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Spatial Cognition in 3D Virtual Spaces and in 2D Interfaces – Object Placement Dependent Changes in Information Processing and Recall

Doctoral Theses

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Contents

1 Motivation and research goals

In recent years, Virtual Reality (VR), and to a broader extent Augmented, Mixed and other Extended Realities (AR / MR / XR) have become poised to change the landscape of computing in substantial and lasting ways. With the appearance of spatial content, spatial relationships, and more generally, spatial reference frames for all digital content in modern XR platforms, the way in which humans conceive of digital affordances and therefore think about, reason about and plan for digital interactions is radically altered. This dissertation explores ways in which this new digital environment is having an impact on human cognitive capabilities.

Over the past 20 years in studying spatial cognition and navigation, virtual reality has become a widely used technology. It has numerous capabilities that researchers can take advantage of during the evaluation of simulations of real situations, both in terms of environmental settings, and cognitive states [6, 10, 17]. Virtual reality provides researchers with better opportunities for monitoring, controlling, and measuring real-life situations [20] in an environment that is safer, easier to create, and easier to reproduce. VR has many advantages, one being that it facilitates a learning mode that, unlike more traditional e-learning environments, does not require any mental transformation of 2D objects into 3D objects [5]. Put differently, VR encourages a spatial encoding that comes more automatically to most users. This feature of VR may be essential in helping to reduce the cognitive load associated with many digital tasks. The goal of cognitive load theory is to clarify how increased information processing demands within learning tasks can impact students' capacity to take in new information and store it in long-term memory [23, 21, 22, 19]. In recent years, many researchers have aimed to measure the cognitive load associated with learning, task-solving, or problem-solving in virtual and augmented reality[24, 14, 9, 15]. These findings are extremely important in the current world where the number of distant learners and remote workers are increasing and need solutions where the cognitive load could be decreased.

The main research topic of this dissertation is how the transition from 2D to 3D interfaces in everyday computing impacts human performance and cognitive capabilities, as well as the cognitive load experienced in performing common tasks.

2 Methods

The dissertation explores a research domain situated at the interdisciplinary intersection of computer science and cognitive sciences. While the primary focus is on information technology, the investigation of research inquiries necessitated the application of measurement methodologies derived from cognitive psychology. As a result, it became possible to quantitatively assess users' behavior, experiential aspects, individual cognitive attributes, and overall performance.

In my research, I have performed several cognitive measurements in a desktop virtual reality environment called MaxWhere. I used between and within-subject research designs in order to compare the performance of two or more groups. These comparisons included virtual reality versus 2D measurements as well as 3D versus 3D measurements. Through the course of my research, I logged the user's positions and orientations in the virtual environment and used eye-tracking technology in order to measure the cognitive load based on the pupil dilation of the subjects. Later on, I analyzed the data with different statistical methods, corresponding to the given sample size, experimental design, and the research question. Statistical methods used included Independent samples t-test, Mann Whitney U test, Chi-square test, and Fisher's exact test, Correlation analysis, ANOVA, Mauchly's test of sphericity and Greenhouse–Geisser correction.

3 Theses

Thesis 1 – Relevant publications: [25, 27]

Through extensive usage statistics based on more than 22,000 data points, I have shown the existence of hierarchically organized prominent viewpoints, pivot points and well-defined regions within task-oriented 3D desktop VR spaces containing 2D content layouts. I have shown that these viewpoints, pivot points and regions are generally linked to the content within such spaces, and play a significant role in enabling users to solve the task at hand while limiting the need for excessive navigation between 2D content clusters.

- **Subthesis 1.1:** Through extensive usage statistics in a task-oriented 3D desktop VR space, I have shown the existence of distinct nodes that are visited by users more frequently than others as they are carrying out tasks in a 3D desktop VR space. Given the ratio between number of such distinct nodes and the data volume collected per user, while keeping the workflow fixed, I have shown that such nodes enable a navigation compression rate above 95%.

