as a type of simulation that places humans in a central role, requiring the exercise of motor control skills (e.g., flying an airplane), decision-making skills (e.g., committing fire control resources to action), or communication skills, for example, functioning as members of an air traffic control team (Hancock et al., 2008). It is necessary to add that next to the training, in the field of psychology, virtual simulation also has enormous diagnostic potential (see, e.g., Juřík et al., 2021).

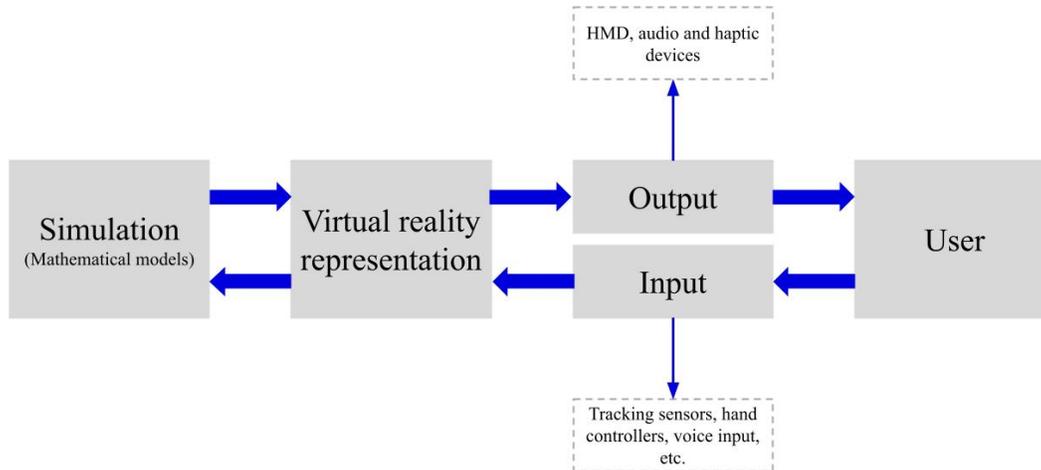
Virtual simulation, a computer-based technology for bringing individuals into immersive, artificial contexts, gained significance only recently with the development of computer graphics; while originated in 1960' and was re-discovered around 2011, it continuously develops, making a promise of remote but fully immersive social activities, living in alternative worlds or places and potentially even promoting something we can label as mental teleportation – virtually transport human mind regardless physical body into an entirely different context. This progress includes developing new VR hardware forms (e.g., displays), computers' rapidly increasing computational power, and growing user support and base. Nowadays, virtual reality is utilized to

simulate situations in various domains. *Virtual simulation* is creating and conducting a simulation of a particular system, environment, or event using computer programs and VR technologies. This simulation allows users to interactively explore and experiment with the modeled system or environment through a computer interface. Virtual simulation can include various elements such as graphics, sound, motion, and interaction to simulate the real environment or event as faithfully as possible. In the context of this thesis, virtual simulation is considered human-centered because it involves a human actor/operator. However, since it can be enhanced by various computer technologies (Ugwitz et al., 2021) such as interactive, automatic, or semi-automatic environment properties, triggering, AI-based agents or processes, it can be considered partly constructive, i.e., hybrid, as discussed above (Andrews et al., 1998).

The generic virtual simulation model was developed by Renganayagalu (2019) and can be seen in Figure 10. The scheme illustrates the functioning of a VR-based simulation. The VR system comprises input and output devices, which interface with the simulation's mathematical models. Users engage with the VR system through these input and output devices, and the virtual environment within the simulation is updated in near real-time based on the user's inputs.

**Figure 10**

*The generic model of virtual simulation*

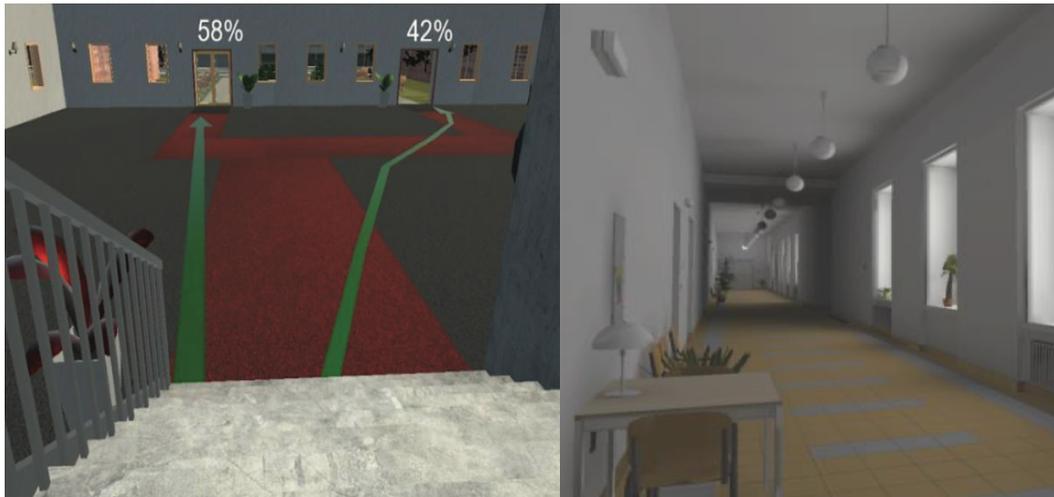


*Note.* Adapted from Renganayagalu (2019).

Virtual simulation can be used in various domains, including training and education (e.g., flight simulators for aviation), industry (e.g., simulation of manufacturing processes), healthcare (e.g., surgical simulators for training), science (e.g., simulation of climate change), and many others. Virtual simulation aims to provide users with a realistic experience and the opportunity to experiment with different scenarios and conditions without the risk of actual harm or costs. The examples of virtual simulation visualization in evacuation research can be seen in Figure 11.

**Figure 11**

*Examples of first-person POV in the virtual simulation of evacuation behavior*



*Note.* Adopted from Snopková et al. (2022; left) and Snopková (2023; right), used with the authors' permission.

As discussed below, virtual simulation offers an excellent opportunity for a realistic but, at the same time, strictly controlled and safe environment (Juřík et al., 2019; Juřík et al., 2018; Juřík et al., 2021; Loomis et al., 1999; Ugwitz et al., 2019; Ugwitz et al., 2021), from which the psychological research may enormously benefit.

## Virtual Reality

Previously confined mostly to movies, today, we encounter it in libraries, gaming arenas, showrooms, shopping malls, universities, media, and social networks. It is one of the most discussed concepts of our time, even though it was first used in 1960'. The increasingly mentioned term "virtual reality," or its

acronym VR, typically refers to the application of computer technologies to generate interactive, three-dimensional environments that give users a sense of presence within them, as argued by Bryson at the end of the last millennium (1999). Like in other areas, there are naturally various definitions of VR. Another recent definition states that VR is an artificial environment based on computer software that convinces people they are in a real-like environment (Quaye-Ballard, 2008). Let us continue. In 2018, VR was described as a computer-generated environment designed to simulate the feeling of a person's physical presence in a specific, reality-like environment or situation (Technopedia, 2018).

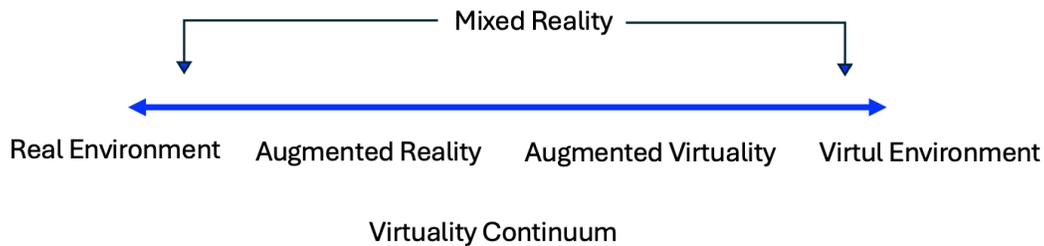
Additionally, VR generally refers to artificial virtual environments and interfaces for human-computer interaction. We will notice a common theme in all these definitions: VR aims to convince or at least compel the user to forget reality and believe they are in an alternative environment, albeit real for them. This ties into a key concept in VR, known as "presence," which is the phenomenological experience of being present in an alternative reality, a topic we will discuss below. Before that, let us offer a classification of various virtuality types.

### *Classification of Virtual Reality*

When it comes to delineating what is and is not virtual reality, we can look at the so-called "virtuality continuum" (see Figure 12) created by Milgram and Kishino (1994).

**Figure 12**

*Milgram and Kishino's Mixed Reality on the Reality-Virtuality Continuum*



*Note.* Adapted from Milgram & Kishino (1994).

On this hypothetical continuum, with the real world/environment at one end, where we live, we encounter, on the way towards artificial virtual environments, what is called "augmented reality" and "augmented virtuality." The reader of this text may have already encountered both. While augmented reality is familiar from movies about fighter pilots who wear a so-called heads-up display showing flight information in their field of view, augmented virtuality is known, for example, from virtual pub tours. Augmented virtuality is a hybrid reality framework that integrates real-world elements into a virtual environment. Unlike augmented reality, which overlays digital content onto the physical world, or virtual reality, which fully immerses users in a digital setting, augmented virtuality focuses on embedding physical elements into a primarily virtual context. Virtuality typically refers to a virtual environment, which a fully interactive spatial layout may not always represent.

As Lucie Mendelová aptly states in her excellent book on virtual reality (2019), the term "virtual reality" is an oxymoron, as it combines two inherently contradictory concepts. The term "virtual," meaning apparent or unreal, is juxtaposed with "reality," which is what we perceive and experience as real and physical. How can the term VR have penetrated professional dictionaries and everyday language? Mendelová (2019) elaborates, arguing that given that the human perceptual system readily adapts to our sensory experiences and because vision, the key sense for current virtual reality technologies, is the most dominant in the perceptual apparatus of higher primates (a million neurons process visual stimuli compared to 30,000 for auditory stimuli; Šikl, 2012), we quickly tend to believe what we see. The unreal suddenly becomes real for our minds, and "virtual reality" becomes meaningful.

When we hear the term "VR," we likely immediately envision a typical virtual reality headset (a so-called Head Mounted Display; HMD). This is the most powerful tool for visualizing virtual worlds until humans are introduced into virtual worlds through direct brain stimulation. Devices for accessing virtual reality can be divided into two categories: VR perception devices and VR manipulation devices. VR perception devices can stimulate human senses and create the illusion of presence in a simulated environment. Virtual reality is usually powered by real-time computer graphics and uses display devices such as computer monitors or VR goggles. Sound can be produced by headphones, which may include spatial signals, creating the impression that sound is coming from different directions. VR manipulation devices typically capture user movements and transmit them into the created environment, for

example, using a mouse or keyboard. Virtual environments consist of various visual elements and are often accessible by displaying images to users and capturing their movements. To elaborate, VR generally refers to an artificial virtual environment and an interface for human-computer interaction. A common theme in all definitions of VR is that, aside from being a computer-generated product, its goal is to create the impression for the user that they are in a real environment. This is a key dimension and the fundamental essence of the technology. The aim is to convince the person, or at least make them momentarily forget, that they are not in the objective reality but in an alternative, yet seemingly real, environment.

Being immersed in a virtual environment is often called *presence* (Lee, 2004; Mania et al., 2006; Mania & Chalmers, 2001; Slater, 2018), the phenomenological experience of being there in an alternative reality. Presence concerns the subjective experience of truly feeling as though one is "there" within the virtual world (Slater & Usoh, 1993). Slater and Wilbur (1997) describe presence as a state of consciousness closely tied to the sensation of being in a particular place, characterized by four key aspects: inclusiveness, vastness, surrounding nature, and vividness. In psychological research, the term presence, or more specifically, spatial presence, describes this immersive experience. A strong sense of presence within a virtual environment is often linked to improved performance outcomes, such as, for instance, enhanced learning (Bailenson et al., 2006).

In virtual reality, presence is a key factor, but it is equally important to consider other phenomena, such as immersion, fidelity, and engagement, which significantly influence the user experience. Immersion in VR is the perception of being physically present in a non-physical world. This perception is created by surrounding the user with images, sounds, or other stimuli that form an engrossing, total environment. Ernest W. Adams (2004) identifies three main categories of immersion: tactical, strategic, and narrative. Tactical immersion occurs during tactile operations that require skill, where users feel "in the zone" as they perform actions that lead to success. Strategic immersion is more cerebral and associated with mental challenges similar to those chess players face when selecting the best solution from multiple possibilities. Narrative immersion involves becoming deeply invested in a story, similar to the experience of reading a book or watching a movie.

Engagement refers to the user's involvement and active participation in the virtual environment. In educational contexts, engagement is linked to the state of "flow," a concept defined by Csikszentmihalyi (1990) and further explored by Hossain and Wigand (2004). Flow represents a state of deep focus and immersion, which significantly affects how users interact with VR. Studies by Goel and Prokopec (2009) also highlight the importance of social aspects in virtual simulations, suggesting that communication within VR can enhance user engagement.

Fidelity, in particular, plays a critical role in the effectiveness of VR simulations. It refers to the degree of accuracy with which the virtual environment

replicates real-world conditions. High fidelity ensures the VR operator can interact with the user interface (UI) effectively. According to Hochmiz & Yuviler-Gavish (2011) and Gopher, Weil, and Bareket (1994), good fidelity enhances the quality of virtual simulations, making them more immersive and functional. Fidelity can be divided into different types. Cognitive fidelity represents the extent to which the simulated cognitive activities mirror the functional aspects of the real world, even if the visual representation is different. As Kaiser and Schroeder (2003) noted, a high level of cognitive fidelity may not replicate every visual detail of reality. However, it maintains the essential features of the interface at a functional level.

On the other hand, physical fidelity aims to simulate all aspects of reality as closely as possible, providing a highly realistic experience. This type of fidelity is often achieved using head-mounted displays, which surround the user with stimuli that mimic the real world. In addition to these types of fidelity, there is also the concept of functional fidelity, which focuses on how well the virtual environment replicates the functional performance of real-world scenarios, and psychological fidelity, which relates to the subjective feeling of immersion that the operator experiences. These different aspects of fidelity contribute to the overall realism and effectiveness of the VR experience.

### *Immersive VR Classification*

Regarding the above-mentioned, the technology-based or device-based continuum offers another perspective on VR classification. We can see desktop VR or so-called low-end VR types, which display three-dimensional images on

a standard computer screen. Contrasting desktop VR is immersive VR (iVR), which utilizes peripheral devices such as head-mounted displays (HMDs) and considerably promotes the above-mentioned presence phenomena. These devices, often supplemented with headphones, microphones, and other sensory inputs, are engineered to provide highly realistic graphical experiences while minimizing external distractions such as visual or auditory noise. Within these virtual worlds, users can be represented through a virtual avatar, which acts as the user's proxy within the VR space, often from a first-person perspective. Alternatively, the user may experience the virtual environment through a virtual camera viewpoint, which does not necessarily include a visible avatar but still allows for interaction and navigation within the space. Immersive VR aims to transport the user entirely from the physical world into a virtual one. Fox and colleagues (2009) described three VR categories based on the level of immersion they provide.

- 1) *Non-immersive VR* (non-iVR) is commonly encountered by individuals in daily life — it is widely accessible and used across various technologies. This type of VR is generated by desktop computers or smartphones, displayed on 2D screens, and controlled using a keyboard or mouse. User actions are captured and reflected in the virtual environment.
- 2) *Immersive VR* (iVR) uses headsets with built-in displays that capture head movements and translate them into the virtual environment. The headset features two LCD screens in front of the user's eyes, providing

a broad stereoscopic view of a computer-generated environment. The user's head movements are captured by an accelerometer, allowing the VR system to render a 3D environment that changes with the head's orientation, creating the impression of real 3D perception.

- 3) *Fully Immersive VR* (fully-iVR) combines immersive VR with numerous room sensors, enabling users to move around and have their movements reflected in the virtual environment projected into their headset. This setup allows users to physically move, with optical or magnetic sensors capturing their position and movements.

The categorization of VR types is inconsistent in the literature and evolves with technological advancements. What was considered immersive VR in the 90s is now seen as non-immersive (Sedlák, 2022). The definition of fully immersive VR is debated, with discussions about incorporating additional sensory modalities into VR interfaces. Future advancements may redefine current categories, potentially creating new classifications or shifting what is now fully immersive VR to a different category.

## Virtual Environments

Alongside the term VR, one may encounter the abbreviation VE (virtual environment) in the literature (Jerald, 2015; Juřík et al., 2018; Ugwitz et al., 2021; Ugwitz et al., 2019), which refers to specific artificial environments. VE stimulates key sensory channels, primarily visual and auditory, with possible extensions to haptic feedback. VR technologies offer the advantage of creating

entirely original, realistic, dynamic, and interactive environments or models while remaining comprehensible despite their complexity. The space bridging the real and virtual worlds can be divided into two key domains: the motor space and the visual space (Argelaguet & Andujar, 2013). The motor space, or the working space, refers to the physical area where user interaction occurs in front of a screen. It is constrained by available degrees of freedom and the features of virtual reality technology, including peripheral devices.

In contrast, the visual space exists behind the screen as the visually perceived representation of the environment, typically created using computer graphics. The accessible visual field defines this space. Designing user interfaces for these spaces is a prominent aspect of human-machine interaction.

#### *Visual Space – The Challenge of Visualization*

Visual space relies on graphical design for representation, known as visualizations. Visualization involves graphically representing specific issues and designing graphical displays in line with information-processing principles (Goettl et al., 1991). Different graphical representations can facilitate or inhibit problem-solving (Bauer & Johnson-Laird, 1993). Computer-generated visualizations are generally presented on 2D screens, which can limit depth perception, but also via fully immersive head-mounted displays, which incorporate various visual cues to simulate real-world properties, including monocular and binocular depth cues, essential for spatial perception (Goldstein, 2009). Monocular cues, such as linear perspective, texture gradient, and shading, offer spatial perception even without binocular vision, while

dynamic monocular cues like motion parallax enhance this perception further. Based on input from both eyes, Binocular cues contribute to stereopsis and depth perception. Different types of 3D visualizations use these cues to varying extents; pseudo 3D relies on monocular cues without requiring 3D devices, while real 3D visualizations use both monocular and binocular cues for a more immersive experience, often requiring stereoscopic technology.

### *Motor Space – The Challenge of Interaction*

In addition to visualization, the interactive aspect of virtual reality plays a crucial role in shaping human behavior. Embodied cognition emphasizes the integration of body schema and motor activity into cognition and human-computer interaction (Anderson, 2003). The interactive level of VR interfaces considers the situated nature of cognition, emphasizing real-time and active engagement (Wilson, 2002). Various tracking and controlling devices enable users to interact with virtual environments, offering different degrees of freedom for movement. These devices, including 3D mice, Leap Motion, Kinect, data gloves, Wii Remote Controller, and motion capture systems, cater to diverse user needs and preferences, enhancing the immersive experience of virtual reality while posing challenges in terms of comfort and usability.

### *Immersive Virtual Environment*

An Immersive Virtual Environment (IVE) is a digitally created simulation that allows users to experience and interact with an environment as if it were real (Chocholáčková et al., 2023; Juřík et al., 2021; Mania et al., 2006). These environments are designed to fully engage the user's senses, often through VR

technologies, creating a sense of presence or immersion (Slater, 2003). This means users feel as though they are physically present in the virtual environment rather than merely observing it. When the simulation's essential perceptual and cognitive elements are effectively captured, these methods are anticipated to assess and potentially enhance performance in corresponding real-world tasks (Borglund et al., 2021; Juřík et al., 2021). One key feature of IVEs is immersion, where the user's sensory input, such as vision, hearing, and sometimes touch, is dominated by the virtual environment, minimizing awareness of the real-world surroundings. Another important aspect is interactivity, which allows users to engage with and influence the environment in real-time, whether by manipulating objects, moving through virtual space, or responding to dynamic changes within the simulation. IVEs also aim to achieve high fidelity, replicating real-world conditions accurately to enhance realism and user engagement. These immersive environments have diverse applications, from education and therapy to training and entertainment (Šašinka et al., 2018). For example, they are used in flight simulators for pilot training, therapeutic interventions for treating anxiety disorders, or educational settings to simulate historical events or scientific phenomena. By providing controlled, immersive experiences, IVEs offer a powerful tool for simulating real-life tasks or scenarios in a virtual context.

## Critical Reflection on the Significance of Virtual Simulation

VR technology is rapidly emerging as a significant tool in psychology, offering new opportunities for research, therapy, and education. As we navigate the intricate relationship between psychology and technology, it becomes crucial to reflect on VR's broader implications and significance within this discipline. This chapter aims to critically explore how VR can bridge the gap between traditional psychological practices and the increasingly technological landscape while addressing the resistance often exhibited by students and professionals towards integrating science and technology into psychological work on one hand and exaggerated expectations on the other.

We must acknowledge that, besides the above-mentioned possibly subjective perspectives, VR technologies challenge several limitations and disadvantages that must be carefully considered. One of the most prominent challenges is cybersickness (Jerald, 2015), a condition similar to motion sickness affecting many users. Symptoms such as nausea, dizziness, headaches, and eye strain can result from the sensory conflict between the visual cues received in the virtual environment and the physical sensations—or lack thereof—experienced by the body. This disconnect can make VR uncomfortable and unusable for some individuals, limiting its wider adoption. Cybersickness affects 40 to 70 percent of users, manifesting through symptoms like headaches, eye strain, and nausea (Gallagher & Ferrè, 2018). This condition arises from a sensory conflict between visual and motor signals. While the eyes perceive motion within the virtual environment, the vestibular system, responsible for

detecting physical movement, senses no corresponding motion (LaViola, 2000). This mismatch confuses the brain, leading to discomfort. Theories suggest that the body interprets this mismatch as a sign of poisoning, prompting nausea as a defense mechanism. Understanding and addressing cybersickness is crucial for the broader adoption of VR technology. Cybersickness is mainly associated with head-mounted displays (HMDs) and other immersive technologies that create a strong sense of presence in a virtual space. Several factors contribute to cybersickness, including the quality of VR technology, the nature of the virtual content and interaction with it, and individual user differences. Lower frame rates, latency issues, and poor graphics can exacerbate symptoms and rapid or unnatural movements within the virtual environment.

Individual susceptibility also varies, with factors like age, gender, and prior experience with VR or motion sickness influencing the likelihood of experiencing cybersickness (Jerald, 2015). Anxiety levels and susceptibility to other forms of motion sickness are also predictive factors (Paillard et al., 2013). Recent studies have focused on mitigating cybersickness to make VR more accessible and comfortable. Strategies include improving visual fidelity and frame rates, implementing motion prediction and stabilization techniques, and designing user interfaces that minimize abrupt movements. Gradual acclimatization to VR environments may also help users adapt and reduce the incidence of cybersickness over time (Rebenitsch & Owen, 2016). Despite ongoing research, cybersickness remains a significant challenge, with continued efforts to enhance VR experiences to minimize discomfort and maximize user engagement and safety. Physical discomfort is another

significant issue associated with VR use. Prolonged sessions can lead to eye strain, fatigue, and even musculoskeletal discomfort from holding certain positions or wearing heavy headsets for extended periods. These physical challenges can discourage long-term use and limit the practicality of VR in various settings.

The cost associated with VR technology is another major drawback. High-quality VR systems require expensive hardware, including headsets, controllers, and powerful computers capable of rendering complex virtual environments. In addition to hardware costs, developing VR content is resource-intensive, requiring significant time, expertise, and financial investment. These factors contribute to the overall expense of VR, making it less accessible to the general public and restricting its use in educational, professional, and entertainment settings. Despite continuous advancements, VR technology still faces several technical limitations. Issues such as low resolution, latency, and demand for substantial computing power can detract from the immersive experience, reducing VR applications' overall quality and realism. These technical hurdles must be overcome to enhance the user experience and broaden the appeal of VR. Content availability is another concern, as the range of high-quality VR experiences remains relatively limited compared to traditional media. Developing engaging and immersive VR content requires significant effort, and as a result, users often find fewer options to choose from. This limitation can reduce the appeal of VR, especially for those seeking diverse and varied experiences.

Moreover, VR can contribute to social isolation, as it often requires users to be fully immersed in a virtual environment, effectively cutting them off from real-world interactions. This isolation can be particularly concerning when social engagement and interaction are important, such as in educational or collaborative work environments. The learning curve of VR technology also presents a barrier to widespread adoption. Many users, particularly those not technologically inclined, may find VR systems challenging to use and navigate. This can lead to frustration and decrease the likelihood of continued use, further hindering the technology's potential. Finally, VR raises ethical and psychological concerns, and in the domain of psychology, it may incline to the issues discussed at the beginning of this chapter. The immersive nature of VR can lead to desensitization to real-world violence or confusion between reality and virtual experiences. These psychological impacts and ethical questions regarding the content and its effects on users underscore the need for careful consideration in developing and deploying VR technologies.

Overall, while VR holds great promise, these disadvantages highlight the importance of addressing its challenges to ensure that the technology can be used effectively and safely in various applications. Despite efforts at demarcation, modern and ever-evolving technology will inevitably catch up with us in every field of human activity. Even young psychologists will recognize that an inherent part of humanity and human culture lies in seeking new paths and creating more effective tools. For even the most clinically oriented individuals, the application of virtual reality in areas such as psychotherapy (Juřík et al., 2024a; Juřík et al., 2024b), treatment of anorexia and

bulimia, or training for neurodegenerative diseases, can be a positive development, bringing the discussion about technology back to its rightful focus: humans. Therefore, at the center of psychologists' research interests, at least three levels of virtual reality research emerge (Fox et al., 2009).

First is represented by VR as a subject of research. This involves investigating VR as a medium, as a technology that influences the human user, their experiences, and emotions. Part of this research also includes the fundamental question of to what extent there is a similarity between experiences in virtual reality and experiences in the real world and the related study of phenomena specific only to VR.

Second, we can focus on researching specific applications of VR — this involves studying the design and functioning of VR applications to solve real problems people encounter. Whether it is sports applications aimed at helping people maintain good physical condition, educational applications, or applications designed for the psychotherapeutic treatment of arachnophobia, VR applications in this category are assessed based on their actual contribution.

Finally, there is a perspective that is particularly exciting for scientists who can view VR as a promising method or tool for psychological research — specifically, the use of VR to replicate or expand previously proposed experiments, which have traditionally been studied despite numerous limitations only in objective reality. Due to the nature of VR, which will be discussed below, we have greater research control over these experiments while still maintaining realism. This also allows us to study phenomena that

would be too costly (in terms of time, logistics, finances, or otherwise) or impossible to observe in the real world.

## Adopting Virtual Simulations for Psychology

The traditional problem of studying human cognition in the context of laboratory experiments was discussed above. Suppose we accept that the goal of science should be to explain and predict real-world processes (Forster, 2002). In that case, it becomes necessary to methodologically discuss the balance between rigorous experimental regimes that maintain the validity of research findings and the use of realistic, interactive, dynamic, and contextually defined stimuli. From this perspective, it seems helpful to consider the possibilities offered by the dynamic advancement of information technologies in recent years. This shifts focus from the real world to dynamic, interactive, and complex experimental simulations achievable in virtual environments. Immersive virtual simulations have the potential to overcome the methodological compromise outlined in the previous chapters, supporting naturalistic environments with high levels of experimental control, which can be systematically incorporated into modern research through virtual simulations.

The attributes of VR, such as realness and fidelity, including accessibility, user support, dynamic modification of virtual environments, interaction, easy dissemination, triggering, adaptive scenario development, logging, and virtual collaboration, make it a holy grail in cognitive research (Ugwitz et al., 2021).

Automatic logging capabilities elevate the potential for VR utilization in psychodiagnostics to a new level. Monitoring eye movements (eye-tracking) is a particularly valuable addition, providing insights into cognitive processes and complementing behavioral and physiological measurements (Juřík et al., 2021; Juřík et al., 2019). Combined with various complementary tools, VR-based research becomes scalable global trends applicable beyond research to industrial practices such as manufacturing and marketing. IVEs for such applications, when appropriately designed and elaborated, can faithfully simulate real-world conditions, as seen in Figure 13.

**Figure 13**

*Building information model visualizations based on the real building*



*Note.* BIM visualizations of the example building (top), modified model for VR (middle), and its actual appearance (bottom). Adopted from Apeltauer et al. (2020), it was used with the authors' permission.

For decades, the cognitive tradition has sought remedies to previously discussed criticisms through strict and methodologically rigorous approaches to uncovering the imperceptible processes of the human mind. Despite calls for ecological validity in psychological laboratory research, there is often a clear definition of what this entails or how to achieve it (Holleman et al., 2020) precisely. However, recent technological advancements, especially in virtual simulations, offer tools to elegantly bridge this compromise by creating convincing simulations of the real world within a research laboratory. VR tools can immerse individuals in artificially created, realistic virtual simulations, offering extensive measurement opportunities for ecologically valid research outcomes. In this direction, immersive and highly realistic *virtual simulations* offer several advantages for psychological research, enhancing the ability to study complex behaviors and mental processes. These advantages include providing a highly controlled environment where researchers can precisely manipulate variables, isolate specific factors, and examine their effects on behavior and cognition without the interference of external variables. Simulations can be easily replicated, ensuring consistency across different experimental runs. This repeatability is crucial for verifying results and establishing the reliability of findings. Virtual simulations provided in the first-person point of view regime enable the study of scenarios that would be ethically or practically impossible to recreate in real life. Researchers can expose participants to potentially harmful or distressing situations in a virtual setting without causing actual harm. Researchers can create various scenarios, from everyday situations to rare or extreme events. This flexibility allows for

exploring a broad spectrum of psychological phenomena and responses. Virtual simulations facilitate the real-time collection of rich, detailed data on participants' behaviors, reactions, and physiological responses. This data can include eye-tracking, movement patterns, and response times, comprehensively understanding the participants' experiences. High-quality virtual environments can create immersive experiences that mimic real-world settings, enhancing ecological validity. Participants may behave more naturally in a realistic virtual environment compared to traditional lab settings. Once developed, virtual simulations can be cost-effective compared to real-world experiments that require physical resources, space, and logistics. Simulations can be reused and modified with relative ease. Virtual simulations can be accessed remotely, allowing researchers to include diverse participants from different geographic locations. This accessibility can enhance the generalizability of findings across different demographics. Virtual simulations can conduct longitudinal studies more efficiently, tracking changes in behavior and cognition over time without the need for repeated real-world setups. Simulations can be tailored to individual participants, adjusting scenarios based on their responses and characteristics. This customization can lead to more personalized and relevant insights. To sum up, virtual simulations offer psychological researchers a versatile, controlled, and ethical tool for studying a wide range of phenomena with precision and depth, enhancing psychological research's overall quality and impact.

As mentioned above, consider at least some assumptions of ecological cognitive psychology and incorporate them into cognitive research. One

possible way could be the shift from traditional laboratory research to dynamic complex experimental environments represented by immersive virtual simulations, usually provided via head-mounted display technology (VR goggles). It may be experienced from the first person's point of view. Increasing computational power provides graphic virtual interfaces that offer immersion (a sense of presence in a virtual world), sensory feedback, and interactivity. Such virtual worlds can immerse a person in a well-controlled yet realistic experimental environment, which is advantageous in many types of research. Robust virtual possibilities provide valid information about human behavior in a world-like environment. Some cognitive phenomena, such as mental representations, are proposed to be easily transferable using virtual technologies. Generally, virtual environments can create visually striking, complex stimuli with great freedom of movement while still adhering to strict experimental standards. The most promising technology for simulating the real world is immersive virtual environments (IVEs; e.g., Šašinka et al. 2019). IVEs typically provide a strong sense of presence, i.e., the feeling of being in a virtual world, and the virtual environment perceptually surrounds users. IVEs are provided through virtual displays, specifically head-mounted displays (HMDs), see Figure 14. An HMD is a type of helmet with goggles displaying a three-dimensional image of the virtual world and typically has head-tracking devices. Additional haptic devices enhance interaction with IVEs, and users can quickly move because an HMD is wearable. Combining a wearable HMD with treadmill technology and sound systems creates a promising tool for

ecologically valid exploration of cognitive processes, especially concerning spatial cognition, perception, attention, etc.

**Figure 14**

*An example of the current VR headset model META Quest 3*



*Note.* Photo by Alexandra Snováková was used with the author's permission.

