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Hierarchy of Cognitive Models for Multimodal Virtual Space Representation

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Abstract: The article investigates cognitive models of virtual reality space representation as a highly immersive computer-generated environment. The study aims to identify and describe the hierarchical structure of cognitive models underlying multimodal perception and comprehension of virtual reality space, as well as to establish general and modality-specific patterns of its representation. The relevance of the study is determined by the insufficient integration of verbal and visual representations into existing research. The methodological framework is based on the cognitive modeling of experimental data obtained from 20 participants who performed perception and representation tasks within a specially designed virtual reality environment. The verbal representations were analyzed with the multimodal annotation method, and with the tools of the Semograph IS, SciVi, and AntConc, while visual representations were processed using Creative Maps Studio followed by the Python-based analysis. The results revealed the multi-level system of cognitive models. The first level comprises verbal and illustrative models reflecting linear and configurational strategies of spatial representation. The higher level is a cognitive model, integrating both modalities and identifying stable cognitive patterns, including cyclic sequences, action coupling, and a transition from general to specific. In addition, a communicative-cognitive meta-level was identified, demonstrating the influence of interaction parameters of spatial experience organization. Thus, the virtual reality space representation is interpreted as a hierarchical multimodal and communicatively conditioned system.

Keywords: virtual reality space, cognitive models, verbal representations, visual representations, multimodal modeling, mental maps, integral cognitive model, communicative cognitive model

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оригинальная статья

Иерархия когнитивных моделей мультимодальной репрезентации виртуального пространства

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Аннотация: В статье исследуются когнитивные модели репрезентации пространства виртуальной реальности (VR) как высокоиммерсивной компьютерно-генерируемой среды. Цель – выявить и описать иерархическую структуру когнитивных моделей, обеспечивающих мультимодальное восприятие и осмысление VR-пространства, а также установить общие и модально-специфические закономерности его репрезентации. Актуальность исследования обусловлена недостаточной интеграцией вербальных и визуальных репрезентаций в существующих работах. Методологической основой является когнитивное моделирование экспериментальных данных, полученных от 20 информантов, выполнявших задания по восприятию и мультимодальной репрезентации (вербальной и визуальной) специально смоделированного VR-пространства. Вербальные репрезентации анализировались с применением мультимодальной разметки и инструментов ИС «Семограф», SciVi и AntConc, а визуальные – с использованием Creative Maps Studio и последующей обработки в Python. Результаты выявили многоуровневую систему когнитивных моделей. Первый уровень включает вербальные и иллюстративные модели, отражающие линейные и конфигурационные стратегии пространственной репрезентации. Над ними формируется интегральная когнитивная модель, объединяющая обе модальности и выявляющая устойчивые когнитивные паттерны (цикличность, сопряженность действий, переход от общего к частному). Также выделен коммуникативно-когнитивный метауровень, демонстрирующий влияние параметров взаимодействия на организацию пространственного опыта. Репрезентация VR-пространства интерпретируется как иерархическая, мультимодальная и коммуникативно обусловленная система.

Ключевые слова: VR-пространство, когнитивные модели, вербальные репрезентации, визуальные репрезентации, мультимодальное моделирование, ментальные карты, интегральная когнитивная модель, коммуникативно-когнитивная модель

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Introduction

This paper analyzes representations of a virtual reality (VR) space, understood as a computer-generated immersive environment mediated by specialized interfaces, differing from physical space in a number of cognitive and communicative parameters [Austermann et al. 2025; Peixoto et al. 2021; Rocabado et al. 2025; Schütze 2024; Slater et al. 2022; Velichkovsky et al. 2016]. These features form specific conditions for the representation of spatial experience allowing us to consider VR space as an independent object of linguistic and cognitive analysis. In linguistics, space is interpreted as a cognitive system of subject orientation, where the reference point, perspective, and ways of structuring the environment play a key role [Apresyan 1986; Fillmore 1975; Levinson 2003]. On this basis, the cognitive foundations of spatial experience representation are formed. These include deictic mechanisms (the position of objects relative to the speaker) [Fillmore 1975; Levinson 2003], pictorial strategies (visual-spatial characteristics and figurative schemes) [Grudeva 2021; Mandler, Pagán Cánovas 2014], dynamic processes (movement and change of perspective) [Lansdale 1998; Lansdale et al. 2013; Taleski, Burlaka 2025], and computational operations (formalization of spatial relations) [Povetkina 2012; Sun 2008]. In this work, these foundations are considered as manifestation forms of a single cognitive organization that create stable cognitive schemes.