- **Subthesis 1.2:** Within the same experimental framework, I have shown that the previously identified nodes, can be clustered into regions, according to a ratio of 3 nodes per region on average. Further, I have shown that such regions are closely related to the clusters of digital content laid out in the virtual space, an observation which can help motivate the automated creation of guided viewpoints in 3D VR workspaces.

Thesis 2 – Relevant publications: [29]

Based on a free content arrangement experiment and accompanying statistical analyses, I have shown that within 3D desktop VR spaces containing 2D content layouts, users have different, but shared preferences in terms of the frequency and size in which different 2D digital content types are presented, and in terms of the topical-versus-typical arrangement of content layouts. I have also shown that in terms of position and orientation, different content types are often associated with unique, semantically charged 3D objects, which can undermine pre-existing topical-versus-typical arrangement preferences. Based on these results, I have formulated a design principle for 3D desktop VR spaces that suggests either the limitation of semantically charged 3D objects, or enabling flexible creation and reconfiguration of semantically charged 3D objects.

- **Subthesis 2.1:** Based on statistical analyses conducted following a free content arrangement experiment in a 3D desktop VR space, I have shown that users have clear preferences in terms of the frequency with which the five most common types of digital content (Web-based content, PDF files, images, videos and PowerPoint files) are displayed in virtual spaces. In particular, significantly more images and video files were laid out in the virtual space than PDF files, PowerPoint files, or Web content; and PDF files were also added to the space significantly more often than PowerPoint files or web content.

- **Subthesis 2.2:** Within the same experimental framework, I have shown that users have clear preferences in terms of the size in which the five most common types of digital content (Web-based content, PDF files, images, videos and PowerPoint files) are displayed in virtual spaces. In particular, PDF files and Web-based content were significantly smaller in size, overall, than the sizes of images, videos, and PowerPoint files. At the same time, no significant differences could be detected between the sizes of the latter three types of content.

- **Subthesis 2.3:** Within the same experimental framework, I have shown that for at least some types of content, users have clear preferences in terms of associating content types with specific features and objects in the 3D environment. I have shown that PDF files and Web-based content are strongly semantically linked with 3D monitors, PDF files are strongly semantically linked with tilted screen-like surfaces, images are strongly semantically linked with vertical boards or panels, and PowerPoint files as well as videos are strongly semantically linked with 3D objects resembling projection screens. In contrast, I have shown that strictly horizontal surfaces are much less preferable for users in terms of content placement. I have concluded that as a consequence, if users are unable to freely modify the type and number of spatial elements, such as tables, monitors, or projection screens, they may encounter limitations that hinder the flexible organization of content.

- **Subthesis 2.4:** Within the same experimental framework, I have identified three groups of users in terms of the cohesion of content layouts, referred to as "content-oriented", "type-oriented" and "mixed" users. I have demonstrated that although users overwhelmingly prefer to organize 2D documents based on their content (topical organization), based on subthesis 2.3, this can be undermined if the space contains 3D objects that inherently engender content type-oriented associations. Based on these results, I have concluded that in general, users can organize their 2D content most flexibly if a 3D space contains few semantically charged

3D objects, or if they are allowed to actively add any number of 3D objects to the space.

Thesis 3 – **Relevant publications: [28]**

Based on an analysis of user performance and eye-tracking data exhibited in two 3D desktop VR environments and a 2D web based environment, I have demonstrated that the cognitive load experienced significantly differs in favor of one of the two 3D desktop VR spaces, while maintaining the same performance level. Based on this, I have identified descriptive cognitive markers that are more pronounced in this optimal space as a result of the architecture of the space, and which reflect newly emergent cognitive capabilities in 3D desktop VR spaces. Based on these findings, I have provided recommendations for the design of 3D desktop VR workspaces with a view towards reduction of cognitive load.

- **Subthesis 3.1:** Based on an analysis of user performance and eye-tracking data exhibited in two 3D desktop VR environments and a 2D web based environment, I have demonstrated that in certain cases, assuming that the task at hand is the same, the use of VR environments can result in a reduction of cognitive load while maintaining the same level of performance.