## Resolving the Control-Validity Tradeoff in Experimental Research

A natural compromise between experimental control and ecological validity, the Gordian knot discussed above in research, can be overcome using virtual displays (Děcký et al., 2024). Immersive virtual simulations (IVS), i.e., virtual simulations conducted with the use of immersive VR technology such as head-mounted display, provide high experimental control while also providing ecological validity (Juřík et al., 2019; Juřík et al., 2018; Loomis et al., 1999). Data collection options are also expanded. A virtual display can place the participant in an ecologically valid immersive virtual environment where all variables are strictly controlled, and the experiment is repeatable. The participant can move freely, and their navigation strategies, including movement trajectories, gaze, interaction with objects, and more, can be precisely tracked. Let us consider, for example, the current theories of cognition, such as predictive processing, discussed above. Here, virtual simulation can be a powerful tool for studying human cognition within the predictive processing framework by providing controlled, immersive environments that allow researchers to manipulate and measure how the brain predicts and processes sensory information. Predictive processing theory posits that the brain constantly generates models of the world to predict sensory inputs and updates these models based on the discrepancy between expected and actual inputs (prediction errors). In virtual simulations, researchers can create highly controlled scenarios that systematically vary sensory inputs or environmental conditions to observe how participants' brains update their predictions. For example, by introducing unexpected

changes in the virtual environment, researchers can study how the brain responds to prediction errors and adapts its internal models. This can help understand the underlying cognitive processes in perception, learning, and decision-making. Moreover, virtual simulations can replicate real-world contexts while allowing precise control over variables, which is difficult to achieve in real-world settings. This control enables the isolation of specific factors that influence predictive processing, such as the role of prior knowledge, context, and sensory feedback. Additionally, using virtual simulations, researchers can gather detailed data on participants' behaviors, such as eye movements and navigation patterns, which provide insights into how predictions are generated and adjusted in real time.

Data measurement possibilities indicate the range of various measurement tools and options available. Experimental interfaces using virtual displays can be maintained in the laboratory, easily supplemented with biosignal measurements such as electroencephalogram, functional near-infrared spectroscopy, electrocardiogram, electromyogram, mechanomyogram, galvanic skin response, as well as motion capture systems, thermography, blood pressure measurements (pulse transit time; photoplethysmography), or saliva analyses. The possibility of combining various measurement tools creates another advantageous dimension of VR, as it can cover most potentially investigated phenomena. Additionally, combining various measurement tools, such as eye-tracking technology (Juřík et al., 2021), creates another advantageous dimension of VR and potentially significantly deepens insights into the studied individual.

Also, regarding VR cost-effectiveness, it has the potential to considerably promote the Reproducibility Project in Psychology<sup>1</sup> (Aarts et al., 2015), which is currently realized in psychology domains. Considering the replication crisis that has challenged traditional methodologies in psychological research, VR has emerged as a promising tool. VR technology provides a unique platform for experiments, offering controlled and immersive environments that can closely mimic real-world scenarios, achieving a level of consistency that is difficult to match in conventional laboratory settings (Juřík et al., 2018; Juřík et al., 2019). This consistency is crucial for replication, as immersive virtual simulations (IVS) ensure that all participants are exposed to identical stimuli, reducing variability from environmental factors.

It is true that in recent years, VR technologies have increasingly been utilized to study various natural phenomena, including simulations that explore organisms within environmental contexts (Kwartler, 2005), emphasizing mainly previously discussed advantages of VR, such as the ability to activate brain mechanisms similar to those used in real-world settings (Alcañiz et al., 2009). In particular, VR displays that entirely isolate users from physical reality (Rangaraju & Turk, 2001) offer high fidelity, which can be understood psychologically as immersion—deep user engagement with virtual content (Slater, 2003). However, empirical evidence supporting the comparability of cognitive and behavioral processes in virtual versus real environments has been limited (Marín-Morales et al., 2019). It typically comes from studies

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<sup>1</sup> <https://osf.io/ezcuj/>

conducted with technologically limited devices and from narrowly defined perspectives. For example, at the physiological level, it has been found that interactive 3D IVEs elicit responses more akin to those in real conditions compared to IVEs with low interactivity (Higuera-Trujillo et al., 2017). Psychologically, lower realism in VR often diminishes the authenticity of mental responses (Higuera-Trujillo et al., 2017). This latter point may be complemented by the ever-increasing quality of IVR technologies, leading to the assumption that better tools will result in higher cognitive fidelity. Studies exploring immersive virtual reality (using, for example, head-mounted displays) compared to human behavior in virtual and real environments indicate that users display similar movement patterns, clearly indicating a general analogy between these two types of environments (Marín-Morales et al., 2019). However, the authors also note that impaired visual identification of components in VR environments (such as the inability to read small text due to display resolution) directly influences patterns of sensorimotor activity, decision-making processes, and user locomotion (ibid). Another aspect to consider is the nature of the task being simulated. Previous research has suggested that goal-oriented performance tasks may exacerbate behavioral differences in VR compared to real environments, with users typically being less time-efficient in virtual simulations (Skorupka, 2008). This inefficiency, similar to the previously mentioned case, can be attributed to the limitations of the technology used (e.g., display quality) but primarily to the form of movement metaphor (i.e., control mechanisms), which may not always be easy or intuitive for users. Despite intensive research (Riecke et al., 2010; Tregillus

et al., 2017; Wilson et al., 2014), discussions about these issues remain ongoing without conclusive results (Lee et al., 2018). Although there is a prevailing assumption that cognitive and behavioral processes demonstrated in virtual simulations align more closely with real-world behavior than other forms of simulations (such as desktop applications), a comprehensive body of evidence on this issue is still lacking, and discussions on this topic continue.

Using immersive virtual simulations in psychological research and practice raises important ethical concerns. The research should focus on participant well-being, highlighting the potential for heightened emotional and physiological responses in virtual environments. It stresses the need for ethical guidelines to protect participants, particularly in therapeutic settings. Additionally, data privacy issues should be addressed, noting the risks of misuse as simulations integrate AI and machine learning and call for robust ethical frameworks to ensure responsible use of the technology and the data collected.

Many disadvantages of virtual displays, which were addressed by psychological researchers in the very beginning, such as imperfections in rendering modeling, limitations of the visual display (e.g., low resolution, limited field of view, fixed accommodation distance), slow graphics update frequency, and significant delay between head tracking and visual display (Loomis et al., 1999) have already been resolved with natural technological progress, especially in the gaming and entertainment industry striving for a better gaming experience. Currently, VR tools are ready for easy use in basic

research and applied research as a therapeutic process or as a tool for training, assessment, and education.

## Virtual Simulations in Human-Centered Applications

Virtual Reality (VR) technology, once primarily the domain of gaming and entertainment, has increasingly found a foothold in diverse fields, demonstrating its potential to revolutionize various aspects of professional practice. This chapter explores the current applications of VR across human-centered domains, including different sectors like medicine, urbanism, and geography, as well as its use in virtual reality exposure therapy (VRET).

In the medical field, VR is utilized in multiple ways to enhance patient care and medical training (Kilmon et al., 2010; Mirelman et al., 2016). One of the most significant applications is in surgical simulation and training, where VR provides a risk-free environment for medical students and professionals to practice complex procedures. VR simulations replicate the human body and surgical environments with high precision, enabling trainees to hone their skills without needing live patients. Additionally, VR is used in pain management, particularly in burn treatment and chronic pain patients. By immersing patients in calming virtual environments, VR can help reduce pain perception, offering a non-pharmacological alternative to pain relief (Mosadeghi et al., 2016).

In urban planning and design, VR transforms how professionals visualize and interact with spaces. VR allows urban planners to create immersive 3D models

of urban environments, enabling them to simulate the impact of different design choices before implementation (Pour Rahimian et al., 2014). This technology helps planners and architects better understand spatial relationships, crowd dynamics, and environmental factors such as sunlight and wind patterns. It also provides a platform for public engagement, where citizens can experience and provide feedback on proposed developments more intuitively and interactively (Portman et al., 2015).

Geography has embraced VR as a powerful tool for education and research. VR allows geographers to recreate and explore distant or hazardous locations virtually, offering a unique perspective on geographical phenomena. For instance, students can virtually visit and study the topography of remote mountain ranges or the biodiversity of inaccessible rainforests without leaving their classrooms. VR also plays a significant role in disaster management training, simulating natural disasters like earthquakes, floods, or wildfires and providing crucial training experiences for emergency responders (Bos et al., 2022).

VR is transforming education by creating immersive learning environments. It is used in schools and universities to teach complex subjects like history, science, and engineering. It allows students to explore historical sites, conduct virtual experiments, or interact with 3D models of molecules or machinery. In an immersive virtual reality (IVR), various factors can significantly influence learners' experiences and learning outcomes. IVR technology offers benefits such as providing extensive sensory input, enhancing visualization, and

enabling dynamic modifications and remote collaboration (Šikl et al., 2024; Ugwitz et al., 2019). It can also stimulate creativity and generate emotions that boost performance and motivation, especially when the environment is highly immersive (Makransky & Petersen, 2021; Parong et al., 2020). However, there are downsides as well. IVR may not be effective for acquiring declarative knowledge, as the rich sensory input and novelty of the technology can distract learners from their instructional goals, leading to difficulties in organizing information in working memory (Makransky et al., 2019; Mayer, 2009; Parong & Mayer, 2018). Additionally, the high level of immersion can lead to cognitive overload, further hindering learning (Bagher et al., 2022; Meyer et al., 2019). IVR also plays a vital role in vocational training, providing realistic simulations for fields such as aviation, military, and emergency response, where hands-on experience is crucial yet challenging to arrange in real life (Radianti et al., 2020).

In manufacturing and engineering, IVR is used for product design, prototyping, and testing. Engineers can create and interact with 3D models of products or machinery in a virtual environment, allowing for detailed inspection and modification before physical production begins (Hilfert & König, 2016; Wang et al., 2018). This reduces costs and time associated with traditional prototyping. IVR is also used in maintenance training, where workers can practice on virtual machines, enhancing their skills and reducing the risk of errors. Beyond video games, IVR is revolutionizing the entertainment and media industries by offering new ways to experience content. IVR films and immersive storytelling allow viewers to engage with narratives more effectively and personally. Music concerts, theater

performances, and sporting events are also being experienced in IVR, providing a virtual front-row experience regardless of physical location (Evans, 2018). IVR is being used in the retail sector to enhance the shopping experience. Customers can virtually try on clothes, preview how furniture would look in their homes, or walk through virtual stores. This technology improves customer engagement and helps reduce return rates by accurately representing products before purchase. IVR also allows retailers to design and test store layouts and product placements in a virtual space before implementing them in real life (Flavián et al., 2019).

IVR offers unique opportunities in the tourism sector by enabling virtual tours of landmarks, museums, and cultural sites. This is particularly beneficial for individuals unable to travel due to physical or financial limitations. Additionally, IVR is being used to preserve and recreate cultural heritage sites that have been damaged or lost, allowing future generations to experience them virtually (Guttentag, 2010). In sports, IVR is used for training and performance analysis. Athletes can practice in simulated environments, replicating real-world conditions like weather, crowd noise, and opponent behavior. IVR also helps analyze an athlete's performance by providing detailed feedback on movement and technique. In fitness, IVR is incorporated into workout routines to make exercise more engaging by turning physical activity into a game-like experience. IVR is widely used in architecture and real estate to create immersive walkthroughs of buildings and properties. Potential buyers or clients can experience a property as if they were physically there, even if it has not been built yet. This helps make design decisions and

understand spatial relationships and marketing properties more effectively (Boeykens, 2011).

The integration of IVR into various fields demonstrates its growing importance and versatility. IVR is becoming an indispensable tool across disciplines, from enhancing medical training and patient care to revolutionizing urban planning and geographical research. Moreover, its application in mental health, mainly through Virtual Reality Exposure Therapy (Juřík et al., 2024a; Varšová et al., 2023; Varšová et al., 2024), underscores its potential to impact therapeutic practices profoundly. As VR technology evolves, its applications will likely expand further, opening new avenues for innovation and improving outcomes in various domains.

#### *Virtual Reality Exposure Therapy*

One of the most impactful uses of VR in mental health care is Virtual Reality Exposure Therapy (VRET). VRET is an advanced form of cognitive-behavioral therapy that uses VR to treat patients with anxiety disorders, particularly those who have post-traumatic stress disorder (PTSD), phobias, and social anxiety. In VRET, patients are gradually exposed to anxiety-provoking stimuli within a controlled and safe virtual environment, allowing them to confront and process their fears. This method has shown considerable efficacy in reducing symptoms of PTSD and specific phobias, offering an effective alternative or complement to traditional exposure therapies (Maples-Keller et al., 2017).

IVR has rapidly evolved into a groundbreaking technology known for its ability to create three-dimensional, multisensory, and interactive experiences that effectively replace physical environments. This advanced technology has gained significant attention in the field of mental health due to its capacity to immerse individuals in simulated, challenging scenarios, offering a unique approach to treatment (Emmelkamp & Meyerbröker, 2021; Slater, 2018). Among its various applications, IVR has shown particular promise in the treatment of anxiety and stress-related disorders, with clinical psychology recognizing its potential as an innovative tool for managing conditions such as anxiety and phobias, including acrophobia (Schröder et al., 2023; Wray et al., 2023).

Acrophobia, characterized by an intense fear of heights, manifests as severe anxiety and avoidance behaviors that can significantly impair a person's daily functioning. When confronted with high places, individuals with acrophobia may experience panic attacks, leading to a restricted lifestyle and even hindering specific professional opportunities (Huppert et al., 2020). Due to the absence of a standardized treatment for acrophobia, therapy must be tailored to each individual to ensure long-term improvement (Freitas et al., 2021). Technological interventions, particularly those based on Cognitive Behavioral Therapy (CBT), have become increasingly prevalent in addressing this condition. Among these, exposure therapy, which is central to CBT, has emerged as a preferred method for treating acrophobia (Arroll et al., 2017; Chard & van Zalk, 2022; Chou et al., 2021).

Through Virtual Reality Exposure Therapy (VRET), IVR offers a novel exposure therapy approach. IVR can replicate in vivo exposure within a controlled virtual environment using visual, auditory, and sensory stimuli. This allows for a more precise and adjustable form of therapy than traditional methods, where it is often difficult to control exposure levels in real-world settings (Dellazizzo et al., 2020). IVR enables patients to confront their fears in a safe and controlled virtual space, leading to significant therapeutic outcomes and marked improvements in the treatment of acrophobia (Donker & Heinrichs, 2023; Varšová et al., 2024; Wechsler et al., 2019).

Despite these promising developments, several barriers continue to hinder the widespread adoption and optimal use of IVR in treating acrophobia. One of the primary challenges is the high cost associated with the technology, which limits its accessibility. The expenses of acquiring and maintaining advanced IVR equipment pose significant obstacles, particularly for smaller clinical practices or those with limited resources (Arnfred et al., 2023; Slater et al., 2020). Additionally, digital divides based on geographic location, ethnicity, gender, and socioeconomic status restrict access to this innovative therapy, leaving specific populations underserved (Saeed & Masters, 2021). As a result, despite its potential, the use of IVR in clinical settings remains relatively limited (Wray et al., 2023).

Another significant issue is developing user experience and interaction design within IVR environments. Creating a practical therapeutic setting in IVR requires a sophisticated synchronization of user movements, visuospatial cues,

and bodily responses, particularly in relation to the phobic stimulus of heights. This complexity demands integrating multiple technologies beyond standard IVR, which poses considerable technical challenges. The realism and accuracy of these components are crucial for effective therapy, as physical cues are integral to the interaction between therapists and clients during VRET (Arnfred et al., 2023; Ong et al., 2024).

Moreover, the integration of biofeedback mechanisms into IVR environments remains underdeveloped. Although some VRET studies incorporate biosignal monitoring, these are often conducted externally via separate devices, reducing the potential for a fully immersive experience. Integrating biofeedback directly into the IVR environment could enhance the therapeutic process by providing real-time data on the patient's physiological responses, thereby improving the sense of presence and the effectiveness of the therapy (Felnhofer et al., 2014; Moldoveanu et al., 2023; Varšová et al., 2024).

The therapist's role is another crucial factor in the success of VRET. While recent advancements have explored the potential of automated therapy for acrophobia, high dropout rates associated with self-led interventions highlight the importance of therapist involvement. Evidence suggests that therapist-led VRET enhances treatment outcomes by establishing a therapeutic relationship and setting goals, which are vital for the success of the therapy (Buchholz & Abramowitz, 2020; Varšová et al., 2024). However, skepticism regarding the realism and effectiveness of IVR, coupled with a preference for traditional therapeutic methods, continues to limit its wider adoption (Lindner et al., 2019).

To overcome these barriers and fully realize the potential of VRET in treating acrophobia, future research and development must focus on enhancing the accessibility, realism, and customization of IVR environments. By addressing these challenges, IVR can become a more robust and accessible tool, significantly improving the effectiveness of therapy for individuals who have acrophobia.

## Virtual Simulations and AI – Contemporary Trends

The rapid growth in artificial intelligence (AI) development has opened new avenues in psychological research, mainly by integrating virtual simulations and machine learning (ML). As ML models become more accurate, they enhance the realism and effectiveness of virtual simulations, providing better data for further model refinement. This iterative process leads to continuous advancements in the quality and utility of virtual simulations and computational models. This combination creates a powerful synergy that significantly enhances the accuracy of modeling, the design of experiments, and the depth of insights into human behavior and cognition. By leveraging the strengths of both virtual and computational methods, researchers can achieve a nuanced understanding of complex psychological phenomena, ultimately contributing to more effective interventions and treatments.

Virtual simulations have emerged as a powerful tool for generating large volumes of high-quality, labeled data for AI training across various domains. This approach offers several advantages, including cost-effectiveness, scalability, and the creation of diverse scenarios (Dahmen et al., 2021; Kerley et al., 2023). In autonomous driving, simulated data has shown promising results, sometimes outperforming real-world data in training object detection models (Johnson-Roberson et al., 2016; Pfeffer et al., 2019). Virtual environments are also used to train and test AI algorithms in military simulations (Smith, 2022) and crewless aerial vehicle applications (Alvey et al., 2021; Leudet et al., 2018). The use of virtual reality for generating training data has been demonstrated

in healthcare applications, such as fall detection (Bui & Alaei, 2022). While synthetic data may not always match the performance of real-world data, it offers a valuable solution to address the scarcity of labeled datasets and accelerate AI development in various fields (Johnson-Roberson et al., 2016; Pfeffer et al., 2019).

Furthermore, computational simulations can expand the insights gained from virtual simulations by modeling large-scale, complex systems that involve many interacting variables. ML models trained on data from virtual simulations can be used to predict population-level behaviors or social dynamics. For example, simulations of public health interventions can be used to predict how different strategies might impact the spread of diseases, offering valuable data for policymakers to make informed decisions. Additionally, integrating virtual simulations with machine learning establishes feedback loops that continuously improve both the simulations and the models. This chapter explores the integration of AI and virtual simulations in psychological research, focusing on two key categories: AI within VR simulations employing autonomous systems and enhanced AI based on data from virtual simulations.

### AI in Virtual Simulations - Autonomous Systems

Machine learning (ML) has shown great promise in personalizing virtual simulations in real-time based on participants' responses, providing a highly adaptable platform for various applications (Rodenburg et al., 2018). This capability stems from the fact that ML algorithms can analyze ongoing data streams and dynamically modify simulation parameters. Adjusting the virtual

environment according to user inputs and behaviors, these algorithms help create more tailored, engaging, and relevant experiences (Kritikos et al., 2021; Ray & Fukuoka, 2019). Adapting virtual simulations in real-time is particularly beneficial in research settings, where maximizing ecological validity is a priority. When virtual environments reflect the real-world scenarios or behaviors of participants more closely, researchers can collect more accurate data and be more representative of the participants' natural responses.

For instance, this adaptability in clinical or therapeutic contexts ensures that VR systems can be highly customized. In a VR therapy session designed to treat anxiety disorders, machine learning algorithms can monitor a patient's physiological responses, such as heart rate, skin conductance, or breathing patterns. Based on this continuous feedback, the system can automatically adjust the difficulty of the therapeutic scenario, such as by altering the intensity of the stimuli or the speed at which challenges are introduced, as was discussed, for instance, by Juřík (2024). This real-time adjustment provides a more personalized therapeutic experience and increases the likelihood of success by adapting to the patient's specific needs and emotional states (Badesa et al., 2014; Kritikos et al., 2021).

Furthermore, this approach can be applied to various fields beyond therapy, such as education, training, and entertainment. In educational simulations, for example, machine learning can be employed to adjust the complexity of a problem or the pacing of a lesson based on a student's learning progress and cognitive load. Similarly, real-time adjustments can simulate varying degrees

of difficulty in training environments for skills such as surgery or aviation, providing professionals with a learning experience that closely mimics real-world challenges. By continually refining virtual environments through machine learning, it becomes possible to create simulations that are not only interactive but also deeply personalized and aligned with the user's abilities, preferences, and behaviors (Ray & Fukuoka, 2019; Rodenburg et al., 2018).

This level of precision in tailoring experiences underscores the transformative potential of machine learning in creating dynamic, individualized environments that enhance both the user experience and the outcomes of research and practical applications.

### AI Systems Based on Virtual Simulations

One of the primary benefits of integrating virtual simulations with machine learning is the ability to generate large volumes of high-quality, labeled data (Johnson-Roberson et al., 2016). These virtual environments can be meticulously designed to capture detailed behavioral and physiological responses, creating rich datasets crucial for training ML models (Banerjee et al., 2021). For instance, specific emotional responses can be elicited in virtual settings and used to train ML algorithms to recognize and predict similar reactions in real-world scenarios. Regarding the above-discussed features such as scalability and easy dissemination, and considering the above-mentioned reproducibility arguments, immersive virtual environments can be easily distributed among research teams all around the globe to gather a satisfactory amount of data, which is necessary for ML. Data suitable for ML are

considerably lacking (Carrillo et al., 2019). Since the IVS are discussed as valid regarding the measurement of behavior and other human responses, this synergy between data generation and ML training may significantly enhance the robustness and accuracy of not only psychological models and theories (Alber et al., 2019; Gao et al., 2023). The detailed data obtained from virtual simulations enable the creation of computational models that mimic complex human behaviors. Machine learning algorithms can analyze patterns within this data, allowing researchers to predict how individuals might respond in various scenarios. For example, it is possible to model social dynamics and predict outcomes such as conflict resolution or group decision-making processes by simulating social interactions in virtual environments. This approach provides a deeper understanding of intricate psychological phenomena often challenging to study using traditional methods.

Additionally, combining data from virtual simulations with machine learning improves the predictive validity of psychological models (Jacobucci & Grimm, 2020; Marín-Morales, 2021). ML algorithms can identify subtle patterns and correlations that might be missed by traditional analysis methods, leading to more accurate behavioral predictions. For instance, predictive models for mental health conditions can be refined using data from virtual simulations, thereby enhancing their ability to forecast the onset or progression of disorders based on early behavioral indicators. Furthermore, data from virtual simulations serve as a valuable tool for validating computational models, as previously suggested in non-VR research (Humphries & Gurney, 2007). By comparing model predictions with actual behaviors observed in virtual

environments, researchers can assess the accuracy and reliability of their models. This validation process is crucial for ensuring that computational models are grounded in empirical data and accurately reflect real-world behaviors, ultimately strengthening the overall quality and applicability of the research findings.

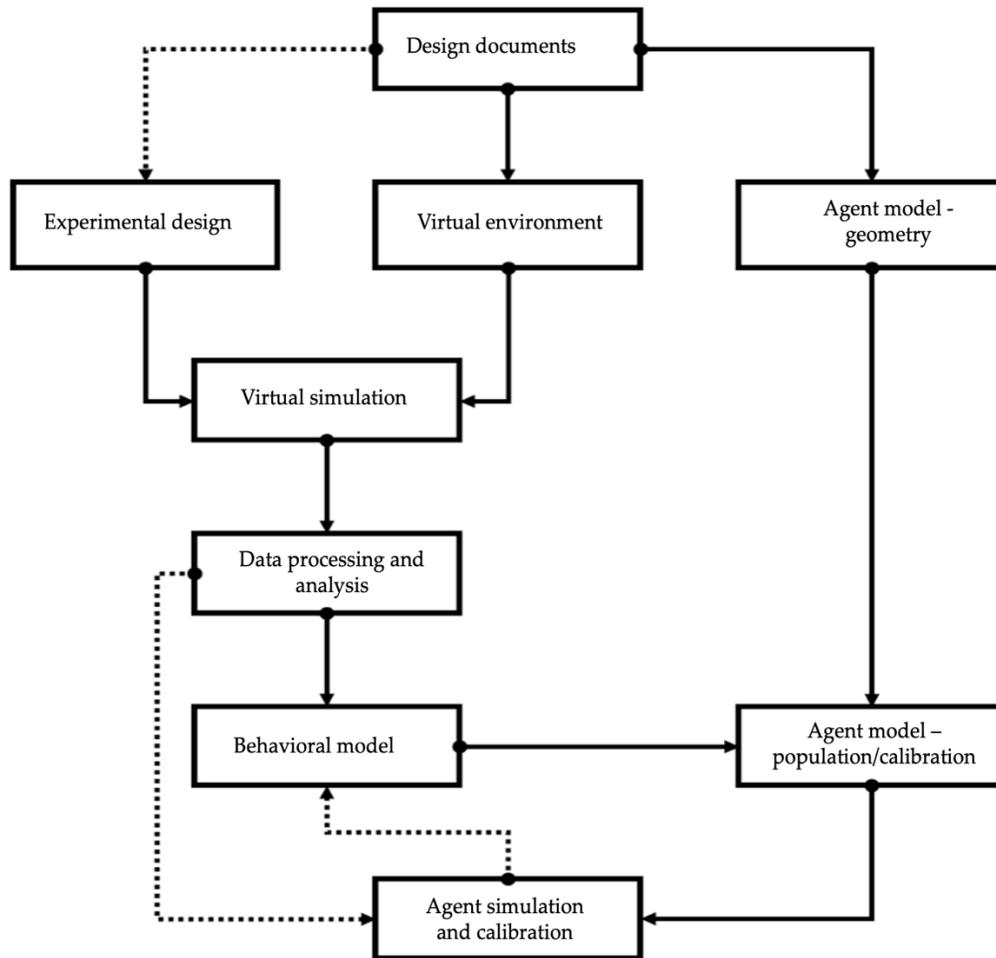
## Agent Simulations Based on Virtual Simulations

As discussed above, virtual simulations have emerged as reliable tools for studying behavioral patterns. It can be mainly applied in evacuation scenarios (Juřík et al., 2023; Snopková et al., 2022). VR models mimic real-world movement effectively, with potential artificial agent movements in simulations closely following human trajectories. Human behavior in IVS can be effectively recorded and analyzed. This allows for incorporating less common phenomena, such as detours or getting lost during evacuations, which are often overlooked in default models. These nuances, particularly in critical evacuation contexts like fractional effective dose or the slowest evacuees, highlight the benefits of using VR-based models over traditional Agent-Based Evacuation Models (ABEMs), which typically lack variance in predicted evacuation times or trajectories. The strength of human-centered virtual simulations lies in their ability to capture the distribution of evacuation times, including outliers like extremely slow evacuees, who are particularly vulnerable during emergencies. These models emphasize the importance of focusing evacuation procedures on those in the third quartile of evacuation times, as they are most at risk. Empirical observations from evacuation drills,

made possible by IVS, are crucial for identifying these outliers and anomalies, thereby enhancing safety protocols (Juřík et al., 2023). A significant advantage of VR experiments – the above-discussed controllable and safe environment for empirical testing – can be represented by a hyper-realistic digital twin of a specific environment. This allows dynamic modulation of scenarios, such as fires or toxin spread, to study deviations from expected behavior patterns. These deviations, which may cause delays and affect decision-making at critical points, can significantly influence exposure to hazards and, ultimately, the final fractional effective dose (a measure used in fire safety to estimate the risk of harm or fatality from exposure to toxic gases and heat during a fire). VR-based models preserve the benefits of VR experiments, including cost-effectiveness, speed, accessibility, and data logging capabilities, making them valuable during the planning phase of buildings. In this regard, virtual simulations are proposed to be used in the applied areas, such as agent-based modeling in evacuation issues (see Figure 15).

**Figure 15**

*Process of experiment preparation and subsequent ABEM model*



*Note.* Adapted from Apeltauer et al. (2020), used with the authors' permission.

This methodology aims to leverage virtual reality simulations as a data source for developing agent-based evacuation models (ABEM). The process is structured to ensure that the behavioral models generated through this approach accurately reflect real-world human behavior during evacuation

scenarios, thereby enhancing the reliability of the ABEM. The methodology begins with creating or acquiring a Building Information Model (BIM), which serves as the foundational dataset for both the virtual environment and the agent-based model. The BIM should be detailed enough to capture the essential architectural features of the building, including floor plans, material properties, furniture placement, and lighting configurations. These details are crucial for creating a VR environment that is both realistic and functional. Once the BIM is in place, it is used to develop the VR environment and the ABEM geometry simultaneously. The VR environment is constructed to provide an immersive, high-fidelity simulation of the building, where visual and interactive elements are carefully optimized to ensure smooth performance. This involves converting the BIM into a VR-compatible format and making necessary adjustments to balance visual detail with computational efficiency. For instance, complex objects like furniture might be simplified, while other elements, such as lighting, might be enhanced to maintain the realism of the VR simulation.

Parallel to the development of the VR environment, the ABEM geometry is prepared, typically using a simplified version of the building's layout in a 2D format. This simplification focuses on the key aspects of evacuation, such as the arrangement of escape routes and obstacles, ensuring that the agent-based model can simulate movements within the defined space without unnecessary complexity. With the VR environment and ABEM geometry established, the next step involves designing the VR experiment. This begins with thoroughly inspecting the building's layout to identify potential evacuation routes and

scenarios. These scenarios reflect the building's intended use, accounting for various factors such as the time delay before occupants begin evacuating and the different behaviors they might exhibit during an emergency, like gathering personal items or choosing alternative exit routes. The experiment design is crucial, as errors or oversights can lead to inaccurate predictions in the subsequent simulations.

A representative sample of participants is then selected for the VR experiment. This sample is chosen to reflect the demographic characteristics of the building's expected occupants, ensuring that the data collected is representative of the population that would use the building in real life. Participants are introduced to the VR environment, where they navigate through the virtual building under controlled conditions that simulate an evacuation. Their movements, decisions, and interactions within the environment are meticulously recorded, providing a rich dataset for subsequent analysis. See the example of the experimental laboratory for VR (Figure 16).

**Figure 16**

*Demonstration of testing site and testing tool*



*Note.* Experimental tool — VR glasses, keyboard, and mouse. The operator may monitor the progress of the experiment on adjacent monitors. Photo by Vojtěch Juřík.

After the VR experiment, the collected data is processed to remove invalid or outlier trajectories, ensuring that only accurate and relevant data is used to inform the behavioral model. This involves analyzing various parameters, such as movement speed, decision-making times, and proximity to other evacuees and obstacles. The processed data is then used to develop a behavioral model, which describes how individuals are likely to behave during an evacuation based on the empirical evidence gathered from the VR simulation. This behavioral model is integrated into the ABEM, which informs the actions and movements of virtual agents within the simulation. In modeling software, such as Pathfinder (Thunderhead Engineering Consultants, 2019), agents are programmed with specific behaviors and profiles that dictate how they navigate the environment and make decisions during an evacuation. These behaviors are based on the data collected from the VR experiment, ensuring that the simulation accurately reflects actual human behavior.

Once the behavioral model is integrated, the ABEM is run using a Monte Carlo simulation approach. This involves performing multiple iterations of the evacuation scenario to account for variability and uncertainty in human behavior. The results of these simulations are then validated against the original VR data to ensure that the model accurately predicts real-world outcomes. If discrepancies are found, the model is refined, and further simulations are conducted until the predictions align with the observed behaviors from the VR experiment.

This methodology demonstrates how virtual simulations can be effectively employed as a data source for agent-based modeling. By using VR to generate realistic behavioral data and integrating it into ABEM, it is possible to create highly accurate models of human behavior during evacuations. These models can then be used to optimize building designs and evacuation procedures, ensuring they are tailored to accommodate real-world behaviors and improve safety during emergencies.

### Virtual Simulations and Human-in-the-Loop

The concept of "*human-in-the-loop*" (HITL), which was discussed above, gains significance here since it is a fundamental aspect of machine learning that emphasizes the ongoing interaction between humans and machines throughout the AI development process (Narayanan & Kidambi, 2011). This interaction is crucial for creating machine learning models that are accurate, reliable, and adaptable to real-world situations. HITL leverages human expertise to enhance machine learning at various stages, including data collection, labeling, quality control, and continuous feedback. At the core of machine learning lies the essence of data—often vast, unstructured, and unlabeled, such as images or text. For an algorithm to learn effectively, it must first be trained on data imbued with meaningful context, a task that cannot be accomplished without human intervention. Humans provide the essential labels that enable machines to recognize patterns and make accurate predictions. This process is particularly crucial in supervised learning, where the algorithm learns to predict outcomes based on the labeled data it has been

trained on. The psychological methodology was applied to gather data suitable for machine learning even in the context of the Czech Republic (Pešán et al., 2024).

However, the role of humans in the machine-learning process extends far beyond the initial phase of data labeling. As the model makes predictions, it requires fine-tuning to ensure it does not become too specialized—a problem known as overfitting. Overfitting occurs when a model becomes excessively tailored to the specific data it was trained on, rendering it less effective when faced with new, unseen data. Here, human input is critical. By identifying and addressing overfitting, humans guide the model through edge cases or unexpected scenarios, ensuring it generalizes better and improves performance in real-world applications. As the model progresses to the testing phase, human involvement remains indispensable. During this stage, the model's predictions are meticulously assessed by humans, focusing on instances where the model might exhibit undue confidence in incorrect predictions. This feedback loop is vital for refining the model, reducing errors, and enhancing accuracy. By continuously incorporating human insights, the model becomes more intelligent, reliable, and capable of handling complex tasks.