The identification of such patterns is accomplished through cognitive modeling, which can reconstruct the hidden processes of perception, memory, and thought based on observed data and their representation as analytical models. This approach allows us to consider spatial representations as hierarchically organized cognitive structures that differ in perspective, format, and the level of processing [Chomsky 2006; Povetkina 2012; Sun 2008].

In cognitive science, a distinction is made between egocentric representations, which relate objects to the observer's position, and allocentric representations, which present relationships between objects independently of the subject [Levinson 2003]. Based on their organizational method, a distinction is made between metric and topological representations, which in actual cognitive functioning are combined and adapted for orientation and navigation tasks [Saveleva et al. 2023; Tversky 1993]. In terms of representation format, space can be presented visually (in the form of mental maps) [Tversky 1993; Zelyanskaya et al. 2016] and verbally (in the form of texts and narratives) [Taleski, Burlaka 2025] with an active interaction between these formats. Additionally, kinesthetic and motor representations are distinguished, as well as multimodal and conceptual representations that integrate various sensory channels and abstract schemas [Kushnir et al. 2024; Luchinkina 2024]. This paper analyzes the processes of representing space in two modalities – verbal and visual (illustrative). Verbal representations, possessing a linear and temporal organization, reflect spatial description strategies, including the distribution of attention, hierarchy, and connections between objects [Ozhereleva 2019]. Illustrative representations have a synthetic nature and convey configurational and topological relationships between objects, serving as a means of reconstructing mental maps and spatial schemes [Mandler, Pagán Cánovas 2014; Stea 2017; Tversky 1993; Zelyanskaya et al. 2016].

Despite a well-developed theoretical framework, verbal and illustrative representations of VR space are often considered in isolation, making it difficult to identify holistic cognitive mechanisms and their interactions. In this regard, the structural approach based on hierarchical cognitive modeling of multimodal representations of VR space is particularly relevant. Combining verbal and visual data allows us to consider cognitive models as elements of a single multi-level system, where deictic, pictorial, dynamic, and computational components are interconnected and mutually complementary. This approach is consistent with the concept of the integration of mental spaces [Fauconnier 1994], multimodal analysis of cognitive representations [Taleski, Burlaka 2025; Wang 2017], and studies of the hierarchical organization of cognitive models in spatial narratives and illustrative representations [Grudeva 2021].

The aim of the study is to identify and describe the hierarchical structure of cognitive models underlying the multimodal representation of VR space, as well as to establish general and modality-specific patterns of its perception and reconstruction depending on cognitive, perceptual, and communicative parameters. The study hypothesis is that the architecture of this structure is not formed only by the representation channel but also by a complex of determinants, including the parameters of the communicative situation. Achieving this goal and testing this hypothesis require a comprehensive experimental study and formalized cognitive modeling procedures that allow us to examine verbal and illustrative representations of VR space under controlled conditions.

Methods and materials

The study is based on a three-stage experiment, the general structure and parameters of which are described in detail in [Taleski, Burlaka 2025]. This article presents only the key points necessary for results interpretation.

Twenty people participated in the experiment. During the first stage, they interacted with a specially simulated VR platform within a VR setup implemented with the Unreal game engine (fig. 1). The VR platform presented a café interior having three scenes and a set of standard reference objects, a virtual interlocutor (avatar), and specified communicative parameters, such as the scene type (personally oriented or spatially oriented), the position of the communicants (face-to-face, interlocutor behind the speaker, interlocutor next to the speaker), the delineation of internal

Fig. 1. Simulated VR platform based on the Unreal game engine
Рис. 1. Смоделированная VR-платформа на базе игрового движка Unreal Engine

and external communication spaces, and the presence of reference points within or outside the participants' field of view. The main task of this stage was to follow the avatar's instructions, presented in the form of verbal cues. Based on the scene structure and the cues, 40 zones of interest were identified, corresponding to specific reference points in the VR space. The cues included egocentric, allocentric, and geocentric reference points [Bryant 1992; Levinson 2003] used for navigation and pointing to objects in the VR environment. The scene parameters and the set of cues were borrowed from [Taleski 2024] and adapted for this study in accordance with its objectives.

