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

Doctoral Dissertation

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Contents

Declaration

I, **Sudár Anna (AICV8O)**, hereby declare that the work presented in this dissertation is my own work, and that I have used external sources while carrying out my work only to the extent indicated in this dissertation. Such external sources are indicated in the form of either footnotes or references in the relevant locations within the text, in such a way that the sources can be precisely identified, in keeping with the generally accepted standards of citation.

The results presented in this dissertation, including both analytical derivations and case studies, are based on my own work and are, to the best of my knowledge, correct and authentic.

Győr, 2023-08-28

Sudár Anna
author

Part I

Introduction

1. Goals and Structure of the Dissertation

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.

The dissertation consists of 5 parts: Introduction, Methods, Research Achievements, Summary and Theses as follows:

- **Part I: Introduction**
    - Chapter 2 gives an overview of cognitive theories relevant to how information is processed, grouped, and recalled, especially in the context of the visual modality. The chapter also describes some of the foundations of Cognitive Load Theory, which will be relied upon on later parts of the dissertation.
    - Chapter 3 gives an overview of the scientific background behind the nascent fields of Cognitive Infocommunications (CogInfoCom) and Cognitive Aspects of Virtual Reality (cVR), as well as their relevance to the study of how information is organized in 2D versus 3D inferfaces, and how this can impact cognitive load.

  - Chapter 4 summarizes the main research questions addressed in the dissertation.

- **Part II: Methods**
  - Chapter 5 presents the key features of MaxWhere, a 3D virtual reality platform that I used to carry out several experiments during this research.
  - Chapter 6 summarizes the background of the field of cognitive pupillometry, as well as the theoretical and practical foundations of eye tracking as a tool in conducting resarch on attention and cognitive load.
  - Chapter 7 summarizes the statistical tests that were used to evaluate the results of the experiments conducted during this research.

- **Part III: Research Achievements**
  - Chapter 8 describes experimental investigations aimed at finding out whether users in 3D VR spaces exhibit signs of having preferences toward specific viewpoints while carrying out specific tasks, as well as if and how such salient viewpoints can be characterized. The investigations also address the question of how users prefer to interact with 2D content display interfaces in 3D VR spaces.
  - Chapter 9 describes experimental investigations aimed at finding out whether users exhibit signs of having preferences toward the size and location of 2D content elements laid out within 3D VR spaces, and if so, how factors such as content type and spatial environment (i.e. 3D objects within the VR space) influence such preferences.
  - Chapter 10 describes experimental investigations aimed at finding out whether and to what extent the transition from 2D interfaces to 3D spaces can impact users' performance and the cognitive load experienced. The chapter also identifies new cognitive capabilities that are naturally enabled by the use of 3D VR spaces instead of 2D interfaces for certain tasks.
  - Chapter 11 proposes a set of guidelines for the design of 3D VR workspaces based a set of general principles derived from the research results presented in earlier chapters.

- **Part IV: Summary** contains a brief summary of the results in the dissertation.
- **Part IV: Theses** provides a formal summary of novel scientific findings presented in the dissertation, in the form of 3 theses.

2. Human Cognitive Capabilities

The goal of this chapter is to provide an overview of cognitive theories relevant to how information is processed, grouped, and recalled, especially in the context of the visual modality. The chapter also describes some of the foundations of Cognitive Load Theory, which will be relied upon on later parts of the dissertation.

Human cognitive capabilities include a wide array of mental processes that play a fundamental role in coordinating everyday life in various situations. These cognitive functions enable individuals to perceive, interpret, and interact with the spatial dimensions of their real and also with their digital environment. By seamlessly processing spatial information, humans can navigate intricate landscapes, construct mental maps, and efficiently plan routes [28, 18, 13].

2.1 Classical theories of visual-spatial cognition

2.1.1 Processing, grouping and recall of visual objects

In this section, an overview is given of cognitive theories relevant to how information is processed, grouped, and recalled, especially in the context of the visual modality. The key takeaway from this overview is that the way in which humans process spatial information, navigate in space, and conceptually represent spatial relationships is dependent on many factors, some of which may span perceptual, high-level cognitive and even emotional aspects. For this reason, predicting user preferences in 3D virtual environments is far from a trivial exercise, and such predictions need to be supplemented by usability experiments.

Perception of Objects, Shapes and Forms

Historically, the first psychophysical model that described the organization of perceived images into objects was the Gestalt theory. This concept was developed through the contributions of Wertheimer, Koffka, and Köhler. The Gestalt approach emphasizes that the object (the "whole") is more than the sum of its parts (i.e., the segments that make up the objects). Gestalt psychologists focused their work on three main areas [148, 69, 71, 9, 115]: 1) The relationships between shape and background; 2) Grouping rules; and 3) The "goodness" of shapes.

Within these areas, they identified six Gestalt principles: the Law of Similarity, the Law of Good Figure, the Law of Proximity, the Law of Continuity, the Law of Closure, and the Law of Common Region.

The *Law of Common Region* and the *Law of Proximity* play a particularly important role in understanding the grouping of information and in cases where the goal is to actively facilitate the speed and quality of the comprehensibility and recall of an image, both of which can be highly relevant in the use of VR to communicate information at a high level. In particular, based on the *Law of the Common Region*, the human brain is expected to group together elements that are located in a common, closed region. Even today, user interface and user experience designers rely on this principle when organizing information on specific elements in a closed area and using the same color, whether in, e.g., games or on social interfaces. In the case of the *Law of Proximity*, objects that are closer to each other are more likely to be considered as a group of related elements. Using this principle, it is also possible to communicate the association of information clearly, even if it is not possible to create closed regions [98, 91].

Human Spatial Behavior

Despite the relative limitations of the human senses and locomotion skills, we can navigate our surroundings skillfully. This indicates that effective spatial orientation is not simply a question of perceptual and/or motor performance. The ability of people to deal effectively and purposefully with their immediate environment is often referred to as human environmental competence [101].

Human environmental competence consists of several components [101, 129]:

- The perceptual component means the identification, highlighting, and prioritization of the essential characteristics of the environment.
- The cognitive component performs the interpretation of features highlighted during perception, as well as the storage, organization, and recall of the features that acquire meaning in this way. This results in environmental knowledge.
- The components of the affective component are positive and negative emotional and motivational responses to the characteristics of the environment, behavioral reactions, and personal dispositions that mediate between the former components.

Categorization and Conceptual Representation

Tversky's research published in 2003 discusses several types of mental spatial reference frames by which people place themselves in space. Each cognitive subsystem of the complex, multifaceted mental space serves a different function and includes different spatial elements and frames of reference. Although it can be assumed that each of them has a different mental structure, all of them are characterized by schematization. This reduces the load on memory, stimulates information processing, and allows for the integration of a wide variety of information, albeit at the cost of some error and distortion. Two general forms of schematization are categorization and chunking [138, 139].

In the world in general, as well as in one's narrow environment, one comes across a lot of information that one will need to recall at some point. This is supported by several cognitive processes, including categorization. This mostly happens automatically and can affect all modalities. The cognitive processes that help categorization make it possible for people to differentiate between objects classified in different categories based on certain properties, but in the case of objects belonging to the same category, they ignore minor differences and pay attention to common properties.

In addition, organizing information into blocks can also help make both processing and recall more efficient. In this context, one of the most significant research results in cognitive science has been the discovery of '*chunking*'—a cognitive process in which information is broken down into smaller, more manageable units to make the information more understandable [49, 4]. It is a strategy for memorization that can be applied consciously, but can also occur unconsciously through experience, which allows people to recall larger amounts of information [21, 117, 116]. We have known for a long time that the capacity of working memory is limited in terms of processing and storing information; however, with the help of this cognitive strategy, the amount of information to be processed at a given time can be reduced [10]. Additionally, the efficiency of this process is further supported by the fact that it is often based on an organizing principle that not only uses smaller building blocks but also makes semantic sense, thus resulting in memories that are easier to recall [21, 68].

In many cases, however, information-acquisition models have proven to be incomplete in the past because they did not take into account the cognitive state of users, as well as the cognitive strategies they may employ. Pirolli and Card's 1999 information search model identifies this shortcoming and states that people searching for information search and organize information in clusters to minimize the information search cost of searching between clusters [106]. These clusters appear in both physical and digital forms. Another very important aspect is the user's mental model, which also explains the different information search behaviors. Differences in the mental model are often determined by the cognitive demographic and social variables of the given user [99].

2.1.2 Spatial cognition and spatial navigation

Spatial ability can be understood in some sense as the ability to generate, retain, retrieve, and transform well-structured visual images. However, the concept of spatial ability is not a unitary construct. There are particular spatial abilities and each highlight different aspects of the process of image generation, storage, retrieval, and transformation [83]. Spatial ability, then, is defined by two major psychometric constructs: spatial orientation and spatial visualization [90]. Within the relative limitations of the human sensory and motor system, humans are skilled in navigating and orienting in their environments. This means that spatial orientation is not merely a perceptual and / or motion-related task, but is also strongly related to visualization and imagination [37]. Of all cognitive abilities, gender differences in spatial abilities are said to be the largest [82]. Spatial abilities and orientation skills have different characteristics. For instance, orientation skills always involve an environment and imply a movement (actual navigation or imagined map scanning) and the acquisition of information about the surroundings [34].

Today there is still no real consensus among researchers in terms of the meaning of spatial visualization. According to definition from the 1990s, "*spatial visualization is the mental manipulation of spatial information to determine how a given spatial configuration would appear if portions of that configuration were to be rotated, folded, repositioned, or otherwise transformed*" [118]. Another definition says that "*spatial visualization [involves] complicated, multi-step manipulations of spatially presented information*" [82]. A third definition states that "*spatial visualization is the ability to manipulate an object or pattern in the imagination*" [61]. In order to resolve some of these differences, researchers started to categorize spatial skills to account for the fact that there is no one, all-encompassing definition of spatial visualization skills [128].

Spatial visualization and orientation

With the help of the spatial visualization skill, people are able to mentally move an object, while the spatial orientation skill pertains more to the mental movement of the subject's own viewpoint as the object itself remains fixed in space [128].

Spatial orientation is a complex process that depends on numerous basic cognitive functions [34] and is perceived as one's ability to imagine the appearance of an object from different perspectives [151].

Spatial orientation and perception has been a hot topic in both the cognitive sciences and CogInfoCom for years now, as science has made great progress in the exploration of the neuroanatomical background of the spatial representations. In addition to the discovery of place cells [95] and grid cells [51], scientists have also come closer to an accurate understanding of the role of each brain area [93] in spatial navigation.

Many studies have also been conducted with the goal of measuring spatial orientation skills in users, e.g. in both real and virtual environments. Real environmnents considered include a university campus [120], the interior of a building as part of an indoor wayfinding task [78], and even a woodland environment [84]. Since the early 2000s, spatial orientation tasks have been increasingly simulated in virtual 3D environments [136, 104, 110].

Spatial navigation

Spatial navigation is also a core cognitive ability in humans. Navigation is defined by the capacity to move oneself throughout the physical world by using spatial information. In everyday life, spatial navigation is very often required whether or not in a familiar environment [121]. Human spatial navigation has typically been classified into three general types of knowledge: landmark, route, and survey knowledge [126].

Spatial navigation has been at the center of research for decades, due to the fact that it has an important role in integrating and linking functions of cognition, memory, learning and neuropsychology [53, 81]. It is also intertwined with the previously mentioned capability of spatial orientation. In this contenxt, there are two types of navigation that can be used: Active navigation allows the user to freely explore the environment, while in contrast passive navigation fixes the user to an observational position [27]. There are studies that highlight the cognitive components of active navigation that are beneficial for memory [89].

Visual-spatial cognition, a fundamental aspect of cognitive processing, plays a pivotal role in how individuals perceive and navigate their surroundings. This cognitive function is intricately intertwined with Cognitive Load Theory, as the efficient utilization of visual-spatial processing can significantly impact the allocation of cognitive resources, affecting the overall cognitive load experienced during tasks. Recognizing the interplay between visual-spatial cognition and cognitive load theory provides valuable insights into optimizing information presentation and design for optimized cognitive efficiency [67, 64].

2.2 Cognitive Load Theory

A widespread theory in educational psychology, Cognitive Load Theory (CLT) seeks to describe and demonstrate how the human cognitive system processes information and what it means for instructional design. The goal of cognitive load theory is to clarify how increased information processing demands within learning tasks (not only from an educational point of view but in workspaces as well) can impact people's capacity to take in new information and store it in long-term memory [134, 131, 133, 108, 96]. Note that in order to be able to learn something, we humans need to process new information and that requires sourcing our working memory, which is well-known for its limited capacity [35, 137, 140]. In cases when learners exceed these limitations and overly demanding requirements are enforced, cognitive overload occurs [135]. The process of acquiring and applying knowledge fails when the cognitive load exceeds a particular threshold. This may occur as a result of inadequate presentation strategies (used, for example when trying to instruct people on a subject) as well as additional external distractions [133]. In order to design and create appropriate working or educational environments and frameworks, it is necessary to understand the types and effects of cognitive load.

2.2.1 Categories and effects of Cognitive Load

Sweller and his colleagues identified 10 cognitive load-related effects [131]: the goal-free effect, the redundancy effect, the expertise reversal effect, the guidance fading effect, the imagination effect, the self-explanation effect, the element interactivity effect, the worked example effect, the split-attention effect and the modality effect. The last three effects are particularly relevant from the perspective of the dissertation, as in the design of digital environments and the use of digital content, the issue of optimizing cognitive load holds significant importance.

- *The worked example effect / Problem completion effect* is a phenomenon whereby students who are given working examples to study perform better on future tests than those who are required to solve the same problem independently. Van Merrienboer and Crook conducted research on a computer programming course and they showed that those students who received a partial solution to a problem had lower cognitive load because of the reduced extraneous cognitive load associated with having to look for examples by themselves.
- *The Split-Attention effect* occurs when learners have to split their attention (spatially or temporally) between at least two related information sources which cannot be understood without mental integration. This kind of learning requires the user to mentally integrate the given information in order to learn the material. In those instructional strategies and formats where the materials are in an integrated format more effective learning can be observed than in scenarios in a split-attention format.
- *The modality effect* is closely related to the split-attention effect and relies on the structure of the working memory that processes visual and auditory information over different channels. This could be advantageous and can reduce the extraneous cognitive load if the textual information along with pictures, and animations are presented in an auditory form.

2.2.2 Measuring Cognitive Load

Several types of methods have been developed in the last 40 years for measuring cognitive load and its related effects. Back in the 1980s, cognitive load was treated as an assumed concept rather than a directly measured construct.

- Indirect measures

  Sweller and his colleagues [132] built computational models so that quantitative distinctions could serve as proxies for cognitive load. These kinds of indirect measures consist of analyzing knowledge acquisition or learning performance. However, such models cannot be used for the continuous measurement of cognitive load during learning activities [22, 108, 24, 96].

- Direct measures

  Subjective measures are very common in the literature to assess the cognitive load. Paas's [97] subjective rating scale and the NASA TLX [52] are widely used methods. One benefit of employing these approaches is the ability to utilize subjective rating scales across various learning contexts, encompassing diverse subject matter and participant groups and these provide valid information about the experience of the measured individuals. However, there are limitations in validity and reliability and in some cases in the lack of data provided [7, 22, 144, 32].

  Objective methods offer a range of possibilities. Such measurements are capable of continuous behavioral and physiological assessment via very detailed data acquisition. Some examples of objective measures include:

  - secondary task performance [23, 38, 100]
  - functional magnetic resonance imaging [142, 149]
  - electrodermal activity [25, 80]
  - electroencephalography [6, 43]
  - heart-rate measurement [127, 145]
  - eye-tracking and pupillometry analysis [60, 152, 45, 141, 125, 103]

In the next chapter, we will transition from focusing on human cognitive capabilities to the foundational cognitive theories relevant to contemporary technology-driven contexts. Thus, while in this chapter the goal was to consider the characteristics of the human visual modality in particular, the next chapter will shift its emphasis to the practical application of these theories in the domains of Cognitive Infocommunications (CogInfoCom) and Cognitive Aspects of Virtual Reality (cVR). These domains are intricately connected to our understanding of how information is structured, experienced, and navigated within 2D and 3D interfaces. This transition effectively bridges the theoretical groundwork with real-world, technology-centric results, reflecting the seamless integration of cognitive theories into modern digital contexts.

