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3D Sketch Maps: Concept, Potential Benefits, and Challenges

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Abstract

Studying the 3D aspect of spatial information has become increasingly important due to changes in the way we interact with the surrounding environments as well as technological innovations. Current pen-and-paper approaches of sketch mapping have a limitation in investigating 3D spatial knowledge as they are forced to be drawn on 2D interfaces. In this paper, we propose the concept of 3D sketch mapping as a tool to study human spatial knowledge by externalizing the mental models of spatial information with 3D representations. The goal of this paper is to introduce the concept, discuss its potential importance and challenges, and share our vision for future research directions.

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1 Introduction

The spaces we live in are naturally three-dimensional. Although many aspects of spatial cognition [10], such as navigation, have been predominantly studied with a focus on the horizontal plane, there are situations in which the vertical dimension is equally important. The 3D aspect of spatial information is an increasingly important issue and it is due to the changes in the environment surrounding us (e.g., more complex buildings) as well as technological advancement (e.g., 3D virtual-reality simulations or flying a drone). Thus, understanding how people perceive, navigate, and interact with spaces while accounting for the 3D aspect has become essential for various applications such as training pilots or wayfinding in multi-level buildings.

One of the popular methods to study human spatial knowledge is the use of sketch maps. Sketch maps are drawings of spatial environments typically made based on spatial memories of the person and they have been a popular research tool to study human spatial understanding and decision making [13]. However, one of the limitations regarding the use of sketch maps in contemporary research is that they are forced to be drawn on 2D interfaces, often on a piece of paper. Studying the understanding of the 3D aspect of spatial knowledge with 2D sketch maps is challenging as drawing mental models that potentially contain 3D information on a 2D interface requires a set of mental transformations that can be highly prone to distortion and errors [14].

In this paper, we introduce the concept of sketch mapping in 3D. A variety of recent technological developments from desktop-based 3D drawing software to extended reality (XR) devices opens new possibilities to implement novel digital interfaces for 3D sketch maps. We argue that 3D sketch maps can enable studying people's understanding of 3D spatial information directly with 3D interfaces, which may seem intuitively plausible, but it can also introduce potential complexity to a simple drawing process. The aim of this paper is to propose the concept of 3D sketch mapping, with a particular focus on XR technologies as a means of implementing it, and to discuss potential research topics and challenges while comparing it with the conventional 2D method.

2 Background

2.1 Mental models of spatial information

A mental model of spaces is a mental representation of the relative locations and attributes of phenomena in spatial environments [5]. For example, it is required for a pilot to construct a mental model of a flight path together with the relative locations of weather-related spatial information in order to perform the task of flying an aircraft. Similarly, a nurse navigating between wards in a large hospital, a shopper visiting shops in a complex mall, and a commuter going through a large underground interchange, all have in common a need for a mental model of their environments.

Understanding and assessing mental models of spatial information has been an important research topic in the field of cognitive science. Especially for navigation and wayfinding domains, the majority of studies have been based on spatial objects and associated relations lying on a horizontal surface. With respect to 3D, researchers have been interested in the unique characteristics of mental representations along the vertical axis compared to the two horizontal dimensions. For example, previous research has revealed an anisotropy of vertical and horizontal spaces – people are better at navigating horizontally (e.g., within floors) than vertically (e.g., between floors) [8].

One major barrier to probing people's mental models of spatial information for the tasks in which the vertical dimension is important is the lack of appropriate tools to externalize such models. Traditional media only allow the depiction of spatial information on a 2D screen or paper. In response to this barrier, researchers have explored different methods to examine the vertical aspect of mental models such as structure mapping, 3D pointing, and object recognition [8, 4]. Despite these efforts in exploring the 3D aspect of spatial knowledge, it is still largely undiscovered what makes the difference in human cognitive processes and how people perceive and understand 3D spatial information, especially with regard to navigation. Moreover, many previous studies utilized the 2D-based approach to assessing spatial knowledge for the environments and tasks where the vertical dimension is important. This is largely due to the absence of a standardized method for studying spatial understanding of the vertical component of spatial knowledge.