The second stage of the experiment began after the first one, during which the perceived VR space was recorded. Participants were divided into two equal groups (10 people each). The first group created verbal representations of the VR space in the form of oral narratives, while the second created illustrative representations in the form of mental maps (fig. 2). Instructions for the second stage were presented only after the first stage, which reduced the influence of conscious control on the participants' behavior.

Thus, the study material consisted of 20 representations of the virtual space obtained in the second stage of the experiment (10 verbal texts and 10 mental maps). 1,575 text units identified in the verbal representations,

a b

Fig. 2. Verbal and illustrative representations of VR space: a) fragment of an oral story; b) fragment of an illustration (mental map)
Рис. 2. Вербальная и иллюстративная репрезентации VR-пространства: а) фрагмент устного рассказа; б) фрагмент иллюстрации (ментальная карта)

as well as 5,920 operations and actions recorded during the process of creating illustrations were taken as analysis units.

The obtained data were subjected to a comprehensive analysis using a number of analytical tools. Verbal representations were recorded (fig. 2a) and tagged multimodally in the Semograph information system [Belousov et al. 2017], which ensures the synchronization of verbal and nonverbal communication components. Within the tagging, syntagmas with spatial semantics were identified, for example: *on the left (слева), along the window (вдоль окна), next to tables (рядом со столами),* and then they were used for convergent data processing. Processing was carried out using SciVi software [Ryabinin et al. 2017] for identifying and visualizing sequential patterns in the form of interactive graphs, AntConc for frequency analysis of lexemes and distribution of keywords throughout the text, as well as Python tools (NLTK, pandas) for tokenization, bigram frequency counting, statistical processing, and data visualization.

Illustrative representations were created in Creative Maps Studio, a cognitive graphics editor designed for constructing and analyzing digital mental maps [Chumakov et al. 2021]. In addition to the editor's capabilities for correlating reference points with their textual occurrences, additional data processing procedures in the Python environment were employed. These included extracting object bigrams from illustrative representations (NLTK, Counter), calculating frequency links, analyzing coordinate and visual parameters of objects (position, size, transparency), and vector analysis aimed at calculating structural characteristics, such as the density of the reference points, compositional patterns, and the dynamics of object interactions.

This comprehensive analysis leads to the construction of cognitive models. The overall experimental design is presented schematically in figure 3.

Results

As a result of the experimental analysis, a hierarchy of cognitive models for the multimodal representation of VR space was created. The processes of comprehension, reproduction, and reconstruction of VR space are organized not as a set of isolated mechanisms, but as a multi-level system of cognitive models differing in modality, functional focus, and the level of abstraction.

The first level of the hierarchy (fig. 4) of cognitive models for representing VR space is determined by the modality of spatial experience and includes verbal and illustrative models. This modality distinction reflects differences in the methods of encoding, structuring, and updating the spatial information, as well as in the methods of cognitive operations involved in their reproduction.