The integration of human expertise in the machine-learning process offers several profound benefits. Foremost among these is the enhancement of model accuracy, as human input serves to correct errors and address biases that the machine might otherwise overlook. Moreover, the involvement of humans in

the decision-making process increases transparency in AI systems, transforming them from enigmatic "black boxes" into more understandable and trustworthy tools. Human participation in machine learning also allows for greater adaptability in models. By keeping humans in the loop, models become better equipped to handle unexpected scenarios and extreme cases, making them more robust and reliable across diverse applications. This collaboration between humans and machines shifts the focus away from striving for "perfect" algorithms and towards developing models that deliver the most practical and beneficial outcomes in real-world contexts.

Ultimately, while the field of artificial intelligence continues to advance rapidly, the role of humans remains irreplaceable in developing sophisticated and accurate machine-learning models. The concept of "Human in the Loop" underscores the significance of human judgment and expertise in crafting AI systems that are efficient and aligned with human preferences and needs. Rather than aiming to replace humans, AI systems designed with HITL seek to augment human capabilities, creating a synergy that leads to more robust, transparent, and valuable applications.

In conclusion, integrating virtual simulations and machine learning marks a significant advancement in psychological research. By combining these technologies, researchers can develop more accurate models, design better experiments, and gain deeper insights into human behavior and cognition. This comprehensive approach enriches the study of complex psychological phenomena and contributes to developing more effective interventions and

treatments. As these technologies evolve, their influence on psychology will likely grow, offering new tools and methodologies for understanding the human mind.

## Part II – Empirical Evidence

# Evidence of Virtual Simulation Use in Psychological Research

Previous chapters discussed the significance of human-centered simulations in psychological research and applications. As argued, within this context, immersive virtual simulations (IVS) have considerable advantages from which the follow-up research may benefit. In the following section, several studies engaging immersive virtual reality to resolve various research challenges will be analyzed and critically evaluated regarding the current research discussion.

In the first chapter, the current issue of the replication crisis is raised and addressed using IVS as an effective replication tool in the framework of psychological science. In the second chapter, IVS as a geography education tool is presented, empirically tested, and critically reflected. In the third chapter, novel applications of IVS for virtual reality exposure therapy are introduced and critically evaluated. In the fourth chapter, IVS is used as a tool for studying evacuation behavior during escape from the buildings in the case of emergency scenarios, which results can be used in the engineering application. Finally, in the fifth chapter of this section, IVS is presented as a tool for collecting valid data, which can be used for agent-based modeling of human evacuation behavior and further for refining AI-based prediction tools. It means that the IVS will be considered within the context of five main sub-topics: replication, education application, clinical application, engineering application, and agent-based modeling. Within these chapters, published research articles by the

author of this thesis engaging IVS in various of the above-discussed perspectives are introduced and critically evaluated.

# Chapters on Virtual Simulation Application in Psychology

## Virtual Simulation as a Replication Booster<sup>2</sup>

In 2011, a respected social psychologist, Daryl Bem, based on research conclusions of his empirical study (Bem, 2011), claimed to provide evidence for precognition, suggesting that future events could influence actual human behavior. His methodology was standard for psychological research, but the claims challenged fundamental scientific principles, especially causality. The publication sparked loud debate and skepticism, leading to several failed replication attempts. These replication failures highlighted deeper issues in psychological research, such as problems with statistical methods, publication biases (favoring positive over negative or null results), and the overall reproducibility of experimental psychology. This prompted other researchers to reconsider existing research practices. As a result, the last decade has become crucial for psychological science, now called the replication crisis. The replication crisis describes a systemic issue where many psychological studies—once considered valid—failed to produce consistent results when their experiments were replicated. This crisis has led to deep introspection within the discipline about the validity and reliability of its scientific findings.

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<sup>2</sup> This chapter is based on the study: Chocholáčková, M., Juřík, V., Ružičková, A., Jurkovičová, L., Ugwitz, P., & Jelínek, M. (2023). Context-dependent memory recall in HMD-based immersive virtual environments. *PLOS ONE*, 18 (8), 1-15. (Vojtěch Juřík is a corresponding author)

A series of replication failures have highlighted unresolved methodological and statistical practices commonly used in psychological science, revealing significant negative evidence in once-reported results. The psychology community has undertaken rigorous efforts to reform research practices in response to these revelations. This includes the adoption of preregistration, where researchers publicly share their study's hypothesis and methodology before collecting data to prevent data manipulation, and open science practices, such as sharing data and experimental materials, have also been encouraged to enhance transparency and accountability. Among others, Uli Schimmack's Replicability-Index or R-index (Schimmack & Kesavan, 2014) is particularly noteworthy. This R-index is designed to assess the statistical power of research findings and predict their replicability. The R-Index addresses the problem of publication bias by providing a measure that reflects the likelihood that the reported positive findings are not just statistical flukes but are genuinely replicable. In the context of the replication crisis in psychology, a "replication project" refers to a concerted effort to systematically replicate previously conducted studies to assess their reliability and validity. These projects are critical for establishing whether scientific findings are reproducible and trustworthy.

One of the most notable replication projects is the "Reproducibility Project: Psychology<sup>3</sup>," initiated by the Center for Open Science. This project involved a large-scale collaborative effort in which over 270 researchers sought to

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<sup>3</sup> <https://osf.io/ezcuj/>

replicate 100 empirical studies published in three prominent psychology journals in 2008 (Aarts et al., 2015). The findings, published in 2015, were eye-opening: Only about 36% of the replicated studies yielded significant results, starkly contrasting the original studies' 97% rate of significant findings. This discrepancy highlighted widespread issues in psychological research, including practices like p-hacking (selectively reporting favorable data), publication bias (the tendency to publish positive findings over non-significant or negative ones), and other methodological weaknesses.

The implications of the replication crisis are still profound for psychology. It has prompted reevaluating what constitutes reliable scientific evidence in the field. The crisis has affected research practices and how findings are interpreted and applied in practical settings, such as clinical psychology, organizational behavior, and educational reforms. In this issue, the use of VR in psychological research has emerged as a promising tool, particularly in the context of the replication crisis that has challenged the field's traditional methodologies (Juřík et al., 2019). VR technology offers a unique platform for conducting experiments, providing controlled, immersive environments that can simulate real-world scenarios with a level of consistency challenging to achieve in traditional laboratory settings (Juřík et al., 2018; Juřík et al., 2019). This consistency can be pivotal for replication, as IVS ensures that all participants experience the same stimuli in an identical setting, potentially reducing variability coming from environmental differences.

However, the integration of IVS into psychological research has challenges and overlaps significantly with the broader issues highlighted by the replication crisis. For instance, while IVS can standardize experimental conditions, it also introduces new variables, such as the participant's familiarity with virtual environments and the potential physiological effects of VR, which may influence outcomes. Furthermore, the high costs associated with VR technology and the expertise required to develop and run VR-based experiments could limit the widespread replication of these studies, potentially exacerbating the issues the technology aims to resolve.

Despite these challenges, VR holds considerable promise for enhancing the replicability of psychological experiments by enabling precise control over complex experimental setups. This can be particularly useful in cognitive, social, and clinical psychology, where replicating naturalistic social interactions or psychological responses in a lab setting is often difficult. As the field continues to refine VR methodologies and address these challenges, VR may become an integral tool in the quest to overcome the replication crisis and advance the rigor and reliability of psychological research. An example of such an endeavor is represented by the experimental research conducted by Chocholáčková and her colleagues (2023). Based on the above-mentioned, we considered IVS a promising tool for replications, so the described study builds upon the above-discussed potential of the VR technologies since it presented a novel experiment utilizing immersive virtual reality to investigate context-dependent memory recall in humans, focusing on both accurate and incorrectly implanted semantic memories.

*Research on virtual reality in the false memories domain*

False memories, which are vividly detailed yet incorrect or completely fabricated but confidently believed, are a well-documented cognitive phenomenon (Loftus, 2003). Research on false memories has traditionally focused on episodic memory. However, a key development in studying false memories within semantic memory was made by Deese (1959). He created 36 lists, each containing twelve semantically related words to evoke a strongly associated but absent word, known as a "critical lure." These lists were presented auditorily and followed by immediate free recall sessions. Roediger and McDermott (1995) further investigated the effectiveness of these lists in generating false memories. They expanded the methodology to include word recognition tests and free recall, establishing the Deese-Roediger-McDermott (DRM) paradigm (2017). This paradigm has demonstrated that false memories can be consistently evoked across diverse conditions, persisting even in lists translated into other languages, with the most pronounced effects observed when presentations are in the participant's native language (Arndt & Beato, 2017; Cabeza & Lennartson, 2005; Dodson & Schacter, 2001; Gallo, 2010). Interestingly, the likelihood of generating false memories increases in a speaker's dominant language compared to a non-dominant language. However, this difference disappears when speakers possess equal fluency in both languages (Suarez & Beato, 2021).

In the DRM paradigm, memory formation is shaped by semantic connections, overlapping features, phonological links, and orthographic or lexical

associations, with these effects remaining relatively consistent across different ages (Coane et al., 2021). Typically, DRM studies use word lists paired with contextually relevant visual or auditory stimuli, such as images or voice recordings, that conceptually align with the words (Lyle & Johnson, 2006; Roediger et al., 2004). It is well-established that such contextual cues play a vital role in enhancing memory performance (Isarida & Isarida, 2014). During the learning phase, 'critical lures' are thought to be generated spontaneously. Reintroducing the original learning context during recall can significantly improve memory accuracy by reinforcing both verbatim and gist traces—the former preserving specific item details and the latter capturing the general theme of the items (Brainerd & Reyna, 2002; Roediger et al., 2001).

Context-dependent memory (CDM) refers to the phenomenon where recall is more effective when the contexts during learning and recall are the same. This was famously illustrated by Godden and Baddeley (1975), who found that divers remembered words better when learning and recalling occurred underwater or on land. Subsequent studies have confirmed these findings (Smith & Vela, 2001). The term "context" can refer to various factors, including the physical environment and an individual's mood and mental state (Smith & Vela, 2001). However, in recognition tests, the ability to directly compare studied items with new ones often provides more substantial cues than context alone (Eichenbaum, 2022).

Matching the encoding context with the retrieval context has significantly enhanced recall efficiency. Neuroimaging studies confirm that memory

performance improves when these contexts align, while misaligned contexts impede recall (Smith et al., 2018; Staudigl et al., 2015). Additionally, even imagined contexts that align with the encoding environment can boost recall (Schwoebel et al., 2022). Research in VR underscores the importance of context in learning complex materials, such as foreign language vocabulary, where appropriate contextual cues significantly improve retention (Essoe et al., 2022). However, the effect of varying VR environments on memory recall remains uncertain, with studies showing mixed results on the impact of contextual variability (Rocabado et al., 2022; Smith & Vela, 2001). There is a consensus that visual contexts rich in meaningful content are more likely to be encoded into memory alongside the primary material (Murnane et al., 1999; Smith & Vela, 2001). This includes visual materials like photos or videos (Smith & Manzano, 2010).

As extensively discussed above, VR technology offers a controlled yet realistic platform for studying cognitive processes by mimicking real-world interactions and enhancing the sense of presence, which is crucial for activities like learning (Alcañiz et al., 2009; Hirose et al., 2009; Kwartler, 2005; Paradis et al., 2019; Parsons, 2015; Reggente et al., 2018; Richardson et al., 1999; Sherman & Craig, 2018; Sowndararajan et al., 2010; Wilson, 1997). IVS, especially with head-mounted displays, has improved recall accuracy compared to traditional desktop setups, likely due to enhanced spatial awareness (Krokos et al., 2019). Additionally, studies by Wälti and colleagues (2019) and Shin and colleagues (2021) have investigated the effects of varying visual backgrounds and interactive environments within VR on memory. They found that contextually

relevant interactions within IVS can enhance recall and reduce false memories when the original learning context is reinstated during tests.

This ongoing research highlights the intricate relationship between memory, context, and technology, emphasizing the need for further exploration of context-dependent and false memory phenomena, mainly through the advanced capabilities of VR technology (Goodwin, 2013; Woods & Dewhurst, 2019; Yonelinas et al., 2019).

By employing conceptual replication, the study by Chocholáčková and her colleagues (2023) aims to deepen understanding in these areas by adapting Roediger and McDermott's methodologies to VR environments, focusing on how context variations during learning and recall phases affect memory accuracy and the creation of false memories. Additionally, this research investigates potential gender differences in memory performance, considering previous findings that suggest biological and hormonal factors influence different memory types (Loprinzi & Frith, 2018; Postma et al., 2004; Hamson et al., 2018). This examination seeks to elucidate how these differences appear in controlled cognitive experiments using VR, providing insights into the nuanced mechanisms of memory.

#### *Experiment Description and Research Methodology of False Memories Research*

The methodology for this study involved a well-defined participant group and carefully selected materials and stimuli to ensure the reliability and relevance of the findings. The study recruited 92 healthy individuals from Masaryk

University, predominantly psychology and humanities students. The participant group consisted of 33 males and 59 females, with a median age of 22 years and a standard deviation of 4.61 years (Chocholáčková et al., 2023). All participants were proficient in Czech and capable of speaking and reading the language, though not all were native speakers. The sample included 74 Czech and 18 Slovak nationals, reflecting a mix of native and second-language speakers. Participants were required to have no serious health issues, visual disorders, or any other medical conditions that might interfere with the experiment. The use of glasses was permitted, and participants were advised to wear contact lenses, if possible, to facilitate head-mounted displays. Participation was voluntary, and no compensation was offered. Informed consent was obtained before the experiment, which included an explanation that the study aimed to explore memory recall under specific conditions. However, full details of the study's purpose were withheld until the session's conclusion. Participants were also informed about the potential for experiencing motion sickness from the HMDs, with reassurances that they could withdraw at any point without needing to justify their decision. They were randomly assigned to either an experimental or a control group. Despite concerns about virtual reality-induced sickness, known as cyber sickness, no significant incidents were reported, and no participants withdrew from the study, probably because of the static/non-dynamic nature of the virtual simulation. All data collected was included in the final analysis.

The experimental materials were based on previously established research within the DRM paradigm. For this study, five specific word lists were selected

based on their likelihood of inducing false memories of a critical lure. Originally in English, these lists were translated into Czech with modifications to better align with the linguistic context. Changes included removing words uncommon in Czech or lacking a direct connection to the critical lure and substituting some words with more frequently used Czech equivalents. Each list was designed to evoke a single critical lure, with the targeted lures being "window," "sleep," "doctor," "sweet," and "chair." The presentation of these lists was unified into a single session, with five-second pauses between each sublist to demarcate them. This structured approach aimed to facilitate focused attention on each set of words, thereby optimizing the conditions for memory encoding and subsequent recall testing.

Upon arrival at the laboratory, participants were greeted and introduced to the experimental setup and the potential risks involved, notably the possibility of experiencing cybersickness. Before the experiment day, participants received preparatory instructions via email, which were reiterated in person to reinforce understanding. After a comprehensive review of the experimental protocol, participants gave their informed consent by signing the requisite documents. The initial phase of the experiment involved acquainting participants with the head-mounted display VR technology. They were given time to adjust to wearing the HMD and seated comfortably beside a table to mitigate potential nausea. Once acclimated, participants were immersed in the virtual environment, where they remained throughout the experiment to maintain consistent exposure to the VR settings.

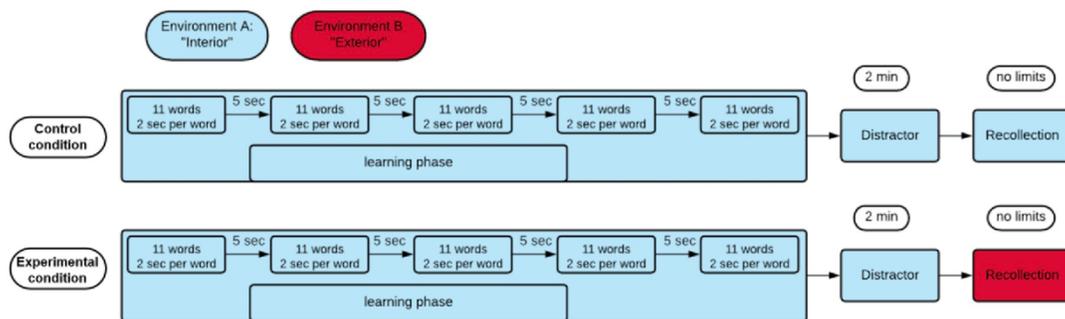
The experiment adhered closely to the DRM paradigm, with adaptations to minimize confounding variables and ensure isolation during testing. Participants could explore the virtual environment by moving their heads, which adjusted the virtual camera accordingly, aligning with methodologies prioritizing free recall over recognition to enhance memory accuracy by reducing contextual dependencies. Words from previously validated lists were chosen for their standard usage and likelihood to trigger contextual memory recollection. In this between-subjects design, participants were pseudo-randomly assigned to one of two conditions based on reported biological sex. Each participant was initially placed in virtual Environment A, where they engaged with visually presented words designed to prime false memory recall.

The structured experimental procedure involved a learning phase where participants familiarized themselves with Environment A by visually exploring the room. This sensory engagement was intended to enhance environmental authenticity and the participant's sense of presence. Words were then displayed through the HMD, floating in the center of the virtual scene based on the viewer's gaze, each appearing for two seconds with short intervals between the five thematic sub-lists. Following the learning phase, a distraction task involving a simple mathematical equation was introduced to prevent rehearsal of the words. The recollection phase differed between groups; the control group remained in Environment A, while the experimental group was transported to a distinct outdoor virtual Environment B. In both scenarios, participants were prompted to freely recall the memorized words aloud without constraints on the order or frequency of recall, except that fabrications

or guesses were discouraged. The verbal responses were recorded and later transcribed, with repetitions and uncertain responses excluded from the analysis. See Figure 17 to inspect the experimental procedure.

**Figure 17**

*Chocholáčková's (2023) experimental procedure*



*Note.* Adopted from Chocholáčková et al. (2023), used with the author's permission.

The virtual environments, powered by the HTC Vive Pro HMD and equipped with dual AMOLED displays, ensured high-resolution visual fidelity and responsive head-tracking, essential for maintaining immersion and the integrity of the environmental simulation.

The scenes, sourced and adapted from the Unity Asset Store, featured a detailed indoor setting (see Figure 18) with furniture and an outdoor courtyard with architectural elements (see Figure 19), providing diverse sensory stimuli conducive to studying memory under varying contextual influences.

**Figure 18**

*Indoor virtual environment used in the experiment*



*Note.* Photo by Pavel Ugwitz, used with the author's permission.

**Figure 19**

*Outdoor virtual environment used in the experiment*



*Note.* Photo by Pavel Ugwitz, used with the author's permission.

Finally, the procedural integrity and sequence of events were managed using the Toggle Toolkit (Ugwitz et al., 2021), which facilitated the precise delivery and timing of visual stimuli and transitions between environments, with system logs providing a reliable audit trail of the experimental operations. Participants were debriefed after the session, thanked for their contributions, and provided insights into the study's broader objectives and their role.

### *Data Analysis and Results*

Data analysis was conducted using linear mixed-effects modeling (LMER) to evaluate correctly recalled and falsely induced words. The dependent variables were the total number of words correctly recalled from the lists and the number of falsely recalled words matching the defined critical lures (window, doctor, sleep, sweet, and chair). Each correctly recalled or falsely induced word was assigned a score of 1, and the totals for each category were summed up and analyzed separately. Given the asymmetrical distribution of the correctly recalled words, a logarithmic transformation (logit) was employed to stabilize variance and normalize the data. Fixed factors in the analysis included the experimental condition and the biological sex of the participants. Additionally, the native languages of the participants—Czech and Slovak—were incorporated as random intercepts within the model due to their potential influence on recall accuracy despite the close relation between these languages (see more details in Chocholáčková et al., 2023). All statistical analyses were conducted using R software, utilizing the 'lme4' and 'lmerTest' packages to fit and test the linear mixed effects models.

The linear mixed effects model for correctly recalled words revealed significant main effects for sex ( $t = 2.955$ ;  $z = 0.217$ ;  $p = .004$ ; 95% CI [1.062, 6.262]), but not for experimental condition ( $t = -1.832$ ;  $z = -0.128$ ;  $p = .070$ ; 95% CI [-4.649, 0.311]). Specifically, women recalled words from the list more accurately than men. On average, men recalled 16 words ( $M = 16.24$ ;  $SD = 5.77$ ), while women recalled about 20 words ( $M = 20.20$ ;  $SD = 6.28$ ). No significant main or interaction effects were observed beyond this sex difference. Visual analysis indicated that recall performance in an alternative environment did not differ significantly from recall performance in the same environmental context ( $N = 47$ ;  $M = 19.72$ ;  $SD = 6.49$  vs.  $N = 45$ ;  $M = 17.80$ ;  $SD = 6.156$ ).

For the falsely recalled words, also called critical lures, the linear mixed effects model showed no significant effects related to the experimental condition ( $t = -0.725$ ;  $z = -0.182$ ;  $p = .470$ ; 95% CI [-0.673, 0.309]) or sex ( $t = -1.018$ ;  $z = -0.268$ ;  $p = .311$ ; 95% CI [-0.786, 0.248]). There was no significant difference in the production of critical lures between participants in the same versus an alternative environmental context ( $N = 47$ ;  $M = 1.57$ ;  $SD = 1.26$  compared to  $N = 45$ ;  $M = 1.44$ ;  $SD = 1.14$ ).

#### *Discussion of Results in the Context of Virtual Simulation*

In the above-presented study, immersive virtual simulation was used to create an experimental context, allowing for conceptual replication of the previous study. This research aimed to examine the impact of changing environmental contexts on memory recall and the induction of false memories, employing advanced virtual reality technology and utilizing the Deese-Roediger-

McDermott paradigm. As shown above, the study was able to identify significant results. A significant gender difference in memory performance was noted ( $p < .004$ ), with men recalling fewer words (average of 16) than women (average of 20), observed across both experimental and control conditions. In memory recall across different environments, however, no significant differences ( $p = .070$ ) were detected; participants who were transferred to a different virtual environment did not recall fewer words than those who remained in the initial environment. These findings critically reviewed the original study's findings since they instead support previous studies questioning the actual CDM effect (Rocabado et al., 2022; Smith & Vela, 2001; Wälti et al., 2019). In this case, despite the strong theoretical background supporting VR as activating similar brain processes as it would be in the real world (Alcañiz et al., 2009), it is still possible to argue about the validity of the virtual simulation as a suitable replication tool. The number of participants, conceptual replication, or specific technical issues during the experiment could be hypothesized as potential causes of the inconclusive results of the study.

Regardless of the given empirical evidence and conclusions made, in the case of this study regarding VR simulation use, several main arguments discussed in the previous chapters were demonstrated. The authors successfully developed an innovative computer-generated virtual environment designed to study the influence of specific virtual contexts on context-dependent memory recall in humans, as suggested in previous research (Loomis et al., 1999; Ugwitz et al., 2019). This groundbreaking approach marks a significant advancement in memory research, as it not only conceptually replicates

previous findings but also introduces the integration of virtual reality (VR) technology into the study of cognitive processes. By employing VR, the study showcases the potential of this technology to enhance the precision and reliability of experimental designs, offering a novel way to explore how environmental cues influence memory recall.

The experimental procedure employed in this study is particularly noteworthy for its use of VR as a research tool. VR is emphasized as a cost-effective and highly adaptable platform, capable of creating a wide range of experimental conditions that are both realistic and controllable (Juřík et al., 2021; Juřík et al., 2019; Ugwitz et al., 2021). This adaptability allows researchers to simulate environments with a level of ecological validity that is difficult to achieve with traditional laboratory setups. The immersive nature of VR provides participants with a more engaging and lifelike experience, which is crucial for studying cognitive processes in a manner that closely mirrors real-world situations.

Moreover, creating a standardized VR interface significantly facilitates replication projects like those discussed above (Aarts et al., 2015). By developing a unified platform, researchers can ensure that experiments can be easily replicated across different studies and settings, reducing the variability that often complicates replication efforts in psychological research. This standardized approach not only enhances the consistency of experimental conditions but also enables a broader range of researchers to engage in

replication studies, thereby strengthening the reliability and validity of the findings.

Furthermore, the study promotes the discussion based on previous research showing memory processes in virtual environments to correspond closely with those observed in the real world (Alcañiz et al., 2009; Slater, 2018). The immersive qualities of VR make it an especially promising avenue for future research, as it allows for manipulating environmental variables in ways that are not feasible in physical environments. This opens up new possibilities for investigating a wide range of cognitive phenomena, particularly those related to context-dependent memory, and supports the idea that VR can be effectively employed in further replication studies to validate and extend existing research findings. The above-presented points are summarized below:

- The authors successfully developed an original computer-generated virtual environment designed to study the impact of specific virtual contexts on context-dependent memory recall in humans.
- This study effectively replicated existing memory research on a conceptual level by integrating VR technology, highlighting its utility in controlled experimental designs.
- In the experimental procedure, virtual reality is emphasized as a cost-effective, highly adaptable, and ecologically valid tool, providing a realistic and immersive experience for studying cognitive processes under controlled conditions.

- Building on previous research, the study provided new empirical evidence on memory processes, which can be further considered in the follow-up research, suggesting that immersive VR technologies are a promising tool for future cognitive research, with the potential for promoting replication projects.
- To facilitate replication projects, the study proposes the creation of a standardized interface that can be shared with other research teams, enabling the execution of large-scale replication studies across multiple labs.

In summary, this study further pushes the boundaries of experimental design by incorporating VR technology. IVS offers significant cost, adaptability, and ecological validity advantages, making it a valuable tool for studying cognitive processes. Developing a standardized VR interface further facilitates replication efforts, ensuring that experiments can be consistently reproduced and validated across different research settings. The findings support the idea that VR environments can effectively simulate real-world memory processes, positioning immersive VR technologies as a promising tool for future cognitive research and exploring new research topics.

#### *Limitations and Future Directions*

Several limitations could have influenced the findings of the study. The context change occurred only during the recall phase, not during learning. A fully crossed design, where contexts vary during learning and recall, might provide

more conclusive results. Additionally, this setup combined various effects, such as impaired memory from context changes that were neutralized by a potentially more conducive outdoor environment for recall. The non-significant differences in word recall across different environments mirror findings by Wälti and colleagues (2019) and may relate to the sample size. Therefore, we employed linear modeling to describe and critically assess observed trends. Further studies with larger samples are necessary to better understand CDM effects in immersive VR environments. Other potential limitations are more closely connected to the VR technology and should be addressed in the follow-up research since the IVSs allow for relatively easy resolution. The semantic association between the recalled words and the visuals of the environments (for instance, the word "window" appeared in both virtual settings but was visually distinct in each) possibly affected associative memory triggers. Careful consideration of such details in the virtual environments created for specific experiments is crucial when designing experimental stimuli for memory studies. Similarly, the study has restricted interaction options within the virtual environments. Participants could only look around without moving or interacting more dynamically, which some studies suggest could enhance memory performance. While the research adhered to the DRM paradigm's methods by limiting physical interactivity and maintaining controlled yet realistic immersion levels through head movement, more interactive and visually rich virtual environments should be explored in future studies.

Regardless of the above, overall, the study successfully challenged the expected impact of environmental changes on memory recall while demonstrating the usefulness of VR in cognitive research. This research is significant as it provides direction for replication studies and highlights the practical context of VR technology in creating realistic experimental settings.

## Virtual Simulation in Education<sup>4</sup>

Immersive virtual reality (IVR) has rapidly evolved into a significant educational tool, finding applications across various disciplines. Immersive virtual simulations are currently employed in engineering, biology, foreign language learning, geometry, emergency management, physics, design, and geography. Additionally, IVS has been employed in specialized areas such as martial arts training and enhancing communication skills for individuals with autism or collaborative learning (Šašinka et al., 2018). Although virtual environments, including IVS, have long been incorporated into geographical research and education, it is only recently that user experiences have been more thoroughly documented.

The growing interest in IVR technologies within the education sector is evidenced by the increasing body of empirical research exploring this technology as an educational tool. This research spans diverse fields such as biology, physics, medicine, architecture, engineering, emergency management, and communication skills training for individuals with autism. IVR is often heralded as a promising educational innovation, generating high expectations for its potential to transform learning (Villena-Taranilla et al., 2022). However,

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<sup>4</sup> This chapter is based on the study: Šikl, R., Brücknerová, K., Švedová, H., Děchtěrenko, F., Ugwitz, P., Chmelík, J., Pokorná, H., & Juřík, V. (2024). Who benefits and who doesn't in virtual reality learning: An experimental study comparing two types of school. *Journal of Computer Assisted Learning*. Wiley.

the effectiveness of VR in education has produced mixed results, with some studies highlighting its advantages while others question its impact (Coban et al., 2022).

On the one hand, several studies have demonstrated that IVR can enhance academic performance compared to traditional teaching methods, suggesting that virtual environments can lead to superior learning outcomes (Chiquet et al., 2023; Liu et al., 2022). On the other hand, other research has found no significant difference in learning outcomes between IVR and conventional approaches (Behmadi et al., 2022; Makransky et al., 2021). In certain instances, IVR has even been associated with reduced learning effectiveness relative to other media (Parong & Mayer, 2021).

The variability in research findings may be attributed to the dominance of technology-centered approaches, which emphasize the capabilities of new technologies rather than focusing on the needs and preferences of students. These approaches often fail to comprehensively evaluate the potential learning benefits of IVR, leading to inconclusive or contradictory results. Sorden (2012) provided a historical perspective, noting that past educational technologies—such as radio, television, computers, and the Internet—were initially expected to revolutionize education simply because of their advanced nature (Mayer, 2009). Similarly, when evaluating the educational effectiveness of IVR, it is essential to understand the specific dynamics of learning within this environment, consider how different media impact diverse learners, and adapt the technology to serve students' needs better.

A learner-centered approach, which considers factors such as student motivation, satisfaction, and academic self-efficacy (Xie et al., 2023), is crucial for effectively integrating IVR into educational settings. Despite the growing enthusiasm for VR, there is a notable scarcity of research comparing IVR learning outcomes across different types of schools. Given the complexities involved in integrating IVR into school curricula, it is critical to determine which students are most likely to benefit from this technology and which may not before it is widely implemented in educational settings.

While IVR holds significant promise as an educational tool across various disciplines, its effectiveness remains debatable. The mixed results underscore the importance of adopting a learner-centered approach that considers the specific needs of students and the broader educational context. As research continues to explore the potential of VR in education, especially when combined with collaborative and game-based learning environments, it is essential to approach its implementation cautiously to ensure it meets the diverse needs of all learners. This was also the case in the study conducted by Šikl and his colleagues (2024). Regarding the above-discussed potential of IVR technologies in education, Šikl's study succeeded in creating an original VR education environment for learning contour lines in the domain of geography. It assessed the learning incomes compared to alternative learning methods.

#### *Research on the Learning Geography in Immersive Virtual Reality*

Immersive virtual environments (IVEs) offer unique opportunities for learning by providing immersive virtual simulations of realistic processes, but they also

present challenges. Various factors within IVEs can influence learners' experiences and subsequently affect their learning outcomes. On the positive side, IVR technology immerses learners in a rich sensory experience, enabling them to visualize learning material engagingly and interactively. This immersion allows for the dynamic modification, triggering, updating, and adaptation of virtual content (Ugwitz, 2021) and facilitates remote collaboration among users in a shared virtual space to complete tasks (Liu, 2022). Additionally, IVR can stimulate creativity and imagination in both learners and educators, given the nearly limitless range of stimuli generated within these environments. The high level of immersion can also evoke strong emotional responses, which may enhance performance and motivation, especially when the environment is highly realistic and offers a strong sense of presence (Makransky & Petersen, 2021; Parong et al., 2020).

However, not all aspects of IVR are conducive to learning. While engaging environments can be motivating, they may not necessarily support the construction of knowledge, particularly when it comes to acquiring declarative knowledge (Makransky et al., 2019; Mayer, 2009). The impressive graphics and sensory overload of IVEs, combined with the excitement of using new technology, can sometimes distract learners from the instructional goals, diverting their attention to irrelevant details. This distraction can interfere with the organization of information in working memory, which is essential for building new knowledge (Parong & Mayer, 2018). Additionally, the heightened immersion in IVEs can increase cognitive load, leading to more

frequent cognitive overload than less immersive instructional methods (Bagher et al., 2022; Meyer et al., 2019).

To mitigate these challenges, Mayer's (2009) cognitive theory of multimedia learning can be applied to design IVR experiences that minimize extraneous cognitive load, manage essential processing, and foster generative learning. This theory includes principles such as coherence (avoiding irrelevant content) and signaling (using visual cues to highlight important information) to reduce unnecessary cognitive load. Other principles, such as segmenting (breaking content into manageable pieces), pre-training (providing preliminary information), and modality (using narrated animation instead of text), help manage essential cognitive processing. Personalization (using conversational language) and voice (employing a human narrator) can enhance generative processing.