3. Emergent Cognitive Capabilities from a CogInfoCom Perspective

In this chapter, an overview is provided of the scientific background behind the nascent fields of Cognitive Infocommunications (CogInfoCom) and Cognitive Aspects of Virtual Reality (cVR), as well as their relevance to the study of how information is organized in 2D versus 3D inferfaces, and how this can impact cognitive load.

3.1 Cognitive Infocommunications

Cognitive infocommunications, also known as CogInfoCom, is an interdisciplinary research field aiming to enhance the interactions between humans and computers while augmenting both human and artificial cognitive abilities. A key idea within the field is that humans and infocommunications systems can be increasingly seen to co-evolve rather than simply interact. This has the implication that new kinds of hybrid cognitive capabilities are emerging that are neither purely human, nor purely artificial. It also necessitates that this long-term co-evolution be studied separately from simple action-reaction type interactions normally addressed in Human-Computer Interactions (HCI) and related fields [11, 12]. Virtual reality (VR) technology is deeply intertwined with Cognitive Infocommunications, exemplifying the interconnected development of technology and human abilities.

3.2 Virtual Reality

Virtual reality (VR) is a rapidly advancing domain encompassing diverse technological systems designed to generate simulated three-dimensional (3D) environments for a multitude of applications. In recent times, VR has transcended its origins in the entertainment industry and has extended its reach beyond entertainment and seen widespread adoption in emerging sectors, including but not limited to education, medical training, engineering, robotics, manufacturing, and the paradigm of Industry 4.0. According to Steuer[130], the definition of virtual reality (VR) should focus on the human experience rather than a purely technological viewpoint. The concept of presence is identified as the crucial element in understanding this perspective. One benefit of adopting this definition is its applicability to various technologies across different time periods, including past, present, and potentially future advancements. Unlike definitions tied to specific devices, such a definition can focus on the broader human experience. Additionally, this shift in perspective from machines to individual perception helps to specify the units of analysis as the unique experiences of each user.

3.3 Cogitive Aspects of Virtual Reality

Visualization, simulation, and 3D graphical rendering are in some sense related (and interrelated) communication tools that can be employed to provide a deeper understanding of some subject matter. At a conceptual level, the precise benefits of using these tools can be hard to appreciate; nevertheless, with time they often empirically become clear. For example, in an industrial application, it may be the case that useful feedback information and alerts could still be provided to the relevant stakeholders, even without a digital twin; yet, the ability to navigate a manufacturing environment based on spatial relationships true to its real physical layout, and the ability to localize information, including alerts within such a topologically valid representation can make a big difference in terms of lowering cognitive load and increasing the speed of decision making. As highlighted by Power et al., access to realistic simulations can reasonably be expected to have a beneficial impact on decision makers' perception and understanding, whereas more simplified simulations, being as they are simplifications of a complex situation, can introduce biases [109].

In a convincing example of the benefits of visualization and simulation, Pfeil et al. describe several applications in a car part manufacturing company (Visteon) that rely on a model/simulation based decision-support system (DSS) with the aim of increasing productivity [105]. In one instance, a simulator-based training scenario was developed, for productivity training purposes, in which employees could modify parameters associated with the number of production days, preventive maintenance staffing/schedules; and then simulate the resulting machine uptime, cycle time and scrap rate based on those parameters. In a second instance, the actual parameters of the production line, along with productivity metrics were measured for longer periods of time, and proposed updates were simulated using the previously developed simulator. By incrementally modifying (improving) the model within the simulator, to better match real-life data, and by performing what-if simulations, the company was able to achieve a 30% increase in productivity.

The surprising conclusion of studies such as the one carried out at Visteon is that even though the levers through which modifications can be effected in a system (such as production and maintenance schedules) are seemingly not very complex, and even though the visualization aspects of the simulation were not particularly realistic, the end result of optimization can still be non-obvious and can provide significant improvements.

More recently, in part based on earlier successes such as the one at Visteon, researchers have turned towards the use of 3D virtual environments, as opposed to 2D simulations with spatial aspects. Several authors have highlighted that virtual worlds have a unique potential to foster creativity in a way that the traditional Web cannot [70, 94, 3].

O Riordan et al. observe that in a 3D environment such as Second Life, the ability to explore locations of interest while communicating with others and also having access to the Web by switching to a different browser tab all serve to speed up the process of obtaining information and facilitate the making of connections between otherwise distant sources of experience [94]. In a similar vein, Alahuhta et al. reach the conclusion that the combined effects of avatars, changes in users' frame of reference, feeling of co-presence, immersion, facilitated communication, and the availability of tools for collaboration in 3D environments leads to a significant improvement in creativity [3].

Aside from fostering creativity, as virtual reality has moved closer to commercial viability, various other aspects of the technology have also come under closer investigation —including business potential, entertainment value, deep tech/engineering issues as well as (most importantly for our current topic) the influence of VR on cognitive capabilities. In this regard, the key question is what humans can accomplish through the use of spatial technologies as opposed to without them. Can they achieve the same goals faster? How do differences in individual cognitive capabilities translate to differences in performance gains achieved by users? What subjective mental states do users experience while using VR, and what psychological models are best suitable for explaining their behaviors, both individual and social? These are just some of the questions that are of interest.

Hence, it is worth considering the benefits that even desktop 3D environments, as compared to traditional 2D interfaces, can bring to the forefront from various aspects. In what follows, I summarize recent results that are relevant from the perspective of cognitive burden, memorization/recall, digital guidance (i.e., understanding workflows), and content management.

In an experiment conducted by Lampert et al. [77], a group of test subjects were tasked with carrying out a specific workflow in the shortest possible time on different platforms. In order to control for differences in test subjects' background knowledge, a simple task was chosen, in which the goal was to count the number of dogs versus cats on a large set of images, pdfs and videos. In total, 379 test subjects were involved in the experiment, and had to carry out the task in 3 different scenarios: when the files containing the images were shared as e-mail attachments, when the files were shared via an e-learning platform called Moodle, and when the files were shared within a 3D VR space. The conclusion of the study was that users were able to complete the task at least 50% faster in the VR space than on the two competing platforms. One additional result in the paper by Lampert et al. was that they also proposed a qualitative framework (based on numeric degrees) with which to characterize the complexity of workflows. One can conceptualize a workflow as a control flow graph similar to the way algorithms are formally described, and the characteristics of different kinds of loops within the graph can be associated with the complexity of the workflow [77].

In a follow-up study, Horváth and Sudár proposed a quantitative framework for better understanding the complexity of different user operations, which also helped explain the results obtained by Lampert and colleagues from a different angle [Sudar7]. Among others, they proposed to distinguish between elementary operations (or machine operations) and complex operations. Elementary operations can be thought of as a single interaction, such as hitting a key, or clicking once or twice on an icon, directed at a specific functionality. Complex operations, in contrast, are a sequence of at most 3 elementary operations, such as copying and pasting text, or dragging and dropping an item from one folder to another. By analyzing the workflow that formed the basis of the experiment in the paper by Lampert and colleagues, Horváth and Sudár showed that the task carried out in 3D inherently required significantly less operations, both in terms of elementary and complex operations. This provides theoretically more grounded evidence that the content organization afforded by virtual spaces is qualitatively different from—and superior to—more traditional ways of organizing content.

In another follow-up study, Horváth systematically compared the effectiveness of the use of a well-known project management software, Trello, on Windows versus the MaxWhere 3D environment [56]. For this analysis, Horváth used the same Elementary versus Complex operations metrics devised in the previous study. The results showed that in 3D, users had to carry out 72% less elementary user operations, and spent 80% less time on overview-related tasks, that is, tasks related to context switching between views and tabs. In the paper, Horváth also introduced the concept of monitoring density, which is a metric that characterizes the number of information elements that can be seen and comprehended at the same time. Here, information element refers to any digital unit that needs to be considered and understood separately in the context of a workflow. Using quantitative arguments, Horváth showed that this metric can be hugely increased in 3D, given that a large number of different frames, graphs, charts, forms and other units can be displayed simultaneously in a 3D space.

3.4 Information organization in 2D and 3D interfaces

In this section, I provide a brief overview of how information is generally organized and visualized in 2D and 3D environments, highlighting some of the advantageous ways of using each for improved comprehensibility and information throughput, as well as highlighting some relative benefits of 3D environments versus 2D environments in this context.

Two-Dimensional Interfaces

With the advent of the digital world and the advancement of graphical interfaces, as well as the growth of digital information and the emergence of computers as mass products, there arose a need for the numerous digital content types—stored on computers, phones, tablets, or other electronic devices—to be organized according to a specific principle. Typically, 2D interfaces employ logically hierarchical solutions to this, displaying files as belonging to a given folder within a folder hierarchy. In such cases, users have no other option than to access the content of a given file using its location in the hierarchy, its extension and name [14, 39, 150].

Difficulties of Task-Oriented Clustering on 2D Interfaces

The key challenge in using folder-file hierarchies is that it is difficult to conceptually associate a given file with a *unique* folder, and it is often difficult for users to recall which folder a given file can be found in.

Gwizdka et al. tried to investigate this problem when they looked at how managing emails on 2D interfaces could be improved, i.e., made faster and more efficient. The physical environment in which people perform everyday activities is highly spatial and flexible. They expected that bringing some of these features into the e-mail environment would better support the various tasks performed in an e-mail. Here, too, the goal was to be able to cluster the messages into a working (i.e., task-based) order, thus making it easier to manage them and reply to them [50]. Other works have also aimed at solving similar problems [20].

Two-Dimensional Information Clustering Approaches on Computers

Although folders can be a temporary solution to store documents in a more structured way, it can still be difficult to provide users with universal signals, based on which a stranger can find information with the same speed as the creator of that particular system.

Nowadays, people often use two monitors during their work because they obtain their information from several sources. In real life, this would correspond to someone opening several open books or several papers next to each other in some arrangement, but on a computer, it can still be a struggle to map this feature.

To some degree, the split screen provides a solution to this, and is often used in cases where certain information is needed together to solve a task. In this case, the monitor can display more than one document at the same time and keep it active for the user. In many cases, however, using a split screen can cause scale changes in a given document, which can make its use or interpretation difficult. In addition, without a special configuration, such layouts are generally temporary and need to be re-created again and again through extra effort.

If one looks at the solutions of the two dominant operating systems for grouping applications on computers and how they are used, we come across similar solutions. Both Windows and Mac OS versions offer a view in which applications running parallel to each other are displayed to the user in smaller windows on one screen (e.g., Figure 3.1). This is certainly useful from the point of view that one can see how

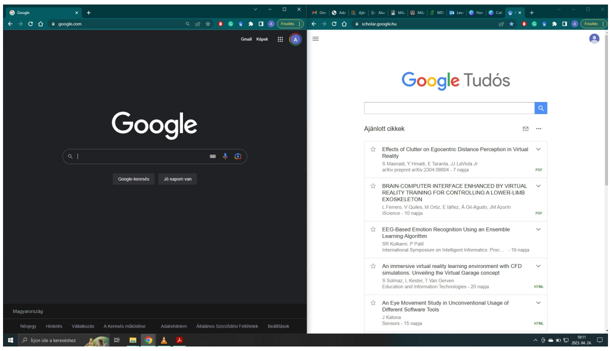

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Figure 3.1: Laptop screen with a split screen view on Windows OS.

many content elements and how many types of documents are open in parallel, but it does not help the user in grouping them. It is possible to imagine that one would like to work on several tasks at the same time, each of which has some number of documents/applications. In addition, it is common for certain tasks to occupy people's capacities for days, weeks, or even longer periods; thus, the content needed to solve them must be continuously available. Last but not least, document access needs are often contextual: for example, it may be the case that after working hours, the user might prefer to consume other types of content.

As a solution to this, the major desktop operating systems came up with a new concept, which Windows calls "*Virtual Desktop*" and Apple calls "*Spaces*". The essence of these is that the user can have several tables open simultaneously, such that they can easily switch between them. On the other hand, users are only allowed to change the order of these tables but cannot make any other layout changes (Figure 3.2).

Although this solution is much closer to the organization strategies that occur in reality, it is still confined to the limits of 2D and can hardly communicate relative importance, or the order in which tasks need to be carried out through, e.g., differences in the size of individual content elements and their spatial arrangement.

Three-dimensional Interfaces

PC and console games have already demonstrated the importance of spatial layout in processing, understanding, and recalling information. However, with the expansion

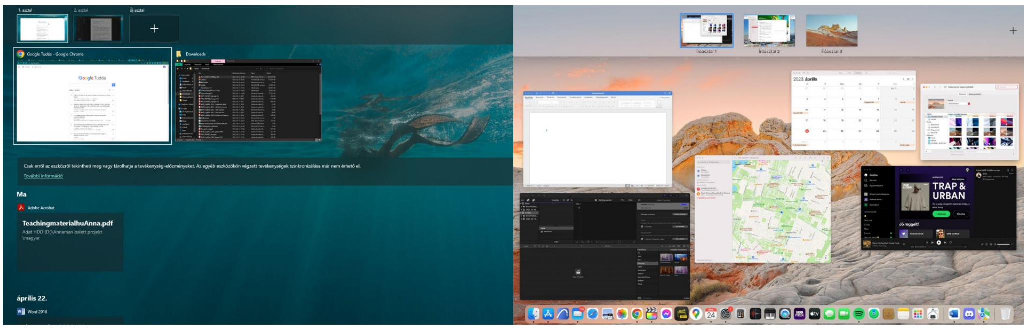


Figure 3.2: The Windows virtual desktop and the Mac mission control and space view.

of non-gaming uses of virtual reality, the question of what purposes such applications should serve has become even more relevant. Virtual reality mimics real life in many respects, but its significant advantage is that it can enhance it in many ways to help users tackle their everyday tasks. The Virtual Desktop VR application, introduced in 2016, offered an intriguing solution to the aforementioned information and document visualization and grouping issue by placing the user's desktop within a fully immersive environment (`https://www.vrdesktop.net/` (accessed on 30 April 2023)). This allows the user to fully utilize the available space, maximizing the sense of presence and accommodating more windows on a larger surface, in a way similar to the setup shown on Figure 3.3.

In 2021, Meta released the Horizon Workrooms virtual office and meeting room application, which also works in immersive VR, and requires a headset, but is already suitable for collaboration. One can even work in a shared virtual office with their colleagues, thus facilitating cooperation during task-solving.

These solutions can already leverage the benefits provided by the virtual world by showcasing content within the context of a 3D environment featuring 3D objects, which can substantially aid user recall [36]. However, the head-mounted display itself presents significant limitations, such as inducing motion sickness in a considerable number of individuals, having a short battery life, and still being relatively expensive.

The advantages offered by virtual reality, without the limitations of VR headsets, are used by those applications that provide the opportunity to exchange information, work, study, organize events, etc., using traditional 2D content in desktop VR.

Figure 3.3: Virtual desktop-like control panel as viewed on the Pico 4 headset. Source: `https://en.wikipedia.org/wiki/PICO_4` (accessed on 30 April 2023)—License: Creative Commons Attribution-Share Alike 4.0 International.

Spatial (`https://www.spatial.io/` (accessed on 30 April 2023)), a cooperative VR platform, allows 2D content, including documents, images, and videos, to be imported into virtual workspaces. In VRChat (`https://hello.vrchat.com/` (accessed on 30 April 2023)), a social VR platform, users can bring 2D content such as images and videos into their virtual realm using the Media Player feature, while ENGAGE (`https://engagevr.io/` (accessed on 30 April 2023)) allows for importing videos, websites, and documents through the WebBrowser feature. MaxWhere VR (`https://maxwhere.com` (accessed on 30 April 2023)) features smartboards that can be integrated into 3D spaces, capable of displaying any content type that a Chrome browser would support (PDFs, images, videos, audio files, local or remote web content).