- **Subthesis 3.2:** Based on further analysis of these results, I have identified the descriptive markers of "holistic overview" and "alternating mode", which are supported to a higher degree in VR spaces which, by architectural design, emphasize clusters of content in a circular arrangement. Based on these results, I have concluded that in such environments, newly emergent cognitive capabilities appear which allow users to quickly understand different groups of content, as well as their relationships with less navigation and, hence, at a lower cognitive load.

4 Applicability of results

A large volume of scientific studies support the idea that user experience (UX) design is crucial, as good UX design has been shown to enhance engagement, motivation, and can help maintain user attention for longer durations compared to traditional 2D interfaces [1, 18, 8]. These effects also extend to 3D spaces, as they allow users to create, visualize, and recall information in visually appealing and persuasive learning environments [7, 2].

Based on my research findings, my goal is to formulate design principles that can assist in the development of desktop VR environments. One primary consideration in designing spatial elements is to take into account human spatial perceptions. Accordingly, it is recommended to design virtual spaces as open areas or, in the case of closed spaces, with high ceilings [4]. When designing desktop VR spaces that function as workspaces, determining the size of the space is a primary consideration. Large spaces requiring extensive navigation can cause users to lose time and exposes them to unnecessary cognitive load due to the multitude of stimuli directed at them. To avoid this, it is suggested to create content groups placed in a circular arrangement, supporting holistic and alternating overview modes in the virtual space, which facilitates task status monitoring from prominent points [27, 29]. Previous studies by Berki have shown that users utilizing a 3D environment to execute tasks on documents have a superior capacity to retain supplementary information regarding the task's present state and gain a more comprehensive perspective on the project's status compared to users who perform the same task using a conventional 2D interface [3].

In addition to spatial elements and objects, there is significant importance in the type and spatial relationships of digitally placed content [29]. The most commonly used digital content used by users during individual or cooperative task-solving includes PDF files, images, PowerPoint presentations, video files and web-based content. Among these content types, images are the most frequently used, but their function extends beyond information delivery as they often serve as decorative elements. Alongside images, videos conveying audiovisual information and PDF files are common based on user preferences.

In addition to content type, the size of the content is also an important consideration, which can be compared to their physical counterparts based on my measurement results. PDF and web-based content require significantly smaller displays compared to the other three content types. For the latter, it is important to observe their details, emphasizing the importance of appropriate sizing [29].

Once the spatial elements and content types are determined, the next step is placing the digital content into the virtual space. In certain cases, the interaction between digital content types and specific 3D objects can be observed.

Typically, PDF and web-based content are associated with monitors, while video and PPT formats are associated with large projector screens. These preferences also reflect real-life analogies, as we often view PDF and web files on smaller digital displays such as laptops, tablets, or phones. On the other hand, videos and PPTs are more commonly viewed on projection screens in educational environments, and audiovisual materials typically provide a better experience when viewed on larger displays. It should be mentioned that this type of display is invariably vertical or slightly inclined, as users seemed to completely neglect horizontal content displays [29].

The previously mentioned examples involved the relationship of predefined spatial elements. However, based on my measurement results, these elements can both provide assistance and impose limitations if their number cannot be increased or decreased according to preference, and / or if their location or size cannot be changed. To counterbalance this, it is suggested to place panels in the space that act as boards or designated areas, providing a frame for content while allowing users themselves to determine the layout, number, size, and relationships of the placed content [29].

As a crucial element in the arrangement of virtual spaces, the grouping and clustering of content plays a significant role, whether a person or a group of people furnish a space with content for users or users are allowed to freely place their digital content. My research has demonstrated that the majority of users group digital content not based on its type but rather on the content itself. Creating these groups helps users gain an overview of the entire content within the space, manage related information as a whole, and assess the quantity of content [29]. The aforementioned prominent viewpoints and pivot points [27, 25], which facilitate user comprehension by allowing users to revolve around them or pause at a single useful viewpoint, aid in navigating these groups, enabling faster and more efficient task completion and the recall of placed content [16, 2], [13].