Learning outcomes in IVR are influenced by the technology's advantages and disadvantages as well as various learner characteristics. Factors such as spatial ability (Sajjadi et al., 2021), the ability to filter out distractions (Chiquet et al., 2023), and prior knowledge (Mayer et al., 2002; Meyer et al., 2019) can significantly affect how efficiently a learner processes information in IVR environments. As a result, students with stronger academic skills and achievements are expected to benefit more from IVR interventions.

In educational systems characterized by significant disparities, such as those found in countries like Israel, the United Arab Emirates, France, Germany, Hungary, Peru, and the Czech Republic, the impact of IVR may vary

depending on the type of school. Socioeconomic inequities are often linked to differences in digital literacy and access to technology (Fraillon, Ainley, Schulz, Friedman, & Duckworth, 2020). However, some scholars argue that information and communication technologies can promote inclusion (Kim, Yi, & Hong, 2021). Adaptive multimedia learning technologies, like IVR, can increase motivation and satisfaction, especially in underprivileged schools (Xie, Li, & Tang, 2023). This raises the question of whether IVR can help bridge the educational gap between different types of schools or whether it might exacerbate existing inequalities. There is no data on whether students from various types of schools benefit equally from integrating IVR into their curriculum.

This issue is particularly relevant in the Czech Republic, where the education system is marked by high levels of inequality (OECD, 2019). In lower secondary education, these inequalities are evident in the distinction between multi-year gymnasiums (gymnasium is Czech equivalent to grammar school), where a select group of students is admitted at age eleven, and comprehensive schools, which serve the remainder. This division contributes to significant disparities in educational outcomes, as evidenced by Programme for International Student Assessment scores, which reflect differences in socioeconomic status, academic aspirations, and the availability of quality teachers (Ministry of Education, 2020; Šťastný & Chvál, 2023).

In geoscience, IVR is seen as a valuable tool for explaining complex phenomena that are difficult to convey through traditional teaching methods. Including

IVR in the educational process could benefit topics such as map projections, planetary orbits, geomorphological processes, migration patterns, and climate change threats. This study focuses specifically on topography and the use of contour lines.

Despite their frequent use, topographic maps are often challenging for students to understand. The main difficulty is translating a three-dimensional landscape into a two-dimensional map (Boardman, 1989; Swenson & Kastens, 2011). Students often struggle to visualize the spatial relationships represented by contour lines, leading to misconceptions. For example, they may misinterpret the absence of elevation values, misunderstand the spacing of contour lines, or confuse elevation with steepness (Boardman, 1989). The study hypothesizes that the 3D visualization capabilities of IVEs can help students better understand spatial relationships in topography by allowing them to engage in mental rotations and visualize landscape structures in ways that are impossible with 2D maps. This approach could make the abstract concept of contour lines more accessible, helping students gain deeper insights into the material.

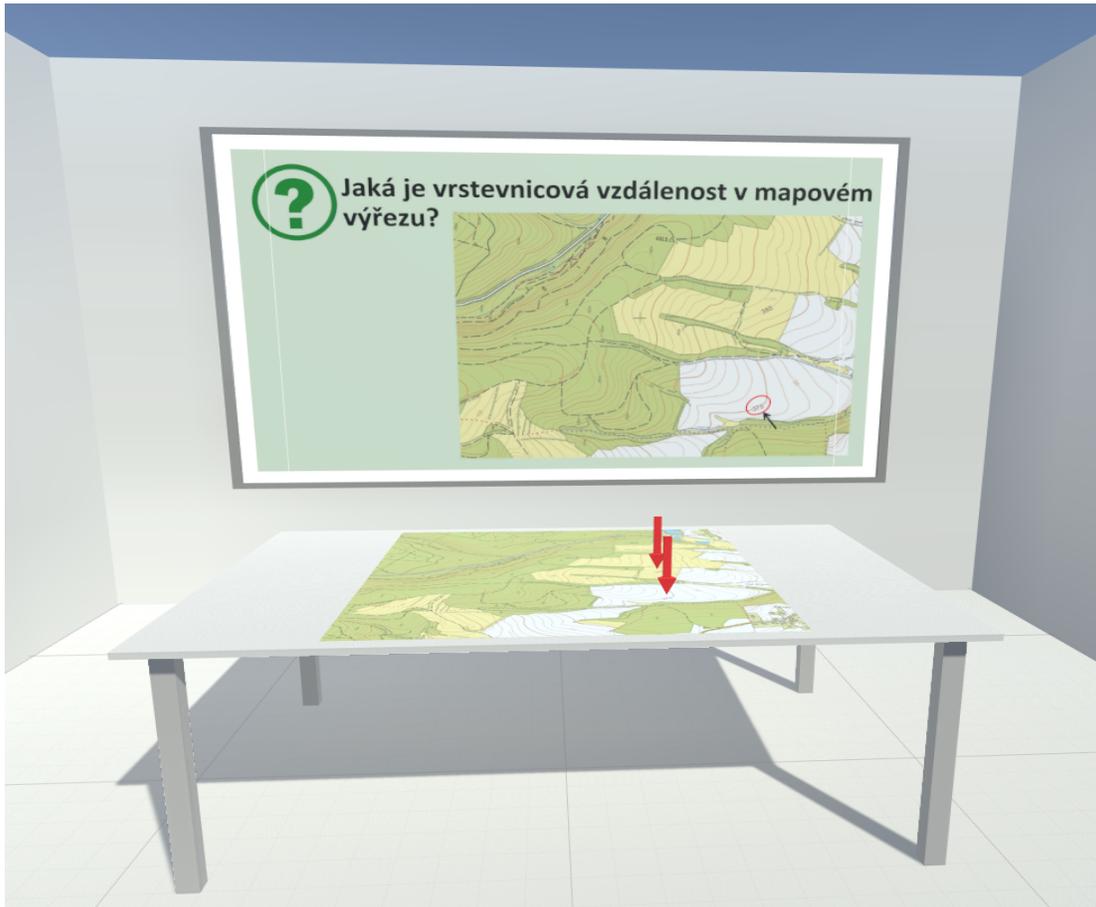
#### *Experiment Description and Research Methodology of Education Experiment*

The study investigates the influence of school type and technology-enhanced teaching methods on students' learning outcomes in geography, specifically focusing on understanding and applying contour lines in topographic maps. The research involves two groups of lower secondary students: one from a selective multi-year gymnasium and another from a non-selective

comprehensive school. The core objective is to compare the learning gains of these groups in two educational settings: an immersive virtual reality (IVR) environment and a traditional PowerPoint (PPT) slideshow. To assess the impact of these educational interventions, the study employed a transfer test administered in three phases: before the lesson (pre-test), immediately after the lesson (immediate post-test), and one month later (delayed post-test). The transfer test evaluated the students' ability to apply the knowledge acquired during the lesson while working with a map. The three testing phases measured the students' baseline knowledge, immediate learning gains, and knowledge retention over time. See the example of the IVR environment (Figure 20).

**Figure 20**

*An example of an immersive VR environment used in the study*



*Note.* Adopted from Šíkl et al. (2024). Photo by Pavel Ugwitz, used with the author's permission.

In addition to the transfer test, a subtest from the SRT-911 spatial reasoning test was administered. This test was included because previous research has shown that students with higher spatial ability tend to achieve greater learning gains from animations, particularly in subjects involving spatial topics like topography (Mayer, 1994; Sudatha et al., 2018). The study hypothesized that

students with higher spatial reasoning scores would perform better on the pre-test and post-test. This would be particularly evident in students exposed to the IVR intervention. The study's hypotheses were as follows: It was anticipated that gymnasium students would outperform comprehensive school students on the transfer pre-test and show more remarkable improvement in the immediate post-test (Hypothesis 1).

Additionally, gymnasium students were expected to retain more knowledge, as evidenced by a smaller score decline between the immediate and delayed post-tests (Hypothesis 2). Furthermore, it was predicted that students in the IVR group would achieve higher scores on the immediate post-test than those in the PPT group (Hypothesis 3) and retain more knowledge over time (Hypothesis 4). Among gymnasium students, those in the IVR group were expected to show more remarkable improvement on the immediate post-test than those in the PPT group (Hypothesis 5), and the same was expected for comprehensive school students (Hypothesis 6). Finally, it was hypothesized that students with higher spatial reasoning scores would perform better on the transfer pre-test and show greater improvement on the immediate post-test (Hypothesis 7).

The study's participants included 262 students (134 males and 128 females) aged 12 to 16, with an average age of 13.6 years. The study used a  $2 \times 2$  between-subjects experimental design, where the type of school was the first factor, the learning environment (IVR vs. PPT) was the second factor, and spatial ability was included as a covariate. Participants were distributed across the four

experimental conditions, with 47 students in the IVR/gymnasium group, 29 in the PPT/gymnasium group, 91 in the IVR/comprehensive school group, and 95 in the PPT/comprehensive school group. The IVR learning environment was carefully designed to adhere to Mayer's (2009) principles of multimedia learning, focusing on reducing the cognitive load to enhance learning. The IVR environment was intentionally simplified, avoiding graphically rich or narratively complex elements to keep students focused on the key concepts. The instructional content was broken down into small, manageable segments, and the virtual environment primarily featured a 3D model of a topographic map that students could interact with visually. The content delivered in the IVR setting was matched as closely as possible with that delivered in the PPT setting, with both groups receiving the same instructional slides and narrative, the only difference being the medium through which the content was presented. Students in the IVR group experienced the lesson through a head-mounted display (HTC Vive Pro), which immersed them in a virtual room where the instructional slideshow was projected onto a wall. A 3D model of the map was also placed on a virtual table in the room, providing a dynamic visual representation of the terrain. This model would rise and change to visually represent different aspects of the terrain as the lesson progressed. The lesson in the PPT group was displayed on a standard computer monitor, with students listening to the exact narration as in the IVR group, but without the immersive 3D environment.

Both lessons were designed to last approximately eight minutes. Before the experiment began, students who agreed to participate provided written

parental consent. They were then randomly assigned to the IVR or PPT group within their respective schools. The pre-test phase involved administering the transfer test to establish the students' baseline knowledge of contour lines and their ability to apply it in map reading. After the pre-test, students completed the spatial reasoning test (SRT-911). The geography lesson, conducted three to ten days after the pre-test, was the core of the learning intervention. Following the lesson, students immediately took the post-test to measure the knowledge gained. A month later, they completed the transfer test again to assess knowledge retention.

The transfer test comprised 13 four-alternative forced-choice questions designed to measure the depth of understanding of contour lines and apply this knowledge in map reading. For example, students might be asked to identify the height difference between two points on a map or to determine the steepest segment of a route based on contour line spacing. The test was scored out of 13 points, with each correct answer receiving one point. The study used three equivalent versions of the transfer test across the different phases (pre-test, immediate post-test, and delayed post-test) to ensure consistency in difficulty and content. The spatial reasoning test (SRT-911) assessed students' spatial orientation ability, which was considered potentially influential in their performance in the IVR environment. The test included three items that required students to identify the perspective from which a particular spatial configuration was observed. The reliability of the test, though somewhat low ( $\alpha = .45$ ), was deemed sufficient for this study.

Data were analyzed using R software, employing two primary analytical approaches. First, two three-way mixed ANOVAs were conducted—one to compare pre-test and immediate post-test scores and the other to compare immediate post-test and delayed post-test scores. These analyses aimed to assess the effects of school type, learning environment, and the interaction between these factors across different testing phases. Additionally, the study tested multiple contrasts to evaluate the individual hypotheses more directly. For more details, see the study of Šikl and colleagues (2024). The study's results and scripts are publicly available on the Open Science Framework repository (<https://osf.io/caubj/>), allowing for transparency and further examination by other researchers. This commitment to open science enhances the reliability of the study's findings and supports the broader academic community in conducting similar research or building upon these results.

#### *Data Analysis and Results*

The study began by investigating whether the groups differed in demographic characteristics. An independent-sample t-test revealed no significant age difference between gymnasium students ( $M = 13.6$ ,  $SD = 0.92$ ) and comprehensive school students ( $M = 13.6$ ,  $SD = 0.97$ ,  $t(259) = 0.33$ ,  $p = .743$ ). Similarly, no significant age difference was observed between the IVR and PPT groups ( $t(259) = -0.48$ ,  $p = .631$ ). A Chi-square test indicated no significant gender difference between the gymnasium and comprehensive school groups ( $\chi^2(1) = 0.92$ ,  $p = .337$ ). However, there was a significantly higher proportion of males in the IVR group (59%) compared to the PPT group (42%,  $\chi^2(1) = 6.98$ ,  $p$

= .008). Gender was not included in the analysis to avoid small groups for individual tests.

The pre-test, immediate post-test, and delayed post-test scores for the four experimental groups on the transfer test were measured. The average pre-test score across all groups was 7.89 out of 13 (SD = 2.79), indicating that while students had some prior knowledge, there was still room for improvement. Notably, no correlation was found between age and pre-test scores ( $r = .07$ ,  $p = .259$ ) or between age and learning improvement ( $r = -.01$ ,  $p = .899$ ), suggesting that learning outcomes were independent of age and that even younger students could effectively understand and learn from the intervention.

The first research question explored whether gymnasium students gained more from the intervention than comprehensive school students. Gymnasium students scored 72% (SD = 18%) in the pre-test, 79% (SD = 17%) in the immediate post-test, and 86% (SD = 13%) in the delayed post-test. Comprehensive school students showed similar accuracy levels across all three measurements: 56% (SD = 21%) in the pre-test, 56% (SD = 22%) in the immediate post-test, and 58% (SD = 24%) in the delayed post-test.

Gymnasium students had significantly higher scores than comprehensive school students in the pre-test ( $t(260) = 5.99$ ,  $p < .001$ ,  $d = 0.74$ ) and showed greater immediate learning gains (post-test vs. pre-test:  $t(260) = 2.44$ ,  $p = .015$ ,  $d = 0.30$ ). Specifically, gymnasium students' scores significantly increased from the pre-test to the immediate post-test ( $t(75) = 2.78$ ,  $p = .007$ ,  $d = 0.32$ ). In contrast, comprehensive school students did not demonstrate any significant

improvement ( $t(185) = -0.27, p = .787, d = -0.02$ ). These results confirmed Hypothesis 1.

Retention analysis also revealed significant differences between the groups, with gymnasium students showing superior retention (immediate post-test:  $t(260) = 8.28, p < .001, d = 1.02$ ; delayed post-test:  $t(260) = 9.69, p < .001, d = 1.20$ ). Gymnasium students scored significantly higher on the delayed post-test than on the immediate post-test ( $t(75) = 3.11, p = .003, d = 0.36$ ). In contrast, this difference was insignificant for comprehensive school students ( $t(185) = 1.34, p = .181, d = 0.10$ ). Therefore, Hypothesis 2 was supported. Overall, gymnasium students learned more and retained their knowledge better than comprehensive school students.

The second research question investigated whether the learning medium (IVR vs. PPT) influenced academic performance. The IVR group had an average accuracy of 61% (SD = 22%) in the pre-test, 64% (SD = 22%) in the immediate post-test, and 66% (SD = 25%) in the delayed post-test. The PPT group had similar accuracy, with 60% (SD = 21%) in the pre-test, 60% (SD = 24%) in the immediate post-test, and 66% (SD = 25%) in the delayed post-test.

Contrary to expectations, the IVR learning intervention was not more effective than PPT, as evidenced by the lack of significant differences in immediate post-test scores ( $t(260) = 0.75, p = .452, d = 0.09$ ) and delayed post-test scores ( $t(260) = 0.97, p = .335, d = 0.12$ ). Thus, Hypotheses 3 and 4 were not supported. Further analysis using ANOVA with condition and school type as factors showed no significant differences in immediate learning gains between the conditions

( $F(1,258) = 0.23$ ,  $p = .635$ ,  $\eta^2p < 0.01$ ) and no interaction between condition and school type ( $F(1,258) = 0.31$ ,  $p = .575$ ,  $\eta^2p < 0.01$ ). Similar results were obtained for knowledge retention, with no significant differences between conditions ( $F(1,258) = 1.37$ ,  $p = .243$ ,  $\eta^2p = 0.01$ ) and no interaction between condition and school type ( $F(1,258) = 1.41$ ,  $p = .236$ ,  $\eta^2p = 0.01$ ). Thus, the study concluded that students did not learn or retain knowledge better when the material was delivered via IVR compared to PPT.

The third research question examined whether the type of school moderated the effect of the learning medium on academic performance. Gymnasium students who experienced IVR scored significantly higher on the post-test than on the pre-test ( $t(46) = 2.35$ ,  $p = .023$ ,  $d = 0.34$ ). At the same time, those in the PPT condition also improved, but not significantly ( $t(28) = 1.59$ ,  $p = .124$ ,  $d = 0.29$ ). However, the difference in immediate learning gains between the two conditions was insignificant ( $t(74) = 0.23$ ,  $p = .819$ ,  $d = 0.05$ ), thus not supporting Hypothesis 5. Comprehensive school students did not show significant improvement in either the IVR condition ( $t(90) = 0.32$ ,  $p = .748$ ,  $d = 0.03$ ) or the PPT condition ( $t(94) = 0.65$ ,  $p = .516$ ,  $d = 0.07$ ). The difference between these conditions was also insignificant ( $t(184) = 0.70$ ,  $p = .488$ ,  $d = 0.10$ ), concluding that Hypothesis 6 was not supported. The study concluded that neither group of students learned or retained knowledge better when the material was delivered via IVR compared to PPT.

Lastly, the study explored the relationship between spatial reasoning and transfer test performance. The gymnasium students scored significantly higher

on the SRT-911 test ( $M = 1.84$ ,  $SD = 0.77$ ) than the comprehensive school students ( $M = 1.59$ ,  $SD = 0.99$ ,  $t(260) = 1.97$ ,  $p = .050$ ,  $d = 0.24$ ). A moderate correlation was found between SRT-911 scores and pre-test scores ( $r = .29$ ,  $p < .001$ ), but the correlation between learning gains and pre-test scores was not significant ( $r = .05$ ,  $p = .382$ ). When analyzed separately by school type, gymnasium students showed no correlation between SRT-911 scores and pre-test scores ( $r = -.04$ ,  $p = .702$ ). However, they did show a significant correlation between SRT-911 scores and learning gains ( $r = .28$ ,  $p = .013$ ). Conversely, comprehensive school students showed a significant correlation between pre-test scores and SRT-911 scores ( $r = .35$ ,  $p < .001$ ) but no correlation between SRT-911 scores and learning gains ( $r = -.04$ ,  $p = .605$ ). This suggests that in gymnasium, students with higher prior knowledge and spatial ability enhanced learning from the intervention, while in comprehensive school students, higher spatial ability was linked to better pre-test performance but did not lead to significant learning gains from the intervention. Therefore, Hypothesis 7 was partially confirmed.

#### *Discussion of Results in the Context of Virtual Simulation*

The study examines the effectiveness of immersive virtual simulation in learning, focusing on how learner characteristics like school type and spatial ability influence outcomes. Results show that school type significantly impacts learning, with gymnasium students improving more over time than comprehensive school students. Spatial ability also played a role in better learning outcomes, particularly for gymnasium students. The study found no

clear advantage of IVR over traditional methods like PowerPoint, highlighting that the design of the learning experience and learner traits are more crucial than the technology itself.

The study moves beyond simply determining whether IVR learning is effective, exploring when and how it works, as Buchner and Kerres (2023) suggested. It examined the impact of learner characteristics, such as the type of school and spatial ability, on the effectiveness of IVR compared to traditional media like PPT. Unlike comprehensive school students, the results highlighted that the type of school significantly influences learning outcomes, with gymnasium students showing continued improvement a month after the intervention. Spatial ability also played a role, particularly for gymnasium students better prepared to benefit from the instruction.

Interestingly, the study found no clear advantage of IVR over PPT in immediate recollection or knowledge retention, aligning with previous research suggesting that technology is not the most crucial factor in learning. Instead, the learning experience's design and the learners' characteristics are more important. The study concludes that the medium used may not necessarily impact learning achievements. It emphasizes the importance of considering learner characteristics and educational context when assessing the potential of IVR as a teaching tool. Additionally, the study's approach to measuring knowledge retention over time and its effort to align the content and format of the lessons in both media contribute valuable insights into the effectiveness of IVR in education.

Regarding these conclusions, which highlight other factors that are more important in the learning process than a specific form of visualization, the other benefits of the study should be discussed. The learning simulation employed in this study exemplifies the potential of immersive virtual simulation in the educational domain. It demonstrates its utility as a powerful tool for enhancing the learning experience, as discussed by Juřík and his colleagues (2016a). The virtual environment created for this study enables a unique form of education by allowing the visualization of complex phenomena in ways that are possible only within a virtual reality setting. This capability was one of the primary motivations behind the study, as it sought to explore how IVR can be harnessed to make abstract or intricate concepts more accessible and comprehensible to learners. Moreover, the study provides a detailed demonstration of the methodological design that can be implemented within the specific features of IVR environments used in real-world educational settings. By outlining the precise procedures and considerations, the research offers a practical framework that educators and researchers can adopt and adapt to their teaching or experimental needs. This methodological clarity is essential for ensuring that IVR can be effectively integrated into school curricula, where the benefits of virtual reality—such as immersive engagement and interactive learning—can be fully realized.

Additionally, within the experimental procedure, VR is highlighted as a cost-effective, easily adjustable, and ecologically valid tool, which aligns with the previous research (Šašík et al., 2018; Juřík et al., 2016a). Its ability to offer a realistic and immersive experience under controlled conditions makes it an

ideal medium for studying cognitive processes related to learning. The study underscores how VR's adaptability allows for creating environments tailored to the educational content being taught, thereby enhancing the relevance and impact of the learning experience.

Furthermore, the educational environment developed through this study is designed to be easily transferable and disseminatable. This means that the virtual learning environment can be a ready-made tool for other researchers or educators who wish to conduct replication studies or apply the simulation in different educational contexts, which boosts both the possible application and replication potential. By offering a standardized and accessible platform, the study supports the broader adoption of IVR in education. It facilitates large-scale replication projects, which are crucial for validating the effectiveness of virtual reality in enhancing learning outcomes across diverse settings. The specific points are summarized below:

- The learning simulation utilized in this study exemplifies the potential applications of immersive virtual simulations in the educational field, effectively demonstrating its practical utility.
- The virtual environment created for this study enables a form of education that allows for the visualization of complex phenomena in uniquely achievable ways through virtual reality, which was one of the primary motivations behind this research.

- The study provides a detailed methodological framework that can be specifically adapted to the features of immersive virtual environments used in real educational settings, offering a replicable design for future research and practical applications.
- Within the experimental procedure, virtual reality is emphasized as a cost-effective, highly adaptable, and ecologically valid tool that provides a realistic and immersive experience for studying cognitive processes under controlled conditions.
- The educational environment developed through this research is easily transferable, making it available as a ready-made tool for further replication studies or educational use in diverse settings.

In summary, this study offers valuable insights into how different educational technologies and school environments affect students' learning outcomes in geography. By rigorously comparing IVR and PPT learning interventions in selective and non-selective school settings and considering the role of spatial reasoning abilities, the research contributes to a deeper understanding of the factors that influence effective learning in geography, particularly in topics requiring spatial reasoning. The study's findings are expected to inform educational practices and technology integration in classrooms, particularly in designing interventions to improve students' spatial understanding and map-reading skills.

### *Limitations and Future Directions*

The study faced several limitations, beginning with the assumption that the immersive virtual simulation would offer an advantage due to its 3D spatial visualizations, which were expected to make geographical concepts easier to grasp. However, participants did not significantly benefit from these features, possibly relying more on the slideshow information. It remains uncertain whether a higher level of immersion might have better supported cognitive processes or whether it would have led to distractions and cognitive overload. Recent studies suggest that more complex and instructional elaborate VR conditions can yield better results (Büssing et al., 2022; Stavroulia & Lanitis, 2023). However, this study maintained identical instructional activities across mediums for comparability, potentially sacrificing some ecological validity. The study's limitations include the unbalanced sample sizes between the multi-year gymnasium and comprehensive school groups (76 vs. 186 students, respectively), which may considerably question the conclusions. Data collection was halted prematurely due to the COVID-19 pandemic, preventing the balancing of sample sizes. Despite this, the study's conclusions remained consistent even after reanalysis with statistical corrections for unbalanced groups.

Another limitation was the limited scope of the sample, as only one school of each type was included. Future research should include multiple schools of the same type to enhance the robustness of the findings. Regarding the use of IVS, the experimental design can be easily offered to other research teams and

disseminated to gain more robust research data. Additionally, the use of a traditional transmissive teaching style may not have been the most effective for the IVS setting. The intervention did not address students' preconceptions or provide ongoing feedback on their understanding, leaving gaps in assessing what students learned from the instruction. While this teaching method is standard in Czech schools, introducing alternative approaches like collaborative learning or problem-solving might have impacted the results, mainly if students were unaccustomed to such methods.

In conclusion, the study highlights the importance of considering students' characteristics when evaluating learning outcomes in different educational contexts. The findings suggest that when learning environments are closely matched in content and cognitive load, the medium (e.g., IVR vs. PPT) may not significantly impact learning gains. Instead, students' academic backgrounds play a more critical role, especially in educational systems with significant disparities, such as the Czech Republic. Students with stronger academic skills are more likely to benefit from interventions, with these differences being evident in both immediate recall and long-term knowledge retention. Therefore, further research on this topic involving various student groups is needed.

For practical implications, introducing IVR technologies in schools, particularly comprehensive ones, may not fulfill expectations. A more nuanced approach to education is necessary in settings with many underqualified teachers using transmissive methods. Mayer (2009) highlighted the importance

of pre-training in multimedia learning to enhance outcomes, a principle that applies to IVR learning (Mayer et al., 2002; Petersen et al., 2020). Additionally, incorporating scaffolding and summarizing strategies into IVS-based instruction could help students from non-selective schools better grasp and retain key concepts. These methods involve breaking down complex problems, assessing comprehension through tasks, and connecting new information to prior knowledge, enhancing students' understanding and learning outcomes.

## Virtual Simulation as a Psychotherapeutic Tool <sup>5</sup>

In recent years, VR technology has become a critical tool across various disciplines, including geography, entertainment, medicine, rehabilitation, architecture, engineering, education, and simulation training (Juřík et al., 2024a). These advancements are driven by VR's affordability, safety, accessibility, and user-friendliness frequently discussed by many researchers in different domains (Boeldt et al., 2019; Juřík et al., 2018; Juřík et al., 2023; Radianti et al., 2020; Ugwitz et al., 2021). Additionally, integrating VR with biosignal measuring devices has significantly enhanced the scope of research by enabling the collection of accurate physiological data from users, providing deeper insights into human behavioral responses within an ecologically valid context (Ihmig et al., 2020). This capability has notably increased VR's utility in fields such as psychotherapy, where virtual reality exposure therapy (VRET) is gaining prominence as a valuable treatment and training tool (Freeman, 2017; Chou et al., 2021; Lindner, 2021) as discussed above.

VR technology replaces the physical world with a simulated one, aiming to create experiences that are as immersive, convincing, and high-quality as possible but simultaneously safe and controllable. Recent innovations have led to the development of highly interactive and realistic HMDs, which have

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<sup>5</sup> This chapter is based on the study: Varšová, K., Szitás, D., Janoušek, O., Jurkovičová, L., Bartošová, K., & Juřík, V. (2024). Virtual reality exposure effect in acrophobia: Psychological and physiological evidence from a single experimental session. *Virtual Reality*, 28, 1-14.

become increasingly accessible to researchers and the general public at lower costs (Lindner, 2020). These HMDs allow for dynamic customization and interaction within virtual worlds, significantly enhancing the user experience (Ugwitz, 2019), which brings VR applications close to actual practice/use. Activating brain mechanisms through VR closely mimics real-world experiences, establishing a solid foundation for its application in psychotherapy (Alcañiz et al., 2009). Applying cognitive behavioral therapy (CBT) principles through digital media marks a significant shift in therapeutic interventions. Exposure therapy, a key CBT technique, is effectively administered through VRET. Imagination techniques used when a client is exposed to a phobic situation (such as, for example, flying) — i.e., the mental simulations discussed earlier — are replaced here with virtual simulations. Virtual avatars are essential in engaging patients, fostering empathy, and efficiently conveying health information. The psychotherapeutic potential of VR is especially noteworthy. Its immersive nature and ability to dynamically modify environments hold promise for treating various mental disorders. VRET has become increasingly prevalent, offering new ways to enhance therapeutic processes and remote therapist training. Effective in treating conditions such as anxiety disorders and eating disorders, VR interventions may reduce the overall need for traditional therapy sessions, thereby advancing the availability of effective psychological treatments. VR models can also effectively engage in the augmented reality regime (see the example of arachnophobia treatment mode in Figure 21), creating engaging and highly realistic virtual simulations.

**Figure 21**

*Example of VR spider used in the arachnophobia VRET*



*Note.* Brave Mind platform, a photo by Oto Janoušek, is used with the author's permission.

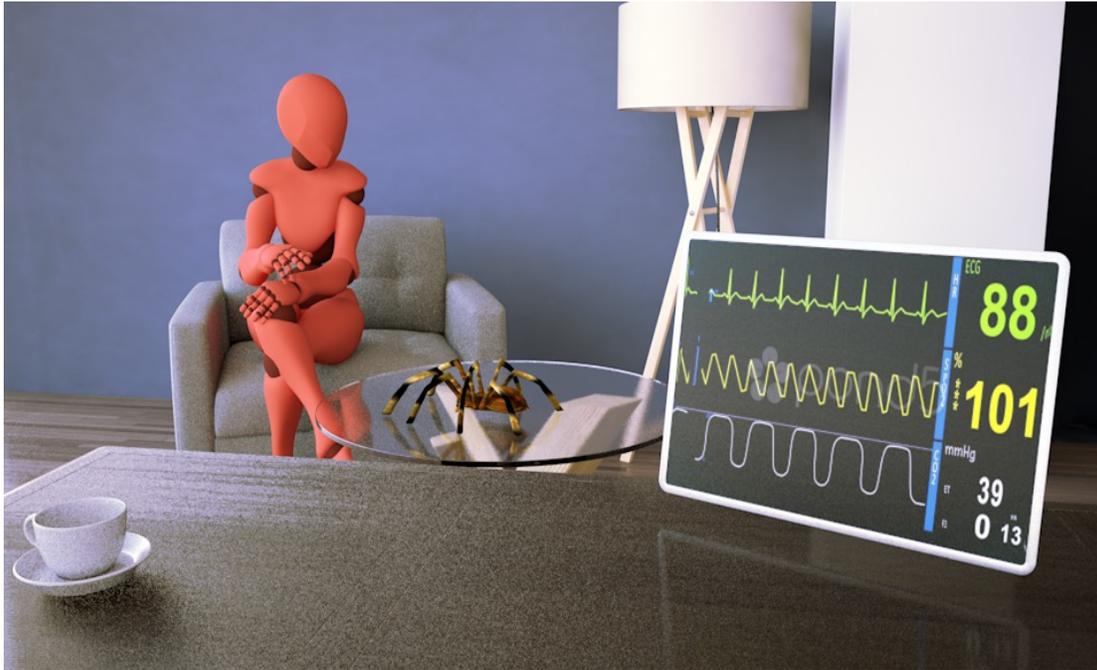
The therapeutic potential of VR is vast, with proven efficacy in treating a wide array of mental disorders, including but not limited to eating disorders, schizophrenia, substance abuse, autism spectrum disorder (ASD), attention deficit hyperactivity disorder (ADHD), post-traumatic stress disorder (PTSD), obsessive-compulsive disorder (OCD), and various phobic disorders (Lindner, 2019). VR is particularly transformative in CBT, where exposure therapy—a method aimed at reducing fear and anxiety through gradual exposure to feared stimuli—is a cornerstone technique. VRET allows clients to confront these stimuli within safe, controllable virtual settings, eliciting genuine

psychological and physiological responses that mirror those experienced in real situations (Emmelkamp & Meyerbröker; Chou et al., 2021). This capability validates the therapeutic environment and enhances the therapy's overall effectiveness, as supported by studies demonstrating significant physiological changes, such as heart rate variability during exposure (Varšová et al., 2024). The potential use involves interventions and training for psychotherapists, which is often resource-intensive, involving a blend of academic learning, personal therapy, self-exploration, and extensive supervised practice. This traditional approach, while effective, comes with high costs and logistical challenges, especially in facilitating hands-on experience and role-playing exercises with real clients or standardized patients, usually under direct supervision.

The rise of VR technology offers a transformative solution to challenges in psychotherapy training. Collaborative Immersive Virtual Environments (CIVEs) provide interactive virtual spaces where trainees and supervisors can engage without being limited by physical proximity (Churchill & Snowdon, 1998; Juřík et al., 2016b; Radianti et al., 2020; Šašinka et al., 2018; Wright & Madey, 2008). These platforms promote flexibility, reducing the need for travel, thereby cutting costs and offering access to a broader range of expert guidance. See the example of CIVE for VRET in Figure 22.