The effectiveness of such type of VR applications compared to 2D applications has been examined from many aspects in the past years. Significant results in past studies have highlighted the ability of desktop VR to reduce cognitive burden [77, 56], [Sudar7, Sudar15] and improve information recall [15, 16]. Desktop virtual realities also enhance digital information and content management [122, 73, 123, 44] and can help the user with digital guidance solutions [Sudar14, Sudar13].

3.5 The role of VR in research on spatial cognition

Over the past 20 years in studying spatial cognition and navigation, VR 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 [33, 54, 92]. VR provides researchers with better opportunities for monitoring, controlling and measuring real-life situations [114] in an environment that is safer, easier to create and easier to reproduce.

In previous research conducted with the participation of 431 high school students, scientists measured various factors contributing to learning effectiveness in a virtual reality-based environment and found significant differences between a research (VR) and the control (2D graphical user interface-based interaction) group. The results indicated better performance among the students of the VR group [79]. 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 [31]. 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.

3.6 Information arrangement in 3D

Despite the advantages of 3D spaces, Setti et al. have argued that a key obstacle in terms of integrating 2D content into 3D spaces is that users cannot change the existing 2D layouts (comfortably or at all), thus their thinking is forced into the constraints of the currently existing layouts, leading to reduced effectiveness and ease of use [122]. However, it is also clear that no single layout is suitable for all tasks. This is related to the suggestion from Krokos et al. that the ability to reconfigure spaces could have an impact on user performance [73].

Needless to say, editing and reconfiguation in 3D is far from a trivial task. According to Setti et al., it is generally not a trivial question how the camera (the viewpoint of the user into the space) should interact with the operations used to transform the displays [122]. If a display is being moved towards a wall or some other object, and the camera is in a stationary location, it will become difficult to determine when the display has reached a particular distance from the wall/object, and during rotation of the display, to determine whether the angle between the display panel and the wall/object is as desired. However, if the camera viewpoint is modified automatically in parallel with the display panel manipulations, users will be unable to re-position themselves with respect to the objects and display panels of interest as freely as if the camera viewpoint is independent of the manipulations. This is a key dilemma, which is referred to as the "*camera-object independence dilemma*".

To resolve this and other challenges, Setti et al. proposed a set of operations—aiming at both comprehensiveness and minimality—that primarily involve either the duplication of existing displays, or the snapping of new displays onto existing surfaces, followed by fine-tuning operations such as translation of displays on their own plane, or modification of size and aspect ratio. Test subjects were able to use these operations to re-create existing layouts in empty versions of the same spaces at a high accuracy in less than 45 s per display.

Based on this editing methodology, Setti et al. proposed a general design paradigm referred to as "*doing when seeing*" [123]. This means that an operation is best carried out in the context of, and in relation to, already existing elements inside the virtual space. For example, if there is a wall, or an existing 2D display, then a new 2D display can be created by snapping it to the wall, or by duplicating the existing display. Doing when seeing also entails that in general, no other operation is necessary (other than some local, fine-tuning operations relevant to the object itself, and independent of its relationship to other objects).

The "*doing when seeing*" paradigm can also be applied to 3D objects or higher-level configurations such as existing content groups/layouts. By attributing metadata and content to layouts, it is possible to create a '*3D file system*', which extends the 'doing when seeing' paradigm to the duplication of existing projects [123]. This idea can be further extended to the problem of searching for content or projects, in that search terms that are entered and subsequent interactions can be linked together, thereby bootstrapping a search functionality that looks and feels like a semantic search functionality but really just links together search entries with behaviors close in time [124].

Based on such capabilities, 3D environments can provide a flexible interface for organizing multiple content types in a spatial arrangement, based on semantic relations (spatial proximity) and relations of relative importance (spatial size).

3.7 Cognitive load in virtual spaces

There is a limit to how much information the brain can process in any given timeframe. Cognitive load theory suggests that if this limit is exceeded, the performance will reduce and the mental strain will increase [134, 131, 133, 108]. Besides several beneficial factors of virtual reality, most of the time it requires active engagement and presents an active and rich immersive experience hence it could inadvertently lead to increased cognitive processing. However, with careful design, perhaps the complexity and cognitive load associated with a virtual environment can be controlled.

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. Several measurements proved the reduction of cognitive load in these spaces [135, 74, 42, 76], some showed, on the contrary, an increased cognitive load in virtual spaces [5] and some measurements did not show a significant difference in cognitive load between identical tasks in real life and in virtual reality [8]. It is worth noting that there are cases when these results are of outstanding importance, for example, when it is essential to test how a real place/event will affect people before it becomes real [8, 42]. These findings are extremely important in the current world where the number of distant learners and remote workers is increasing and need solutions where the cognitive load could be decreased.

4. Key Research Questions

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.

The specific research questions investigated in this dissertation are as follows:

- Generally speaking, can it be expected that a VR space can be characterized by salient points, i.e. virtual viewpoints which are more useful than others for a given task, and to which users routinely return to? If so, what are the key features of these salient viewpoints and how can they be identified?
- If users are given the option of arranging 2D content elements in a 3D virtual space, based on what factors do they make their choice in placing specific content elements in specific locations? Are there differences in the preferred location and size of different content elements depending on their format or content? Are there notable preferences in terms of the visual context (i.e. surrounding objects) into which specific content elements are routinely placed?
- How do performance and cognitive load metrics change when performing similar tasks using 3D interfaces as opposed to 2D interfaces? What factors shape the cognitive load that is experienced in 3D spaces with different spatial architectures?

Part II

Methods

5. The MaxWhere VR Platform

MaxWhere (`https://maxwhere.com`) is a 3D virtual reality platform and associated cloud service that can be used to host dynamically re-configurable 3D spaces. The core vision behind MaxWhere is that in the same way that character-based interfaces (e.g., DOS) were replaced in the late '90s by windowing systems (e.g., Windows), so should the widespread use of 2D windows soon be superseded by 3D spatial content. Just as the irreversible transition between DOS-like and Windows-like systems led to a significant increase in user effectiveness, so too would this transition between windows and spaces yield even greater benefits.

MaxWhere is unique among its competitors in that it enables the integration of so-called smartboards, which are 2D display boards that appear in the 3D space capable of displaying any kind of content that a classical web browser is capable of rendering (e.g., webpages, PDF documents, common image formats, audio files and web-optimized video formats). The spatial arrangement of such smartboards can help create a more logical structure for the content that is displayed, helping users to more quickly find the content they are looking for and to better retain what they have seen in the 3D space.

A second core feature of MaxWhere is that it provides a dynamic 3D document object model (called WOM, for Where Object Model) that allows spaces to be programmed and even dynamically re-configured as they are running and as a function of user interactions.

The MaxWhere platform was in the focus of numerous scientific research works in the past [17, 26], [Sudar7], [72, 47, 19, 56, 55]. It was shown that MaxWhere considerably improves the effectiveness of collaboration, work and learning [77], enabling users to accomplish their tasks more quickly [Sudar7], while exhibiting better performance in retention [15].

6. Cognitive Pupillometry and Eye Tracking

6.1 Cognitive Pupillometry

Research connected to pupillometry goes back almost 60 years. Kahneman and Beatty showed that expanding the length of a string of digits to be remembered is directly linked to an augmented burden on memory, which in turn leads to an enlargement of pupil size [63]. Kahneman's [62] explanation of the pupillary response as a measure of "attentional capacity load" remains relevant, as numerous subsequent investigations have demonstrated a clear association between pupil dilation and the demands imposed by executive load or working memory load [143, 146, 75]. To better understand why pupil dilation increases with increasing task demands it is important to know about the underlying biological and cognitive processes. The pupil exhibits size variations in reaction to three specific types of stimuli, which can provide valuable insights into underlying processes of perception, attention and cognitive engagement. Specifically, it narrows when exposed to bright light (pupil light response) and when focusing on nearby objects (pupil near response); conversely, it expands when there is heightened cognitive activity, such as increased arousal or mental effort (psycho-sensory pupil response) triggered either by an external stimulus or spontaneously [85].

The process of pupil dilation is governed by the iris dilator muscle. This particular muscle is regulated by the sympathetic nervous system, which is a component of the autonomic nervous system responsible for functions such as arousal, wakefulness, and the fight-or-flight response. The connection between pupil dilation and the sympathetic nervous system clarifies why pupils tend to be larger when an individual is experiencing heightened arousal [147, 119]. The size of the human pupil typically ranges from approximately 2 to 8 mm in diameter [87, 147].

Currently, measuring pupil dilation has become comparatively straightforward. The availability of affordable eye trackers has made it feasible to obtain sufficient temporal resolution and accuracy for detecting even minor alterations in pupil diameter.

6.2 Eye-tracking

The history of eye-tracking devices and the method itself does not have a long tradition, but it has played a significant role in the last decade of the 20th century and continues to do so today. Eye tracking, as a research tool, is gaining increasing popularity among researchers and is being applied in various scientific fields. The direction and duration of our gaze are influenced not only by attention but also by cognitive processes such as perception, memory, language, and decision-making. Although the connection between the eyes and the mind is not absolute, it is generally true that the eyes reflect the mental processing of what we are looking at in a given moment [113]. As a result, eye tracking is widely used in studies investigating cognitive processes. Due to its high temporal sensitivity, eye tracking can provide moment-to-moment insights into the progression of cognitive processes, rather than simply presenting the end result [29]. Moreover, eye movements are mostly beyond conscious control, so they cannot be easily or rarely influenced. Individuals can choose what and when they look at it, but the finer details of eye movements are mostly reflexive; people generally do not remember exactly where they looked. Therefore, the eye-tracking method can be useful in examining non-conscious processes as well. During eye-tracking measurements, several types of eye movements can be observed, including fixation, saccades, smooth pursuit, vergence, and pupillary dilation, which refers to the enlargement and constriction of the pupil regulated by the sympathetic and parasympathetic nervous systems [112]. In addition to all this data, valuable information is provided by the so-called regions of interest, which researchers designate when studying how many times and for how long participants in their study focus on specific points of an image, text, or even a person's face. In these cases, predetermined zones, referred to as regions of interest, are identified [29].

7. Parametric and Non-Parametric Statistical Tests

7.1 Independent samples *t*-test

The independent *t*-test is employed when there are two experimental conditions with distinct participants assigned to each condition (known as a between-subject design). It compares the disparity between two means with a distribution of differences in mean scores. To determine the significance value for t in unrelated samples, one approach involves assuming equal variances when the variances of both sets of scores are approximately the same. To assess the equality (homogeneity) of variances, a test called Levene's test is necessary. If Levene's test yields a significant result ($p < .05$), it indicates that the variances of the two samples are unequal, requiring a correction. One commonly used correction for unequal variances is the Welch correction [41, 65, 46].

7.2 Mann Whitney U test

The non-parametric counterpart to the independent groups t-test is employed when the group sizes are either too small or unequal. In such cases, resilience against the violation of parametric assumptions necessary for the t-test becomes important. Additionally, whenever a study involves a discrete ordinal variable, the Mann Whitney U test is recommended.

The key idea behind this test is to examine whether two independent samples originate from the same population by utilizing the rank ordering of the data [66, 111, 41].

Note that under specific circumstances, this non-parametric test may fail to identify a relationship that the parametric alternative is capable of detecting.

7.3 Chi square test and Fisher's exact test

If the objective is to examine the presence of a relationship between two categorical variables, the Pearson's chi-square test can be employed. This test is nonparametric and specifically designed for nominal independent variables. It involves comparing the observed frequencies in specific categories with the frequencies one would expect to obtain in those categories by chance. However, the chi-square test has a limitation, namely that the sampling distribution of the test statistic follows an approximate chi-square distribution. In situations with small sample sizes, this approximation may not be sufficiently accurate, rendering the significance tests based on the chi-square distribution unreliable. In such cases, Fisher's exact test is a suitable alternative method. It calculates the exact probability of the chi-square statistic and provides accurate results when dealing with small sample sizes [41, 88, 107].

7.4 Correlation

Contingency tables are utilized to analyze the relationship between different variables and examine how correlations vary across different groupings of variables. They serve as a valuable tool in identifying patterns, trends, and probabilities within raw data. Correlation examines how variables change together and can involve various types of variables, such as scale or ordinal variables. Assessing the validity of a new measure often involves correlating it with existing measures known to evaluate the variable of interest.

The two most commonly used types of correlations are the Pearson product-moment correlation and the Spearman rank-order correlation. The Pearson correlation is suitable for analyzing normally distributed scale data with linear relationships and no outliers. On the other hand, the Spearman correlation is applicable to ordinal data or non-normally distributed data. It addresses the presence of outliers by converting scores to rank order, bridging the gap between outliers and the remaining data points [2, 41].

7.5 Repeated measures ANOVA

This method is employed when examining and comparing multiple experimental conditions simultaneously. In this case, all groups are considered dependent, indicating that each score in one group is linked to a score in every other group. This dependency may arise due to the involvement of the same subjects across all groups or through subject matching. One notable advantage of Repeated Measures (within-subjects) ANOVA in comparison to Independent Groups (between-subjects) ANOVA is that the subjects themselves act as their own control measures [41, 48, 59].

7.6 Mauchly’s test of sphericity and Greenhouse–Geisser correction

Mauchly’s Test is employed to evaluate the statistical assumption of sphericity in the context of repeated-measures ANOVA. If the p-value obtained from Mauchly’s Test is less than .05, it indicates a violation of the assumption. In such cases, the Greenhouse-Geisser correction is applied to address this common violation [86, 41].

Part III

Research Achievements

8. Task-Specific Spatial Points of Interest (Thesis 1)

This chapter presents the research results I have achieved which support the assertions made in Thesis 1 of this dissertation.

Thesis 1 – Relevant publications: [Sudar12, Sudar14]

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.

In this chapter, the results of an experiment are described which I conducted in order to better understand the existence of and the qualities of salient spatial viewpoints in 3D VR spaces, as well as common ways of interacting with 2D content in 3D VR.

8.1 Aim of the Study

The aim of my study was to extend my former research presented in the 10th IEEE International Conference on Cognitive Infocommunications [Sudar12]. In the earlier study, I was able to identify preference points in the virtual space (Figure 8.1) which users were more likely to visit in order to find the spots that best allowed them to oversee the space and solve their tasks (e.g. around the questionnaires, in front of the main table in a position where every display can be seen). Further, I gave an analysis on the activation modes most often used when accessing the smartboards laid out in the 3D space.

The current study complements this earlier one with an experiment in a second virtual space in which the layout of the 2D display boards (referred to as "smartboards" in MaxWhere jargon) was significantly different. In this new environment, the arrangement of the smartboards consisted of a larger number of distinct groups, and the groups themselves also comprised more smartboards. The main challenge underlying passive navigation is that someone – the creator of the space or the designer of its content – has to create a set of viewpoints (referred to as the story, or guided tour in MaxWhere) by intuiting which points of view will be the most useful for most users. A useful feature, then, would be able to generate such stories without the need for human intuition, based on patterns of past usage alone.

Figure 8.1: The MaxWhere 3D VR space in which the former study was conducted.

8.1.1 Modalities of interaction at the center of analysis

In MaxWhere, users can interact with smartboards in two different ways as outlined below.

- Capsule-based activation

  On the one hand, smartboards can be activated and deactivated using the “capsules” which are placed on the top and center part of each smartboard window. If the user clicks once on the smartboard, it will become activated while the user remains at the same point in space. The tradeoff is that in this case the smartboard will be activated but not set to fullscreen. To get a close-up view of the content in the smartboard, the user needs to click on a blue icon (a “capsule”) that appears at the top center of the screen. To exit the smartboard, and return to 3D spatial navigation, users can click on a red icon (“red capsule”) right next to this blue one (8.2).