2.2 Sketch maps: A tool to externalize mental models

Sketch maps have been an established tool to externalize mental models and assess spatial knowledge of an environment [2]. They have been widely used in the fields that study human spatial decision-making and information processing, such as navigation and wayfinding [12]. Sketch maps are particularly well suited to extracting survey knowledge of environments because they require combining multiple spatial relations in a single sketch. This can be a good indicator of overall spatial knowledge of larger environments [11]. Sketch maps are routinely distorted in an inconsistent way [14] but not all information in sketch maps is distorted inconsistently – some qualitative spatial relations remain invariant [15]. This is one reason why the key challenge in analyzing sketch maps is to decide on what information to extract from them [11]. The main approaches focused on analyzing sketch maps' type, their metric accuracy, the correctness of qualitative relations represented on them, and the level of generalization [13].

One of the limitations of using sketch maps is that it enforces the use of a 2D sketch for representing spatial knowledge of an environment. For example, imagine a person trying to create a 2D sketch map of a complex university building. They can try to either project all the information on a plane (i.e., flatten the vertical information), create separate sketches for each floor, or draw from an isometric point of view. These options, however, make them choose to represent only a subset of information and this is against the main advantage of sketch maps which is the ability to represent all information at once. Humans can maintain and utilize 3D spatial information, however, it is unclear how they could externalize this information in an accessible and intuitive way.

3 Sketch mapping in 3D

The limitation in the current practice of using sketch maps for 3D spatial information motivated the conceptual development of 3D sketch maps. Our hypothesis is that it will be more effective to study 3D spatial knowledge with 3D sketches as this requires less mental projection compared to 2D ones. Although the idea of representing 3D spatial knowledge with 3D interfaces may seem natural, it is necessary to carefully consider the consequences of adding one more dimension. The main research question that needs to be addressed in the study of 3D sketch maps is whether it can be an adequate method for extracting mental models of 3D spatial information from individuals. Answering this research question will require investigating 3D sketch mapping from different perspectives: (1) *conceptual* and *methodological* perspective that looks into the validity of the concept and the methodology, (2) *cognitive* perspective for understanding underlying cognitive processes, and (3) *technological* perspective on how to design an interface for 3D sketch mapping, especially using XR technologies. As shown in Table 1, we have developed research questions for each aspect which will be discussed in the following.

3.1 Conceptual and methodological perspective

The validity and effectiveness of 3D sketch mapping can vary depending on its use cases. While the main goal of 3D sketch mapping is to assess the knowledge of 3D spatial information, there exist differences among the use cases in different domains of spatial cognition [10] in terms of the purpose of using sketch mapping, their requirements, and user characteristics. For example, one use case of 3D sketch mapping can be in the field of aviation where the pilots' spatial knowledge of flight routes and weather situations needs to be assessed.

Table 1 Research questions to be addressed for 3D sketch maps.

	Research questions
Conceptual and methodological perspective	- For which use cases do 3D sketch maps allow the creation of more valid and reliable sketch maps compared to the 2D approach? - How should 3D sketch maps be analyzed?
Cognitive perspective	- What are the cognitive processes underlying the creation of 3D sketches? - How do 3D sketch maps differ from 2D ones with regard to their conveyed information? - What are the behavioral features suitable for analyzing the cognitive processes involved in 3D sketch mapping?
Technological perspective	- Where on the reality-virtuality continuum are tools that optimally enable 3D sketch mapping? - Can XR-based 3D sketch mapping tools be more valid and reliable than the 2D pen-and-paper method? If so, in which aspect?

Another use case is to measure the accuracy of mental representations of laypeople for the task of navigating buildings. In addition, some groups, such as architects, might be much more used to encoding and storing vertical aspects of spatial knowledge; a tool that makes 3D sketch maps easy to draw will allow us to study these mental processes, and their different development between professionals and laypeople. Understanding the similarities and differences among these cases will help define 3D sketch mapping as a tool.