**Figure 22**

*Visualization of CIVE for VRET of arachnophobia*



*Note.* Design and photo by Jiří Chmelík, used with the author's permission.

Additionally, VR's ability to simulate complex real-life scenarios allows trainees to practice their skills in a safe, controlled setting. It is particularly valuable for training therapists to handle rare or challenging disorders. Conversational agents and other technological tools within VR platforms can simulate patient interactions, providing realistic training experiences with immediate feedback, a critical factor in developing practical counseling skills (Juřík et al., 2024a; Tanana et al., 2019). Psychotherapy training traditionally requires significant time and resources, encompassing education, personal therapy, and supervision. While VR has been explored in psychotherapy, its

application in training is still underutilized. IVR represents a significant technological advancement, enabling simulated experiences that replace physical environments with virtual ones. Key features include its three-dimensional nature, multisensory stimulation, and interactivity. CIVEs are designed for multi-user collaboration, offering a shared virtual workspace (Šašinka et al., 2018), and their integration across sectors promises to improve efficiency, productivity, and learning outcomes. Despite the potential of IVR and CIVEs, several challenges hinder their full adoption. One major issue is the lack of guidelines for tailoring virtual environments to specific tasks, particularly in psychotherapy training (Varšová et al., 2023). The exploration of VRET within CIVEs remains limited, and specialized tools for such environments are still underdeveloped. To improve VR-based therapy, including VRET, it is essential to configure collaborative virtual environments that incorporate therapeutic elements, consider user preferences, and minimize distractions during sessions. CIVEs offer a promising solution by enabling global collaboration and providing trainees access to a broader range of expertise. However, technological challenges, high costs, and cybersickness remain barriers to full adoption. Furthermore, the limited research and lack of standardization are key issues that must be addressed to ensure VR's practical use in psychotherapy training, preventing variations in training quality among professionals. Next to IVR, augmented reality can be effectively employed for VRET, as seen in the example in Figure 23.

**Figure 23**

*Example of VRET therapy session used for arachnophobia treatment*



*Note.* Brave Mind platform, photo by Vojtěch Juřík.

The future of psychotherapy and rehabilitation will likely see increased IVS utilization, driven by its growing commercial viability and accessibility. VR interactions mimic in-person interactions and provide an immersive alternative to traditional telehealth methods. Studies have shown IVS's superiority over conventional platforms in therapeutic effectiveness, realism, and the sense of presence among participants. An example of an empirical study (Varšová et al., 2024) that tested the potential of IVS in VRET and considered the role of human psychotherapists in the whole VRET process is more closely introduced below.

#### *Research on the Virtual Reality in Exposure Therapy*

Recent advancements in VR technologies have captivated mainstream users and garnered significant interest from scholars and practitioners across various fields. This growing fascination is due to VR's capacity to serve as an efficient, cost-effective, and user-friendly tool that extends its utility beyond mere entertainment to substantial academic and practical applications (Boeldt et al., 2019). It can be scalable, and it is safe and easily controlled. VR systems can create highly realistic, immersive virtual environments enriched with interactive elements tailored to human engagement and detailed sensory feedback. Additionally, VR's integration with technologies for measuring biosignals enhances its research capabilities, offering valuable insights into users' physiological, behavioral, cognitive, and emotional responses. In this regard, we have adopted this approach and empirically tested given

hypotheses, which results were published in Springer's prestigious journal *Virtual Reality* (Varšová et al., 2024).

This study discusses the multifaceted utility that has led to VR's widespread adoption in numerous domains, including psychotherapy. In psychotherapy, VR is predominantly utilized in so-called Virtual Reality Exposure Therapy (VRET; Emmelkamp & Meyerbröker, 2021; Freeman et al., 2017; Chou et al., 2021), an immersive virtual simulation of the therapeutic session. Despite the extensive use of VRET, its nuanced aspects remain relatively underexplored, particularly the interplay between psychological and physiological responses during exposure sessions in varied settings. Our study aimed to fill this gap by coupling biosignal measurement with psychological assessments during VRET sessions. We specifically examined the variance in anxiety levels among individuals with moderate acrophobia when exposed to simulated heights, with and without psychological support. At its core, VR is a technology that simulates experiences by creating a sense of presence that substitutes the real world with a virtual one (Price & Anderson, 2007). The last few years have witnessed a surge in high-quality yet increasingly affordable immersive VR technologies, such as HMDs. These devices offer a realistic and interactive VR experience and enhance the way virtual environments are presented, thanks to advancements in computer graphics (Lindner et al., 2020; Muhanna, 2015). One of VR's notable strengths is its dynamic adaptability, enabling users to alter, update, or customize virtual worlds as needed (Ugwitz, 2019). This adaptability facilitates collaboration among users in different locations who can interact within the same virtual space to accomplish specific tasks (Juřík et

al., 2016). Moreover, immersive VR closely mimics real-world scenarios by activating similar brain mechanisms, making it an effective tool for simulating authentic experiences (Alcañiz et al., 2009; Slater, 2018). These capabilities enhance VR's effectiveness in VRET and offer promising applications in psychotherapeutic settings.

IVS offers a transformative solution by transporting individuals into simulated scenarios of challenging situations within a safe, controlled environment. This technology facilitates the teaching and training appropriate responses and deepens our understanding of specific disorders (Freeman et al., 2017). Phobias, particularly acrophobia—a profound and irrational fear of heights often accompanying other mental health conditions like anxiety disorders and depression—represent a common area of application for VR (Kapfhammer et al., 2016). Acrophobia is notable for being one of the most prevalent phobias related to the natural environment, characterized by symptoms such as increased sweating, accelerated heart rate, chest pain, palpitations, nausea, tremors, dizziness, and balance issues (Kapfhammer et al., 2016; Kapfhammer et al., 2015). Cognitive Behavioral Therapy (CBT) stands as the predominant psychotherapeutic approach for treating acrophobia, impacting various facets of a person's psyche, including thoughts, emotions, and behaviors (Beck, 2011). The most frequent CBT technique employed is exposure therapy, predicated on the notion that repeated direct engagement with the feared object or situation can mitigate fear (Arroll et al., 2017; Chou et al., 2021). A recent meta-analysis by Chou et al. (2021) underscores the efficacy and acceptability of VR as an instrumental technology in this domain. VR environments can elicit

realistic behavioral and physiological responses, with participants exhibiting reactions in VR settings that closely mimic real-world environments (Kisker et al., 2021; Morina et al., 2015). Moreover, even budget-friendly VR has been shown to alleviate negative symptoms associated with acrophobia (Donker et al., 2019). The utility of IVS in exposure therapy, particularly VRET, has been further validated through systematic reviews and meta-analyses covering studies from 2012 to 2017, presenting IVS as a safe and cost-effective alternative to in vivo exposure (Botella et al., 2017).

Another critical dimension of VRET to consider is whether the presence of a psychologist is crucial to the therapy's effectiveness and how it influences the treatment process. Previous research primarily focused on therapist-assisted VR interventions for phobia treatment (Anderson et al., 2013; Kampmann et al., 2016). However, technological advancements have prompted a shift toward automated psychological therapy (Freeman et al., 2018; Lindner et al., 2020; Miloff et al., 2019). Despite this, evidence suggests that psychologist-led sessions foster a more potent therapeutic alliance through agreed tasks and goals, leading to better treatment adherence and outcomes (Buchholz & Abramowitz, 2020). The necessity of psychological guidance in exposure therapy remains under-investigated yet critical, considering the significant potential of VR interventions.

Exploring physiological responses associated with acrophobia sheds light on the anxiety experience. Commonly measured non-invasive physiological indicators include Heart Rate (HR) and Heart Rate Variability (HRV). HR, the

number of heartbeats per minute, is an objective stress indicator, reflecting increased metabolic demands and brain oxygen consumption during anxiety (Filo & Janoušek, 2022a). HRV, representing the time variation between consecutive heartbeats, illustrates changes in the autonomic nervous system's activity and provides insights into the organism's adaptive strategies during stress (Duong et al., 2020; Shaffer & Ginsberg, 2017). HRV analysis, therefore, offers a comprehensive view of the complex biosignal responses to anxiety-inducing stimuli, which is crucial for assessing mental states during VRET (Ihmig et al., 2020). Integrating VR and HR measurement technologies can significantly enhance the effectiveness of CBT practices in VRET, providing detailed data on specific mechanisms and processes within various therapeutic settings.

The efficacy of therapist involvement in VRET remains an area that has not been thoroughly investigated. Despite the recognized potential of VR as a therapeutic modality in various studies (Coelho et al., 2009; Maples-Keller et al., 2017; Ose et al., 2019), the specific contribution of psychological guidance within this context is less clear. This research aims to delve into how the presence or absence of a therapist influences participants' anxiety levels during VRET. To achieve this, we measure subjective experiences of anxiety using the State-Trait Anxiety Inventory (STAI-Y1) alongside HRV assessments, which serve as objective markers of anxiety (Felnhofer et al., 2014; Wiederhold et al., 2002).

Although some researchers have combined objective and subjective measurements to assess anxiety during exposure therapy, there is a scarcity of studies that directly compare these methods within the context of confronting phobic stimuli. This gap points to a need for a detailed examination of potential disparities between perceived and physiological responses to anxiety-inducing situations. The study of Varšová et al. (2024) seeks to address this gap by focusing on the comparative analysis of anxiety experiences in individuals undergoing VRET with and without psychological support. Additionally, this study intends to scrutinize the role of psychological guidance during VRET sessions. Prior research suggests that the presence of psychotherapists during exposure therapy necessitates a focus on the patient's interpersonal interactions and behaviors during treatment (Maiwald et al., 2019). However, concrete conclusions regarding the specific impacts of such guidance in VRET settings remain elusive.

The primary objective of the study was to explore and identify patterns of self-reported anxiety in two distinct groups subjected to simulated height exposure. One group would receive psychological guidance during the exposure (the Psychological Guidance group, PG), while the other would proceed without such support (the No Psychological Guidance group, NPG). The aim was not only to document the self-reported anxiety levels but also to analyze the fluctuations in HRV, offering insights into the physiological underpinnings of the participants' anxiety responses. This dual approach will clarify the role of therapeutic intervention in VRET and potentially guide future therapeutic practices.

### *Experiment description and research methodology of VRET research*

The study (Varšová et al., 2024) focused on individuals with a moderate fear of heights, determined using the Heights Interpretation Questionnaire (HIQ; Steinman & Teachman, 2011). The research sample included 36 young adults, with 24 females (66.7%) and ages ranging from 19 to 36 years (mean age = 24.6 years, SD = 4). Recruitment was conducted via a combination of online and offline methods. Social media platforms, particularly Facebook groups and flyers distributed at the Faculty of Arts, Masaryk University in Brno, were used to attract diverse participants for this VR-based study.

The study adhered to rigorous ethical standards, with approval from the Ethical Panel of the Department of Psychology at Masaryk University. This ensured that all procedures complied with the Declaration of Helsinki guidelines. Participation was voluntary, and all participants were required to read and sign an informed consent form that outlined the study's procedures, potential risks, and data confidentiality. Participants were also informed of their right to withdraw from the study at any time without facing penalties or forfeiting compensation. To ensure transparency and maintain trust, participants received a detailed briefing on the study's design, activities, and data handling before the experiment began. They were reassured that any anxiety induced by the experimental conditions was temporary and would not lead to long-term health issues. This approach facilitated informed consent and addressed ethical concerns, ensuring participants felt safe and respected throughout their involvement.

The experiments took place in the Grey Lab at Masaryk University. High-fidelity VR equipment was utilized here, including the HTC Vive Pro headset, which features 1440 x 1600 pixel AMOLED screens and a 90 Hz refresh rate for a seamless visual experience. The VR setup was supported by a high-performance desktop PC equipped with an Intel i7 8700 K CPU and an NVIDIA GTX1070 GP graphics card to handle the demanding graphics of the VR software without lag.

For height exposure simulation, the authors used the "Richie's Plank Experience" VR application, which placed users at the top of an 80-story virtual skyscraper. Participants walked on a virtual wooden plank extending from the building. A physical wooden plank was placed in the lab to enhance realism, aligned with the virtual plank to create a tangible haptic interface (see Figure 24). The sensory experience was further enriched by auditory cues, such as city background noises and the sound of the plank creaking. To mitigate stress and anxiety post-exposure, participants used the "Guided Meditation VR" application, offering 27 serene environments for relaxation and reflection. Various instruments were employed to capture psychological and physiological responses to VR height exposure. Questionnaires were adapted for the Czech context through a dual translation process, followed by back-translation to ensure accuracy (Behling & Law, 2000). The HIQ, consisting of 16 items, measured fear, anxiety, and avoidance related to heights. Participants rated their fear on a five-point Likert scale. The initial inclusion criteria, set at scores between 29 and 55, were adjusted to 26-55 points to include additional participants with near-moderate distress levels due to recruitment challenges.

**Figure 24**

*The experimental setting in the VRET research*



*Note.* Adopted from Varšová et al. (2024), photo by Kristína Varšová, used with the author's permission.

The State-Trait Anxiety Inventory (STAI), developed by Spielberger in 1989, was used to measure anxiety. The authors focused on the STAI-Y1 subtest, which assesses state anxiety reflecting immediate emotional states.

Participants responded to statements on a scale from "not at all" (1) to "very much" (4). This tool was selected based on its efficacy in similar VR settings and the need for real-time fear assessment (Concannon et al., 2020; Felnhofer et al., 2014).

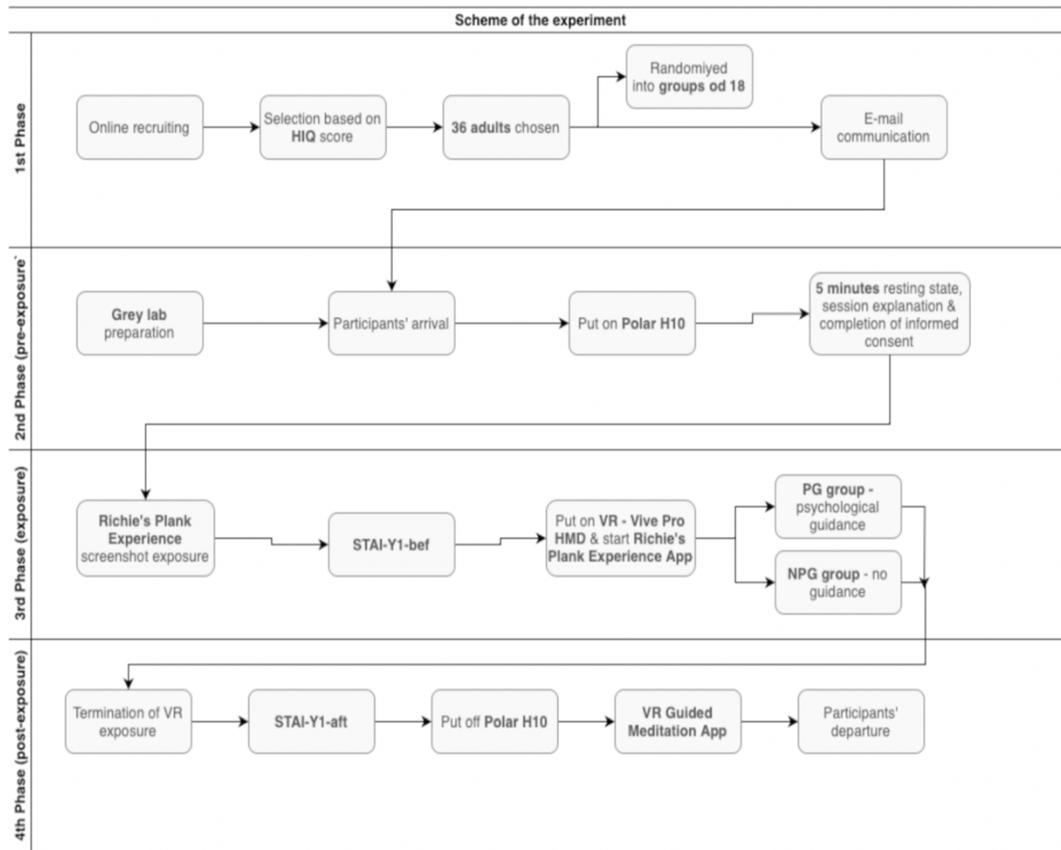
Continuous heart rate (HR) monitoring was performed using the Polar H10 chest strap, known for its precision and non-invasive nature. Operating at a sampling frequency of 1000 Hz, the device transmitted data to the Elite HRV app via Bluetooth, allowing accurate tracking of physiological responses during the VR experience.

The experimental procedure began with an initial HIQ screening to assess participants' baseline fear of heights. Based on their scores, participants were invited to the laboratory study and randomly assigned to either the Psychological Guidance (PG) or No Psychological Guidance (NPG) group. This assignment determined the level of interaction they received during the VR exposure. Baseline HR was recorded using the Vernier Go Wireless device for at least five minutes to establish an accurate measure of physiological responses. Participants were then shown a screenshot from the "Richie's Plank Experience" app to familiarize themselves with the virtual environment. Following this introduction, participants completed the STAI-Y1 questionnaire to assess their initial anxiety levels. During the VR exposure, participants wore a Head-Mounted Display (HMD) and were instructed to enter a virtual elevator and ascend to the top floor. Upon reaching the top, they walked to the end of a virtual plank and returned to the elevator within their comfort limits.

This simulation aimed to provide a realistic yet safe height exposure. After completing the task, participants descended back to the ground floor via the elevator. Participants in the PG group received psychological guidance developed in collaboration with an expert CBT therapist. After the VR session, participants removed their VR headsets and completed a second STAI-Y1 questionnaire to measure changes in anxiety levels. HR was monitored for another five minutes to capture any lingering physiological effects. The session concluded with a relaxation exercise using the "Compassionate Body Scan" mode from the Guided Meditation app. This final phase was designed to help participants unwind and process the VR experience in a calming virtual environment, ensuring they left the study feeling settled and composed. For the procedure, see Figure 25.

**Figure 25**

*The scheme of the experimental procedure used in VRET research*



*Note.* Adopted from Varšová et al. (2024), photo by Kristína Varšová, used with the author's permission.

### *Data analysis and results*

Data analysis for the study was conducted using JASP (version 0.16.1) and Python (version 3.6, Pandas 1.5.0), which facilitated effective handling and analysis of complex data sets. The primary psychological variables assessed were anxiety scores from the State-Trait Anxiety Inventory (STAI-Y1) collected

before (STAI-Y1-bef) and after (STAI-Y1-aft) the virtual reality (VR) exposure. Homogeneity tests confirmed the suitability of repeated measures ANOVA for these measures. Additionally, Spearman's correlation coefficient was used to explore the relationship between post-exposure anxiety scores and mean heart rate during exposure.

Heart rate (HR) data were converted into normal-to-normal (NN) intervals and linearly detrended. Using the pyHRV toolbox, various HRV metrics were computed, including mean and standard deviation of heart rates, interbeat interval metrics, and various HRV indices. Statistical evaluations were performed with ANOVA and post hoc Tukey's tests. Baseline physiological states were measured before VR exposure, showing similar mean heart rates between the Psychological Guidance (PG) group (89 bpm) and the No Psychological Guidance (NPG) group (87 bpm). This initial equivalence ensured that observed differences during the experiment were attributable to the VR conditions rather than pre-existing disparities.

Self-reported anxiety levels were analyzed using the STAI-Y1, revealing increases in anxiety from pre- to post-VR exposure across both groups. Repeated measures ANOVA indicated a significant increase in anxiety levels post-VR exposure for both groups ( $F = 395.636$ ;  $p < .001$ ;  $\eta p^2 = 0.921$ ). Post hoc comparisons confirmed substantial increases in anxiety within both the PG and NPG groups. However, there were no significant differences in anxiety levels between the PG and NPG groups ( $F = 0.153$ ;  $p = 0.698$ ;  $\eta p^2 = 0.004$ ), suggesting that psychological guidance did not significantly alter immediate anxiety

responses to VR exposure. Spearman's correlation analysis of post-exposure anxiety scores and heart rate variability did not reveal significant correlations in either group (PG:  $r = -0.002$ ,  $p = 0.993$ ; NPG:  $r = 0.172$ ,  $p = 0.496$ ). This indicates that changes in heart rate did not statistically correlate with self-reported anxiety levels following IVS. See the original study for more details/statistics (Varšová et al., 2024).

The study demonstrated a significant increase in anxiety following IVS but no differential effect between groups with and without psychological guidance. The absence of significant correlations between anxiety levels and physiological responses suggests that while IVS effectively induces anxiety, the immediate impact of psychological support on this response was not evident.

#### *Physiological Responses During VR Exposure*

The study assessed physiological responses to VR stress using HRV and HR metrics. Initially, both groups—those receiving PG and those without NPG—showed similar levels of anxiety during the anticipation phase, as evidenced by comparable mean HRV ratios. This baseline similarity was crucial for evaluating how VR exposure affected subsequent physiological responses.

During the VR stress phase, both groups experienced increased HRV, signaling heightened physiological arousal. However, their recovery patterns post-exposure differed significantly. The PG group exhibited a sharp decrease in HR following the VR session, dropping to levels lower than those observed

during the anticipation phase. In contrast, the NPG group's HR decreased gradually, eventually stabilizing at similar levels before the VR exposure.

A closer examination of the data revealed that participants in the PG group experienced a rapid and intense spike in anxiety immediately after the VR stimulus, which then diminished quickly with only minor fluctuations. Conversely, participants in the NPG group showed a more variable anxiety pattern with periodic fluctuations. Further statistical analysis provided more profound insights into these physiological responses. Both groups showed a significant increase in mean HR during the stress phase, reflecting an acute stress response. In the catharsis phase, mean HR dropped below the anticipation levels for both groups, indicating a state of relaxation or relief after the VR challenge. No significant differences were found between the PG and NPG groups regarding their mean HR levels. This suggests that psychological guidance did not influence the overall HR response to the VR stimulus. Detailed results indicated that while the standard deviation of HR increased during the stress phase and decreased during recovery, significant differences were observed between the anticipation and stress phases and between the stress and catharsis phases. Specifically, in the PG group, the standard deviation of HR was notably higher during stress compared to anticipation ( $U = 39, p = 0.001$ ) and decreased significantly from stress to catharsis ( $U = 306, p = 0.001$ ). Similarly, in the NPG group, significant changes were observed in HR standard deviation from anticipation to stress ( $U = 23, p = 0.001$ ) and from stress to catharsis ( $U = 273, p = 0.001$ ). Sample entropy analysis, which measures the complexity of HR data, revealed significant phase-related variations. Both

groups exhibited a decrease in sample entropy during the stress phase, with recovery to near-baseline levels in the catharsis phase. Significant differences were noted between the anticipation and stress phases and between stress and catharsis phases, reflecting changes in HR data complexity due to the VR exposure. See the original study for more details/statistics (Varšová et al., 2024).

In summary, while both groups experienced increased anxiety during the VR exposure, the recovery patterns differed. The PG group showed a more pronounced decrease in HR post-exposure, while the NPG group's HR stabilized more gradually. These findings highlight the nuanced physiological impacts of VR exposure and suggest that psychological guidance might influence immediate and residual stress responses differently. Further research could explore these dynamics to optimize VR interventions for managing anxiety and stress.

#### *Discussion of results in the context of virtual simulation*

This investigation assessed how individuals with a moderate fear of heights respond within an IVS. The primary aim was to examine both the subjective feelings of anxiety and the physiological reactions these individuals experienced when introduced to the IVS. The authors mainly focused on comparing two groups: one that received psychological guidance (PG group) and one that did not (NPG group).

The methodology involved using the State-Trait Anxiety Inventory (STAI-Y1) and heart rate variability (HRV) analyses to evaluate stress levels. Findings

from repeated measures ANOVA indicated a marked increase in anxiety levels post-exposure to the VR environment compared to pre-exposure levels, demonstrating a substantial impact of VR-induced height exposure on both the PG and NPG groups. This was consistent with HRV measurements, which showed heightened anxiety during the VR phase. Notably, the average heart rate significantly spiked during this stress phase, reinforcing the powerful effect of VR on inducing physiological changes akin to actual stress responses. This supports previous research asserting the efficacy of VR in therapeutic settings (Kisker et al., 2021; Morina et al., 2015).

Contrary to our expectations, there were no significant differences in the anxiety levels reported between the PG and NPG groups, as measured by the STAI-Y1 questionnaire. The HRV analysis, however, revealed interesting trends that provided more profound insights into the dynamics of anxiety during the VRET. We observed that while the mean heart rate in both groups significantly increased during VR exposure, it decreased to even lower than pre-exposure levels once the stressor was removed, with no significant differences between the groups. Further analysis of the HR standard deviation in the third 'catharsis' phase of our experiment revealed that non-guided participants experienced fluctuating anxiety levels, suggesting that anxiety was not felt continuously but rather in varied bouts. This variability in heart rate indicates different coping mechanisms in response to stress, with the NPG group showing more pronounced compensation for the stress reaction. This aligns with the principle of habituation found in phobic stimulus exposure techniques, where the response to a phobic stimulus does not endlessly

escalate but rather peaks and subsequently diminishes (Benito & Walther, 2015; Beck, 2011; Ihmig et al., 2020).

The findings suggest that psychological guidance may enhance the effectiveness of the autonomic nervous system's response, moderating both the fight-or-flight and relaxation responses more efficiently. In contrast, participants without such guidance seemed to endure more erratic and intense emotional states, underscoring the potential benefits of therapeutic support in managing VRET processes (Freeman et al., 2018; Maiwald et al., 2019). The analysis of heart entropy showed similar patterns in both groups, suggesting that the essential function of the heart remains consistent regardless of psychological guidance.

The authors of this study adopted a commercial virtual simulation application to test a scientific hypothesis, successfully identifying significant trends in their research. By leveraging virtual simulation, they created an experimental context that addresses a challenging and often inaccessible area of psychotherapeutic research: the role of the psychotherapist during exposure therapy. This innovative approach enabled them to explore how virtual environments can replicate real-world therapeutic processes, particularly in inducing anxiety, which is a crucial component of exposure therapy. The findings demonstrated that the virtual simulation effectively promoted anxiety, confirming that the processes occurring in virtual environments closely mirror those in the real world, thus highlighting the promise of immersive VR technologies in cognitive and behavioral research. Furthermore, the study

employed instrumental triangulation and novel technological solutions to combine psychological and physiological measures, an advancement made possible through IVS. This integration allows for a deeper understanding of cognitive and behavioral processes within the context of psychotherapeutic research. The authors emphasize the potential for this research to be translated into practical applications, mainly through the development of Brave Mind technology (Juřík et al., 2024b), which is currently being refined by the research team.

As with previous studies, the experimental procedure in this research underscores the advantages of virtual reality as a cost-effective, highly adaptable, and ecologically valid tool. VR offers a realistic and immersive experience that is invaluable for studying cognitive processes under controlled conditions. The therapeutic environment created through this study is easily transferable and disseminable, making it applicable to many individuals. Moreover, this form of virtual simulation enables the visualization of complex phenomena that would otherwise be difficult, if not impossible, to present within the confines of a traditional psychotherapeutic setting. This capability further underscores the potential of VR to revolutionize the way we understand and conduct therapy, offering new avenues for research and practice in the psychotherapeutic domain. The summary of the above-mentioned conclusions is presented below:

- The authors utilized a commercial IVS application to test a scientific hypothesis, successfully identifying expected statistically significant trends in the data.
- They employed IVS to create an experimental context for a challenging area of psychotherapeutic research—specifically, the role of the psychotherapist during exposure therapy.
- The authors implemented a triangulation approach and novel technological solutions to combine psychological and physiological measures made possible through immersive virtual technology. This approach enhances the understanding of cognitive and behavioral processes in this research domain.
- The IVS produced the anticipated effects in exposure therapy, proving to be an effective tool for inducing anxiety within this therapeutic context. This suggests that processes in virtual environments closely align with those in the real world, indicating that immersive VR technologies are promising tools for cognitive research.
- The study focused on a topic with significant potential for practical application, particularly in developing the Brave Mind technology (Juřík et al., 2024b), which is currently being advanced by the research team.
- As in previous studies, the experimental procedure highlighted IVS as a cost-effective, highly adaptable, and ecologically valid tool, providing

a realistic experience for studying cognitive processes under controlled conditions.

- The therapeutic environment created through this research is easily transferable, disseminatable, and applicable to various individuals.
- This form of IVS also enables the visualization of complex phenomena that would otherwise be difficult or impossible to present within a traditional psychotherapeutic setting.

In conclusion, this study confirms that IVS can effectively simulate real-world stressors in a controlled laboratory setting, triggering significant physiological and psychological responses. These insights are invaluable for refining therapeutic strategies and understanding the underlying dynamics of anxiety and stress reactions in virtually simulated environments.

#### *Limitations and future directions*

While contributing valuable insights into the use of VRET, this research is subject to several limitations that warrant discussion (Varšová et al., 2024). Primarily, the limited scope of our research sample stands out as a significant constraint. The complexities of conducting this study during a global pandemic introduced heightened logistical and technical challenges, consequently reducing the participant pool and potentially affecting the robustness of our statistical conclusions. As such, the study's findings should be viewed as an initial exploration into integrating psychological and physiological measures within the context of VRET. Another critical limitation

pertains to the context of actual therapeutic processes. The study did not replicate the nuanced and ongoing relationship typically developed between a client and therapist in a therapeutic setting. The psychological guidance provided was based on CBT techniques, yet it did not encompass the depth of a full psychotherapeutic intervention. Future research could benefit from examining the effects of VRET within the framework of a more extensive therapeutic relationship to amplify the outcomes observed in this preliminary study. Future research could explore alternative forms of psychological support or adjustments to VR scenarios to further investigate the dynamics of anxiety responses in virtual environments.

Participant expectations represent an additional variable that may have influenced the results. Preconceived notions about the study, shaped by prior experiences or external information, could have biased their emotional responses. Despite our efforts to minimize such biases through comprehensive pre-session briefings, the influence of these expectations is an area that requires further scrutiny. Future studies should consider detailed assessments of participants' prior VR experiences and passive exposure to similar contexts and possibly collect data on factors like cybersickness. Adjusting selection criteria to create a more homogeneous sample could help clarify the influence of pre-existing expectations on study outcomes.

The methods used to measure subjective anxiety also pose limitations. The State-Trait Anxiety Inventory (STAI-Y1) effectively assesses anxiety levels before and after VR exposure but fails to capture moment-to-moment stress

fluctuations during the sessions. The integration of a simple self-report measure, such as the Subjective Units of Distress Scale (SUDS), could provide a more dynamic understanding of anxiety responses. Unfortunately, the commercial application did not support this functionality, preventing a more nuanced analysis of stress responses during exposure. Additionally, the study did not include pre-testing for negative emotions triggered explicitly by the VR environment, apart from the stress induced by the height simulations. Assessing participants' reactions to various stressful but unrelated scenarios before VR exposure could further elucidate the specificity of emotional responses to VR stimuli. Such pre-testing in future research could deepen our understanding of emotional reactions and enhance the generalizability and validity of our findings.

Addressing these limitations in subsequent studies could significantly enrich our understanding of the dynamics of anxiety in exposure therapy and refine the therapeutic potential of VR technologies in clinical psychology.

## Virtual Simulation for Engineering Application - Evacuation<sup>6</sup>

Human evacuation behavior during emergencies is shaped by a complex interaction of environmental, cognitive, and social factors, including individual characteristics, health, knowledge, past experiences, and the specific conditions at the time of the event (Chu et al., 2014; Sagun et al., 2013). The nature of the hazard—whether it involves natural disasters, gas leaks, terrorist attacks, or fires—plays a crucial role in shaping responses, as do situational and building design contexts such as the building type, layout, and safety features. Given the impracticality of conducting safety evacuation drills with all potential occupants of a building, especially considering the unpredictable nature of emergencies in terms of type, origin, timing, and scope, the design and structure of the building itself become paramount. Architects and urban planners must carefully optimize these elements to mitigate risks to human life and property (Lin et al., 2020b).

Factors influencing evacuation behavior include the building's occupancy, architectural layout, ongoing activities, and safety features such as alarms and evacuation plans. While effective evacuation signage is essential, it often fails to achieve its full potential due to poor visibility or improper placement,

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<sup>6</sup> This chapter is based on the study: Snopková, D., Ugwitz, P., Stachoň, Z., Hladík, J., Juřík, V., Kvarda, O., & Kubíček, P. (2022). Retracing evacuation strategy: A virtual reality game-based investigation into the influence of building's spatial configuration in an emergency. *Spatial Cognition & Computation*, 22(1-2), 30-50.

leading individuals to overlook or disregard the signs. In real emergencies, people frequently resort to familiar routes, such as exiting a building the way they entered, even if that path is unmarked (Snopková et al., 2022). This behavior deviates from the strategies typically modeled in engineering practices, such as computer-based evacuation simulations, which often fail to capture the variety of wayfinding strategies people use during actual emergencies. As a result, these simulations can oversimplify and misrepresent human behavior during evacuations.