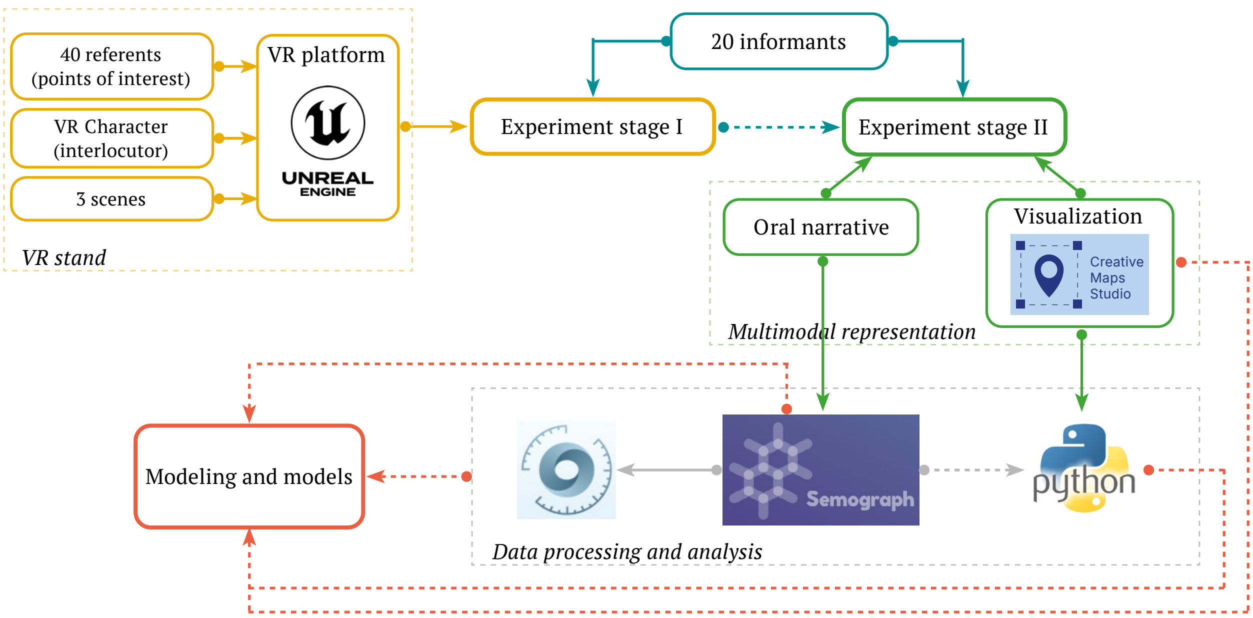

Fig. 3. Schematic representation of the experimental design
Рис. 3. Схематическое представление дизайна эксперимента

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Verbal cognitive models of VR space representation are formed through the linear, temporally organized linguistic description. They rely on the sequential distribution of attention, the hierarchy of objects, and the explication of spatial relationships by linguistic means. The space is reconstructed as a chain of cognitive foci linked by deictic, relational, and evaluative parameters, allowing us to identify the spatial description strategies, including the choice of reference point, perspective shifts, and methods for grouping landmarks. The verbal data analysis reveals several stable types of cognitive models reflecting various aspects of spatial and mental experience: deictic, pictorial, static, and dynamic models directly related to spatial organization, as well as mental models that mediate spatial experience through the subject's cognitive and emotional reactions. A separate group consists of computational models that capture the quantitative and statistical characteristics of spatial structure.

The deictic, pictorial, static, and dynamic models in verbal representations reflect various aspects of the cognitive comprehension of space. Deictic models provide orientation relative to reference points, and they are realized through verbal landmarks and points, such as *with me (со мной), at his place (у него), on the left (слева), next to me (рядом), now (сейчас)*, etc., as well as the accompanying pointing gestures (fig. 2a), forming integral patterns of spatial navigation. Pictorial models convey the descriptive characteristics of objects (color, shape, size, etc.), such as a *yellow radiator (желтый радиатор), square tables (квадратные столы), an iron leg (железная ножка), a bitten pizza (откусанная пицца)*, etc., and they can be reinforced by nonverbal gestures, forming indexic-pictorial structures. Static and dynamic models record the location of objects or their sequence, movement, and processes, reflecting the connection between the spatial description and the subject's cognitive and perceptual activity (see [Taleski, Burlaka 2025]).

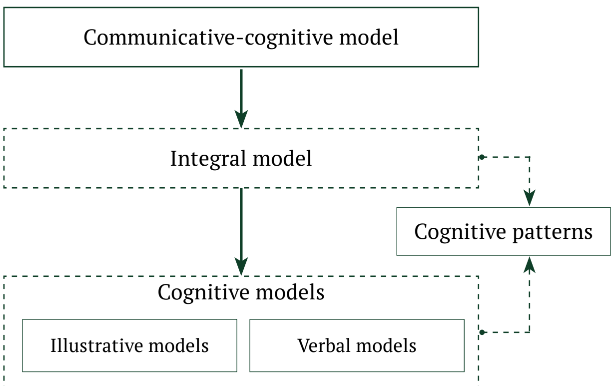
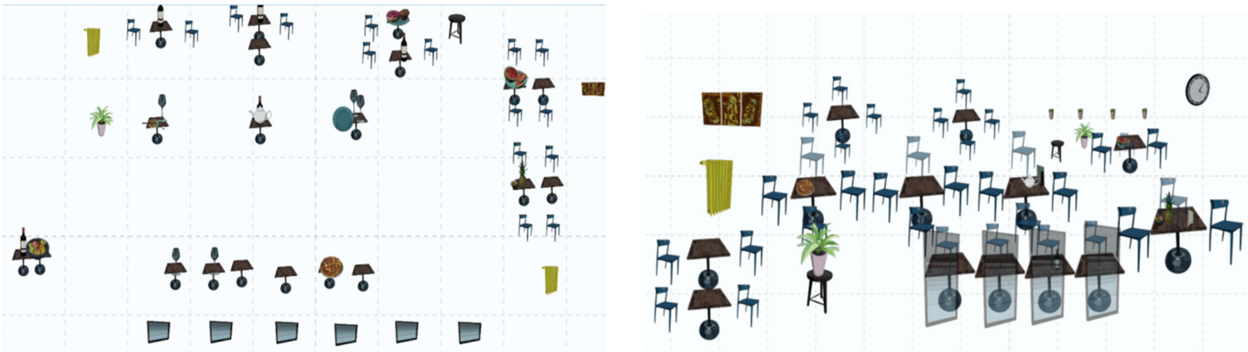