- Gesture-based activation

  On the other hand, there is a more natural way to activate and deactivate smartboards. With a double click, the smartboard will become active and the camera will zoom in towards it automatically. By subsequently moving the cursor to the left or the right edge of the screen, the smartboard can be automatically deactivated, without any need to click a button.

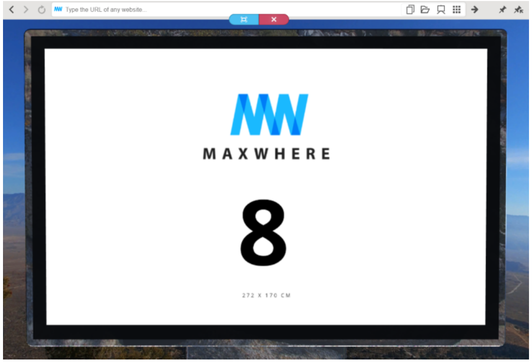


Figure 8.2: The "Blue" and "Red" capsule used for the activation and deactivation of the smartboards.

I hypothesized that it would be possible to find preference points in the 3D virtual space in which users spend more time to solve a given task. I also hypothesized that there would be differences between the activation an deactivation modalities used when interacting with the smartboards.

8.2 Methods

8.2.1 Subjects

Twenty-nine typically developing participants (28 male and 1 female) took part in the experiment. All participants were typical Hungarian university students ages 20 to 26 years old. The mean age was 22.68 (SD:1.63). All participants took part in the experiment voluntarily, and all of them had a basic end-user familiarity with the MaxWhere software, having had prior experience in using it. The participants were native Hungarian speakers.

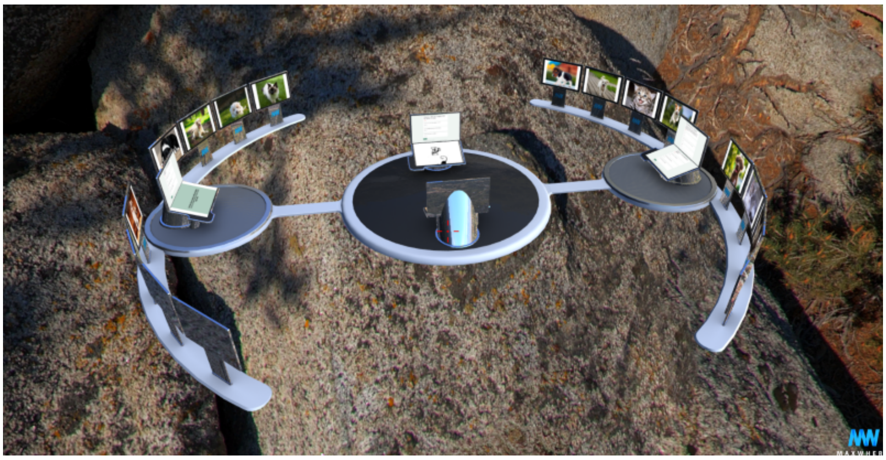


Figure 8.3: The MaxWhere 3D VR space, where the measurement was conducted.

8.2.2 Maxwhere Virtual Reality Environment

The experiment was conducted in a copy of the Fly Podium space that was created for the sharing and arrangement of documents and webpages. The space includes 22 Smartboards (Figure 8.3).

8.2.3 Procedure

When the experiment began in early 2020, the measurements were conducted at the Széchenyi István University, but after the disruptions caused by the COVID'19 pandemic, all further communication was carried out online, with remote logging incorporated into the space. In this case, the task remained the same but the students were given the necessary information via email. From the time users entered the virtual space, it took them no longer than 10 minutes to solve the required tasks and to fill out the relevant questionnaires.

The participants were asked to fill out four questionnaires (tests) related to the content placed in the virtual space and a general form on which they gave their consent to us storing their data for the purposes of this research. Participants were also asked about their habits connected to video games in order to assess their familiarity with Desktop VR.

The tasks were easy from the point of view of the content, however, they required complex navigational movements from the users. The questions related to the digital content required nothing more than counting different types of animals – similar to the experiment described in [Sudar12, Sudar7]. The questionnaire contained essential information relevant to the spatial arrangement of the smartboards (e.g.: “*This answer sheet belongs to the PDF placed under this smartboard*”) which were necessary to answer the questions (e.g.: “*How many cats are on the pictures?*”). There was no required sequence in solving the tasks.

8.2.4 Measurements Recorded

Spatial Preference Points

During the experiment, the camera positions and orientations visited by the participants were logged once every second. Based on these recordings (more than $22,221$ camera poses), a frequency analysis was performed. Results are visualized in Figure 8.4 and 8.5.

Activation and deactivation of Smartboards

The differences between the activation and deactivation modalities used when interacting with the smartboards were recorded, in terms of number of clicks on the blue and red capsules and the times when the participants chose to zoom in automatically by double-clicking instead of single clicking the smartboards. Results are visualized in Figure 8.6.

Video game usage habits

At the beginning of the experiment, the participants were asked to fill out a general questionnaire which had elements that surveyed their computer and video game usage habits.

8.3 Results

8.3.1 Spatial Preference Points and Orientations

The log files were analyzed following the test sessions, and out of more than $22,221$ camera poses, 34 nodes and orientations were found (Figures 8.4 and 8.5) which occurred more frequently than the others. On Figure 8.4, all visited points in the virtual space are visualised. The figure shows the nodes and clusters where the navigation activity was concentrated. Figure 8.5 in turn shows some examples of the preference points with respect to the position and the orientation of the users. Such preference points are concentrated close to the answer sheets and in front of information groups where the necessary information could be easily viewed from a holistic perspective in order to solve the task of the questionnaires as quickly and efficiently as possible.

Based on an analysis of these 34 nodes (Figure 8.5), 12 areas (clusters) could be identified which were located close to the questionnaires and to the different content types.

8.3.2 Activation and deactivation of Smartboards

Based on a Friedman's ANOVA test, results showed a statistically significant difference in the deactivation but not the activation of smartboards ($X_F^2(2) = 20.155, p < .001$) (Figure 8.6); i.e., post-hoc pairwise comparisons revealed no significant differ-

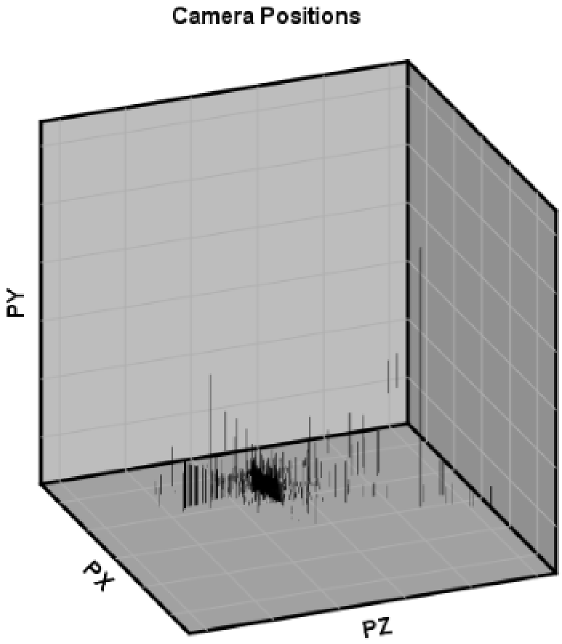


Figure 8.4: Frequency histogram of the nodes visited in the virtual space

Figure 8.5: Some of the most frequently visited camera poses within the virtual space

ence between the blue capsule and the double click, nevertheless the users left the smartboards with the red capsule click significantly more often ($Z = 3.28, p < .001$) than by turning away from them.

8.3.3 Video game usage habits

In the general questionnaire, participants were allowed to mark more than one platform which they use for playing video games, but the most preferred type was the PC. 86 percent of the students use a personal computer or laptop for video gaming, however there was no difference between the 2 consoles (PlayStation, Xbox) and out of the 29 subjects, only 4 claimed (1 female, 3 male) that they do not play video games at all and only one participant responded that he was a Nintendo user.

In general, the results of the questionnaire reinforced the idea that Desktop VR is a familiar environment for many users, worthy of further investigation in terms of its effectiveness in everyday computing tasks.

8.4 Discussion

29 university students (28 male, 1 female) participated in the study who had prior experience with the MaxWhere Virtual Reality Platform. Participants were asked to fill out five questionnaires (one general and 4 specific) and to aim for both speed and accuracy while filling them out. Based on the answers given on the general questionnaire, the students spend 5.69 hours/day using a computer. Only four of the participants do not play video games, and of those that do, 86.2 percent play them on a PC. The use of other consoles is less common. In terms of video game genres, the participants were more divided. The most played genre (88.5 percent) was Action games, but Strategy (65.4 percent) and Role-Playing games (57.7 percent) were also popular. In general, these results reinforce the idea that Desktop VR is a popular media format worthy of further exploration in terms of its effectiveness in everyday computing tasks.

More than 34 nodes were found among the camera poses in this study which confirmed my hypothesis that not all nodes (among over 22 thousand candidates) would measure equally. Considering that the task at hand was fixed (i.e. all subjects carried out the same workflow), on average, there were about $22,221/29 \approx 760$ points

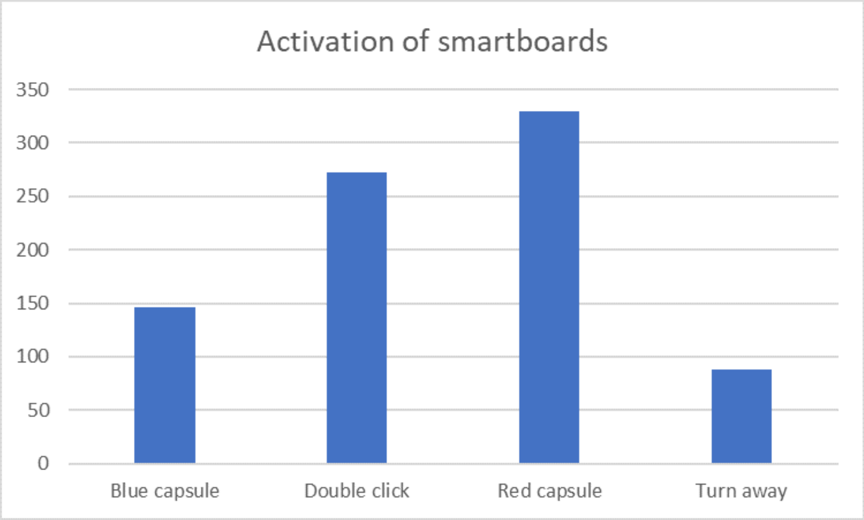


Figure 8.6: Activation of smartboards

measured (corresponding to 760 seconds of recorded interactions, since the sampling rate was 1 pose per second). Considering the ratio between the 34 nodes identified out of 760 measurements, one can conclude that in terms of navigation complexity (i.e. camera poses visited), the existence of such nodes can provide a compression rate of above 95%.

Besides the identified nodes, a further 12 regions were clearly distinguishable in which the camera positions were mostly concentrated. These preference points were located in the area of the questionnaires and the different content types. Participants were able to find special locations that gave an overview of the documents (the middle of the space, a plan view, and two positions in the semicircles in the back) and thus provided them with the most information necessary to look through the tasks and the content that belonged to them. While solving their tasks, the users minimized their movements and navigated naturally in order to solve their task as precisely as possible and find a point where they were able to look through the required content. With this active exploration of the virtual space, a map can be outlined based on which we can set a storyline consisting of preference points. This setting will guide the user and it decreases the navigational movements and operations, making the process of solving tasks faster and helping users to experience less cognitive load in the meantime [Sudar7]. In addition, some of the uncovered usage patterns more generally reflect the possible emergence of a new kind of cognitive capability in VR spaces: the capability of positioning oneself so as to obtain a holistic overview of multiple content elements simultaneously – something that is not possible in 2D interfaces.

Some of the nodes that I identified were located in front of the smartboards which displayed the questionnaires, but an interesting observation was that the users chose to navigate to and ‘stand’ in front of every well-separated group of tables, even if they would have needed to simply turn towards the left and right to gather all the information necessary to fill out a particular questionnaire. Another counter-intuitive observation was that the users did not seem to follow the configuration of the floor-like elements in the space during navigation. No distinct pattern could be detected in this regard, which perhaps shows that the space could have been better designed in terms of its capability of guiding the users’ active navigation.

Besides these results, significant differences were measured between the two modalities of smartboard deactivation. Participants used the capsule-based option more often than the option of turning away from the smartboards. The alternative option of turning away would have required them to drag the mouse to the very edge of the screen. The use of this option was not uncommon (and also suggests the emergence of a new cognitive capability unknown from 2D interfaces), but occurred significantly fewer times. In my former study in [Sudar12], the results showed significant differences in terms of activation of the smartboards, with users choosing the option to double-click significantly more times (in that study, de-activation was not investigated). The results of the current study point did not confirm this, though the option to double-click was still more popular.

The finding that users preferred double-clicking in one case, and the exit capsule in the other seems contradictory in that the “gesture-based” equivalent of double-clicking to activate a smartboard would be turning away from the smartboard. However, considering what comes naturally to users based on years of experience with traditional 2D graphical user interface (GUI) metaphors, both the double-click and the X (exit) button for closing a window seem to be iconic metaphors deeply rooted in users’ intuition. Thus, despite the fact that turning away may be a more natural movement to carry out in a kinesthetic sense, the common experience of clicking a red X button could have been an overriding factor. These results may therefore suggest that old habits can be hard to change, and therefore further studies may be helpful in separating out the factors of habit and convenience in determining user interactions.

9. Content Arrangement Preferences (Thesis 2)

This chapter presents the research results I have achieved which support the assertions made in Thesis 2 of this dissertation.

Thesis 2 – Relevant publications: [Sudar16]

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.

This chapter describes experimental investigations aimed at finding out whether users exhibit signs of having preferences toward the size and location of 2D content elements laid out within 3D VR spaces, and if so, how factors such as content type and spatial environment (i.e. 3D objects within the VR space) influence such preferences.

9.1 Motivations Behind Free Spatial Arrangement Study

As discussed in the literature review, it has been shown in recent years that traditional 2D systems are beginning to outgrow the amount of information that humans and machines interact with. Three-dimensional systems have a much greater potential for information exchange and can serve increasing human needs. With increasing information pressure, users often prefer digital environments that allow them to increase the clarity of relationships among digital content and enable them to organize their content into groups not only hierarchically but also in a workflow-based order, and in persistent ways. Although platforms that enable this are increasingly available, in general, little guidance is provided to users as to how they might want to lay out their content in the 3D space. In particular, how real-life physical experiences and preferences influence users' preferred choice of layout is not well understood, and as a result, they are rarely articulated through the design choices based on which 3D environments are created.

Key questions of this study include: Do the layout conventions that users are accustomed to—based on their frequency of occurrence in real life—also manifest in virtual spaces? Are there differences in terms of the size in which users prefer to display content in VR, depending on the type of content (e.g., text-based, image or audio–visual), depending on the subject matter (with content focusing on the same topics go together), or depending on the geometry of the 3D space (such that e.g., text-based documents are placed on tables, while videos are placed on vertical surfaces)?

For example, if real-world physical environments are anything to go by, one might expect that:

- Videos would preferably be placed on large-sized screens, TV sets, or monitors, which are mostly vertical surfaces;
- PDF files would preferably either be placed on computer screens or on horizontal, flat surfaces such as tables—perhaps depending on the age group of the user, i.e., whether they conceive of PDF files as being consumed on electronic devices or as being closer to physical, printed documents
- PPT files would preferably be placed on large screens, as they are consumed on personal computers
- Images would preferably be placed on vertical, or close to vertically inclined surfaces, as pictures in real life are often hung on walls or placed on furniture.

While the above arrangements may seem reasonable from the starting point of physical reality, it is also possible that users may choose to exploit qualities of 3D virtual reality that result in the arrangement of content being less tethered to such physical metaphors. To find out which is the case and what kinds of novel interaction patterns users might choose to employ (if any), we carried out the experiment described in this section.