In addition to these factors, a properly designed and content-filled virtual space can reduce cognitive load compared to traditional 2D interfaces, thereby placing less burden on working memory during task completion. Overall, well-designed spaces facilitate users' comprehension of placed content, reduce the time required to perform tasks, and alleviate the cognitive load. Furthermore, integrating different types of digital content and modalities within the virtual space can be beneficial. This allows for the personalization of virtual spaces to cater to different learning styles and types, and ongoing research is exploring personalized and automated solutions in this regard [12, 11].

Desktop VR environments can serve as a viable alternative and future direction for distance learning compared to traditional 2D interfaces. Considering their numerous proven advantages, it is worth considering their implementation in the broader society.

References

[1] Afrooz, A., Ding, L., and Pettit, C. "An immersive 3D virtual environment to support collaborative learning and teaching". In: *Computational Urban Planning and Management for Smart Cities 16* (2019), pp. 267–282.

[2] Berki, B. "2d advertising in 3d virtual spaces". In: *Acta Polytechnica Hungarica* 15.3 (2018), pp. 175–190.

[3] Berki, B. "Desktop vr and the use of supplementary visual information". In: *2018 9th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*. IEEE. 2018, pp. 000333–000336.

[4] Cha, S. H., Koo, C., Kim, T. W., and Hong, T. "Spatial perception of ceiling height and type variation in immersive virtual environments". In: *Building and Environment* 163 (2019), p. 106285.

[5] Chen, C. J. "Are Spatial Visualization Abilities Relevant to Virtual Reality?." In: *E-Journal of Instructional Science and Technology* 9.2 (2006), n2.

[6] Cogné, M., Taillade, M., N'Kaoua, B., Tarruella, A., Klinger, E., Larrue, F., Sauzeon, H., Joseph, P.-A., and Sorita, E. "The contribution of virtual reality to the diagnosis of spatial navigation disorders and to the study of the role of navigational aids: A systematic literature review". In: *Annals of physical and rehabilitation medicine* 60.3 (2017), pp. 164–176.

[7] Csapó, Á. B., Horvath, I., Galambos, P., and Baranyi, P. "VR as a medium of communication: from memory palaces to comprehensive memory management". In: *2018 9th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*. IEEE. 2018, pp. 000389–000394.

[8] Evangelista Belo, J. M., Feit, A. M., Feuchtner, T., and Grønbæk, K. "XR-gonomics: facilitating the creation of ergonomic 3D interfaces". In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 2021, pp. 1–11.

[9] Frederiksen, J. G., Sørensen, S. M. D., Konge, L., Svendsen, M. B. S., Nobel-Jørgensen, M., Bjerrum, F., and Andersen, S. A. W. "Cognitive load and performance in immersive virtual reality versus conventional virtual reality simulation training of laparoscopic surgery: a randomized trial". In: *Surgical endoscopy* 34 (2020), pp. 1244–1252.

[10] Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., and Lovelace, K. "Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning". In: *Intelligence* 34.2 (2006), pp. 151–176.

[11] Horváth, I. "The 4th dimension of personalization in VR". In: *2022 1st IEEE International Conference on Cognitive Aspects of Virtual Reality (CVR)*. IEEE. 2022, pp. 000085–000088.

[12] Horváth, I. and Csapó, Á. B. "Motivations and Tools Relevant to Personalized Workspaces in VR Environments". In: *Electronics* 12.9 (2023), p. 2059.

[13] Horváth, I. and Sudár, A. "Factors contributing to the enhanced performance of the maxwhere 3d vr platform in the distribution of digital information". In: *Acta Polytechnica Hungarica* 15.3 (2018), pp. 149–173.
Independent citations: 130, self-citation: 18.

[14] Küçük, S., Kapakin, S., and Göktaş, Y. "Learning anatomy via mobile augmented reality: Effects on achievement and cognitive load". In: *Anatomical sciences education* 9.5 (2016), pp. 411–421.