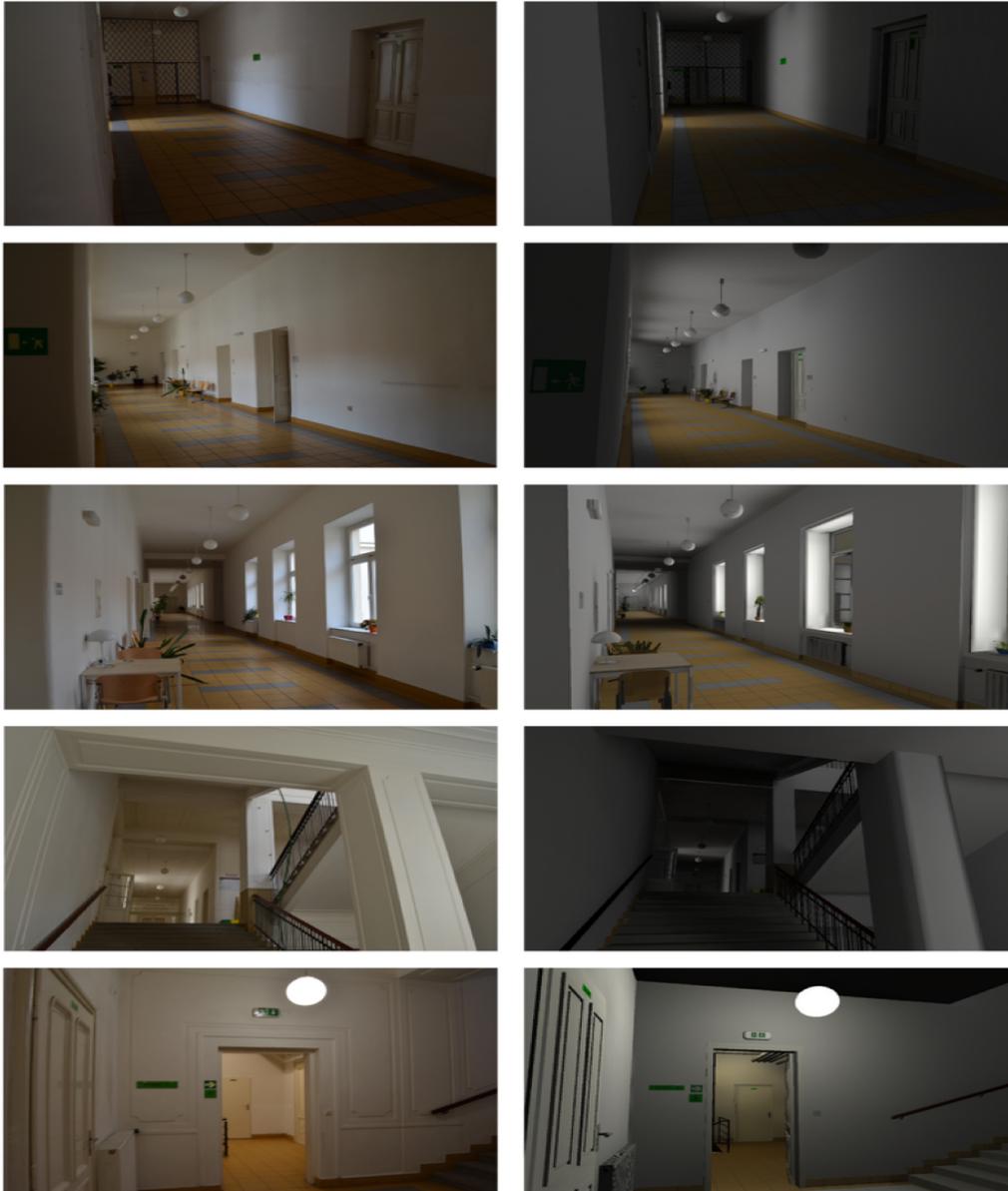
Evacuation behavior varies widely among individuals, particularly in how they respond to emergencies. When assessing a building's safe capacity, engineering practices often focus on the outliers—those who take the longest to evacuate. This approach increases the overall evacuation time estimates and underscores the importance of understanding and modeling these outlier behaviors to improve the reliability of evacuation predictions. Space syntax theory, which suggests that a building's topology significantly influences human decision-making during navigation (Snopková et al., 2023), offers tools for quantifying and comparing different layouts. Navigation behavior has been found to correlate with specific metrics derived from space syntax, such as "least angle," "fewest turns," "follow their noses," and "straight initial segment" strategies. The theory also incorporates visibility, which is crucial in decision-making, using metrics like isovists to represent the visual area accessible from a particular point. These metrics have been shown to correlate with wayfinding performance and human comprehension of enclosed spaces, even subconsciously influencing people's choices (Snopková et al., 2023). Despite

the proven utility of space syntax in studying everyday navigation, its application to evacuation scenarios remains relatively underexplored.

Research into evacuation behavior within existing buildings presents significant challenges due to the potential disruption of regular activities and the inability to modify building parameters to test different spatial configurations. IVS offers a compelling solution by providing the flexibility and functionality to simulate various scenarios without physically altering the environment. The use of IVS in behavioral research has seen considerable growth, particularly in studies focused on human behavior during evacuations. IVS tools are especially promising for exploring scenarios that are difficult to access or logistically complex in the real world. The COVID-19 pandemic has further highlighted the importance of remote data collection methods, making IVS and web technologies increasingly pertinent for research (Snopková et al., 2023). An example of a real environment adopted for the immersive virtual simulation used for evacuation exercises can be seen in Figure 26.

**Figure 26**

*The example of a real environment transferred into IVE*



*Note.* Adopted from Stachoň et al. (2025) with the permission of Elsevier.

In a study by Snopková et al. (2022), immersive virtual simulation was employed to examine evacuation processes, providing critical insights into how spatial configuration affects individual navigation behavior during emergencies. The study found that people often prefer to retrace familiar routes rather than follow evacuation signage during evacuation. This tendency can be undesirable or even fatal in real emergencies. The methodology and conclusion of the study are introduced and discussed below.

#### *Research on the Virtual Simulation Use in Evacuation*

Indoor wayfinding is a vital aspect of building safety, particularly during emergencies, as it significantly impacts the effectiveness of evacuations and the survival chances of individuals. Their spatial understanding profoundly influences human navigation abilities within indoor environments (Golledge, 1999; Maguire et al., 1998). This becomes especially crucial during evacuations when people must swiftly navigate from hazardous areas to safe zones. This process aided wayfinding and relies heavily on evacuation signage and building plans to guide individuals to safety (Wiener et al., 2009). Effective signage is crucial in reducing the time it takes for individuals to make critical decisions during emergencies (Xie et al., 2011). However, studies have shown that even when evacuation plans and signage are present, they are often ignored, particularly by those familiar with the environment (Johnson, 2005; Proulx, 2001; Xie et al., 2011). This behavior suggests that in the chaos of an emergency, people do not always use these aids as intended, which can undermine the effectiveness of the evacuation process.

When people bypass evacuation signage, their wayfinding shifts towards a path search aimed at familiar destinations, such as the building's entry point, rather than the designated assembly areas. This behavior, known as retracing, is particularly prevalent in unfamiliar buildings where individuals rely on the limited spatial information they remember from when they entered (Johnson, 2005; Kurkjian et al., 2003; Proulx, 2001). Retracing can be problematic, as it may cause individuals to overlook closer exits and lead to corridor bottlenecks, potentially exacerbating life-threatening situations (Kurkjian et al., 2003). Therefore, retracing is generally viewed as an undesirable behavior during emergencies. People frequently choose routes that deviate from designated evacuation paths (Wood, 1972). The decision on which exit to use is influenced by several factors, including the openness of the space, visibility, familiarity with the environment, and the movement of crowds (Haghani & Sarvi, 2016; Sime, 1983). While some evacuation behaviors may seem irrational, they often arise from the limited and ambiguous information available during the crisis (Proulx, 2001; Quarantelli, 2000).

Occupants might delay their evacuation due to incomplete information about the severity of the situation, leading them to continue with their current activities (Geyer et al., 1988; Johnson, 2005; Proulx, 2001; Proulx & Fahy, 1997; Proulx & Sime, 1991). Perceived risks influence their decisions, visible cues such as fire or smoke (Cornwell, 2003), past experiences, and the actions of others, all of which introduce a level of uncertainty. Consequently, building design is critical in reducing hesitation and uncertainty, decreasing the likelihood of retracing during evacuations. Proulx (2001) emphasized that

building design is a controllable factor that can significantly shape evacuation behavior. Alterations to a building's spatial configuration are most effectively implemented during the design phase or through simulations. The advent of digital technologies and Building Information Modeling (BIM) has introduced new data sources, enabling the creation of virtual 3D environments and virtual reality (VR) simulations (Paradis et al., 2019). VR technology allows for realistic yet controlled experimental setups, offering a valuable means to study human cognition and behavior in evacuation scenarios (Fuad, 2019; Juřík et al., 2019; Loomis et al., 1999). Numerous studies have validated the effectiveness of VR as a tool for studying evacuation behavior (Cao et al., 2019; Kinateder et al., 2014; Smith & Ericson, 2009). The insights gained from these VR studies are crucial for informing building design and enhancing safety measures.

The decision-making process in navigation has been extensively studied using space-syntax methods, which indicate that the spatial configuration of a building significantly affects how people perceive and navigate through space (Hillier et al., 1976; Penn, 2003). In non-emergency situations, individuals often favor routes that involve the least angle or the fewest turns rather than the shortest distance (Dalton, 2003; Golledge, 1995; Hillier & Iida, 2005). They are also more likely to choose paths with a straight initial segment or continue in their initial direction (Bailenson et al., 2000; Meilinger et al., 2014). Visibility, strongly influenced by a building's spatial configuration, is critical in navigation (Hölscher & Brösamle, 2007; Nenci & Troffa, 2006). Isovist analysis, a method that visualizes the area visible from a specific point, has been used to predict navigation behavior (Franz & Wiener, 2005; Meilinger et al., 2012) and

to enhance understanding of spatial perception (De Cock et al., 2020; Dosen & Ostwald, 2016). By quantifying spatial configurations, space-syntax theory facilitates the generalization of human behavior patterns across different layouts, providing insights that can optimize building designs for safe evacuation routes through agent-based evacuation models (Penn & Turner, 2002).

Snopková and her colleagues (2022) applied immersive virtual simulation to study the abovementioned issues. Her study specifically examined how evacuation aids and corridor configurations influence decisions to retrace one's steps or follow designated evacuation routes. Retracing, a typical behavior in unfamiliar buildings (Johnson, 2005; Kurkjian et al., 2003; Proulx, 2001), can disrupt orderly evacuations and increase risks. The hypothesis was that participants who noticed and understood evacuation plans and signage would follow these aids rather than retrace their steps. However, real-world evacuation observations reveal that individuals often disregard signage, with their route choices heavily shaped by the building's configuration (Proulx, 2001). To test these hypotheses, Snopková manipulated corridors' width and direction in a virtual hotel setting to observe evacuation behavior, hypothesizing that wider, straight corridors would decrease the likelihood of retracing. The study employed an IVS, allowing for high levels of experimental control and ecological validity. Participants interacted with a story-based evacuation scenario, a method aligned with those used in previous studies by Smith and Ericson (2009). Virtual reality enabled the creation of controlled

scenarios, automated data logging, and comprehensive analysis of movement and interaction, further enriched by self-report questionnaires.

#### *Experiment description and research methodology of VRET research*

In this study, the researchers initially recruited 81 participants. However, due to significant motion sickness experienced by nine individuals, the final analysis included data from 72 participants, 42 females and 30 males, aged between 19 and 35 years, with an average age of 22.18. The participants were primarily healthy young adults from Masaryk University, with 64% studying psychology, 14% in other humanities, 18% having a technical background in civil engineering and informatics, and 4% in geography. Recruitment was conducted via social media platforms, and the participants were divided into four experimental groups, balanced by sex, age, and educational background. Before participation, individuals were pre-screened for visual impairments and other medical conditions and were fully informed of their right to withdraw from the study at any time.

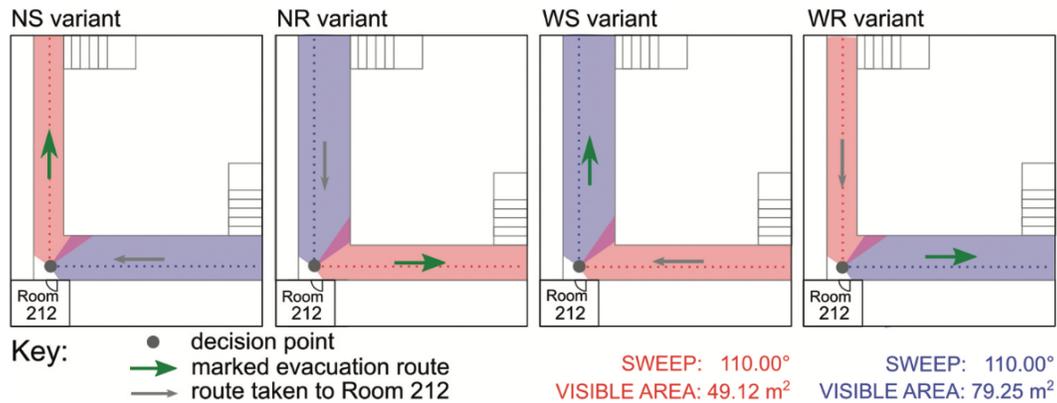
The IVS was conducted using an HTC Vive Pro VR HMD, complemented by a keyboard and mouse for interaction. The virtual environment was created using the Unity graphics engine, optimized to run efficiently on a PC equipped with an Intel i7 8700K CPU and a Nvidia GTX1070 GPU, maintaining a consistent frame rate of 90 frames per second. The VR environment simulated the interior and exterior of a hotel building, modeled after an actual hotel. It featured an L-shaped foyer with staircases leading to an L-shaped hallway on the first floor. Participants' movements and interactions within the virtual

environment were meticulously logged using a custom Unity logger script and the Toggle Toolkit (Ugwitz et al., 2021), with data sampled every 250 milliseconds and stored in CSV files for subsequent analysis. Data visualization and analysis were performed using R version 3.6.0 (R Core Team, 2017) and PostgreSQL 10.0 with the PostGIS extension, while additional map visualizations were generated using QGIS 3.10.

To investigate the effects of spatial configuration on evacuation behavior, the researchers created four variations of the virtual environment, each differing in corridor width and the direction of the initial corridor segment leading to room 212. The variations included a wide corridor with evacuation signs indicating a narrow, straight-leading corridor (NS variant), a wide corridor with signs indicating a narrow, right-leading corridor (NR variant), a narrow corridor with signs indicating a wide, straight-leading corridor (WS variant), and a narrow corridor with signs indicating a wide, right-leading corridor (WR variant), see Figure 27. At a critical decision point outside room 212, participants had to choose between a familiar corridor they had previously used and one marked with evacuation signs. Both corridors were designed to be 27 meters long, ensuring the evacuation distance and time were identical. The spatial configurations at these decision points were quantified using partial isovists in Isovist 2.4 software (McElhinney, 2018), with a 110° field of view to match the HTC Vive Pro headset.

**Figure 27**

*The corridors' spatial configuration in Snopková's study*



*Note.* Adopted from Snopková et al. (2023) with the authors' permission.

Participants' subjective experiences and decisions during the IVS were assessed using an online questionnaire, which included sections on telepresence (with questions adapted from Kim & Biocca, 2006), orientation abilities, observation and use of the evacuation plan and signage, and personal data. The questionnaire featured single-choice questions and items rated on a seven-point Likert scale. The experimental design utilized a between-subjects approach with four environmental conditions (narrow-right, narrow-straight, wide-right, wide-straight). The study investigated three main factors: the environmental variant, participants' compliance with the official evacuation plan (measured on a Likert scale from 1, representing exclusive plan-following, to 7, representing complete disregard), and the ease of VR movement control, a known predictor of performance (Ugwitz et al., 2019).

The primary metric in this experiment was whether participants employed a retracing strategy, which is defined as using the same route for exit as for entry. Based on the logged VR positions, this behavior was coded as 1 (retracing used) or 0 (retracing not used). Additional metrics included task completion time, total exit time, and the choice of doors during the exit, considering previous research suggesting that people prefer already open doors in emergencies (Haghani & Sarvi, 2016; Sime, 1983). The study also recorded participants' prior gaming experience and their attention to evacuation signage.

The procedure began with participant recruitment through social media, obtaining informed consent, and collecting demographic data upon arrival at Masaryk University. Participants were briefed on the experiment, presented as a spatial navigation task in a virtual building. The true purpose of examining evacuation behavior was concealed to maintain the study's realism. After calibrating the VR device, participants received a brief training session on movement controls and followed sequential text instructions within the virtual environment. The VR task was embedded in a story-based scenario where participants started outside a hotel, entered the building, and picked up a blue watering can near a staircase before finding room 212 on the first floor. An evacuation plan was visible upon entering the room, though participants were not explicitly instructed to study it. After watering two of the three withered plants in the room, a fire alarm sounded, signaling the need to "leave the building." Participants then encountered a T-junction where they had to choose between a familiar corridor and one marked with evacuation signs, both leading to a staircase. On the ground floor, they had to choose between a

familiar, closed door and an unfamiliar, open door for exit. The simulation ended once participants exited the building, and the screen faded to black. The entire procedure was standardized across all participant groups to ensure consistency. The Ground floor (left) and first floor (right) of the experimental environment can be seen in Figure 28.

**Figure 28**

*The virtual environment for experimental IVS*



*Note.* Adopted from Snopková et al. (2023) with the authors' permission.

### *Data analysis and results*

The data on retracing behavior were analyzed using generalized linear models (GLM). This analysis treated retracing behavior as a binomial dependent variable (1 = retracing, 0 = no retracing). The spatial configuration, which included four different environmental variants, was included as a fixed factor. Additionally, the adoption of the evacuation plan, measured on a Likert scale, was included as a second factor to monitor whether participants noticed and

utilized the evacuation plan during the process. Another crucial factor in the VR-based experiment was the ease of using the movement controls, which was also measured using a Likert scale and considered a potential predictor of participant behavior. These three factors were incorporated into a generalized linear model using R version 3.6.0 (R Core Team, 2017) along with the lme4 (Bates et al., 2015) and largest (Kuznetsova, Brockhoff, & Christensen, 2017) packages. P-values were computed using the Satterthwaite approximation for degrees of freedom.

The generalized linear model for retracing tendency showed an adequate fit (Hosmer–Lemeshow Test:  $\chi^2(8, N = 72) = 6.56, p = .585$ ) and revealed significant effects. Specifically, conditions involving wide, straight corridors were associated with a reduction in retracing behavior ( $\beta = -2.13, z = -1.97, p = .048$ ; 95% CI  $[-4.55, -0.20]$ ), as was the condition involving a wide right corridor ( $\beta = -2.16, z = -1.98, p = .048$ ; 95% CI  $[-4.59, -0.21]$ ). Additionally, participants who actively observed and utilized the evacuation plan demonstrated significantly less retracing ( $\beta = 0.57, z = 3.73, p < .001$ ; 95% CI  $[0.29, 0.90]$ ). This finding indicates that participants who engaged with the evacuation plan retraced less frequently. Despite 40.28% of participants acknowledging that they saw the evacuation plan (NS 36.84%; NR 35.29%; WS 38.88%; WR 50.00%), most did not actively use the information provided for evacuation ( $M = 5.51, MIN = 1$  [strongly agree],  $MAX = 7$  [strongly disagree],  $SD = 2.33$ ).

The self-reported ease of using the VR movement controls, incorporated into the generalized linear model, was significantly correlated with the total time

spent on the experimental task ( $r_s = 0.62, p < .001$ ), exit time ( $r_s = 0.513, p < .001$ ), gaming experience and gender ( $r_s = 0.45, p < .001$ ), and task completion ( $r_s = 0.29, p = .013$ ).

In terms of the impact of evacuation signage, variance analysis (Welch's ANOVA) showed that observing evacuation signage significantly influenced the choice of retracing strategy ( $F(2) = 31.5, p < .001; \eta^2 = 0.369$ ). Post-hoc tests revealed specific differences: Participants who noticed signage after leaving the room were less likely to retrace their steps than those who saw the signage only upon entering the building ( $t(2) = -3.69, p = .002$ ). Additionally, participants who did not see any signage retraced their steps significantly more often than those who observed it during evacuation ( $t(2) = -8.02, p < .001$ ). No significant difference existed between those who noticed signage immediately upon entering and those who did not. Frequency analysis showed that participants were more likely to notice evacuation signage in wide corridors than narrow ones ( $\chi^2(2, N = 72) = 6.43, p = .040$ ).

Finally, the study examined participants' exit door choices, finding that the presence of an open door significantly influenced their decisions. Despite the proximity, 27.78% of participants chose a farther, open door over a closer, closed one. This choice was primarily driven by the door's openness, as indicated by 20.83% of participants, while others based their decision on proximity (55.56%) or ease of VR movement control (15.28%).

### *Discussion of results in the context of virtual simulation*

This study explored the suppression of retracing behavior during evacuations using virtual reality (VR) simulation tool, focusing on how building spatial configurations and observing evacuation signs and plans influence evacuees' decisions. The hypothesis was that wider and straighter marked evacuation corridors and the observation of evacuation signage would reduce the likelihood of participants retracing their steps. The analysis yielded significant insights into evacuation strategies. Generalized linear modeling (GLM) revealed that spatial configuration considerably impacted retracing behavior. Specifically, the width and direction of corridors were critical factors. Retracing was most common when the evacuation route involved a narrow, right-angled corridor. These findings align with previous research, which showed that narrow, right-angled corridors discourage their selection as evacuation routes (Bailenson et al., 2000; Meilinger et al., 2014). Conversely, wider corridors significantly reduced retracing behavior, suggesting that a larger visual area in the direction of the evacuation route encourages more effective evacuation. This is likely because wider corridors are associated with feelings of openness and safety (Dosen & Ostwald, 2016), making them a preferred choice for evacuees, particularly first-time visitors who often favor more integrated and centrally connected pathways (Hölscher et al., 2005; Li & Klippel, 2016).

Participants who noticed and observed the evacuation plan were less likely to retrace their steps, indicating that awareness and knowledge of it can override more spontaneous, instinctual choices. This finding supports the hypothesis

that visual accessibility and engagement with evacuation plans generally reduce the tendency to retrace during emergencies. Additionally, participants who noticed evacuation signage during the evacuation phase were less likely to exit the building the same way they entered than those who failed to see the signs. This suggests evacuation signage significantly influences behavior, provided it is noticed at the right time. Interestingly, no significant difference was found between participants who saw the signage upon entering the building and those who did not, indicating a human preference for relying on the most immediately accessible information during emergencies. The study also found that wide corridors encouraged their use during evacuations, as they provided clear and direct views of evacuation signage. This observation was supported by frequency analysis, which suggested that wide corridors are more effective evacuation routes. However, no configuration eliminated retracing behavior, underscoring the need to account for the probabilistic nature of human decision-making in evacuation models. The ease with which participants used the VR movement controls also played a significant role in their evacuation performance, correlating with total task time, exit time, gaming experience, and gender. Notably, women were generally slower and reported more issues with VR controls, a difference that likely stems from greater gaming experience among male participants rather than gender alone (Ugwitz et al., 2019). Gaming experience enhanced efficiency in the artificial VR environment, leading to faster response times. The study's findings on exit choices corroborated previous research (Haghani & Sarvi, 2016; Sime, 1983), with nearly one-third of participants opting for a more distant but open door.

This emphasizes the importance of immediately visible cues in decision-making during evacuations.

Regarding the use of virtual simulation, the authors supported several arguments discussed above. The authors successfully developed an innovative computer-generated virtual simulation that enabled participants to freely navigate the spatial layout of a building, allowing them to actively engage in evacuating from a first-person point of view. This virtual simulation provided a highly realistic context, immersing participants in a scenario closely mimicking real-life emergencies. What sets this approach apart is its ability to allow precise manipulation of the experimental conditions, particularly the spatial layout, which would be challenging or impossible to achieve in a real-world setting. This capability highlights the significant potential of immersive virtual simulations in research focused on human behavior during emergencies, as it offers a level of control and flexibility that enhances the accuracy and relevance of the findings.

Moreover, virtual reality (VR) is underscored as a cost-effective, highly adjustable, and ecologically valid tool within this experimental procedure. VR provides a realistic experience for studying cognitive processes under controlled conditions, making it an invaluable researcher asset. The realistic nature of the simulation ensures that participants' responses and behaviors are authentic, thereby increasing the validity of the data collected. This data is particularly valuable for engineering applications, especially in building construction, where it can be utilized to refine agent-based modeling. By

understanding how people navigate and make decisions in an emergency, architects and engineers can design safer and more efficient evacuation routes, potentially saving lives in real-world situations.

Furthermore, the study demonstrates the broader applicability of virtual simulations as a tool that can be further developed and used in applied engineering domains. IVS can generate data that would be difficult or impossible to obtain through traditional methods, particularly when studying active participants in real-life contexts. The ability to gather such data from controlled yet realistic scenarios makes virtual simulations a powerful tool for advancing research and practical applications in various fields, from cognitive science to building design. The success of this study supports the continued development and use of VR technology in research, suggesting that it holds significant promise for future studies and practical implementations where realistic, context-driven data is essential. The arguments are summarized in the points below:

- The authors successfully developed an original computer-generated immersive virtual simulation that allowed participants to freely navigate the spatial layout of a building from a first-person perspective, actively engaging in evacuating the building and creating a controlled and valid experimental context.
- The virtual simulation provided a realistic context while enabling precise manipulation of the spatial layout, a level of control difficult to achieve in real-world experimental settings. This capability underscores

the significant role of IVS in research focused on human behavior during emergencies.

- The use of virtual simulation in this experimental procedure is highlighted as a cost-effective, highly adaptable, and ecologically valid tool that offers a realistic environment for studying cognitive processes under controlled conditions, which can be effectively disseminated to promote, e.g., replication projects.
- The study generated valuable data that can be applied to engineering, particularly in building construction, where it can inform and refine agent-based modeling for safer and more efficient evacuation planning.
- Virtual simulations were validated as a tool with significant potential for further development in applied domains, offering the ability to gather data from realistic scenarios that would be difficult or impossible to obtain through traditional methods.

In conclusion, using IVS, the study demonstrated that building layout and the visibility of evacuation signage significantly influence evacuation behavior. IVS proved to be a valuable tool for examining these effects, offering controlled scenarios and detailed data collection that can inform the design of safer buildings and more effective evacuation strategies. Future research should further consider integrating complementary technologies, such as eye-tracking, to enhance the understanding of sensorimotor activity during evacuations.

### *Limitations and Future Directions*

The study highlighted the significant influence of spatial configuration, evacuation signage, and VR control ease on retracing behavior during an emergency evacuation. Wide corridors and effective use of evacuation plans were associated with reduced retracing, while the visibility of evacuation signage was crucial in guiding participants to follow the designated routes. Additionally, the choice of exit door was influenced by whether the door was open, with some participants opting for an open door even if it was farther away. These findings underscore the importance of spatial design and clear, visible signage in improving evacuation efficiency and safety.

However, this study has some limitations that should be acknowledged (Snopková et al., 2022). The participant pool was reduced due to dropouts during the VR simulation. Additionally, using a retrospective self-report questionnaire to gather information about participants' experiences during the evacuation may have introduced information loss or bias. However, this method was chosen to avoid influencing participants' decision-making and strategies during the evacuation, which a real-time think-aloud commentary could have altered. Future research could benefit from incorporating embedded VR eye-tracking, as suggested, for example, by Juřík et al. (2019, 2021), to allow for objective measurement of participants' sensorimotor activities. Future studies should delve deeper into demographic analysis, the development of user interfaces, and virtual environments tailored to more complex spatial configurations. Integrating BIM, AI, eye-tracking, and other

emerging technologies could lead to more precise recommendations for building design and agent-based evacuation simulations (Penn & Turner, 2002). The potential of combining eye-tracking, machine learning, and brain-imaging technologies points to a future where algorithms and computer models could significantly enhance human efforts in evaluating and improving VR environments (Zhang et al., 2018).

## Virtual Simulations in AI Domain – Agent-based Modeling<sup>7</sup>

Railway stations, shopping malls, and public buildings are high-density environments where managing emergencies and evacuations poses significant challenges. In such settings, the concentration of people significantly increases risks, as uncontrolled evacuations can sometimes present greater dangers than the emergency itself. Thus, developing and optimizing safety plans (even when buildings do not physically stand) is crucial for effective emergency management, with a strong focus on safeguarding individuals and property. To address these challenges, modern technologies like artificial intelligence (AI) and virtual reality (VR) are becoming integral to designing and evaluating safety plans (Apeltauer et al., 2021). A prominent tool in this field is agent-based evacuation models (ABEMs), which simulate and visualize various evacuation scenarios by accounting for human movement within buildings and the dynamics of emergencies. With contemporary statistical methods, ABEMs can predict and manage various emergency scenarios, providing detailed and theoretically unlimited evacuation simulations. However, the effectiveness of these models relies heavily on the quality of the input data. Acquiring high-quality data on human movement and evacuation behavior is challenging due to ethical constraints and the high costs and technical

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<sup>7</sup> This chapter is based on the study: Juřík, V., Uhlík, O., Snopková, D., Kvarda, O., Apeltauer, J. & Apeltauer, J. (2023). Analysis of the use of behavioral data from virtual reality for calibration of agent-based evacuation models. *Heliyon*. Elsevier Ltd, 9 (3), 1-14. ISSN 2405-8440.

difficulties associated with real-world studies. Safety assessments must be conducted for new buildings during the design phase before the physical structure exists, making empirical testing impossible. Recent advancements in VR technology offer a viable solution. Modern VR systems can simulate emergency scenarios with high visual fidelity and include other sensory experiences, such as haptic and olfactory feedback. VR-based evacuation experiments are a promising alternative to costly and potentially dangerous real-world tests. They provide valuable insights for psychological and technological research and engineering practices, with significant implications for public building design (Veling et al., 2016). In this case, as broadly discussed in the theoretical background of this work, we speak about combining AI and VR technologies or, in the context of this thesis, about merging the human-centered virtual simulations with computational agent-based simulations to gain better predictions about selected systems.

The reliability of agent-based models is determined by their verification, validation, and calibration processes. Verification checks the mathematical accuracy of the model by comparing theoretical values with simulation results. Validation assesses how well the model represents real-world scenarios, and calibration involves adjusting model parameters to reflect specific conditions, such as population composition and movement speeds. Fundamental parameters for evacuation models include pre-movement time, movement speed, exit usage, route availability, and traffic flow state (Gwynne et al., 2012). Accurate representation of these parameters is essential for effective safety planning and evacuation strategies. These parameters must be measured in

real-world contexts, which may not always be available due to logistical, financial, or situational constraints. In engineering practice, target locations are specific and predefined or may still be in the design phase, making empirical experiments impractical. At this point, the Human-in-the-Loop (HITL) approach (Karwowski, 2006; Wu et al., 2022) helps to resolve this issue since it may promote validation of the ABEMS by the interaction between human-centered and agent-based simulations. This is crucial for the accuracy and reliability of the models adaptable to real-world situations. Here, the human input is crucial since, with immersive virtual simulations, the model's predictions can be assessed by humans and further refined. This feedback loop is vital for reducing errors and enhancing accuracy over time. The model becomes increasingly intelligent, reliable, and adept at managing complex tasks by continuously integrating human insights. VR technology offers a practical and efficient way to gather necessary data for calibration, even when the building is still in the design phase or when real-world evacuation experiments are complicated by safety or organizational reasons.

IVS, typically delivered through head-mounted displays, creates highly realistic virtual environments for research and practical applications. With advanced visual graphics, IVS provides convincing realism and immersion, enabling non-invasive and cost-effective data collection on human behavior in simulated yet lifelike contexts. VR is particularly valuable for studying evacuation behaviors in buildings still in the design phase or under conditions challenging to replicate in reality, such as fire or toxic gas scenarios. Data from these IVS-based experiments can inform agent-based modeling, though risks

such as nausea or fatigue from prolonged VR use must be considered (Agić et al., 2020). A key research area at the intersection of VR and agent-based modeling is understanding behavioral phenomena during virtual evacuations. Previous research supported the claim that evacuation behavior is similar in objective and VR settings, supporting VR's potential for developing accurate behavioral models for evacuation scenarios (Stachoň et al., 2025). The findings from IVS-based experiments enable the creation of effective behavioral models with lower logistical, financial, and technological costs. Simulation tools can use these models as probability distributions for phenomena such as pre-movement time, decision-making, route choice, and exit selection.