9.2 Experimental Design

To observe possible regularities based on which users prefer to organize their digital content in virtual environments, we created a 3D space in which participants were free to arrange a partially pre-defined set of digital documents, which they could freely complement with further materials of their choosing.

Figure 9.1: A section of the "Ph.D. Student Room" space used for the purposes of the experiment.

Figure 9.2: A section of the "Ph.D. Student Room" space used for the purposes of the experiment.

To carry out the experiment, we used a space in MaxWhere VR called "Ph.D. Student Room" (Figures 9.1 and 9.2). Once the test subjects familiarized themselves with the basic use of the platform and the architecture of the space, we gave them a set of "*recommended*" documents consisting of five images, three PDF files, three video files, and two PowerPoint files containing content on technology-related topics, mostly—but not exclusively—about augmented reality and virtual reality. The task was for subjects to arrange parts or all of this recommended content, along with other potential content they could freely choose from the Web, into the 3D space.

My goal in allowing such a degree of freedom was to create an ecologically valid scenario, mimicking use cases where users could specify the content of their own

3D virtual space. In addition, the selection of recommended content on the topics of augmented reality and virtual reality was a natural choice, given that the experiment was carried out in a technological (VR) environment; in addition, the number of content elements were selected such that they would be not too large in number as to be difficult to grasp for users, while not too few in number, as to be insufficient for providing an overview of the topic at hand. At the same time, we emphasized to test subjects that these were merely recommended and not compulsory materials; hence, subjects' choice of content—including their topic, layout and size—was not limited in any significant way.

Following the experiment, we analyzed the quantity, relative size, and spatial cohesiveness of the different document types. In terms of cohesiveness, we were curious to learn whether the organizing principle chosen by subjects was centered around the document types (e.g., images separately, PDFs separately, audio–visual content separately), around subject matter (content types on the same topic go together) or around 3D context (e.g., videos placed on monitors, PDFs placed on flat surfaces such as tables).

9.3 Key Hypotheses

Before conducting my experiment, I formulated the following key hypotheses:

1. There is a difference in terms of the frequency with which test subjects prefer to add different content types to their spaces.
2. There is a difference in terms of the size in which subjects prefer to display various content types.
3. For at least some types of content, an interaction of the content type with certain 3D object types can be observed.

9.4 Materials and Methods

To carry out the experiment, I used the MaxWhere VR platform. Recent versions of the software has enabled users to modify smartboard configurations using a smartboard layout editor interface. This feature was necessary in enabling users to explore various configurations according to their own liking.

The virtual space used in the experiment was the so-called "Ph.D. Student Room" (Figure 9.3). The space is an open construction on an island of sand surrounded by water. The building has two floors. On the ground floor, there are three interconnected rooms, with either no walls, or transparent (glass) walls between them, as follows:

- The first of the three rooms has the appearance of a workroom, with a desk, a chair, and three monitors on the desk, as well as a projection screen and a large whiteboard.
- The adjacent lounge area has a few chairs with a coffee table and a large display on the wall.
- The last room looks like a meeting room or information center, with a large table that can be divided into 6 smaller sections. Each of the smaller sections has a chair and a table with a document holder placed on it and tilted at 45 degrees. On the wall, as in the workroom, there is a whiteboard.

On the upper floor, there is a large open terrace and a semi-open exhibition space on one side of the room, with five frames hanging from the ceiling.

At the beginning of the experiment, the virtual space did not contain any smartboards, all of them had to be placed in the space by the participant. The recommended documents given to the test subjects included five images, three PDF files, three videos, and two PowerPoint files, with the following content:

- Three PDFs:

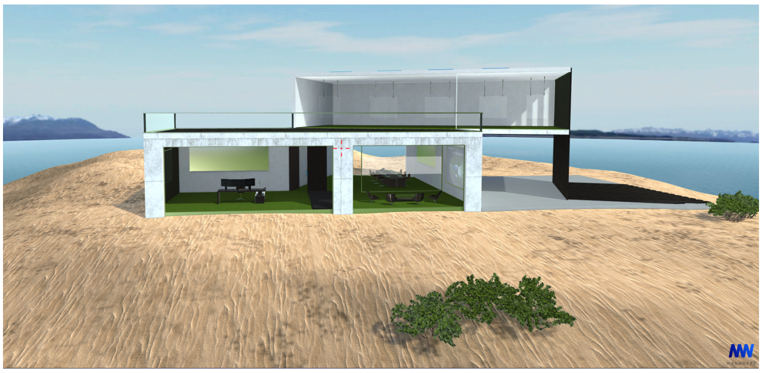


Figure 9.3: Empty version of "Ph.D. Student Room" space used for the purposes of the experiment.

  - Çöltekin, A. et al. (2020). "*Extended reality in spatial sciences: A review of research challenges and future directions*". ISPRS International Journal of Geo-Information, 9(7), 439;
  - Jung, T. et al. (2016). "*Effects of virtual reality and augmented reality on visitor experiences in museum*". In Information and Communication Technologies in Tourism 2016: Proceedings of the International Conference in Bilbao, Spain, 2–5, February 2016 (pp. 621–635). Springer International Publishing;
  - Morimoto, T. et al. (2022). "*XR (extended reality: virtual reality, augmented reality, mixed reality) technology in spine medicine: status quo and quo vadis*". Journal of Clinical Medicine, 11(2), 470

- Two PPTs:
  - Future of Technology (from Canva templates);
  - Future of communications (from Canva templates);

- Three videos:
  - `https://www.youtube.com/watch?v=I-EIVlHvHRM&t=1s&ab_channel=WIRED` (accessed on 30 April 2023);
  - `https://www.youtube.com/watch?v=WXuK6gekU1Y&ab_channel=DeepMind` (accessed on 30 April 2023);
  - `https://www.youtube.com/watch?v=XLP4YTpUpBI&t=9s&ab_channel=Simplilearn` (accessed on 30 April 2023)

- Five images: shown in Figure 9.4.

When solving the tasks, these materials were not presented to the subjects as mandatory items, but only as recommended content or a baseline. They could be varied with other complementary web and local digital content and could be discarded if not deemed necessary for the presentation of the topic, which focused on virtual reality, augmented reality, and mixed reality, but also included some tutorials on the use of artificial intelligence. All of the materials distributed were English-language materials.

9.5 Subjects and Preliminaries

A total of 32 subjects participated in the research voluntarily, with a gender split of 16 men and 16 women. The mean age was 28.594 (SD: 9.462). All participants were neurotypical English speakers and spoke English at least at an intermediate (B2) level. Thirty-one test subjects were native Hungarian speakers, and one test subject was a native Arabic speaker. All participants had 3D experience, through practice using the MaxWhere software itself as well as in many cases from 3D games. Before the experiment, the MaxWhere platform was introduced to the test subjects, and it was made sure that they were comfortable using MaxWhere spaces prior to having them complete the main task. All of the data collected during the experiment were anonymized and used exclusively as input to the statistical analyses detailed in later parts of this paper.

9.6 Procedure

In the experiment, participants went through a free layout creation exercise, where they had to choose any variety of 2D content they wanted, whether from the provided recommended documents, from the Web or from their own device. In all cases, test subjects were asked to remain within the same topics: virtual reality, artificial

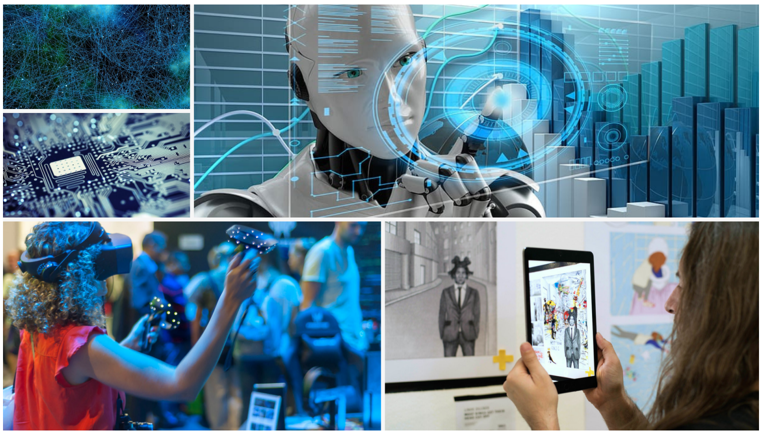


Figure 9.4: Five images included in the set of recommended content.

intelligence and their possibilities for collaboration. Participants were free to place the materials anywhere in the space; there were no restrictions on the number, position, orientation, or size of the content. There was also no time limit for carrying out the task.

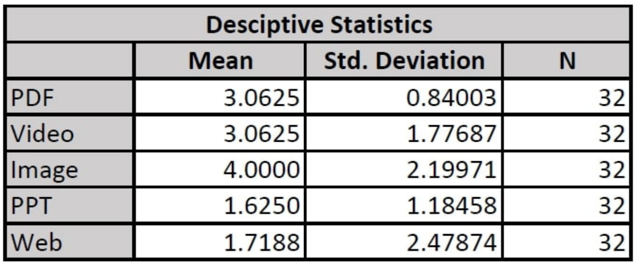
To save the content, everyone created a separate project for themselves with a random nickname to ensure anonymity.

9.7 Results

In this section, I provide an analysis of the recorded data from various angles.

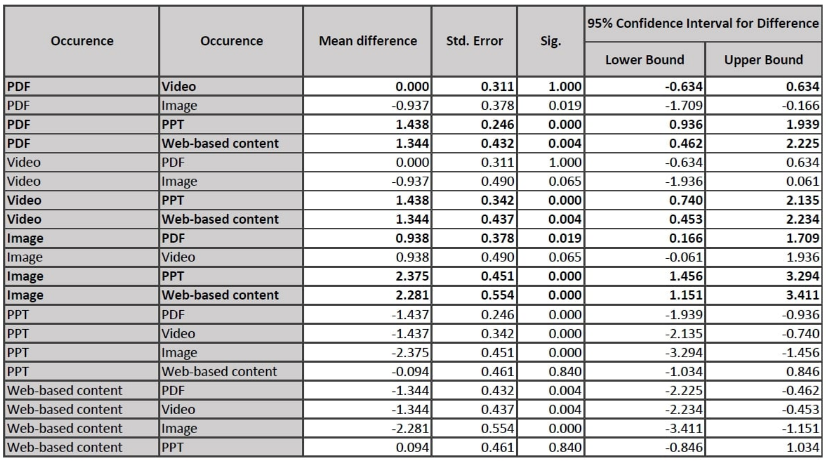
9.7.1 Frequency of Content Types

Figures 9.5 and 9.6 show the results of a repeated measures ANOVA, which points to the conclusion that the number of instances in which the content types were displayed in the case of the different test subjects was significantly affected by the content types, $F(2.98, 92.89) = 11.587, p < 0.000$. Since Mauchley's test of sphericity was violated, the Greenhouse–Geisser correction was used. The Eta squared effect



Desciptive Statistics			
	Mean	**Std. Deviation**	**N**
PDF	3.0625	0.84003	32
Video	3.0625	1.77687	32
Image	4.0000	2.19971	32
PPT	1.6250	1.18458	32
Web	1.7188	2.47874	32

Figure 9.5: Descriptive statistics of the repeated measures ANOVA—number of content types.



Occurence	Occurence	Mean difference	Std. Error	Sig.	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
PDF	**Video**	**0.000**	**0.311**	**1.000**	**-0.634**	**0.634**
PDF	Image	-0.937	0.378	0.019	-1.709	-0.166
PDF	**PPT**	**1.438**	**0.246**	**0.000**	**0.936**	**1.939**
PDF	**Web-based content**	**1.344**	**0.432**	**0.004**	**0.462**	**2.225**
Video	PDF	0.000	0.311	1.000	-0.634	0.634
Video	Image	-0.937	0.490	0.065	-1.936	0.061
Video	**PPT**	**1.438**	**0.342**	**0.000**	**0.740**	**2.135**
Video	**Web-based content**	**1.344**	**0.437**	**0.004**	**0.453**	**2.234**
Image	**PDF**	**0.938**	**0.378**	**0.019**	**0.166**	**1.709**
Image	Video	0.938	0.490	0.065	-0.061	1.936
Image	**PPT**	**2.375**	**0.451**	**0.000**	**1.456**	**3.294**
Image	**Web-based content**	**2.281**	**0.554**	**0.000**	**1.151**	**3.411**
PPT	PDF	-1.437	0.246	0.000	-1.939	-0.936
PPT	Video	-1.437	0.342	0.000	-2.135	-0.740
PPT	Image	-2.375	0.451	0.000	-3.294	-1.456
PPT	Web-based content	-0.094	0.461	0.840	-1.034	0.846
Web-based content	PDF	-1.344	0.432	0.004	-2.225	-0.462
Web-based content	Video	-1.344	0.437	0.004	-2.234	-0.453
Web-based content	Image	-2.281	0.554	0.000	-3.411	-1.151
Web-based content	PPT	0.094	0.461	0.840	-0.846	1.034

Figure 9.6: Pairwise comparisons of the repeated measures ANOVA in the number of content types.

size ($\eta^2 = 0.272$) also indicates that the effect of the type on the number of times each of the content types were employed was substantial.

According to the pairwise comparisons, PDF documents were used significantly more often than PowerPoint files or any other Web-based content, and images were used significantly more often than PDF documents, PowerPoint files or any other Web-based content. Figure 9.7 shows the distribution of the frequency of content types using a bar chart.

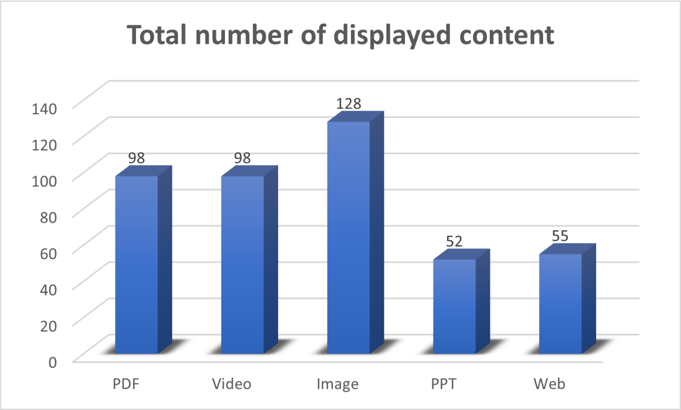


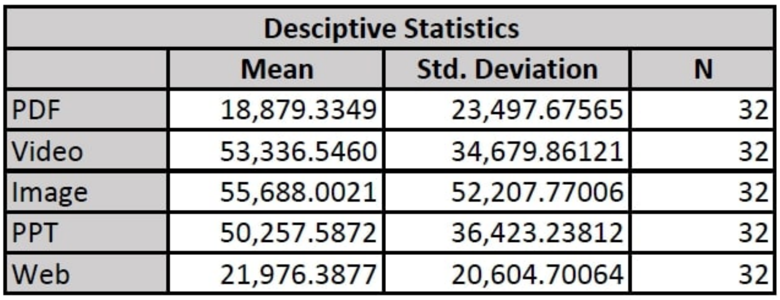
Figure 9.7: The total number of times each given content type was used. Note that although in total, video content was added to the spaces as often as PDF files, the variance among users was such that only the distribution of the use of PDF files was statistically significantly greater than those of PowerPoint files, and Web-based content.

9.7.2 Scale of Content Types

Within the same research design, the preferred size of each content type was also analyzed. The content types were the same: PDF files, videos, images, PowerPoint files, and any other Web-based content. To compute the scale, I multiplied together the length (in centimeters) of the horizontal and vertical axes of the corresponding smartboards. Descriptive statistics of smartboard sizes can be seen in Figure 9.8.