[15] Lai, A.-F., Chen, C.-H., and Lee, G.-Y. "An augmented reality-based learning approach to enhancing students' science reading performances from the perspective of the cognitive load theory". In: *British Journal of Educational Technology* 50.1 (2019), pp. 232–247.

[16] Lampert, B., Pongrácz, A., Sipos, J., Vehrer, A., and Horvath, I. "MaxWhere VR-learning improves effectiveness over clasiccal tools of e-learning". In: *Acta Polytechnica Hungarica* 15.3 (2018), pp. 125–147.

[17] Moffat, S. D., Zonderman, A. B., and Resnick, S. M. "Age differences in spatial memory in a virtual environment navigation task". In: *Neurobiology of aging* 22.5 (2001), pp. 787–796.

[18] Pellas, N., Mystakidis, S., and Christopoulos, A. "A systematic literature review on the user experience design for game-based interventions via 3D virtual worlds in K-12 education". In: *Multimodal Technologies and Interaction* 5.6 (2021), p. 28.

[19] Plass, J. L., Moreno, R., and Brünken, R. "Cognitive load theory". In: (2010).

[20] Rizzo, A. A., Schultheis, M., Kerns, K. A., and Mateer, C. "Analysis of assets for virtual reality applications in neuropsychology". In: *Neuropsychological rehabilitation* 14.1-2 (2004), pp. 207–239.

[21] Sweller, J. "Cognitive load theory". In: *Psychology of learning and motivation.* Vol. 55. Elsevier, 2011, pp. 37–76.

[22] Sweller, J., Merriënboer, J. J. van, and Paas, F. "Cognitive architecture and instructional design: 20 years later". In: *Educational Psychology Review* 31 (2019), pp. 261–292.

[23] Sweller, J., Van Merrienboer, J. J., and Paas, F. G. "Cognitive architecture and instructional design". In: *Educational psychology review* (1998), pp. 251–296.

[24] Thees, M., Kapp, S., Strzys, M. P., Beil, F., Lukowicz, P., and Kuhn, J. "Effects of augmented reality on learning and cognitive load in university physics laboratory courses". In: *Computers in Human Behavior* 108 (2020), p. 106316.

The Author's Relevant Publications

[25] Sudár, A. and Csapó, Á. "Interaction patterns of spatial navigation in VR workspaces". In: *2019 10th IEEE international conference on cognitive infocommunications (CogInfoCom)*. IEEE. 2019, pp. 615–618.
Independent citations: 16, self-citation: 3.

[26] Sudár, A. and Csapó, Á. "An MCMC-Based Method for Clustering Display Panels with the Goal of Generating Navigation Paths in 3D". In: *2021 12th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*. IEEE. 2021, pp. 1009–1014.

[27] Sudár, A. and Csapó, Á. "Interaction Patterns of Spatial Navigation and Smartboard Use in VR Workspaces". In: *Accentuated Innovations in Cognitive Info-Communication*. Springer, 2022, pp. 149–166.
Independent citations: 0, self-citation: 2.

[28] Sudár, A. and Csapó, Á. B. "Descriptive Markers for the Cognitive Profiling of Desktop 3D Spaces". In: *Electronics* 12.2 (2023), p. 448.
Independent citations: 1, self-citation: 2.

[29] Sudár, A. and Csapó, Á. B. "Elicitation of Content Layout Preferences in Virtual 3D Spaces Based on a Free Layout Creation Task". In: *Electronics* 12.9 (2023), p. 2078.

Other Publications of the Author

[30] Sudár, A. "Proposing the hypothesis: Different face perception in autism spectrum disorders during a free browsing task using eye-tracking method compared to typical development peers". In: *2016 7th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*. IEEE. 2016, pp. 000365–000372.

[31] Horváth, I. and Sudár, A. "Factors contributing to the enhanced performance of the maxwhere 3d vr platform in the distribution of digital information". In: *Acta Polytechnica Hungarica* 15.3 (2018), pp. 149–173.
Independent citations: 130, self-citation: 18.