Fig. 4. Schematic representation of the hierarchy of cognitive models
Рис. 4. Схематическое представление иерархии когнитивных моделей

The mental and computational models occupy a special place. Mental models express the speaker's subjective attitude toward the VR space, or more precisely, the thought process itself, including cognitive efforts, doubt, confidence, and emotional reactions, emphasizing the anthropocentric nature of the representation, for example: *I really wanted to stay, if I'm not mistaken, definitely, maybe (Захотелось прям остаться, если я не путаю, точно, возможно)*. Computational models generalize the quantitative characteristics of all other types, using verbal, nonverbal, and statistical tools, performing a meta-analytic function and identifying patterns in the distribution of cognitive models in verbal representations.

The illustrative cognitive models are characterized by a synthetic and configurational method of representing space, where spatial experience is presented as holistic structures. The relationships between objects are defined through their relative positions, scale, density, and composition, while the illustrative modality enables the simultaneous actualization of multiple spatial parameters, facilitating the formation of mental maps with pronounced topological and structural properties of VR space. Unlike verbal models, such representations less rely on a linear sequence, and more on figurative and spatial-structural connections. Within the illustrative modality, a unique set of cognitive models of spatial reconstruction is formed, including perspective, dynamic, and stylistic models, reflecting various organization levels of illustrative experience and cognitive activity.

Perspective models establish a reference point and the logic of object coordination, demonstrating the use of simplifying and structuring space strategies through perspective selection and object placement (fig. 2b; fig. 5). Dynamic models reveal the sequence of operations with reference points, such as adding, moving, and changing parameters, and they can determine the key points and the structure of the scene, including cyclical transitions around significant objects (see [Taleski, Burlaka 2025]). Stylistic models are manifested in the choice of schematic and realistic representations (fig. 5), the degree of detalization, and the intensity of operations with objects, reflecting



a b

Fig. 5. Two types of illustration: a) schematic; b) realistic
Рис. 5. Два типа иллюстрации: а) схематичная; б) реалистичная

individual cognitive styles and the strategy of processing illustrative information.

The analysis of the first-level cognitive models revealed common patterns in the organization of spatial experience in both modalities. They include:

1) transition from general to specific in spatial representation;
2) coherence of object identification and positional indication;
3) cyclical sequences of reference to significant points, reflecting mechanisms for reducing the cognitive load.

The presence of common intermodal patterns can identify an integrated cognitive model of VR space representation, which stands above the verbal and illustrative models of the first level. This model unites various representational modalities into a single system, within which verbal structures provide a linear, logical-semantic unfolding of spatial content, while illustrative structures provide its synthetic, configurational organization. By abstracting from modality-specific forms, the integrated model reveals the underlying mechanisms of virtual spatial experience organization.

At the micro level, these mechanisms are recorded as cognitive patterns of spatial representation, reflecting stable ways of processing and structuring spatial information in both modalities. They include, in particular, cyclical sequences, which in the verbal modality are realized as repeated references to a single point for example, *table-table (стол-стол), window-window (окно-окно)*, and in illustrations as the sequential addition, modification, or movement of objects of the same type (see [Taleski, Burlaka 2025]). Another stable pattern is associated with the cognitive congruence of deictic and pictorial operations: in verbal data, the reference to an object is accompanied by its nomination and qualitative characterization, whereas in the illustrative modality this corresponds to the simultaneous localization and transformation of the object. Similarly, the pattern of space structuring is realized according to the principle of transition from general to particular, which in verbal representation is expressed through hyperonymic nominations with subsequent specification, for example, *furniture – tables, chairs (мебель – столы, стулья)*, and in illustrations through the primary placement of basic elements with the subsequent addition of secondary objects.