The results from previous research (Apeltauer et al., 2021) show that VR user studies may have the potential to considerably enhance predictions of actual evacuation behavior. Calibrated models reflect greater variability in evacuation times, with maximum values crucial for evaluating building safety. For example, agents who follow a retracing strategy have longer evacuation times than those using evacuation signage. VR-based measurements are thus vital for capturing key aspects of human behavior during evacuations. Overall, VR experiments for agent-based modeling represent a promising advancement, offering new opportunities for engineering practice. By providing reliable empirical data on human behavior, VR simulations can enhance evacuation model development and improve building safety assessments, enhancing the accuracy and effectiveness of evacuation planning. It can be considered a blending of computational and human-centered simulations to gain better predictions about the world. One potential direction of using virtual

simulation for refining ABEMS was introduced in the study of Juřík and his colleagues (2023).

*Research on using virtual simulation in Agent-based Modeling*

Evacuation refers to the organized movement of individuals from a hazardous environment to a safe location, typically an assembly point (Juřík et al., 2023). This complex process relies heavily on human behavior and cognition, particularly in unfamiliar indoor settings. Evacuation can be understood as a form of wayfinding, where individuals must navigate to safety by utilizing their cognitive abilities, including decision-making, spatial reasoning, and comprehension of indoor environments (Cao et al., 2019; Golledge, 1999; Maguire et al., 1998). During evacuations, behavioral phenomena often emerge, such as delayed responses to alarms (pre-evacuation behavior) and a tendency to retrace one's steps, returning via the same route used to enter the building. This frequently occurs despite evacuation signage, often overlooked (Johnson, 2005; Kurkjian & Ebbert, 2003; Proulx, 2001; Snopková et al., 2021). Furthermore, evacuees may not always use designated emergency exits, with their behavior being influenced by the environmental cues and conditions during the evacuation (Arthur & Passini, 2002; Kinateder et al., 2018; Wood, 1972).

Several studies have explored how environmental features, such as signage, lighting, landmarks, and sensory cues (visual, auditory, or olfactory), impact evacuation behavior (Arthur & Passini, 2002; Kobes et al., 2010; Lin et al., 2020a; Shih et al., 2000; Taylor & Sucov, 1974; Vilar & Rebelo, 2010; Xie et al., 2011).

The structure and design of the environment itself, such as the availability of clear exits and routes, also play a significant role in evacuation outcomes (Ugwitz et al., 2019; Vilar et al., 2013). As a result, behavioral analysis within specific architectural contexts has become an important area of focus in evacuation research. It is crucial to consider these human factors when developing evacuation models to predict how people will behave in emergency evacuations, mainly how building designs facilitate or hinder movement.

Agent-based evacuation models (ABEMs) are commonly used to simulate and predict evacuation scenarios. These models aim to replicate the movement of individuals during evacuations, allowing for the visualization and analysis of potential outcomes. However, many ABEMs cannot capture the full range of human behavior. Most commercially available models emphasize basic movement patterns, such as selecting the shortest route, without accounting for the complex cognitive and behavioral factors that influence real-world evacuations (Ronchi & Nilsson, 2013). Although smoothing algorithms can generate more natural movement paths (Johnson, 2005), these models often fail to represent the nuances of human movement (Chraibi et al., 2016; Liao et al., 2017). ABEMs typically rely on predefined rules for agents' decisions and select paths rather than adapting dynamically to environmental changes. An alternative to these models is force-based approaches like the social force model, where agents' movements are influenced by the forces exerted by other agents (Helbing & Molnar, 1998). Cellular automata, another type of ABEM, uses a grid-based system with simple rules to model interactions between

agents and their environment (Burstedde et al., 2001). This study employed Pathfinder software, which uses continuous triangulation to model uninterrupted human movement, contrasting with the more rigid, discrete frameworks of cellular automata.

Immersive Virtual Simulations (IVSs) offer an ecologically valid, controllable, and cost-effective method for gathering behavioral data across diverse scenarios. VR has been shown to engage brain mechanisms similarly to those triggered in real-life situations (Alcañiz et al., 2009; Wilson, 1997), making it an effective tool for simulating real-world environments (Paradis et al., 2019). Head-mounted displays (HMDs) enhance realism and facilitate non-invasive data collection, especially when combined with the interactivity and activity-logging features of virtual environments (Ben Amor et al., 2006; Bille et al., 2014; Ugwitz et al., 2021). VR can also bypass the logistical and financial challenges associated with conducting full-scale evacuation drills in physical buildings, allowing for the collection of valuable data to optimize evacuation models. Importantly, VR-based studies can be conducted in virtual environments that do not yet physically exist, such as planned buildings, and can simulate dynamic hazards like fires or toxic spills (Helbing & Molnar, 1998; Kuliga et al., 2015; Ugwitz et al., 2019; Vilar & Rebelo, 2010).

Building Information Modeling (BIM) technology plays a key role in the design of VR environments, particularly for human-centered evaluations (Bille et al., 2014; Kvarda, 2021). Recent VR advancements demonstrate the potential to capture accurate behavioral data in evacuation scenarios (Cao et al., 2019; Lin

et al., 2020b; Lovreglio et al., 2020; Vilar et al., 2013). However, despite its promise, the reliability of specific behavioral insights gained from VR research requires further validation, especially concerning VR tools' technical limitations and how well they reflect real-world evacuation behaviors. For instance, navigation and other actions in virtual settings may differ due to the characteristics of the virtual environment itself (Moussaïd et al., 2016; Shi et al., 2019). Some studies suggest that VR can reduce human performance due to the unnatural interaction with the simulation (Marín-Morales et al., 2019; van der Ham et al., 2015), along with issues related to movement metaphors or imperfect environment representations (Arias, 2021). For example, movement efficiency is often lower in virtual environments (Stachoň et al., 2025). Additionally, VR's limitations include potential cybersickness, reduced ecological validity compared to field studies, and technical constraints that can impact the authenticity of user behavior (Hamad & Jia, 2022; Morganti et al., 2007). These factors must be considered when interpreting results from VR-based studies. Nevertheless, VR has been shown to effectively simulate cognitive processes like decision-making and reaction times similar to real-world conditions (Alcañiz et al., 2009; Higuera-Trujillo et al., 2017). With careful design, VR studies can provide valuable insights into human factors during evacuations, improving agent-based models and enhancing evacuation predictions (Proulx, 2001).

Given current agent-based evacuation models (ABEM) capabilities, the authors selected key behavioral metrics from the referenced study (Stachoň et al., 2025) to enhance the Pathfinder ABEM used in this research. Real-world navigation

and behavior are expected to differ from those in virtual environments due to the unique characteristics of each setting. Previous research has highlighted that VR technology may hinder human performance (van der Ham et al., 2015), often due to the unnatural nature of simulations, imperfect representations, and problematic movement metaphors. One major challenge is the control interface used in VR, particularly the keyboard or joystick. Studies have shown that keyboard-mouse controls (Stachoň et al., 2025) fail to accurately simulate natural speed variations, resulting in constant-speed movement with abrupt stops rather than the smooth accelerations typical of real-world motion. However, as supported by previous findings, cognitive processes such as decision-making, reaction times, and exit choices appear to be comparable between real and virtual settings. These similarities were evident in the analyzed data through overall averages of measured variables or similar trends observed in visual analyses.

In refining VR-based models, the authors focused on behavioral parameters consistent across real and virtual environments. These parameters were categorized into two main groups: general parameters that can be applied across different building types and specific parameters tailored to the building used in this study. To implement these refinements, the Pathfinder model was customized to reflect the gender distribution among evacuees (agents). This ensured that the input values used in the simulations aligned with the gender distribution of the participants in each experiment unless otherwise noted. One of the key parameters integrated into the model was pre-evacuation time, also known as alarm reaction time. This represents the delay between the sound of

the alarm and evacuation initiation. This delay, influenced by cognitive processing and individual or environmental factors, is frequently overlooked in standard engineering practices in the Czech Republic (Uhlík & Apeltauer, 2019). The authors included this delay to enhance model accuracy using a log-normal distribution based on observed data.

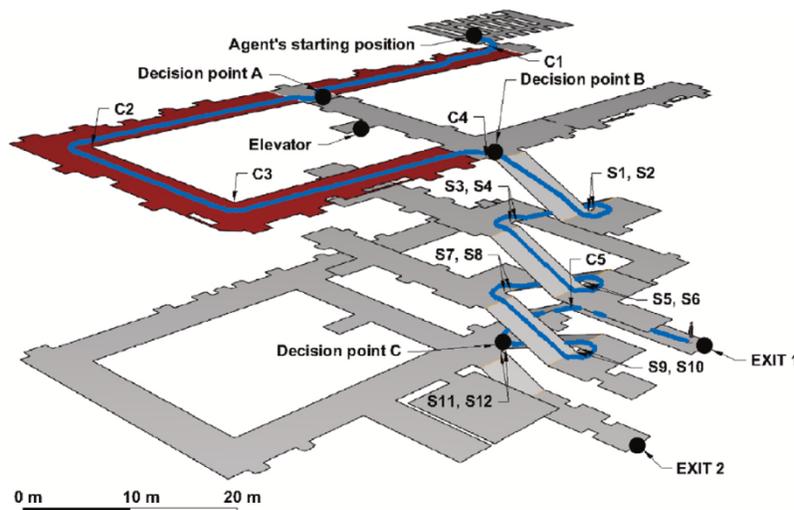
Walking speed, another crucial metric, varied between the real and virtual environments due to differences in movement control. In the real environment, participants walked at their natural pace, while in the virtual environment, movement was constrained to a constant speed controlled by the keyboard and mouse. To account for this, the authors calculated average walking speeds over specific segments of the route, incorporating stops related to movement control. These speeds, aggregated by gender and interpolated using a normal distribution, were then applied as input for the model. Similarly, stair descent speeds were influenced by the movement interface. Participants' average speeds on six identical stair flights were measured, aggregated by gender, and used to adjust walking speeds for staircase segments in the model (see Juřík et al., 2024 for more details).

Additional parameters, such as acceleration time—the time required for an agent to reach maximum speed—could not be directly measured during the experiment and were estimated using default settings. This parameter was not applied in the virtual environment, where speeds were constant. Lastly, the distance participants maintained from walls in building corridors (the wall boundary layer) was measured at several points (C1-5 in Figure 28) and

modeled using a normal distribution, with adjustments for gender. Similarly, the minimum distance from staircase pillars (S1-12 in Figure 28) was measured and incorporated into the model following the same procedure used for the wall boundary layer.

**Figure 28**

*Evacuation path depiction*



*Note.* The diagram depicts the sample evacuation path, key decision points, and adjacent corridors. The evacuation trajectory is shown as a blue line. Corridors marked in red were utilized to calculate unimpeded walking speeds. Points labeled C1 to C5 indicate the corridor corners, while points S1 to S12 represent the staircase pillars. Adopted from Juřík et al. (2023) with the authors' permission.

Decision time at critical junctures plays a vital role in building-specific evacuation models. This parameter represents the time individuals spend making choices at key points, and research has shown its consistency between

real and virtual evacuation scenarios (Stachoň et al., 2025). However, decision time is often overlooked in agent-based simulations, even though it significantly impacts evacuation dynamics. Due to the unique spatial layouts of different buildings, general parameters cannot be universally applied. This study identified and mapped three main decision points along the evacuation route. The first decision point (A) occurred at bars blocking the previous entry route to the lecture room. The second (B) was a junction on the 4th floor, where participants had to choose between an unauthorized elevator or stairs. The third (C) was at the base of the stairs on the 1st floor, where participants could either follow the marked evacuation route or retrace their steps to the original entrance. The time [s] participants spent at these decision points was recorded and integrated into the models.

Additionally, significant deviations, such as movements toward the elevator, were manually added to the model. Another critical parameter is the retracing strategy, which reflects whether individuals retrace their steps during evacuation. Similar to decision time, retracing behavior is influenced by building design. The proportion of people retracing their steps was consistent between real and virtual environments. To account for this, agents were assigned specific exits based on their last waiting point on the first floor. Further details are provided in Table 1.

**Table 1***Values of input parameters for the model simulations in Juřík's study*

Input parameters	Default Settings	Real Evacuation (M = 15, W = 20)		Virtual Evacuation (M = 22, W = 16)	
<b>Gender</b>	–	43% men	57% women	58% men	42% women
<b>Pre-evacuation time [s]</b> location (shape) [min; max]	0 [s]	1,73 (0,38) [3,55; 9,95]	1,65 (0,35) [3; 8,6]	1,82 (0,44) [3.38; 15,72]	1,82 (0,46) [4,23; 14,96]
<b>Unimpeded walking speed [m/s]</b> mean (SD) [min; max]	1.19	1.82 (0.278) [1.42; 2.25]	1.78 (0.379) [1.3; 2.68]	2.22 (0.158) [1.96; 2.54]	2.09 (0.223) [1.66; 2.34]
<b>Staircase walking speed [m/s]</b> mean [m/s] (coefficient [–])	1.19 (1)	1.294 (0.71)	1.176 (0.66)	2.22 (1)	2.09 (1)
<b>Acceleration [s]</b>	1.1	1.1	1.1	0	0
<b>Wall boundary layer [m]</b> mean (SD) [min; max]	0.15	0.922 (0.245) [0.559; 1.41]	0.894 (0.279) [0.465; 1.38]	0.91 (0.333) [0.387; 1.53]	0.9 (0.284) [0.372; 1.44]
<b>Staircase pillars boundary layer [m]</b> mean (SD) [min; max]	0.15	0.642 (0.183) [0.409; 0.954]	0.647 (0.211) [0.37; 1.00]	0.676 (0.239) [0.29; 1.06]	0.625 (0.242) [0.286; 1.03]
<b>Decision time in front of the bars</b> time [s] (distribution [%])	–	0-5 (33) 5-10 (40) 10-15 (7) 15-20 (13) 45-50 (7)	0-5 (30) 5-10 (30) 10-15 (20) 15-20 (5) 20-25 (10) 50-55 (5)	0-5 (50) 5-10 (27.5) 10-15 (5) 15-20 (12.5) 30-35 (5)	0-5 (25) 5-10 (50) 10-15 (13) 15-20 (6) 35-40 (6)
<b>Decision time in front of the stairs on 4. Floor</b> time [s] (distribution [%])	–	0 (86.6) 5 (6.7) Try to use elevator (6.7)	0 (95) Try to use elevator (5)	0 (87) Try to use elevator (13)	0 (93.75) Try to use elevator (6.25)
<b>Decision time in front of the stairs on 1. Floor</b> time [s] (distribution [%])	–	0-2 (53) 2-4 (26) 4-6 (14) 8-10 (7)	0-1 (50) 2-4 (25) 4-6 (5) 6-8 (20)	0-2 (55) 2-4 (45)	0-2 (68.5) 2-4 (18.5) 4-6 (13)
<b>Retracing [boolean ]</b>	–	20.0% yes 80.0% no	30.0% yes 70.0% no	36.4% yes 63.6% no	43.8% yes 56.2% no

*Note.* The table was adopted from Juřík et al. (2023) with the authors' permission.

The Pathfinder agent-based model utilizes building geometry and a range of input parameters to differentiate agents and simulate evacuation scenarios. Wayfinding is governed by probabilistic events, such as selecting waiting points, movement patterns, and exit choices. The simulations are powered by the Monte Carlo method (Naili et al., 2019), where each agent is assigned a unique random seed to generate parameters like movement speed within predefined distributions. This adds variability to agent paths and evacuation times, enabling statistical analysis. Based on Ronchi's method (Ronchi et al., 2014), it was determined that 150 simulations were sufficient to achieve

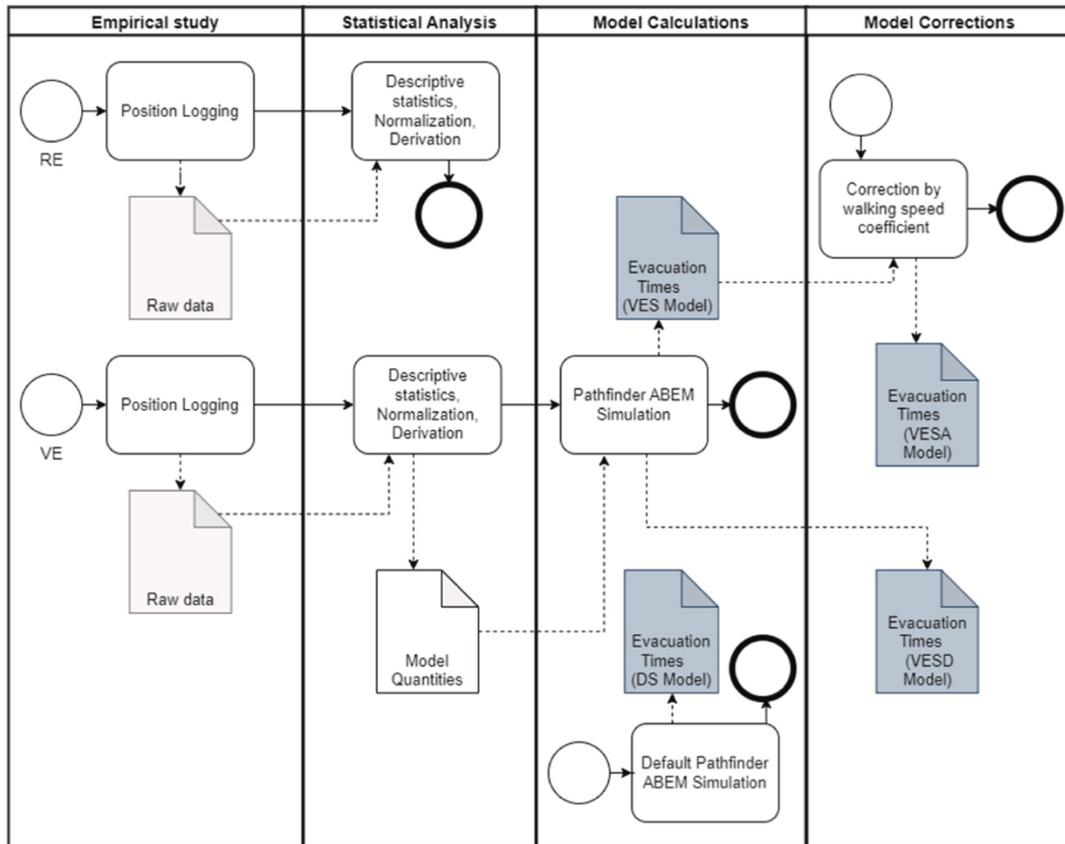
convergence for total evacuation time (TET conv) and standard deviation (SD conv), with thresholds set at TET conv - 1% and SD conv - 5%. An initial 300 runs were conducted to establish this threshold, revealing that beyond 150 simulations, the variance in evacuation times stabilized.

The simulations accounted for various behavioral factors, even rare events like elevator usage. For scenarios with no variability, 35 simulations were performed to assess consistency in evacuation times. Total evacuation time, from alarm to final exit, is the primary output of these simulations. It is crucial for practical applications, as it is often the key measure monitored by investors and regulatory authorities. The geometry was based on a 3D building model (.fbx) generated in Revit Architecture.

Evacuation time is the main focus of these models, especially for engineering and planning purposes. Significant discrepancies between virtual reality (VR) and real-world experiments are often due to differences in movement interfaces. In VR simulations using a keyboard-mouse setup, acceleration is restricted, resulting in a constant speed of 3 m/s, unlike real-world evacuations where participants are unrestricted. Therefore, the study applied mathematical corrections to the Virtual Evacuation Settings (VES) models. The first corrected model (VESA) used real evacuation drill data for unimpeded and staircase walking speeds. The second model (VESD) was derived from the VES model and corrected using a coefficient calculated based on these differences. The overall process of model calculations and application of corrections is depicted in Figure 29.

**Figure 29**

*The diagram of model calculation, correction, and evaluation in Juřík’s study*



*Note.* Adopted from Juřík et al. (2023) with the authors’ permission.

*Data analysis and results*

The evaluation of the calculated models involved four key steps. First, the authors compared the results of the Virtual Evacuation Settings (VES) model with those of the Default Settings (DS) model, which used standard input parameters. Second, the authors assessed the VES model results against empirical data collected in virtual reality (VE). By following the same

experimental procedure in real and virtual environments (Stachoň et al., 2025), the authors could evaluate the VES model results against data from a real environment (RE). Finally, the authors compared the corrected models, Virtual Evacuation Settings Adjusted (VESA) and Virtual Evacuation Settings Derived (VESD). The analysis utilized non-parametric ANOVA (Kruskal-Wallis test) and post hoc Dunn's tests with Holm's p-value and p-value adjustment for multiple comparisons (q-values).

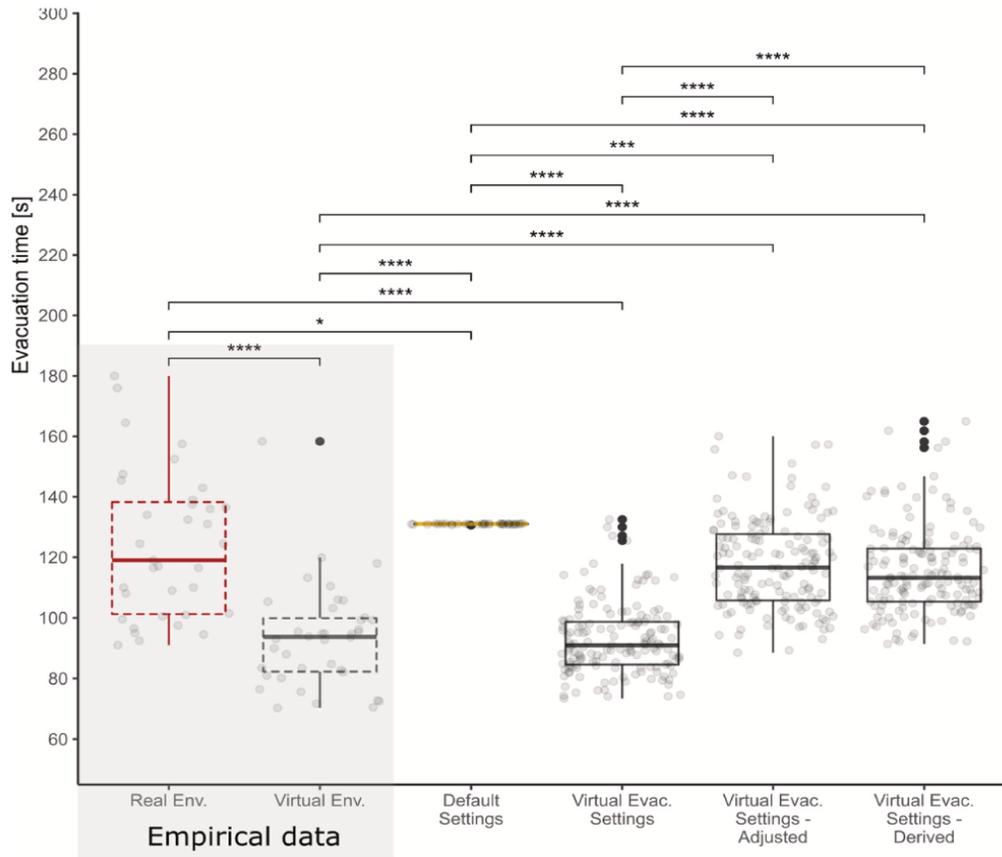
The analysis was conducted using RStudio v. April 1, 1106 (The R Project for Statistical Computing, n.d.) and visualized with the ggplot2 package (Wickham, 2016), providing several insights. First, the authors observed that the DS model produced a different trajectory with no variance. In contrast, the proposed models' simulated agent movements overlapped with the real movement trajectories from the empirical experiment. The variance in trajectories, introduced by using distributions of model input quantities, indicated that agents in the refined models visited similar spaces as real participants, thereby enhancing the reliability of the predictions.

The Kruskal-Wallis test indicated significant differences in evacuation times between observations, with a large effect size ( $\chi^2 = 272.73$ ,  $df = 5$ ,  $p < 0.001$ ,  $\eta^2 = 0.485$ ). Specific differences between conditions, included the following trends: Participants in the VR experiment evacuated significantly quicker than those in the real experiment (RE;  $M = 123.93$  s;  $MED = 119.00$  s;  $SD = 24.39$  s; VE;  $M = 93.38$  s;  $MED = 93.73$  s;  $SD = 17.06$  s). Dunn's post hoc tests further revealed that the real condition evacuation times differed significantly from the DS model

(M = 130.84 s; MED = 130.80 s; SD = 0.14 s). We also noted significant variance in evacuation times in the real environment (RE), with the total evacuation time being longer due to the slowest evacuees. This variance was absent in the DS model, which lacks predictions about upper-limit evacuation values. Based on VR data, the VES model (M = 92.87 s; MED = 90.95 s; SD = 11.62 s) differed significantly from the real condition (RE). However, the corrected models (VESD and VESA) closely matched the real evacuation behavior, with no significant difference from the real condition (VESD: M = 115.62 s; MED = 113.23 s; SD = 14.47 s; VESA: M = 117.80 s; MED = 116.6 s; SD = 15.01 s). For more details, see Figure 30.

**Figure 30**

*Box-plot depiction of computed evacuation times from individual evacuation models*



*Note.* Default Settings - DS; Virtual Evacuation Settings - VES; Virtual Evacuation Settings Adjusted - VESA; Virtual Evacuation Settings Derived - VESD). Adopted from Juřík et al. (2023) with the authors' permission.

Both VR data-based models (VESD and VESA) differed significantly from the DS model, suggesting that the corrected VR-based models provide a more accurate simulation of real evacuation behavior. This correspondence between

the corrected models and real behavior supports the validity of using VR-based models for detailed and reliable evacuation predictions.

*Discussion of results in the context of virtual simulation*

The analysis of the computed models revealed several noteworthy trends. Most notably, participants in the real building evacuation (RE) evacuated significantly faster ( $p < 0.01$ ;  $q\text{-value} < 0.05$ ) compared to agents using the Pathfinder ABEM with default settings (DS model). This discrepancy in evacuation times highlights a limited alignment between actual human behavior and agent simulations, underscoring the potential inadequacy of relying solely on artificial parameter calculations (Kuligowski et al., 2010). To improve prediction accuracy, it is crucial to integrate ecologically valid data into agent-based modeling. Gathering essential data through real evacuation drills is inherently challenging due to various factors. Consequently, this study aimed to evaluate the applicability of accessible VR data for enhancing agent modeling. Comparisons between real and VR evacuations revealed notable differences in evacuation times, with virtual participants evacuating substantially faster than those in real buildings. This discrepancy suggests that raw VR observations may have limited validity. A similar significant difference ( $p < 0.001$ ) was observed when comparing the Virtual Evacuation Settings (VES) model to real evacuations, primarily due to the movement interface used in the VR experiment (keyboard and mouse with constant walking speed), which notably impacted evacuation speed (Stachoň et al., 2025). These results reinforce previous assertions that virtual experiments alone cannot fully

replace real evacuation drills. Raw VR observations alone offer limited insights into evacuation behavior.

Nevertheless, trends from the corrected VR-based models (VESD and VESA) demonstrate that agent models based on VR data, when appropriately adjusted, can be reliable. The VESD and VESA models closely matched real evacuation behavior (RE), yielding comparable results in evacuation time and movement trajectories. This suggests that corrected VR-based models can provide dependable predictions for practical applications.

The data analysis revealed no significant difference between the VESD and VESA models, indicating that both corrected models effectively approximated real-world behavior. This suggests that two viable approaches exist for VR-based agent models. The first method involves adjusting VR data using real walking speeds from a specific evacuation drill suitable for existing buildings. The second method entails post-processing corrections to VR-based model outputs using either theoretical or empirical standardized coefficients, as implemented in the VESD model. This second method has proven reliable and valid for predicting aspects of building evacuation and aligns well with actual evacuation behavior. These results point to a promising avenue for future research, where VR-based/IVS-based experiments can be adapted for use in agent-based evacuation models (ABEMs). Such adaptations offer cost-effective, efficient, readily available, and ecologically valid tools for forecasting evacuation behavior. VR-based ABEMs are poised to become a significant trend in future research and warrant further investigation. Future studies

should focus on exploring advanced haptic interfaces for movement within VR environments, though these would require substantial technological and financial investments.

Models based on IVS data, when integrated with real behavioral patterns, can serve as reliable tools. The alignment between real and simulated movement, as agents in simulations followed actual trajectories, supports the validity of these models in reflecting reality. This alignment allows for considering less common phenomena, such as detours or disorientation, which often occur in real evacuations but are frequently omitted from default models. Further exploration of these phenomena is critical in critical evacuation scenarios, such as those involving fractional effective dose or the slowest evacuees.

Overall, regarding the discussed potential of IVS, this study demonstrated its vitality and supported several claims discussed above (Juřík et al., 2019; Juřík et al., 2018; Juřík et al., 2021). In this study, the researchers successfully transferred the real-world content of an existing building into a digital twin model, enabling the creation of a human-centered virtual simulation of evacuation behavior. This approach allowed for exploring scenarios that would be difficult or impossible to access in the actual building, particularly for buildings still in the project phase. The digital twin provided a hyper-realistic environment where participant behavior could be meticulously tracked and analyzed. This behavioral data was then applied to the domain of agent-based computer simulations, bridging the gap between virtual simulations and the evolving field of AI-driven modeling. Integrating human-

centered data from the virtual simulations with agent-based simulations derived from the digital twin of the actual building proved to be a significant advancement. These simulations were validated against participants' real movement patterns within the building's virtual model, offering critical insights into how people might behave during an evacuation and employing the HITL principle in the process of agent-based evacuation modeling. This validation process confirmed the simulations' accuracy and highlighted the potential of such models to predict human behavior in emergency scenarios, thereby enhancing the safety and efficiency of evacuation planning.

Moreover, the study underscored the value of IVS as a research tool, emphasizing its cost-effectiveness, adaptability, and ecological validity. VR provides a realistic environment for studying cognitive processes under controlled conditions, which is crucial for developing accurate models of human behavior. The findings of this study have direct applications in the engineering domain, particularly in building construction and evacuation routes engineering. The specific methodology employed in this research has been certified by the Czech Ministry of Transportation (Apeltauer et al., 2022), providing a valuable framework for using digital twins and VR technology in practical applications. This certified methodology is a testament to the potential of combining VR, digital twins, and agent-based simulations in the design and evaluation of building safety systems, marking a significant step forward in applying these technologies in real-world scenarios. The whole context is summarized below:

- The real-world structure of an existing building was transformed into a digital twin model, enabling the creation of a human-centered virtual simulation of evacuation behavior. This approach allowed researchers to explore scenarios that would be challenging or impossible to study in the actual building, particularly for structures still in the project phase.
- The authors successfully processed behavioral data from a highly realistic virtual simulation and integrated it into agent-based computer simulations. This work bridges the gap between virtual simulations and AI-driven modeling in the field of computer simulations.
- The agent-based simulations, based on the human-centered virtual simulations derived from the digital twin of the real building, were validated against the actual movement of participants within this virtual environment. This validation helps to predict how people might behave during an evacuation scenario.
- In the experimental procedure, virtual reality (VR) was highlighted as a cost-effective, easily adjustable, and ecologically valid tool that provides a realistic environment for studying cognitive processes under controlled conditions.
- The study's conclusions have direct applications in engineering, particularly in building construction. The specific methodology developed for using this technology has been certified (Apeltauer et al., 2022) and is now recognized as a vital tool for application in the industry.

In conclusion, this study supports the viability of reliable and ecologically valid empirical inputs from virtual experiments for agent-based evacuation modeling. A promising area for future research is the exploration of multi-agent or crowd behavior. While this study focused on individual evacuation behavior, virtual experiments offer possibilities for large-scale data collection from many participants worldwide. Implementing this study's approach for ABEMs with groups of evacuees could provide valuable insights. However, specific research on crowd behavior under real and virtual conditions is needed to support VR use in crowd agent-based evacuation modeling. Multi-agent modeling optimized by empirical experiment parameters remains an exciting direction for future research.

#### *Limitations and Future Directions*

Despite the above-mentioned advantages and research shifts, IVS in studying evacuation behavior has limitations. Common issues such as cybersickness (Davis et al., 2014; Jerald, 2015), particularly while employing HMDs, can lead to higher dropout rates in experiments, necessitating larger sample sizes. Moreover, the optimization of model data is heavily influenced by the specific characteristics of the research sample, which limits the generalizability of the results. To ensure external validity, future studies should adequately represent the target population and account for its specific size. Nonetheless, this study concludes that IVS-based empirical inputs are viable and ecologically valid for agent-based evacuation modeling.

A promising direction for future research is the exploration of multi-agent or crowd behavior (Moussaïd et al., 2016). While this study focused on individual evacuation behaviors and their use in subsequent single-agent simulations, virtual experiments inherently allow for large-scale data collection from numerous participants across various locations simultaneously. The approach used in this study could be adapted for ABEM involving groups of evacuees. However, it is crucial to investigate further potential differences in crowd behavior between real and virtual environments to justify using VR in crowd-based evacuation modeling. The application of multi-agent modeling, optimized by empirical data, remains an exciting and valuable area for future research.