[32] Berki, B. and Sudár, A. "Measuring spatial orientation skills in MaxWhere". In: *The 1st Conference on Information Technology and Data Science*. 2020, pp. 35–36.
Independent citations: 0, self-citation: 1.

[33] Csapó, Á. B., Sudár, A., Berki, B., Gergely, B., Berényi, B., and Czabán, C. "A test space for virtual rotation measurement in maxwhere". In: *2020 11th IEEE international conference on cognitive infocommunications (CogInfoCom)*. IEEE. 2020, pp. 000585–000586.
Independent citations: 2, self-citation: 1.

[34] Csapó, Á. B., Sudár, A., Berki, B., Gergely, B., Berényi, B., and Czabán, C. "Measuring virtual rotation skills in maxwhere". In: *2020 11th IEEE international conference on cognitive infocommunications (CogInfoCom)*. IEEE. 2020, pp. 000587–000590.
Independent citations: 4, self-citation: 4.

[35] Sudár, A. and Berki, B. "Proposing a complex cognitive desktop virtual reality test". In: *The 1st Conference on Information Technology and Data Science*. 2020, pp. 159–160.

[36] Czabán, C., Csapó, Á. B., Berki, B., Sudár, A., and Berényi, B. "Fenntartott figyelem és vizuális emlékezet mérése 3D virtuális környezetben". In: *INFORMATIKA KORSZERŰ TECHNIKÁI KONFERENCIA 2021 „Jövőformáló tudomány" „Fenntarthatóság és digitalizáció" Dunaújváros 2021. november 9.* 2021, pp. 26–29.

[37] Czabán, C., Csapó, Á. B., Berki, B., Sudár, A., and Berényi, B. "Képességspecifikus alkalmasságvizsgálat virtuális valóságban". In: *INFORMATIKA KORSZERŰ TECHNIKÁI KONFERENCIA 2021 „Jövőformáló tudomány" „Fenntarthatóság és digitalizáció" Dunaújváros 2021. november 9.* 2021, pp. 30–32.

[38] Kővári, A., Katona, J., Wizner, K., Ujbányi, T., Nagy, B., Berki, B., and Sudár, A. "Ember - számítógép -, valamint megjelenítő és elemző interfészek alkalmazási lehetőségei". In: *Anyagtudományi terek*. 2021, pp. 195–210.

[39] Kővári, A., Katona, J., Wizner, K., Ujbányi, T., Nagy, B., Berki, B., and Sudár, A. "Ember–számítógép-, valamint megjelenítő és elemző interfészek alkalmazási lehetőségei". In: *DUNAKAVICS* 9 (2021), pp. 45–60. ISSN: 2064-5007.
Independent citations: 0, self-citation: 1.

[40] Sudár, A. and Berki, B. “Végrehajtó funkciók mérésének lehetőségei MaxWhere virtuális valóságban”. In: *DUNAKAVICS* 9 (2021), pp. 43–50. ISSN: 2064-5007.

[41] Sudár, A. and Berki, B. “Different approaches for measuring spatial abilities in MaxWhere virtual reality”. In: *2021 12th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*. IEEE. 2021, pp. 1077–1081.

[42] Wersényi, G., Wittenberg, T., and Sudár, A. “Handheld 3D Scanning and Image Processing for Printing Body Parts-A Workflow Concept and Current Results”. In: *2022 IEEE 1st International Conference on Internet of Digital Reality (IoD)*. IEEE. 2022, pp. 000061–000068.

[43] Horvath, I., Csapó, Á. B., Berki, B., Sudar, A., and Baranyi, P. “Definition, Background and Research Perspectives Behind ‘Cognitive Aspects of Virtual Reality’(cVR)”. In: *INFOCOMMUNICATIONS JOURNAL: A PUBLICATION OF THE SCIENTIFIC ASSOCIATION FOR INFOCOMMUNICATIONS (HTE)* SP (2023), pp. 9–14.
Independent citations: 4, self-citation: 6.