Another important aspect from a methodological perspective is how to analyze 3D sketch maps. Interpretation of 2D sketch maps has been a topic of interest and there exist methods to evaluate them both qualitatively and quantitatively, and classify them based on their type [7]. For 3D sketch maps, it is still a question whether these methods that have been developed for 2D sketch maps are also valid. We can expect differences between the 2D and 3D sketch maps in terms of the types of spatial knowledge that are likely to be expressed in them and also how they are expressed. For example, vertical information might be distorted in a way different from horizontal information and these distortions might weigh differently on the overall quality of the sketch in the given context.

3.2 Cognitive perspective

From a cognitive perspective, the creation of 3D sketch maps can have different underlying cognitive processes compared to 2D ones. Cognitive processes may differentiate themselves from understanding to transforming onto a sketch in 3D compared to 2D. Creating 3D sketch maps might require less cognitive load regarding mental projection, but the added dimension for sketching may naturally increase the cognitive demand. Moreover, there will be additional extrinsic cognitive load related to the interaction with the technology used for enabling 3D drawing, compared to the simple pen-and-paper interface. The pen-and-paper interface is a medium that we are extremely familiar with and such familiarity may facilitate the mental projection process required in sketch mapping, whereas this is not the case with the 3D interaction tools that are currently unfamiliar to most people.

3D sketch maps can have different characteristics in terms of conveyed information compared to 2D ones. Given the additional dimensionality, people may show different behavior regarding the type of information that they tend to express in 3D. The potential difference in conveyed information will directly influence the way they are analyzed. All methods that are currently available for interpreting sketch maps focus only on a subset of all information contained in a sketch map. It is currently unknown how this subset of information differs in 3D sketch maps, e.g., what are the new types of information that are commonly communicated by users when they are asked to represent a space in 3D. To answer this question, an experimental investigation will be necessary that compares 2D and 3D sketch maps in terms of the types of spatial information conveyed in them.

In the research studies of 3D sketch maps, the behavior analysis of how people create them will help understand the underlying cognitive processes. The behavior of users is closely related to the technological implementation of the interface since the way people interact with a tool is often shaped by the interface provided to them and the tool's capabilities. For sketch mapping, analyzing behavior measures such as hand gestures, sequences of lines drawn, or pause/hesitation patterns can help understand the underlying cognitive processes. One particular measure that can provide us with rich information would be eye-tracking data [6] as sketch mapping heavily involves visual attention and perspective changes. Although the use of gaze information is sometimes considered limited and challenging as an input modality in 3D interaction [3], it can be an interesting source of information for analyzing behavior and understanding cognitive processes.

3.3 Technological perspective

One of the reasons for utilizing the 2D approach of sketch mapping even when studying the 3D aspects of spatial knowledge is the lack of technologies that enable 3D sketching. The recent advancement of XR technologies allows us to design an interface that allows 3D inputs from users. For example, there already exist non-professional tools for 3D drawing using XR such as Google Tilt Brush[1] and they enable novel interactions between users and 3D information. As mentioned earlier, we mainly consider XR technologies as a means of enabling 3D sketch mapping in this paper.

The wide spectrum of XR technologies allows for designing different interfaces for sketching. In Figure 1, we show some possible interfaces for 3D sketch mapping using XR together with existing methods where the horizontal axis is the reality-virtuality continuum [9] and the vertical axis is the dimension of the externalized output. The area that corresponds to the research gap this paper aims to address is shown with a rectangle in the figure. To provide an example, a VR-based interface can enable 3D sketch mapping, either with a desktop or with a head-mounted display (HMD). Another possibility is to use mixed reality (MR) to combine a physical object from reality with additional digital information augmented on it. An MR-based interface can augment the vertical dimension on top of the traditional paper interface and allow users to enter and modify 3D information. With different options for implementing the interfaces for 3D sketch mapping, it requires careful consideration in designing and evaluating these technical configurations as they often define the boundaries of what is possible using the interface and affect the behavior of the users. Comparing the positions along the horizontal axis in the figure corresponds to the question of how to realize the 3D representations. This is the opportunity that technological advancements provide for us to explore. Moving vertically from 2D to 3D in the figure corresponds to the question of when it is beneficial to use 3D representations. And this relates back to the importance of considering the purpose and the use case of sketch mapping as discussed earlier.