Building on insights from previous research (Snopková et al., 2023), future investigations in this field can significantly benefit from incorporating VR eye-tracking technologies. Juřík et al. (2019, 2021) highlight that eye-tracking can provide objective measurements of participants' sensorimotor activities, offering a more granular understanding of how individuals navigate and interact within virtual environments. This could greatly enhance our ability to analyze behavioral responses and improve the fidelity of IVS simulations, potentially promoting the precision of ABEM predictions further. Similarly, integrating virtual environments for IVS with AI agents and other cutting-edge technologies can potentially increase the fidelity of evacuation exercises. This could be beneficial, especially when studying crowd behavior.

Since evacuation IVS can be conducted in the laboratory setting, the convergence of eye-tracking, machine learning, and brain imaging offers a promising avenue for future research. By leveraging these tools, researchers can develop algorithms and computer models that more accurately reflect human behavior and improve the evaluation of VR environments. This multi-disciplinary approach could significantly advance our understanding of evacuation dynamics and lead to more effective strategies for enhancing safety in complex building environments (Zhang et al., 2018). In summary, incorporating advanced technologies into VR-based research promises more precise simulations and a deeper understanding of human behavior in emergency situations. Continued exploration of these methods will be crucial for developing robust and practical solutions for building design and evacuation planning.

## Part III – Further Evidence

## Follow-up Spatiotemporal Analysis of Trajectories in Virtually Simulated Evacuation Scenario

The study of Juřík et al. (2023), concerning the actual application needs of the building industry, evaluated total evacuation time as a crucial measure of the evacuation parameters. In this study, however, the specific spatial trajectories of agent movements were not deeply analyzed regarding their similarity, which opens further direction for potential research. It is evacuation behavior as a whole, including specific movement trajectories, which should be considered for potential modeling to understand how individuals navigate during emergency situations and which simulation strategy or model can be beneficial. In this matter, participants' behavior can vary significantly based on factors such as prior knowledge of the environment, stress levels, and individual decision-making strategies, where the total evacuation time does not apply as a transparent and conclusive measure of the evacuation process.

The following insight presents a detailed analysis of participant trajectory data collected during evacuation scenarios and modeled using the agent-based modeling tool Pathfinder (Thunderhead Engineering Consultants, 2019). The primary focus is to compare participant behaviors across distinct behavioral patterns, specifically by examining the distance traveled and time taken to complete the evacuation tasks. This approach employs the above-discussed Human-in-the-loop (HITL) principle in a specific application. Since HITL simulation integrates human operators into simulation processes, combining

human decision-making and interaction with automated systems may bring novel insights into agent modeling. For this purpose, the data from the agent simulation based on the real environmental evacuation data, virtual simulation data, and computer simulation data were analyzed. The follow-up analysis aims to inspect specific spatiotemporal trajectories of 3 specific simulation types – real data-based simulation, virtual data-based simulations, and simulations conducted under the default Pathfinder setting.

### Spatiotemporal Movement Analysis

In movement analysis, studying trajectories offers valuable insights into how individuals or objects navigate through space over time. A trajectory is an entity's path from one location to another over a specified period. When observing multiple participants simultaneously, the analysis of their movement trajectories reveals patterns, interactions, and dynamics within the studied environment. However, capturing these insights necessitates grappling with the intricate relationship between space and time. A fundamental challenge in trajectory analysis lies in managing spatiotemporal divergence—the variation that emerges as participants follow different paths through space and time. As individuals or objects move, their trajectories diverge spatially and temporally, particularly in open or branched environments where paths can split in multiple directions. This divergence complicates efforts to analyze and compare movement patterns comprehensively. Temporal divergence reflects changes in participants' positions over time, with each individual following a unique path. At any

given moment, their positions represent a snapshot of their trajectories, making it challenging to compare movements without accounting for temporal shifts. Spatial divergence, however, captures the variation in participants' locations at a particular time. As trajectories evolve, spatial separation increases, highlighting the need to contextualize these movements within a temporal framework. Researchers employ techniques that integrate spatial and temporal data into unified analytical frameworks to address these challenges. Such approaches enable comparisons that respect both dimensions of movement, drawing on disciplines like spatiotemporal modeling, statistical analysis, and machine learning. A spatiotemporal metric provides a quantitative measure that combines spatial coordinates and temporal data into a single value, capturing movement across both dimensions. Techniques like Dynamic Time Warping (DTW) align temporal sequences to identify similarities, even when the sequences are not perfectly synchronized. The Hausdorff Distance calculates the maximum spatial separation between points on two trajectories, offering a measure of spatial similarity. These metrics facilitate the meaningful analysis of complex movement data. Advanced modeling techniques like Hidden Markov Models and Gaussian Process Regression allow researchers to capture patterns and predict future states in spatiotemporal data. These models are beneficial in environments with irregular or abrupt changes in movement paths.

Meanwhile, machine learning approaches, including sequence modeling with Recurrent Neural Networks, enable the analysis of extensive spatiotemporal datasets, uncovering intricate trajectory patterns. Another option is to apply

fitted 2D Gaussian distributions and quantify the differences between the clusters by Kullback-Leibler divergence (KL-divergence; Cover & Thomas, 1991; Kullback & Leibler, 1951), as it is more closely described below. In this metric, a higher value implies increasing differences among compared clusters.

The ability to analyze trajectories through combined spatial and temporal metrics has diverse applications. In ecology, it aids in understanding animal migration and habitat use. Urban planning benefits from analyzing pedestrian and vehicular traffic to optimize infrastructure—sports analytics leverages trajectory data to assess player tactics, training needs, and performance. In epidemiology, movement mapping assists in tracking infection spread among individuals or populations. These applications demonstrate the necessity of methods that seamlessly integrate spatial and temporal dimensions, ensuring precise and granular analysis. The analysis of spatiotemporal trajectories remains an active research area, as traditional methods that treat space and time independently prove insufficient for complex movement patterns. Researchers unlock more profound insights into movement dynamics by advancing techniques that unify spatial and temporal data with profound implications for science, technology, and policy.

## Methodology

The data for the follow-up analysis was generated by the Pathfinder ABEM simulation tool. The simulations were based on the data collected within the study of Juřík and colleagues (2023); the details are presented in the chapter “Virtual Simulations in AI Domain – Agent-based Modeling” of this thesis.

The data consists of three samples of spatiotemporal evacuation trajectories of agents' movements within a building. The agent movement was the result of an agent-based simulation; however, the movement parameters for two of the three samples were based on real observations of evacuation behavior in a real building (real environment – labeled as RE) and a virtual building (virtual environment – labeled as VE), respectively (see chapter “Virtual Simulations in AI Domain – Agent-based Modeling”). This process brings RE and VE simulations, including the HITL (Human-in-the-Loop) principle, for refining the agent-based simulation process. The third sample labeled DEF represents the default agent-based simulation. For follow-up analysis regarding significant differences in participants using a retracing strategy (Snopková et al., 2022; 2023; Juřík et al., 2023), the data are further organized into three subsequent groups labeled as:

- Retracing (labeled as RA)— Captures participants who retraced their steps during the evacuation task (it means they left the building by the exit they came in).
- No Retracing (labeled as RN)— Focuses on participants who completed the evacuation task without retracing their steps.
- All Data — Includes the trajectories from all simulations (VE and RE) regardless of whether the participant retraced their steps.

This allowed for making five specific groups of agent trajectories, differing based on the condition under which the simulation was conducted.

- DEF – trajectories generated based on default Pathfinder ABEM simulation without any human engagement
- VE-RA – trajectories generated based on the ABEM simulation were refined by human evacuation behaviors observed in the virtual simulation experiment, including retracing cases.
- VE-RN – trajectories were generated based on the ABEM simulation, refined by human evacuation behaviors observed in the virtual simulation experiment, excluding retracing cases.
- RE-RA – trajectories generated based on the ABEM simulation, refined by human evacuation behaviors observed in the physical simulation experiment, including retracing cases.
- RE-RN – trajectories generated based on the ABEM simulation were refined by human evacuation behaviors observed in the physical simulation experiment, excluding retracing cases.

This allowed for a comparative study of agent behaviors. Each group is analyzed using fitted 2D Gaussian distributions, and Kullback-Leibler divergence (KL-divergence; Cover & Thomas, 1991; Kullback & Leibler, 1951) is applied to quantify the differences between the clusters. Each group was further divided into clusters, representing distinct behavioral patterns. The DEF cluster represents a specific group of trajectories generated in the default Pathfinder simulation setting. DEF sample, considered a basic simulation cluster, is being compared against other clusters generated based

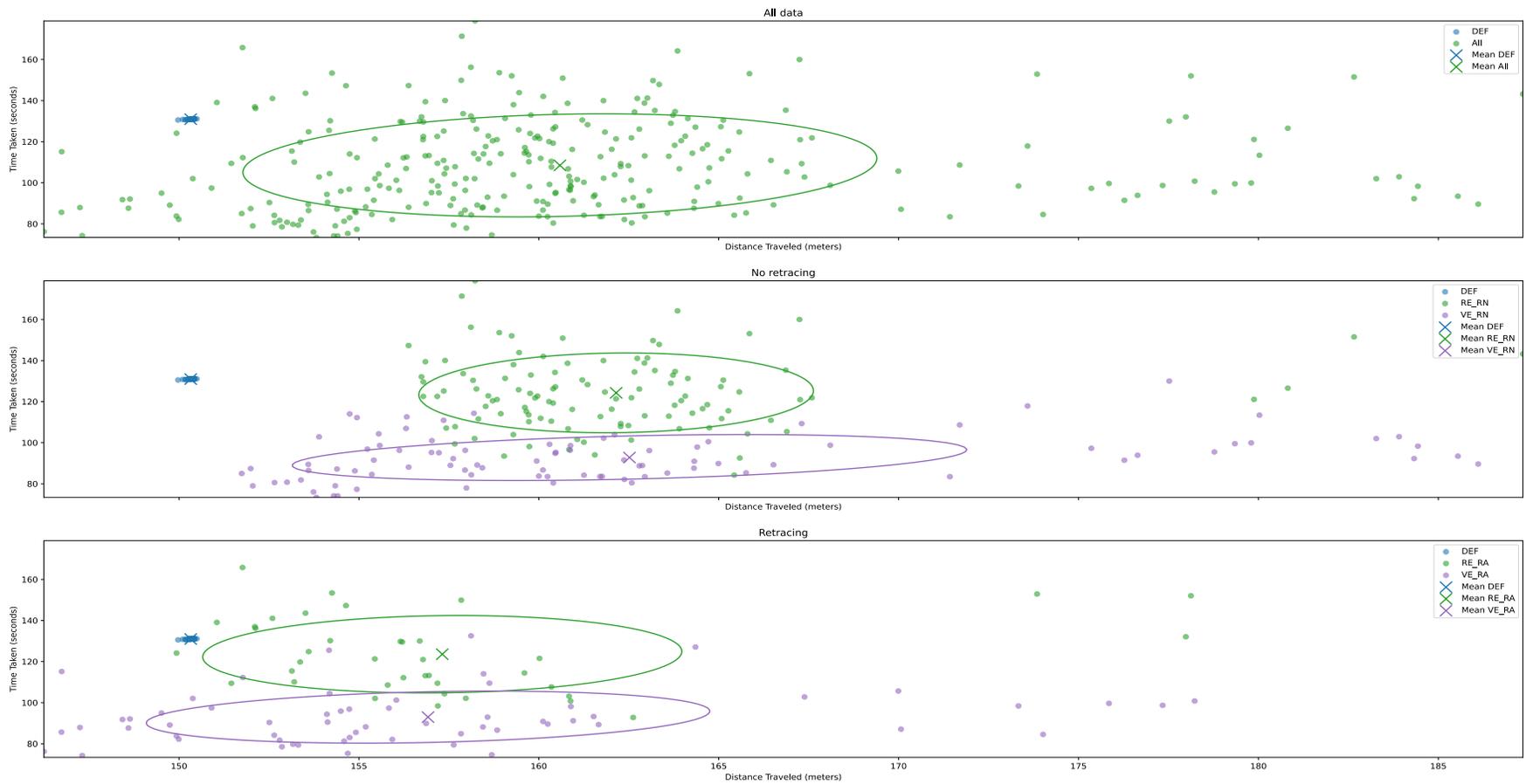
on RE and VE human-engaged measures. Gaussian distributions were fitted to the data to visualize the spread and concentration of the trajectory points. At the same time, KL-divergence was used to measure the dissimilarity between the behavior of different clusters. This combination of visual and quantitative analysis provides comprehensive insights into evacuation behaviors. Data was analyzed using Python version 3.9 (Python Software Foundation, n.d.).

## Results

Data distribution is depicted in Figure 31.

### **Figure 31**

*The data distribution of the spatiotemporal trajectories of agent movements during building evacuation*



*Note.* Retracing group (RA) – down; no retracing (RN) - middle; all data from RA and RN mixed (All) – top). The graph depicts trajectories as the results of ABEM simulation, which was based on the default setting of the simulation tool (DEF) and further based on the HITL-based input from real evacuation (RE) and virtual evacuation (VE).

Analysis was conducted regarding individual groups. The results of the analysis are summarized in Table 2.

**Table 2**

*KL-divergence for clusters of the agent-based evacuation simulations*

KL-divergence between DEF and All	9.875769171346054	All data
KL-divergence between DEF and RE_RN	10.579847043918507	No retracing
KL-divergence between DEF and VE_RN	17.33449306312368	No retracing
KL-divergence between DEF and RE_RA	8.569160533287105	Retracing
KL-divergence between DEF and VE_RA	13.409436128147703	Retracing

*Note.* KL-divergence provides a rigorous measure of the relative difference between clusters of the agent-based evacuation simulation.

The Data presented in Table 2 indicated the range of KL-divergence values from 8.57 to 17.34. Zero KL-divergence speaks for the similarity of distributions; increasing values demonstrate the increasing differences between evaluated distributions, as seen below.

Zero KL-Divergence

$$(D_{KL} (P \parallel Q) = 0)$$

indicates that Q perfectly matches P. There is no divergence between the two distributions.

Positive KL-Divergence

$$(D_{KL}(P \parallel Q) > 0)$$

shows that Q differs from P. The larger the KL-divergence, the more Q diverges from P.

These metrics allow for relative comparison of the similarity of individual samples. The individual comparisons are presented below.

#### *All Data Sample comparison*

*All Data* sample (labeled as All) consists of all provided trajectories from simulations based on VE and RE measures, regardless of retracing. The DEF model trajectories cluster and All human-based trajectories (VE and RE) clusters were compared. This comparison highlights the general distribution of all agents' trajectory behaviors. The scatter plot shows the distance traveled and time taken for each participant, with Gaussian contours providing a visual representation of how the data is distributed within each cluster.

The comparison of the central tendencies of the DEF and All clusters reveals differences in the agents' average behavior, with the means providing a clear indication of the typical evacuation patterns in each group. The KL-divergence between these clusters, calculated as 9.88, indicates a notable distinction between the behaviors of the DEF simulation and the overall agent pool. This divergence value provides a numerical measure of the behavioral uniqueness of the DEF group, with higher values signifying greater dissimilarity.

### *No Retracing Sample comparisons*

The sample labeled as *No Retracing (RN)* contains trajectories that completed the evacuation without retracing their steps. These trajectories were further categorized into three clusters, DEF, RE\_RN, and VE\_RN, based on the origin of input data (i.e., from real or virtual simulation). The fitted Gaussian distributions for these clusters show how agents are spread in the distance-time space. Each cluster's central tendency, represented by the cluster mean, offers insight into the typical behavior of agents within each group.

- The KL-divergence between the DEF and RE\_RN clusters is 10.58, suggesting a considerable behavioral variation between these groups.
- The KL-divergence between the DEF and VE\_RN clusters is 17.33, indicating an even more considerable difference in behavior patterns. This higher value implies that agents in the VE\_RN group exhibit markedly different trajectory behaviors compared to the DEF group.

These divergence values help quantify the extent to which agents' behaviors differ regarding trajectory patterns, providing a deeper insight into RE and VE HITL-based simulations.

### *Retracing Sample comparisons*

Agents who engaged in retracing sought the exit through which they entered the building during the evacuation. The three clusters in this group are DEF, RE\_RA, and VE\_RA. As in the previous case, Gaussian distributions

were fitted to visualize how agents are distributed across the distance-time space. The central tendencies of the clusters offer insights into the typical evacuation behaviors of the agents.

- The KL-divergence between the DEF and RE\_RA clusters is 8.57, reflecting a moderate difference between these groups.
- The KL-divergence between the DEF and VE\_RA clusters is 13.41, indicating a relatively higher degree of dissimilarity between these groups.

These divergence values suggest that agents who engage in retracing strategy exhibit more varied behaviors than the DEF group, especially in the VE\_RA cluster, which shows a larger divergence.

## Conclusions

The above-reported study demonstrates the analysis of spatiotemporal trajectories generated from agent-based evacuation models based on real and virtual evacuation simulations, providing further insight into using virtual simulation for agent-based modeling. The fitted 2D Gaussian distributions across the analyzed samples provide valuable insights into how agents' behaviors are distributed under various simulation conditions. The DEF group exhibits distinctive behavioral patterns in all cases compared to other clusters. The KL-divergence values further quantify the extent of these differences, with higher divergence values indicating greater dissimilarity.

The analysis reveals that agents based on the data from participants who did not engage in the retracing strategy tend to have more varied behaviors, as indicated by the higher divergence values in the No Retracing group compared to the default simulation setting (DEF). In contrast, the Retracing group shows moderate variation, but agents in the virtual-based retracing group (VE\_RA) cluster exhibit considerably different behavior than the DEF group.

The use of Gaussian contour plots and KL-divergence enables both a visual and quantitative understanding of participant behaviors. The central tendencies highlighted by the cluster offer a clear picture of typical behaviors within each group. At the same time, the broader spread of the data points and KL-divergence values provide insights into the diversity and variation of behaviors.

Based on agents' trajectory data, this analysis of evacuation behavior offers a comprehensive understanding of how navigation during emergencies can be predicted with a higher level of ecological validity. The above-provided categorization of data to All Data, No Retracing, and Retracing samples in combination with Gaussian contour plots and KL-divergence offers visual and numerical insights into agent-based simulation based on virtual and physical simulation inputs. These insights can be valuable for improving methodologies for researching evacuation strategies and understanding human crisis behavior.

## Part IV – Concluding Commentary

## Summary and Conclusion

Like many scientific disciplines, the field of psychology is being revolutionized by modern technologies, including immersive virtual simulations as one of the most promising directions for psychological research and application. This thesis has aimed to comprehensively analyze the potential of human-centered simulations, specifically those that employ immersive virtual reality, and their applications within psychological research and practice. The findings from this work have shown that IVR is not only a viable tool for psychological experiments but also presents innovative avenues for addressing key methodological and theoretical challenges the field faces. This conclusion will summarize and expand on the core contributions, discussing how each aim has been fulfilled and reflecting on future directions while integrating empirical evidence and theoretical discussions.

## Objectives and their Fulfillment

This thesis highlighted the role of immersive virtual reality across various disciplines, particularly emphasizing its integration into psychological research and applications. The work provided a comprehensive theoretical framework for understanding the use of first-person POV virtual simulations in psychology, emphasizing their ability to create ecologically valid, safe, and controllable experimental contexts. The thesis critically evaluated key research domains central to the author's recent work by exploring the interconnections between environment-mind research and virtual simulations. This thesis has

demonstrated the immense potential of immersive virtual simulations in psychological research and applications. The work has offered novel insights into the topic by developing a theoretical framework for human-centered simulations, integrating machine learning with virtual environments, and critically evaluating empirical evidence. Virtual simulations offer a solution to the long-standing methodological challenges in psychology, such as the control-validity tradeoff, and provide new opportunities for replicable, ethical, and ecologically valid research. The practical applications of virtual simulations in education and therapy further emphasize their versatility and impact. As virtual reality technology evolves, its applications in psychology will likely expand, offering new research, therapy, and education possibilities.

One of the primary objectives of this thesis was to (1) establish a theoretical framework for human-centered simulations, with a particular emphasis on immersive virtual simulations. The term "human-centered" refers to simulations that focus on human behavior (Rybing, 2018), cognitive processes, and decision-making within a controlled yet dynamically interactive environment. The thesis has successfully created this framework, highlighting how virtual simulations can serve as a bridge between traditional mental and physical simulations. This is particularly relevant in psychology, where the replication of real-world scenarios in a controlled yet interactive environment has long been sought after.

The framework of the thesis (2) offered and discussed novel perspectives on cognitive processes in the human mind, emphasizing the significance of

simulation as a mechanism employed among current theories of human cognition, such as predictive processing (Clark, 2015).

Immersive virtual simulations, by enabling direct interaction between the environment and the human mind (3), were, on the theoretical level, found to provide the necessary platform to test complex psychological hypotheses within an ecologically valid setup. One of the significant challenges in psychological research has been resolving the control-validity tradeoff, where highly controlled experimental settings often sacrifice ecological validity (Juřík et al., 2018; Juřík et al., 2019; Loomis et al., 1999). This thesis argues, with compelling evidence, that IVR bridges this gap effectively. Virtual simulations allow researchers to create realistic, complex environments that are fully controllable and customizable, thus offering a high degree of experimental control and ecological validity. This feature is particularly beneficial for psychological studies investigating behaviors that are difficult to replicate in laboratory settings due to ethical or practical constraints (Juřík et al., 2021). For instance, in social psychology, IVS allows researchers to create dynamic social interactions that would be difficult to model using traditional experimental methods. A notable example discussed in the thesis is virtual reality exposure therapy (VRET), which is already used to treat anxiety disorders, phobias, and PTSD. Virtual simulations expose patients to their fears in a controlled, safe, and customizable environment, offering new therapeutic approaches to psychological interventions (Varšová et al., 2024). The thesis also highlights the role of IVR in cognitive-behavioral therapies, where virtual simulations offer opportunities to manipulate specific variables while maintaining ecological

validity, thus enabling more accurate assessments of cognitive and emotional responses (Juřík et al., 2024). The empirical evidence in PART III of this thesis partially supported this perspective.

Empirical evidence represented by the author's studies on virtual reality within psychological research and applications in PART III was (4) critically evaluated and reflected, providing novel commentary and insights into each research direction. A notable example discussed in the thesis is virtual reality exposure therapy (VRET), which is already used to treat anxiety disorders, phobias, and PTSD. Virtual simulations expose patients to their fears in a controlled, safe, and customizable environment, offering new therapeutic approaches to psychological interventions (Varšová et al., 2024a). The thesis highlights the role of IVR in cognitive-behavioral therapies, where virtual simulations offer opportunities to manipulate specific variables while maintaining ecological validity, thus enabling more accurate assessments of cognitive and emotional responses (Juřík et al., 2024). The ability to tailor virtual environments to specific therapeutic needs, such as phobia treatment or trauma recovery, makes IVR a flexible and versatile tool in clinical psychology. Furthermore, the thesis discusses how virtual simulations can be integrated for psychotherapeutic purposes, where patients can interact with AI-driven agents that respond to their behavior in real-time, offering a new dimension to therapeutic interventions (Juřík et al., 2023). This fusion of virtual simulations and AI offers a future in which psychological treatments are more personalized, adaptable, and accessible to a broader range of individuals.

An important contribution of this thesis is the emphasis on the potential of virtual simulations to enhance the replicability of psychological experiments. Replicability, a pressing issue in psychology, particularly social and cognitive psychology, benefits significantly from using virtual simulations. Traditional experimental methods often face challenges in replicability due to subtle variations in participant behavior, environmental conditions, and researcher biases. Virtual simulations mitigate these issues by providing a highly controlled environment where every variable can be precisely defined and replicated across studies, as it was discussed by Chocholáčková and her colleagues (2023) and Šikl and his colleagues (2024). The ability to create tailored and potentially identical experimental setups in virtual simulations across different research laboratories worldwide may facilitate cross-cultural studies and collaborative research efforts; however, the specific cognitive mechanisms occurring in IVR compared to the real world should be further studied and compared.

The thesis has also commented on innovative empirical applications of virtual simulations, particularly machine learning (ML) integration into psychological research. By combining immersive virtual simulations with ML, the thesis advances the field of psychology by enabling real-time adaptive simulations that respond to participants' behavior. This approach, which can be here labeled as the human-in-the-loop (HITL) principle (Narayanan & Kidambi, 2011), allows for more interactive and dynamic experimental setups that can adjust to participants' decisions and behaviors in real-time, enhancing the ecological validity of the experiments while maintaining high levels of control

(Rybing, 2018). The thesis provides a detailed discussion of how ML can be applied within virtual simulations to model complex human behaviors, such as evacuation scenarios. In the study of Juřík and his colleagues (2023) and Snopková and her colleagues (2022), IVS is demonstrated to improve understanding of human decision-making under stress, offering valuable insights into evacuation behavior during emergencies. Applying agent-based modeling in this context showcases how virtual simulations can generate large-scale behavioral data, which can be analyzed using machine learning algorithms to detect patterns, predict outcomes, and refine psychological theories (Juřík et al., 2023).

Finally, (5) a new research insight in human evacuation modeling by linking the field of IVS and ABEM (broader ML) was presented in PART III of this thesis, representing a genuine analysis of the above-discussed data. This analysis aimed to assess and compare specific spatiotemporal trajectories of agent behaviors during evacuation scenarios using data from three types of simulations: real data-based simulations, virtual data-based simulations, and simulations conducted under the default Pathfinder settings (artificial agents). This analysis aimed to move beyond total evacuation time as a sole measure by examining the distance traveled and time taken to complete evacuation tasks. The study sought to understand individual navigation during emergencies, evaluate behavioral patterns, and identify suitable simulation strategies or models for improved evacuation modeling and planning. The fitted 2D Gaussian distributions and KL-divergence (Cover & Thomas, 1991; Kullback & Leibler, 1951) analyses reveal distinct behavioral patterns

among the three data clusters (real-based simulation, VR-based simulation, and default setting simulation). The DEF group (default simulation setting) consistently demonstrates unique behaviors compared to other clusters, as confirmed by higher KL-divergence values, indicating more significant dissimilarity. Observations in the No Retracing cluster exhibit the most varied behaviors, while those in the Retracing cluster show moderate variation. The retracing agents' cluster stands out for its significantly different behaviors than the DEF group. Gaussian contour plots and KL-divergence provide complementary visual and quantitative perspectives on behavior. Cluster means clarify typical group behaviors, while data spread and divergence values highlight behavioral diversity. This comprehensive analysis of participant trajectories enhances understanding and possible directions in the simulation of evacuation behaviors during emergencies. This interdisciplinary approach, merging psychology with ML, contributes to a more nuanced understanding of human behavior and opens new research avenues in cognitive science, behavioral economics, and social psychology. In this context, using HITL-based simulations offers a promising future direction for research that requires adaptive and dynamic environments, which traditional experimental methods cannot quickly provide.

## Ethical Considerations and Future Directions

Integrating immersive virtual simulations into psychological research and practice presents transformative opportunities but raises significant ethical considerations. These concerns are particularly critical given immersive virtual

reality (IVR) 's heightened emotional and physiological impact on participants. While this thesis has briefly addressed issues related to the psychological well-being (Jeral, 2015; Gallagher & Ferrè, 2018) of participants and data privacy, the topic warrants more profound exploration and further research.

The immersive nature of IVR offers unparalleled opportunities for simulating realistic scenarios, enabling researchers and practitioners to study behaviors and therapeutic responses in controlled environments. However, this same immersion can evoke intense emotional and physiological reactions. Participants may experience distress, anxiety, or other unintended psychological consequences, especially in scenarios involving emotionally charged or traumatic content. For example, therapeutic applications targeting individuals with post-traumatic stress disorder (PTSD) often involve exposure to stimuli designed to trigger symptoms as part of the intervention (Maples-Keller et al., 2017). While such applications hold significant therapeutic promise, they also risk exacerbating psychological conditions if not carefully managed. Ensuring participants' emotional safety and well-being is paramount in developing and applying IVR technologies.

In addition to psychological concerns, IVR raises important questions about data privacy and confidentiality. These systems often collect extensive data, including biometric information, behavioral patterns, and interaction metrics. While such data is invaluable for research and therapeutic purposes, it poses risks if mishandled or accessed without proper authorization. Ensuring secure storage, processing, and sharing of this data is essential to protect participant

confidentiality and comply with ethical and legal standards. Moreover, as IVR becomes increasingly integrated with artificial intelligence and machine learning (Pešán et al., 2024), new questions emerge about informed consent and how participants know how their data will be used during and after the research or therapeutic process.

To address these challenges, transparent and robust ethical guidelines are essential. These guidelines should govern the design, implementation, and evaluation of IVR systems, ensuring participants are fully informed about potential risks and benefits and have the option to withdraw without negative consequences. Safeguards must include thorough risk assessments to evaluate the psychological impact of IVR scenarios, participant screening to identify those who may be particularly vulnerable, debriefing procedures to help participants process their experiences, and robust data security measures to protect sensitive information.

The ethical implications of IVR remain an emerging area of study, and much work is needed to understand and address these challenges better. Future research should focus on investigating the long-term psychological impact of IVR, developing comprehensive ethical frameworks tailored to its applications, and exploring how participants perceive the risks and benefits associated with immersive simulations. Additionally, as IVR technology continues to evolve with enhanced realism and artificial intelligence integration, novel ethical challenges will likely arise, requiring ongoing evaluation and adaptation of ethical standards.

While immersive virtual simulations hold immense potential to advance psychological research and practice, their use must be approached carefully, considering their ethical implications. The field can responsibly harness IVR's power while safeguarding participants' rights and dignity by prioritizing participant well-being, ensuring data privacy, and developing robust ethical guidelines. This thesis underscores the importance of continued research and dialogue in this area, providing a foundation for future explorations into the ethical dimensions of IVR technology.

The future of virtual simulations in psychology is promising and dynamic, fueled by the interdisciplinary convergence of psychology, computer science, artificial intelligence, and neuroscience. This synergy offers vast and ever-evolving possibilities for research and application. As virtual simulation technology advances, its potential to transform psychological research and practice will depend on addressing key areas for development and exploration. One critical avenue for future research lies in refining the integration of immersive virtual reality (IVR) with machine learning to create more sophisticated and adaptive simulations. These systems could tailor experiences to individual needs in real-time, enhancing therapeutic and educational interventions. For example, adaptive simulations could respond dynamically to participant behavior, offering personalized therapeutic stimuli or adjusting educational content to optimize learning outcomes. Such advancements would significantly enhance the efficacy and accessibility of IVR-based interventions. The systems interconnecting agent-based avatar movement in virtual simulation with the real human user, who can, in time, interact with the

simulation, is investigated by researchers at Masaryk University and Brno University of Technology<sup>8</sup>.

Longitudinal studies represent another crucial area for future investigation. While IVR has shown promise in short-term therapeutic and educational contexts, its long-term effects (regarding its only recent existence) remain widely underexplored. Understanding how IVR-based interventions influence participants over extended periods is essential for assessing their sustainability, potential risks, and cumulative benefits. These studies could also provide insights into how repeated or prolonged exposure to virtual environments affects cognitive, emotional, and behavioral outcomes. As virtual simulations become increasingly widespread, cross-cultural research will also be vital. Different cultural contexts may shape how individuals perceive, interact with, and benefit from virtual simulations. By leveraging the unique ability of IVR to replicate identical virtual environments across research laboratories worldwide, psychologists can engage in collaborative cross-cultural studies. Such efforts could foster a global understanding of human behavior, uncovering universal patterns and culturally specific nuances. These findings would enhance the applicability of virtual simulations across diverse populations and contribute to the development of culturally sensitive psychological interventions. Furthermore, the interdisciplinary nature of virtual simulations opens doors to collaborative innovations in related fields.

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<sup>8</sup> Vojtěch Juřík is the co-principal investigator of the above mentioned project funded by the Technology Agency of the Czech Republic entitled "Virtual environment for presentation of outputs of mathematical models of movement of persons" (FW06010581).

For instance, incorporating insights from neuroscience could deepen our understanding of how virtual environments influence brain function and behavior, while advancements in artificial intelligence could enable simulations to become increasingly realistic and intuitive.

In conclusion, the future of virtual simulations in psychology holds immense potential. By focusing on adaptive technologies, long-term effects, and cross-cultural applicability, researchers and practitioners can harness the full capabilities of IVR to address complex psychological challenges. The ability to create standardized virtual environments for global research represents a groundbreaking opportunity for collaboration, driving forward a more comprehensive and inclusive understanding of human behavior. This thesis underscores the importance of continued innovation and interdisciplinary research in shaping the future of virtual simulations in psychology.

# List of the Most Important Abbreviations

ABEM – Agent-based Evacuation Modeling

AI – Artificial Intelligence

ANOVA – Analysis of Variance

BIM – Building Information Model

CBT – Cognitive Behavioral Therapy

CIVE – Collaborative Immersive Virtual Environment

KL-divergence - Kullback-Leibler divergence

GLM - Generalized Linear Modeling

HITL – Human-in-the-loop

HMD – Head Mounted Display

HR – Heart Rate

HRV – Heart Rate Variability

IVE – Immersive Virtual Environment

IVR – Immersive Virtual Reality

IVS – Immersive Virtual Simulation

ML – Machine Learning

VE – Virtual Environment

VR – Virtual Reality

VRET – Virtual Reality Exposure Therapy

VS – Virtual Simulation

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