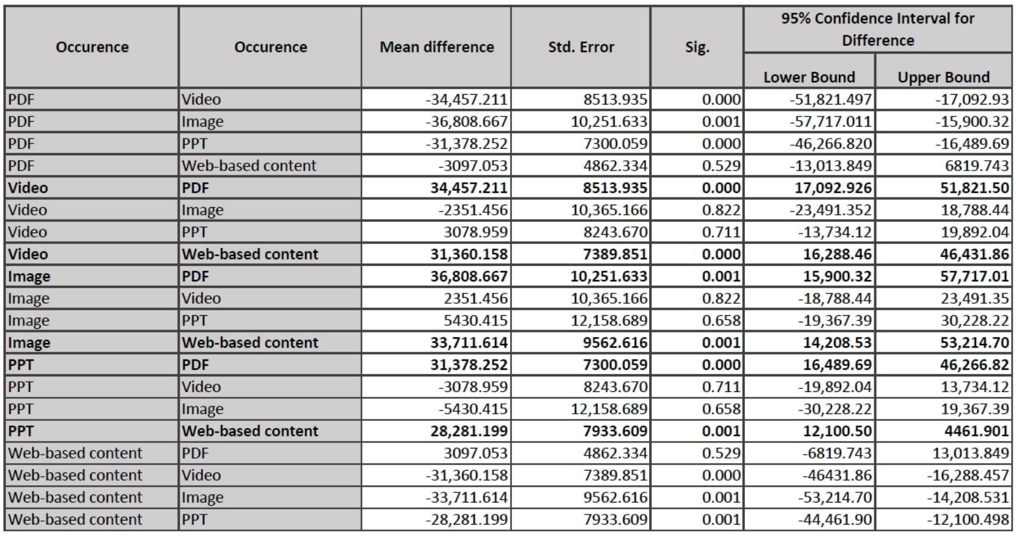
Results of a repeated measures ANOVA show that the size of the displayed content from one group was significantly affected by the type of the group, $F(2.98, 92.89) = 11.587, p < 0.000$. Since Mauchley's test of sphericity was violated, the Greenhouse–Geisser correction was used. The Eta squared effect size ($\eta^2 = 0.272$) also indicates that the effect of the type of content on smartboard size was substantial.

According to the pairwise comparisons, videos, images, and PowerPoint documents were displayed at a significantly larger size than PDF files and Web-based content; however, there were no significant differences between the former three types (Figure 9.9). I note that in cases where a test subject did not add a certain type of file format to their project at all, I set the size for that content type to the average of the sizes specified by all other test subjects. This was necessary to ensure that the number of samples was the same in all cases—a prerequisite for the ANOVA analysis.



Desciptive Statistics			
	Mean	Std. Deviation	N
PDF	18,879.3349	23,497.67565	32
Video	53,336.5460	34,679.86121	32
Image	55,688.0021	52,207.77006	32
PPT	50,257.5872	36,423.23812	32
Web	21,976.3877	20,604.70064	32

Figure 9.8: Descriptive statistics of the repeated measures ANOVA—size of the different content types.



Occurence	Occurence	Mean difference	Std. Error	Sig.	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
PDF	Video	-34,457.211	8513.935	0.000	-51,821.497	-17,092.93
PDF	Image	-36,808.667	10,251.633	0.001	-57,717.011	-15,900.32
PDF	PPT	-31,378.252	7300.059	0.000	-46,266.820	-16,489.69
PDF	Web-based content	-3097.053	4862.334	0.529	-13,013.849	6819.743
Video	**PDF**	**34,457.211**	**8513.935**	**0.000**	**17,092.926**	**51,821.50**
Video	Image	-2351.456	10,365.166	0.822	-23,491.352	18,788.44
Video	PPT	3078.959	8243.670	0.711	-13,734.12	19,892.04
Video	**Web-based content**	**31,360.158**	**7389.851**	**0.000**	**16,288.46**	**46,431.86**
Image	**PDF**	**36,808.667**	**10,251.633**	**0.001**	**15,900.32**	**57,717.01**
Image	Video	2351.456	10,365.166	0.822	-18,788.44	23,491.35
Image	PPT	5430.415	12,158.689	0.658	-19,367.39	30,228.22
Image	**Web-based content**	**33,711.614**	**9562.616**	**0.001**	**14,208.53**	**53,214.70**
PPT	**PDF**	**31,378.252**	**7300.059**	**0.000**	**16,489.69**	**46,266.82**
PPT	Video	-3078.959	8243.670	0.711	-19,892.04	13,734.12
PPT	Image	-5430.415	12,158.689	0.658	-30,228.22	19,367.39
PPT	**Web-based content**	**28,281.199**	**7933.609**	**0.001**	**12,100.50**	**4461.901**
Web-based content	PDF	3097.053	4862.334	0.529	-6819.743	13,013.849
Web-based content	Video	-31,360.158	7389.851	0.000	-46431.86	-16,288.457
Web-based content	Image	-33,711.614	9562.616	0.001	-53,214.70	-14,208.531
Web-based content	PPT	-28,281.199	7933.609	0.001	-44,461.90	-12,100.498

Figure 9.9: Pairwise comparisons of the repeated measures ANOVA size of the different content types.

9.7.3 Relationships among Dimensions of Content Type, Content Subject, and 3D Context

Based on an analysis of the projects created by the test subjects, a preference between given content type and spatial object was observed in many cases.

As shown in Figure 9.10, the projector screen inside the space was used to display video and PowerPoint content three times as often as any of the other predefined types. Equally, the frames hanging from the ceiling were used to hold images much more often than any other type of content.

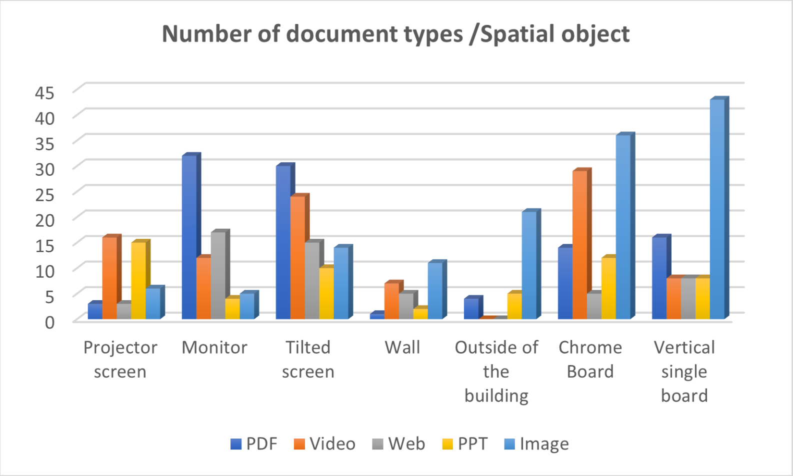


Figure 9.10: The total number of document types used in different 3D contexts.

At the same time, my analysis also showed preferences among spatial objects as receptacles for smartboards in general. Thus, test subjects attached content (in general) more often to spatial objects such as tables, monitors, and projector screens than to any other type of object, including the wall itself.

Based on this observation, I distinguished between “object-dependent” and “object-free” placement of smartboards—with the latter referring to walls or other surfaces with no standalone existence—and characterized users based on their preference (in general) for one or the other category. Object-dependent users placed all or most of their content in close proximity to spatial objects (projector screen, monitors, display boards with standalone existence) inside the building, while object-free users placed most or all of their content on walls (often outside of the building) and sometimes even in mid-air.

Figure 9.11 shows that the split was relatively even among users in the object-dependent/object-free dimension. Figure 9.12 shows 7 examples object-dependent and object-independent locations in the space.

Finally, I examined the patterns with which users preferred to arrange the content, and identified three alternatives:

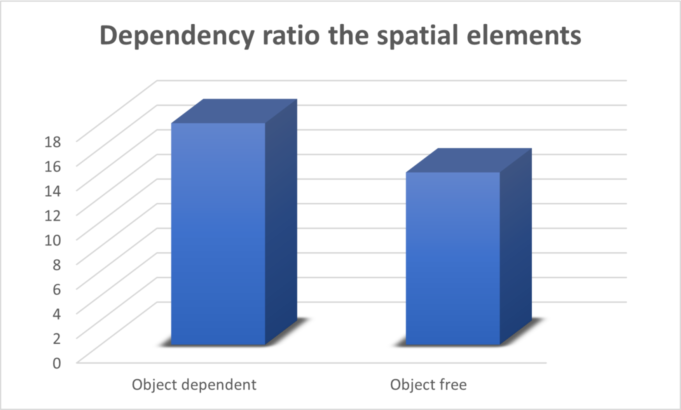


Figure 9.11: The distribution of spatial object-dependent and spatial object-free users.

Figure 9.12: Examples of object-dependent and object-free locations within the 3D space. The first three examples in the top row and the first two in the bottom row are examples of hanging frames, monitors, and projector screens, which are 3D objects with a "standalone existence". The walls on the inside and outside of the building with no descriptive features qualify as object-free locations.

- In the "content case", content types that had a similar subject matter were most likely to be arranged in clusters, in close proximity to each other;
- In the "type case", similar content types were most likely to be arranged in clusters, close to each other;
- Finally, in the "mixed case", a combination of these two approaches was used.

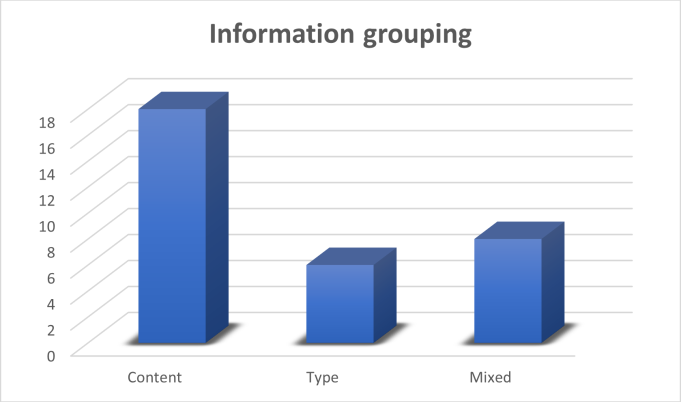


Figure 9.13: Distribution of users among the "content", "type" and "mixed" content arrangement categories. "Content" users created smartboard clusters with content about the same or similar subject matter. "Type" users created smartboard clusters such that different file formats were clustered together. "Mixed" users employed a combination of these strategies.

Figure 9.13 shows the number of users, out of the 32, belonging to each of the three categories.

9.8 Discussion

Based on the results, I return to my original hypotheses to determine whether or not they were confirmed.

9.8.1 Differences in Terms of the Relative Frequency of Content Types

The results obtained from the experiment supported the hypothesis according to which a significant difference would be detected in the occurrence of certain content types within any given project.

The task of the participants was to present a topic in a 3D desktop virtual space, for which they could use a pre-designed virtual space and fill it freely with digital content. I defined five types of content: PDF files, videos, images, PowerPoint files, and Web-based URLs. I gave the participants sample content from each of these types, which they could use if they wanted, but this was not mandatory, i.e., they could search for their own content as well and display it in the space.

The analysis of the data showed that significantly more images were laid out in the virtual space than PDF files, PowerPoint files, or Web content; however, the difference between video content and images was not significant, as both were displayed in high numbers in the space.

The second most common type of content was PDF files, which were also added to the space significantly more often than PowerPoint files or Web content.

The prevalence of images can be explained, on the one hand, by the use of nonfigurative images that served to "decorate" the plain concrete building—a behavior that was observed in multiple cases. At the same time, audio–visual content is often perceived as easier for laypeople to consume, which may also be an explaining factor for the relative popularity of images.

To determine whether the proportion of the information grouping preferences was equal between the three groups (content, type, mixed) a chi-square goodness of fit test was performed. The proportion differed by the users' preferences ($X2 = 7750$, $df = 2$, $p = 0.021$).

9.8.2 Differences in Terms of the Relative Size of Content Types

Differences in the display sizes generally utilized for each of the content types also showed a significant result in the case of certain content types, which confirmed my second hypothesis.

In particular, PDF files and Web-based content were significantly smaller in size, overall, than the sizes of smartboards containing 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.

These results support the assumption that users' preferences for content display in the virtual world reflects to a large degree the patterns existing in real life. In the case of videos, PPTs and images, we are usually used to the fact that these content types appear in front of us in a very large size, and their interpretability, richness of detail, and immersion in their content come into play when their size is large enough.

In my research, I saw a confirmation of this. Importantly, even though the size of the space was limited and one of the most common content types added to the space was video content, sample space was still dedicated by the test subjects to smartboards displaying such content.

In the case of PDFs and Web content, I assume that users are accustomed to reading and interpreting such content on smaller devices. These are typically text-based documents that rarely appear on large surfaces in real life.

9.8.3 Interactions between Subject Matter, Content Type and 3D Context

Perhaps the most interesting hypothesis in this paper is my third hypothesis, stating that for at least some types of content, an interaction of the content type with certain 3D object types would be observed. I was able to confirm this hypothesis, with room for some interesting observations.

Several salient spatial objects were present in the 3D space I used for this experiment. In an overwhelming majority of cases, content that was semantically linked to the object type was placed on any given object, whether they were, e.g., monitors (PDF files, Web-based content), projection screens (videos, PPT files), tilted screens (PDF files, videos), or vertical boards/panels (images). The most prominent of these was the projector projection screen, of which two were available in the space.

In a significant proportion of cases, either a video or PowerPoint file was added to the screen.

This also confirms the previously described theory, according to which, during the free furnishing of the virtual space, if there are spatial elements well known to the users, then the virtual space is arranged based on their own experiences in real life. Since this type of content is usually displayed on these projectors in reality as well, my assumption is confirmed. On the monitor placed on the virtual desk, PDF-type, textual content appeared more than twice as often as anything else, and almost only images appeared on the external wall of the building, whereas the occurrence of other content is negligible on this latter surface.

A further highly notable aspect of the study pertains to the placement and orientation of content within the virtual environment. Despite the availability of horizontal surfaces for users to position the content, not a single instance of this occurred among the numerous content placements. Each user opted to place their content vertically or, in accordance with the spatial elements provided, at an approximate 45-degree angle. This can likely be attributed to the fact that, even in our everyday lives, we seldom position informational content on horizontal surfaces. The possibilities afforded by virtual environments can enhance the fulfillment of needs that are challenging to achieve in the physical world, such as a sizable board on which one can freely arrange content vertically to facilitate a clearer understanding of both the content itself and the relationships among the various components.

Finally, my prior research was corroborated [Sudar15], as the majority of users independently categorized the boards and their associated content into groups without any explicit guidance. This was performed to enhance the visibility of the topic presented and to ensure that adjacent documents provided supplementary information to the observer. Moreover, in six instances, users organized content based on the type of documents (e.g., video, PowerPoint) rather than their subject matter. Participants in the third, most-preferred group typically arranged the documents spatially according to content, yet within each specific area, the primary organizing principle was the type of content.

In addition to the findings, the study suggests key insights based on which a general design principle can be formulated to provide users with increased freedom in virtual reality while mitigating the restrictions commonly faced in real life. Specifically, 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.

This was evident in the study as participants showed a preference for content-oriented arrangements, whereas the ample availability of tables and monitor screens often caused them to gravitate toward content-type-specific usage. Moreover, the inherent size and orientation of such objects imposed constraints on the location and quantity (i.e., spatial distribution) of content elements, leading to sub-optimal solutions when there were an insufficient number of suitable objects available, or when there was insufficient room in their surroundings, making it challenging to place other types of content nearby. Conversely, when a large billboard was mounted on a wall, participants were often able to utilize the space more freely and accommodate a wider variety of content types.

Based on these observations, a tradeoff exists between the utilization of concrete, semantically charged objects and the availability of adaptable space. When incorporating semantically charged objects, it is advisable to ensure sufficient surrounding space to allow for the free arrangement of content types that differ from those dictated by the objects themselves.

10. Comparing 2D and 3D Workflows in Terms of Efficiency and Cognitive Load (Thesis 3)

This chapter presents the research results I have achieved which support the assertions made in Thesis 3 of this dissertation.

Thesis 3 – Relevant publications: [Sudar15]

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.