As 3D sketch mapping is a newly proposed concept for studying human spatial knowledge, it is important to confirm its validity and reliability from a technological point of view. We need to study whether users can create more valid/correct and reliable representations of

[1] Tilt Brush by Google. `https://www.tiltbrush.com`

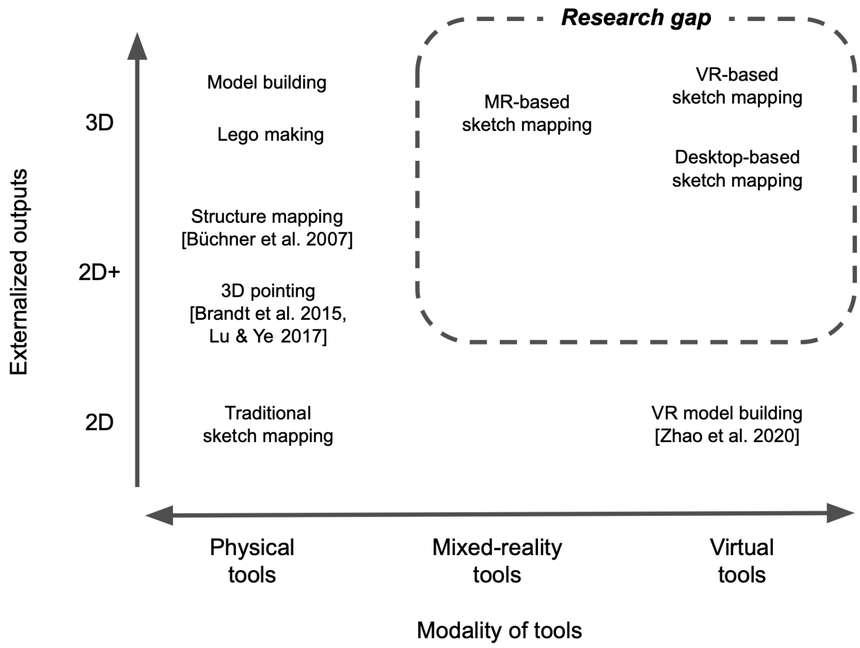

Figure 1 Tools for externalizing spatial knowledge. The x-axis represents the modality of externalizing a mental representation of space, from physical to virtual tools. The y-axis shows different types of produced outputs based on their dimensions – this does not refer to the spatial information that is encoded but to how it is externalized.

their spatial knowledge of environments using an XR-based 3D interface. Previous research shows evidence that free 3D drawing in the air is often less accurate than drawing on 2D surfaces [1]. It can be a concern because accuracy, or quantitative correctness, is one of the core criteria for evaluating sketch maps, and thus it requires empirical validations while considering the technological design of the interface that can improve the accuracy. On the other hand, from a user's point of view, there can be differences between 2D and 3D sketching in terms of perceived workload. It is important to study whether the perceived workload is higher in the 3D case, how the physical and temporal demands are related to the richness of the representation, and how it affects the user experience. Another interesting topic in this direction of research that connects the technological and cognitive aspects is to study the influence of users' spatial abilities on the validity and reliability of the 3D sketch maps that they create.

4 Concluding remarks

In this paper, we introduce the concept of 3D sketch maps while considering its potential benefits and challenges. As the importance of studying human understanding of 3D spatial knowledge has increased recently, we envision that 3D sketch maps can become an effective tool to assess it. It is an exciting time to conduct research in this direction as the recent advances in XR technologies make it possible to implement the interfaces for creating sketches in 3D. There can be different configurations of technologies to design an interface for 3D sketch maps and it is important to compare them both theoretically and empirically in order to make it an effective tool. As discussed in this paper, 3D sketch maps can potentially solve some of the limitations of using the traditional 2D approach, but there exist challenges such as increased cognitive load and reduced accuracy that need to be addressed in future studies. In conclusion, the idea of sketch mapping in 3D proposes interesting directions for spatial sciences research and invites researchers to explore them.

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