The next level is the communicative-cognitive model, which represents a meta-communicative layer in relation to the integral cognitive model of VR space representation. It correlates cognitive processes with the parameters of the communicative situation and allows us to consider the representation of space not only as the result of individual information processing, but also as a phenomenon embedded in the communicative interaction structure.

Essential parameters of this level are the configurations of the scenes themselves and the communicative interactions between communicants and referents, which define the framework for perceiving and understanding space. This is manifested in the relationship between personally and spatially oriented scenes, reflected in deictic models through egocentric, allocentric, and geocentric, as well as temporal-spatial indicators. The dominance of geocentric indicators, such as *on the left (слева), by the wall (у стены), along the window (вдоль окна)*, and others, indicates the prevalence of spatially oriented scenes, in which the coordination of the utterance occurs relative

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to the scene itself and its elements. Egocentric indicators, such as *I (я), in front of me (передо мной), to me (ко мне)*, and allocentric indicators, such as *his (у него), he (он)*, characteristic of personally oriented scenes, are present, but are secondary in frequency. This allows us to interpret the informants' communicative attitude as shifting from the "I-interlocutor" interaction to the task of reconstructing space, which corresponds to a descriptive-navigational, rather than dialogical, type of scene.

The similar trend is evident in the internal and external communication space: when geocentric orientation dominates, referents are removed from the communication zone and form an autonomous scene. This is confirmed in the illustrations by the absence of perspective elements and the interpretation of the images as a top-down view (fig. 5a), corresponding to the observer's remote position.

Further confirmation of the influence of communicative parameters is the distribution of referents within and outside the visual field, as well as the indirect reconstruction of the relative positions of communicants. In dynamic models, verbs of mental and perceptual operations, such as *remember (помню), forgot (забыла), saw (видела), examine (рассмотрела)*, and others, refer to the objects outside the current visual field, preserving their cognitive relevance. Similarly, in the illustrations, there are errors in the positioning of objects, such as paintings, flowers, radiators, and others, indicating their perception in different scenes without visual control. The "face to face" parameter is minimal, "interlocutor behind" is partially manifested through hesitation, self-correction, and laughter, while "interlocutor nearby" predominates, as evidenced by the geocentric orientation, the coincidence of key reference points *table (стол), window (окно), flowers (цветы)*, and cyclical sequences, such as *table – table (стол – стол)*. Under these conditions, the mental map is reconstructed based on specific objects, and communication is built as a joint cognitive focus on one scene, rather than as an interactive correlation of "I-you" positions.

Conclusion

The obtained results demonstrate that representation of VR space is a hierarchically organized multimodal cognitive system, rather than a set of parallel modality-specific processes. Verbal and illustrative representations function as coordinated manifestations of common cognitive mechanisms of spatial perception, organization, and reconstruction, differing in their strategies of a surface information deployment.

At the modal-specific level, verbal representations are oriented toward sequential unfolding, attention management, and hierarchy of spatial referents, while illustrative representations rely on configural, synthetic, and relational coding, forming holistic mental maps of the VR environment. These differences, however, are integrated at a higher level through stable cognitive patterns, such as cyclical sequences, the congruence of actions and objects, and the principle of transition from general to specific, which ensure coherence, stability, and economy of spatial thinking across modalities.

Crucially, the representation of VR space is also determined by the communicative parameters of interaction, including the scene type, the position of the communicants, and the distribution of referents within and outside the perceptual field. This allows us to view the VR space as a communicatively conditioned cognitive construct, in which spatial meaning is formed through the interaction of perceptual, cognitive, and interactional factors. This confirms the hypothesis that the organization of cognitive models is determined by the complex of factors. In general, the study demonstrates that VR space is conceptualized as a hierarchical, multimodal, and communicatively organized system, where cognitive patterns ensure the integrity, adaptability, and efficiency of spatial information processing. The proposed model expands the existing approaches to the study of a multimodal spatial cognition by integrating representational and communicative dimensions, thereby opening new perspectives for further research into the cognitive organization of VR space.

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Contribution: All the authors contributed equally to the study and bear equal responsibility for the information published in this article.

Критерии авторства: Авторы в равной степени участвовали в подготовке и написании статьи.

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