This chapter describes experimental investigations aimed at finding out whether and to what extent the transition from 2D interfaces to 3D spaces can impact users’ performance and the cognitive load experienced. The chapter also identifies new cognitive capabilities that are naturally enabled by the use of 3D VR spaces instead of 2D interfaces for certain tasks.

10.1 Framework for the Experiments Conducted

In order to assess differences in the effectiveness of user workflows, as well as the cognitive load they entail in 2D digital interfaces and different kinds of 3D environments, we chose to develop a specific workflow and a set of experimental guidelines that could be repeated in different environments.

10.1.1 Details of the workflow to be carried out

The workflow to be carried out by test subjects consisted of reading and / or viewing learning materials pertaining to 4 different subtopics within the field of astronomy (“*Universe*”, “*Planets*”, “*Satellites*” and “*Space Research*”), and answering a questionnaire with respect to each of the subtopics.

Mérés az űrhajón (2D)

Kedves Résztvevő!

A mérés során az alábbi honlapon található négy kérdésblokkot kell megválaszolnod, az oldalon elhelyezett információk alapján. Majd töltsd ki a záró kérdőívet. Fontos, hogy mindegyik kérdőívnél add meg az azonosítót, hogy a különböző válaszaidat összegezni tudjuk.

A kutatásban való részvétel önkéntes, az adatokat anonim módon tároljuk, és csak a kutatás céljai szerinti statisztikai elemzésre használjuk.

Amennyiben bármiféle kérdésed van a kutatással kapcsolatban, akkor fordulj a mérésvezetőhöz.

Figure 10.1: Layout and design of the 2D webpage using which the 2D scenario experiments were conducted.

The questionnaires in each case consisted of true-or-false questions, multiple choice questions and questions requiring short answers of one or two words. Three examples of typical questions are:

- True or false?—Black holes can be observed based on the gravitational effects they have on surrounding gases, dust and stars;
- What are the rings of Saturn made of (select all that apply)?—ice, rocks, space debris, gases, asteroids, and/or moons.
- Why were Hubble's mirrors polished at night?

10.1.2 2D setup

In the 2D case, we used a classical Google Sites page (`https://sites.google.com/view/2deyetracking-egyoldalas/f%C5%91oldal`, accessed on 14 January, 2023), loaded into a Chrome Browser, which included all of the learning materials serially embedded into it, interleaved with the questionnaires (also in the form of embedded Google Forms within the Google Sites page). Here, the documents pertaining to each

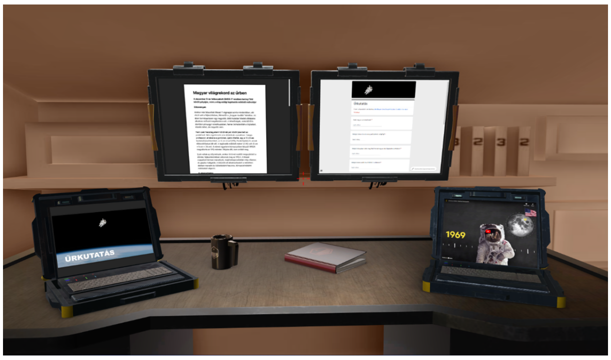


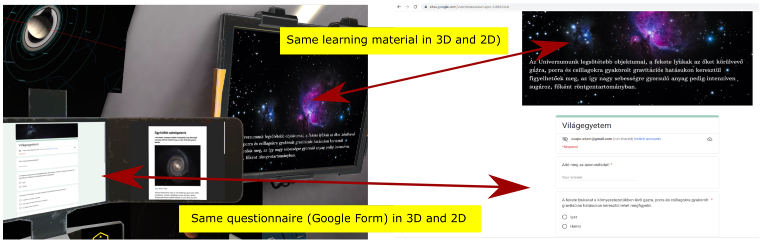
Figure 10.2: Spatial arrangement of 2D content in a 3D virtual space.

Figure 10.3: Spatial arrangement of 2D content in a second 3D virtual space.

of the four topics and the associated questionnaire were embedded strictly in order; hence, users could study 3 documents—PDF files, images or YouTube videos—and then fill out the associated questionnaire for each of the topics, before proceeding to the next topic (Figure 10.1).

10.1.3 3D setup

In the 3D case, the same documents and questionnaires were laid out in different 3D spaces within the MaxWhere platform (`https://maxwhere.com`) – a desktop 3D platform that allows for 3D spaces to be created with freely arranged display panels (so-called "smartboards" in MaxWhere jargon). Importantly, such smartboards can contain any kind of document that a desktop browser could normally display (e.g., webpages, PDF files, images, audio-video files).



Az Univerzumunk legsötétebb objektumai, a fekete lyukak az őket körülvevő gázra, porra és csillagokra gyakorolt gravitációs hatásukon keresztül figyelhetőek meg, az így nagy sebességre gyorsuló anyag pedig intenzíven sugároz, főként röntgentartományban.

Világegyetem

csapo.adam@gmail.com (not shared) Switch accounts

*Required

Add meg az azonosítódat! *

Your answer

A fekete lyukakat a környezetezetükben lévő gázra, porra és csillagokra gyakorolt gravitációs hatásukon keresztül lehet megfigyelni. *

○ Igaz
○ Hamis

Figure 10.4: This figure shows by example that the same documents and questionnaires were used in both the 3D case (left-hand side) and in the 2D case (right-hand side). No materials/questionnaires were added to or removed from the experiment in either case. Here, we can see that the PDF document on the topic of the "Universe" appears on the tilted panel at the back in the 3D case as well as on the upper half of this specific view of the 2D case. Whereas in the 2D case, the questionnaire appears directly below the learning material, in the 3D space, it can be found on the left-hand side of the screenshot.

Whereas in the 2D case, the learning materials were serially embeeded into a Google form and users had to scroll up and down to view different documents and to access the questionnaires, in 3D, free navigation was allowed and expected. Two examples of how documents were laid out in 3D can be seen on Figures 10.2 and 10.3.

It is important to note that the exact same documents and questionnaires which appeared embedded into the Google Sites page in the 2D case were presented to users in the 3D case, with no additional content in either case. The only difference was that the content appeared serially, from top to bottom in the 2D case, whereas it was presented in a spatial layout in the 3D case. The relationship between the 2D and 3D cases is shown in Figure 10.4).

10.1.4 Measurement data collected

The results of the questionnaires were compared in terms of percentage of questions answered correctly and the time taken to answer all of the questionnaires. Note that in the 3D case, time spent with navigation was discounted from the latter metric, so that the actual time spent on the peruasal of the content and the filling out of the questionnaires could be compared directly.

In the meantime, eye gaze and pupil dilation data was recorded to assess test subjects' focus of attention and cognitive load experienced. The latter measurements were obtained using the EyeTribe eye tracker and accompanying software (`https://theeyetribe.com/dev.theeyetribe.com/dev.theeyetribe.com/general/index.html`, accessed on 14 January, 2023).

In addition, the frequency of certain interaction patterns was recorded, including when:

- Users viewed content on a group of smartboards simultaneously from some distance ("holistic overview mode")
- Users alternated focus between different smartboards while remaining in a stationary position but frequently changing their camera orientation ("alternating mode");

Finally, in a post-experiment questionnaire, subjects were asked for demographic data, questions about their digital leisure habits, and questions about subjective assessments about and sense of immersion in the virtual space (in the 3D case). Subjects were also asked to rate the difficulty of the blocks of topics. For those who completed the tests on the two-dimensional interface, the final questionnaire did not include questions on 3D space.

10.1.5 Procedure

Prior to the experiments, written consent was obtained from all participants to use the collected data as follows. All data collected was anonymized and used solely for the purpose of the statistical analyses reported in this paper. All of the experiments were conducted in accordance with the ethical principles laid out in the Declaration of Helsinki.

At the start of the session, test subjects carrying out the required task in 3D indicated whether they were familiar with the MaxWhere software and, if so, approximately how much time they had spent using the software. Participants who were not

Figure 10.5: Layout and design of the 3D space in which the first experiment was conducted, as reported in [Sudar15]

familiar with the software spent approximately 30 min learning about it and acquiring basic user skills. Basic knowledge includes confident navigation in the software, activating and deactivating the display panels and interacting with the content that is displayed on them. Mastery of confident use of the software was assessed by the test administrators.

Following this, the participants were seated in a quiet room in front of a laptop computer. The room was dimly lit without any direct light source so as not to introduce unwanted artifacts into the eye tracking data. For each test subject, the eye-tracker was calibrated prior to the experiment.

Following the calibration, the test administrator explained the task to be carried out. The order in which the questionnaires were filled out, with the selection of the first and the last questionnaire, was left up to the participants.

10.2 Preliminary measurement results

In a first experiment, we compared measurement data obtained from the 2D scenario and one particular 3D space, as reported in [Sudar15].

The space in which the experiment was carried out was a spaceship-themed environment, as shown in Figure 10.5.

10.2.1 Test subjects

In the case of the spaceship-themed VR space, a total of 14 test subjects participated in the experiment, but video data were corrupted for one person. The results from a further four subjects had to be discarded due to there being breaks in pupil dilation measurements midway during the experiment. The remaining nine subjects (three women, six men) were aged between 17–55 years, with a mean age of 32.5 years (SD: 14.15).

A total of seven test subjects (four women, three men) participated in the 2D measurement, and were aged between 25–33 years, with a mean age of 27.83 (SD: 2.93).

The mean age for all participants was 30.84 (11.39) years. All participants were neurotypical Hungarian native speakers who participated in the experiment on a voluntary basis. Informed consent was obtained from all participants prior to the experiment, which was carried out based on and in accordance with the institutional endorsement of the authors' affiliation. All of the data collected during the experiment was anonymized and used exclusively as input to the statistical analyses detailed in later parts of this paper.

10.2.2 Preliminary results

When comparing results from the 2D scenario and this 3D scenario, the data showed that the correctness of answers provided by subjects in the 2D and 3D case was very similar, with no statistically significant differences. At the same time, within the topic of Satellites, subjects completed the questionnaire significantly faster in 3D than in 2D (while there was no significant difference in completion times within the other topics). These results failed to confirm, in a general sense, the hypothesis that subjects would perform better in 3D than in 2D (save for the completion time in the case of the Satellites topic)—although they certainly did not perform worse.

The fact that the 3D environment included a high volume of visual clutter led us to the conclusion that reducing this clutter — perhaps by using a more minimalistic 3D space with less need for navigation (other than rotation of view) — could lead to higher yields in performance in the 3D case.

Regarding subjective evaluations of difficulty and pupil diameter measurements, it was observed that there was no correlation between the two. This was a surprising result. Leaving aside the possiblity that the tasks were actually more difficult when the subjects perceived them to be easier, this counter-intuitive finding may have also been due to the amount of visual clutter, and thus, a degree of excitement experienced by the test subjects.

10.2.3 Motivations behind follow-up study

Based on these points, and our previous experience in designing 3D spaces with custom layouts (see also [Sudar16]), we set ourselves the goal of performing the same experiment using a different VR space and a larger number of test subjects. Our goal was to use a second virtual space in the follow-up study that would more adequately address the following principles:

- The need for navigation and the amount of visual clutter should be limited in order to lower cognitive load
- In the case of virtual spaces containing many spatial elements and accessories, the pupil may be particularly wide as a result of heightened arousal
- The size of the documents should indicate their importance
- The arrangement of documents into clusters should allow the user to conclude that the contents placed there form a content unit
- By creating the same layout for every block, such that the content types are the same in each case (with only the particular topic differing), users should

be able to understand semantic relationships more quickly and at a lower cognitive load

- The digital content inside the virtual space should be displayed vertically or on only minimally tilted panels, as users have been shown to prefer horizontal surfaces for documents to a lesser extent [Sudar16].

Thus, for our follow-up study reported in later parts of this paper, we opted for a virtual space in which there were no unnecessary disruptors, which was much smaller, in which less navigation was needed, and the displays holding the contents were also more organized.

10.3 Follow-up Experiment in a Second VR Environment

Our second experiment was carried out using the same 2D scenario (albeit with more test subjects) and in a second 3D VR space which contained a circular arrangement of content clusters (Figure 10.6).

In the 3D virtual space, the contents were placed on a total of 21 smartboards. The questionnaires were placed in the middle of each cluster, above them was the title slide, and to the right, left and bottom were the documents that contained the answers to the questions contained in the questionnaires.

10.3.1 Subjects

A total of 40 test subjects participated in the research, with an average age of 26.57 (SD: 6.96), 20 women and 20 men.

All of the participants are Hungarian native speakers and individuals with neurotypical development, who participated in the experiment on a voluntary basis.

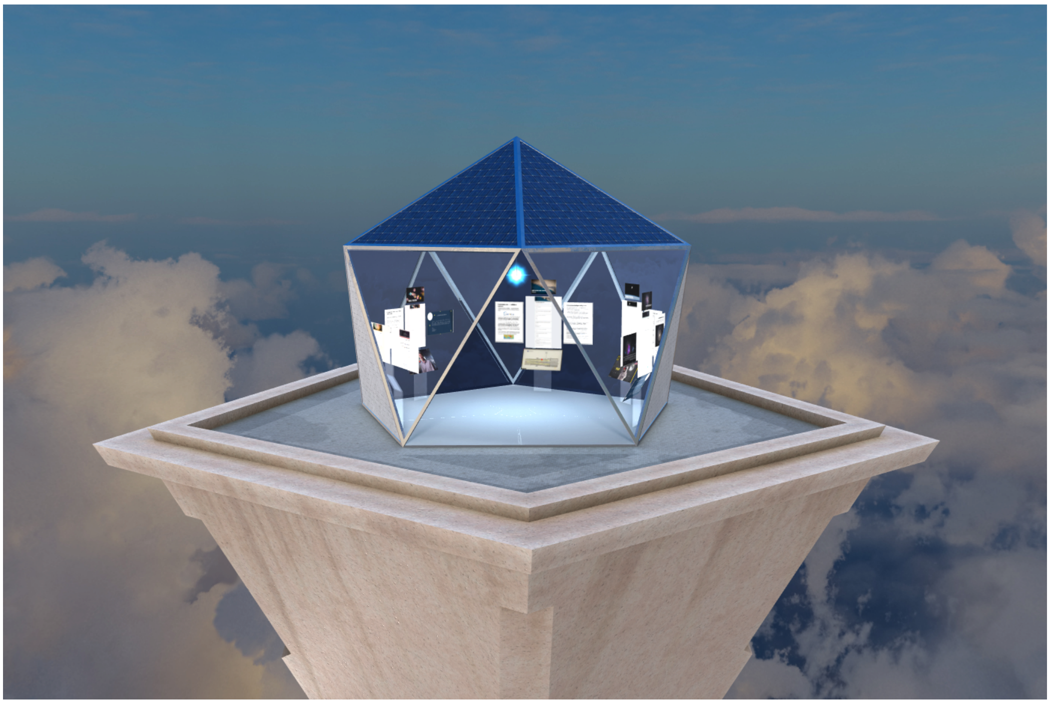


Figure 10.6: Exterior of the 3D space in which the 3D case of the second experiment was conducted.

Informed consent was obtained from all participants prior to the experiment, which was carried out based on and in accordance with the institutional endorsement of the authors' affiliation. All of the data collected during the experiment was anonymized and used exclusively as input to the statistical analyses detailed in later parts of this paper.

In the research, the participants were divided into two groups. 20 people (14 women, 6 men), average age of 27.35 (SD: 6.72) participated in the measurement in 3D virtual space. 5 out of the 20 subjects wore glasses during the experiment. 20 people (14 men, 6 women) participated in the 2D measurement, average age of 25.8 (7.29), 2 out of them wore glasses during the measurement.

10.3.2 Methods

The methods employed in the second experiment were the same as in the first experiment, as described earlier in Section 10.1 on the framework used for our experiments.

In particular, the subjects participating in the 2D and 3D also measurement had to provide feedback on which block they found to be the most difficult in retrospect, as well as some demographic data (gender, age, highest education). In addition to the data listed above, the participants in the 3D measurement had to fill out a series of questions related to their navigation experiences, as well as an IPQ questionnaire consisting of 14 questions, in which they had to evaluate their General Presence, Spatial Presence, Involvement, and Experienced Realism experiences on a 7-point Likert scale.

10.3.3 Key Hypothesises

Prior to conducting our experiment, we formulated the following key hypotheses:

1. Subjective assessments of lower cognitive load, along with lower pupil dilation would characterize the 3D case as opposed to the 2D case;
2. Questionnaires would generally be filled out faster and with more correct answers in 3D compared to 2D.
3. Compared to the previous measurement between the two 3D groups, the 2nd group performed with lower pupil dilatation than the previous 3D group;
4. Subjective assessments, by the test subjects, of the difficulty of questionnaires would correlate with pupil dilation and correctness of answers;
5. Lower cognitive load correlates with a faster completion time.

10.4 Results

Score-based performance in 2D and 3D

The result of the Mann-Whitney test revealed no statistical difference in the final scores of the four tasks between the 3D (M=22.387, SD=2.167) and 2D (M=22.125, SD=1.879) groups.

Completion times in 2D and 3D

The Independent sample t-test showed no statistical difference in the completion times of the four tasks between the 3D (M=36.7, SD=6.959) and 2D (M=37.8, SD=9.059) groups.

Pupil dilation between 2D and 3D

The group descriptives and differences between the two groups are displayed in Table 10.1 and in Figure 10.7. An independent sample t-test revealed that the group who performed the measurement in 2D had significantly larger pupil dilation (M=22.204, SD=3.971) than the 3D group (M=19.464, SD=2.902), (t(34.792)=-2.492, $p<0.018$), (Cohen's d=0.788).

The results showed that the group who filled out the questionnaire in the 3D space (N=20) had smaller pupil dilation with the mean rank of this group being 11.30, while the group who used the Spaceship 3D space for the same task (N=9) had a mean rank of 22.23. A Mann-Whitney test revealed that this difference was statistically significant, U=16, $p < 0.001$, r=0.65 (Table 10.2 and Figure 10.8).

The Spearman coefficient has not shown a correlation between the difficulty of the questionnaires and pupil dilation and has also no correlation between pupil dilation and completion time.

Table 10.1: Descriptives of the pupil dilation data of the 2D and 3D groups.

	Group	N	Mean	SD	SE	Coefficient of variation
Pupil Dilatation	3D	20	19.464	2.902	0.649	0.149
	2D	20	22.204	3.971	0.888	0.179

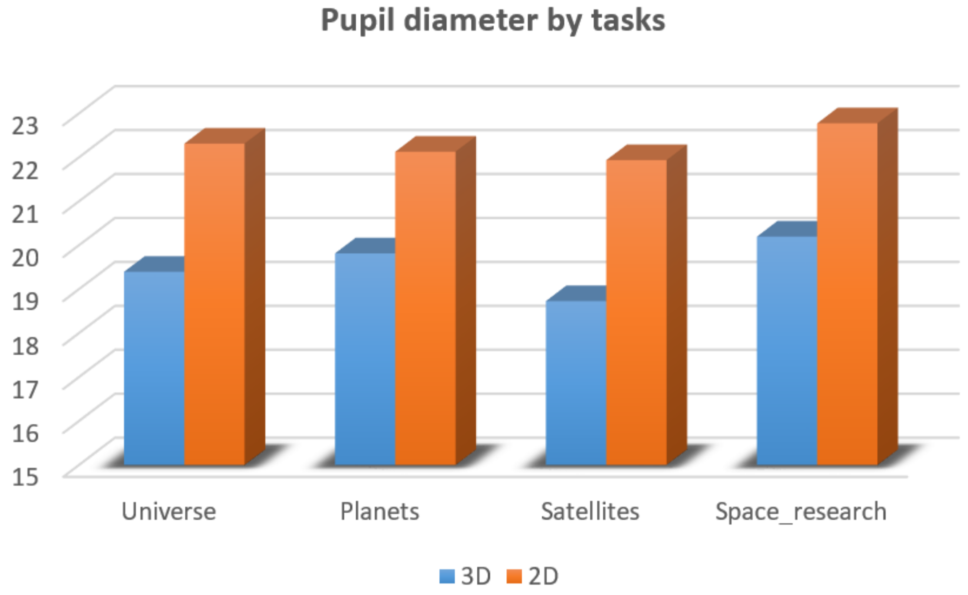


Figure 10.7: Pupil diameter sizes grouped by tasks.

Table 10.2: Descriptives of the pupil dilation data of the previous 3D and current 3D groups.

	Group	N	Mean	SD	SE	Coefficient of variation
PupilTasks	3D sublimus	20	19.464	2.902	0.649	0.149
	3D spaceship	9	26.203	4.371	1.457	0.167

10.5 Discussion

Among the cognitive load effects mentioned in the theoretical introduction, the split-attention and the modality effect are extremely common in the case of online teaching materials. This is because teachers regularly transmit information in the form of separate documents that are related in content. The aim of the research was to create a virtual environment that can reduce the cognitive load for the students and mitigate the effects of these two aforementioned effects.

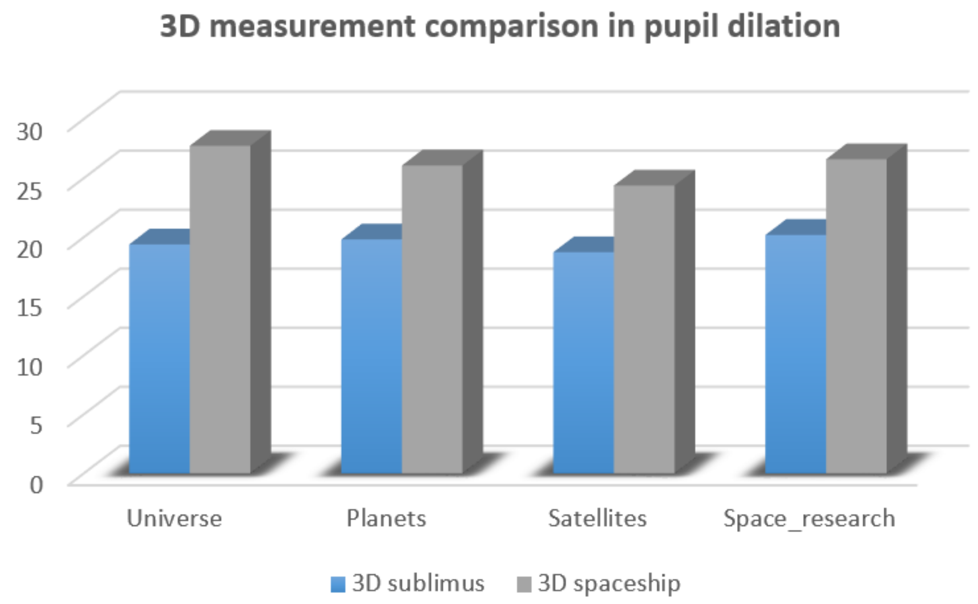


Figure 10.8: Comparison of the pupil diameter size between the previous 3D research results and the current ones.

The results of pupillometry measurements showed a significant difference between the two groups, favoring the second VR scenario. Therefore, it can be concluded that by utilizing the findings of previous research, it was possible to create a virtual space that reduces cognitive load during task-solving in the 3D desktop virtual environment. In this created space, despite the information being presented through multiple modalities and documents, the capabilities of VR enable their interpretation and overview as a single element or block. During the measurements, it was observed that the subjects used an intermediate view, where individual documents were enlarged and blocks or specific elements within a block appeared together in front of the user. I propose to refer to this capability as the “holistic overview” capability (in cases where the user retains the same position, but rotates to view different parts of a block, the term “alternating mode” seems to be a similarly apt description of user behavior). These capabilities can be used to obtain an overview of multiple documents in a way similar to real life situations when documents are placed beside each other on a table or a book stand. Since the created virtual space is clean and simple, all attention can be focused on the content and task solution.

There was no significant difference in completion time and overall score between the two groups. Although the group working in 3D consistently achieved better results, further studies are needed to determine the outcomes with a larger number of subjects. Additionally, the blending of modalities can be observed, particularly with videos in the virtual space. When the questionnaire window is active in front of users, they can respond in real-time based on the audio information from the previously started video. This can also be accomplished on 2D surfaces, but the natural navigational methods in 3D environments give users the sensation that they have simply turned their heads to view other content.

The subsequent correlation analysis did not reveal any significant difference between the perceived difficulty of the given blocks and the dilation of the pupil, nor the time taken to complete tasks, for either group. The 3D virtual space used in the initial measurement, which contained more colors and spatial objects and required greater navigation due to its larger size, was compared to a more simplified and optimized virtual environment with fewer distractions. The statistical analysis demonstrated a significant difference in pupil dilation between the two groups, suggesting that the distractors, which appeared to be established elements at the time of measurement, amplified the cognitive load-increasing effect of the split-attention effect.

Further measurements are necessary to determine whether, despite being disruptive factors in the completion of short-term tasks and understanding certain documents requiring text comprehension, such distractors can still aid long-term memorization based on the principles of the memory palace. To investigate this, not only eye-tracking but also EEG measurements would be useful.

Nevertheless, these results lead me to conclude that 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.

11. Guidelines for 3D Workspace Design

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, 102, 40]. These effects also extend to 3D spaces, as they allow users to create, visualize, and recall information in visually appealing and persuasive learning environments [36, 15].

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 [30]. 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 [Sudar14, Sudar16]. 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 [16].

In addition to spatial elements and objects, there is significant importance in the type and spatial relationships of digitally placed content [Sudar16]. 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 [Sudar16].

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 [Sudar16].

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 [Sudar16].

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 [Sudar16]. The aforementioned prominent viewpoints and pivot points [Sudar14, Sudar12], 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 [77, 15], [Sudar7].

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 [58, 57].

Part IV

Summary of Results and Future Research Directions (English and Hungarian)

Conclusions and Future Directions

Virtual reality has experienced rapid evolution in recent years, encompassing fully immersive and partially immersive software solutions. Both computer science and cognitive science are actively exploring the benefits of desktop VR solutions, with their applications extending to education and the workplace. Spatial experience is a fundamental aspect of human cognition, highlighting the significance of studying spatial cognition in the design of virtual workspaces. The measurement of cognitive load serves as a valuable indicator of task performance and difficulties encountered within these environments. Therefore, in my PhD research I aimed to delve into the subject of spatial cognition and to create a virtual environment that effectively reduces cognitive load.

In the dissertation, I explored a research domain situated at the interdisciplinary intersection of computer science and the cognitive sciences. While the primary focus was 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, experience, individual cognitive attributes, and overall performance.

In my research, I have provided evidence to show that identifiable salient nodes and pivot points can be effectively mapped onto well-defined regions within 3D VR spaces. These nodes play a vital role in task-solving within virtual spaces and contribute to the interpretation of content and spatial arrangement. Furthermore, I have demonstrated the influence of digital content types on their size, multiplicity, and the emergence of patterns indicating the spatial objects most closely associated with specific digital content. Additionally, in the case of freely arranged digital content, I have shown a preference for grouping based on topic rather than type. Based on the observation that a multitude of semantically charged 3D objects can make it difficult to achieve such topical groupings, I have proposed a new design principle that favors either reducing the number of 3D objects, or enabling users to freely create and rearrange 3D objects.

Based on my previous measurements, I designed two distinct virtual space scenarios and conducted a comparative analysis with 2D interfaces in the context of a learning task. Through this research, I have successfully demonstrated that by employing an optimal spatial environment and strategically arranging digital content, it is possible to reduce cognitive load using 3D virtual spaces compared to traditional 2D interfaces.

In the future, attempting to replicate the results of the research presented in this dissertation could help reinforce the obtained results and also further qualify our understanding of their scope. For example, similar experiments might be conducted on larger-sized groups, while incorporating a larger set of tasks and virtual environments. In addition, the measurement setup reported in the dissertation could be complemented by other modalities, including skin conductance, EEG and others. With recent advances in artificial intelligence, the possibility of using large language models to evaluate spatial interaction designs at a conceptual level, and then correlating those evaluations with actual user performance could be an interesting research direction to explore.

Konklúzió és jövőbeli kutatási irányok

A virtuális valóság az elmúlt években egy rendkívül dinamikusan fejlődő területté vált legyen szó akár teljesen immerzív, akár a szemi-immerzív megoldásokról hardverek és szoftverek tekintetében egyaránt. A desktop VR megoldások előnyeit az informatika és a kognitív tudomány egyaránt vizsgálja, alkalmazási területe egyre bővül az oktatás és a munka világában. Az emberi tapasztalás egyik legalapvetőbb jellemzője a térbeliség és ehhez kapcsolódóan a téri kogníció vizsgálata is kiemelt jelentőségű a virtuális munkaterek tervezésében. Az ilyen környezetben történő feladatvégzés hatékonyságának és nehézségeinek mutatója a kognitív terhelés mérése. Disszertációm célja a téri kogníció vizsgálata, valamint a kognitív terhelést csökkentő virtuális környezet kialakítása.

A disszertáció egy olyan kutatási területet mutat be, amely a számítástechnika és a kognitív tudományok interdiszciplináris határterületén fekszik. A fókusz elsősorban az információs technológiákra helyeződik, azonban a kutatási kérdések vizsgálata során elengedhetetlen volt a kognitív pszichológia mérési módszerek alkalmazása. Ennek eredményeként a felhasználók viselkedése, tapasztalatai, egyéni kognitív jellemzői és teljesítménye is mérhetővé vált.

A kutatásomban bebizonyítottam, hogy azonosíthatók kiemelkedő csomópontok és forgáspontok, amik jól elhatárolható régiókra bonathatók. Ezek fontos szerepet játszanak a virtuális térben elhelyezett feladatok megoldásában és a tér tartalmának és elrendezésének értelmezésében. Kimutattam, hogy a virtuális térbe helyezett digitális tartalom típusa befolyásolja annak méretét, számosságát és kirajzolható egy mintázat, amely megmutatja, hogy mely térbeli objektumok állnak leginkább kapcsolatban bizonyos digitális tartalmakkal. Emellett a szabadon elrendezett digitális tartalmak esetében kimutattam, hogy a tartalmak témája szerinti csoportosítás gyakoribb, mint a típus szerinti rendezés, továbbá, hogy ennek a preferenciának az érvényesüléséhez szükséges a térbeli objektumok számosságának korlátozása, vagy pedig azok szabad létrehozásának, illetve átkonfigurálásának lehetővé tétele.

Korábbi méréseim alapján két különböző virtuális környezetet terveztem, melyeket egy 2D felülettel hasonlítottam össze egy szöveg- és tartalomértési feladat során. Kimutattam, hogy egy optimális térbeli környezet és digitális tartalom elrendezése esetén a kognitív terhelés csökkenthető a 3D desktop virtuális valóságban a 2D-hez képest.

Jövőbeli tervként természetesen felmerülhet a disszertációban bemutatott eredmények replikálását célzó kísérletek végrehajtása, melyek a tématerülettel kapcsolatos ismereteinket akár tovább is finomíthatják, amennyiben ezek a kísérletek nagyobb létszámú felhasználói csoportok részvételével történhetnének, és / vagy tágabb tématerületeket, illetve több különböző típusú feladatot érinthetnének. Továbbá az itt bemutatott kísérleti környezet akár további modalitásokkal, így bőrkonduktanciával, vagy EEG-vel is bővíthető. A mesterséges intelligencia területének rohamos fejlődése felveti többek között azt a lehetőséget is, hogy megvizsgáljuk, hogy a nagy nyelvi modellek a 3D terek koncepció szintű leírása alapján kialakult megértése mennyiben használható a tényleges felhasználói teljesítmény előrejelzésére.

Part V

Theses

Theses

In this chapter, I formulate a set of theses derived from the results presented in this dissertation. A list of references to the papers I have published, together with my supervisor, can be found within the heading of each thesis.

Thesis 1 – Relevant publications: [Sudar12, Sudar14]

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: [Sudar16]

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: [Sudar15]**

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.

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