Can You Sketch in 3D? Exploring Perceived Feasibility and Use Cases of 3D Sketch Mapping

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Abstract

Sketch mapping is a research technique that has been widely used to study what people think about the spatial layout of an environment. One of the limitations of the current practice of sketch mapping is that the interface (a pen on paper or digital tablets) forces people to draw on 2D surfaces even when the information to be represented is 3D. For the purpose of studying the 3D aspect of spatial understanding, the recent advancements in extended reality (XR) technologies including virtual reality, augmented reality, and mixed reality are interesting as they provide novel ways to create 3D sketches. In this paper, we investigate how the concept of 3D sketch mapping using XR is perceived by users and explore its potential feasibility and use cases. For this, we conducted semi-structured interviews with 27 participants from three domains: aviation, architecture, and wayfinding. Our findings show that the concept is well-perceived as an intuitive way to externalize the 3D aspect of spatial information, and it has the potential to be a research tool for human cognition research as well as a practical tool that can provide added value in different professional activities.

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1 Introduction

Understanding how people perceive and recall spatial information about an environment has been a research area of interest in the fields of spatial cognition and geographic information science [7, 16, 8]. One straightforward way to study human spatial understanding is sketch mapping as it simply asks people to draw what they think or remember about the spatial layout of the environment [17]. It has been a versatile technique that is easy to apply while providing interesting insights into the spatial understanding of the drawer [5, 19]. In addition to externalizing memory, another use of sketch mapping is decision-making and planning (e.g., in search and rescue [1] and the design of game cartography interfaces [25]).

The traditional way of sketch mapping, which is done using 2D interfaces (pen on paper or digital tablets), was often sufficient for the purpose since most of the studies in spatial cognition predominantly focused on the horizontal plane, that is two-dimensional space [18]. But what if we are interested in understanding how people perceive and remember three-dimensional spatial information? The 2D approach may not be sufficient to study the 3D aspect of the mental representations of spatial environments. There are situations where studying an individual's memory and expression of space along the vertical dimension is of high importance. The number of such situations has been increasing recently due to, first, the changes in our surrounding environments (e.g., more complex buildings and structures that are not bound to a flat surface), and second, technological innovations that enable new ways of interacting with spaces (e.g., flying a drone or 3D virtual-reality simulations). With the traditional sketch maps, studying the 3D aspect of spatial understanding can be challenging as it requires a set of mental transformations for the drawers to express the mental model as a 2D representation, and it can be highly prone to distortion and errors [27].

The idea of 3D sketch mapping is to study the 3D aspect of spatial understanding *directly with 3D representations* [14]. We hypothesize that it can be an effective way to study 3D spatial understanding by allowing people to make 3D sketches as it requires less mental projection compared to creating 2D ones. Making a 3D sketch has become accessible and easier with the recent development of extended reality (XR) technologies such as virtual (VR), augmented (AR), and mixed reality (MR), i.e., the spectrum of blending physical and digital world [28]. There are many commercially available XR devices with a head-mounted display that can show 3D visualization and hand-held controllers that allow direct interactions with surrounding 3D spaces. Using these devices, users can create 3D sketches by doing mid-air drawing, that is simply moving their hands in 3D space.

The goal of this study is to explore how the concept of 3D sketch mapping is perceived by users from different domains and to understand their needs to make it a feasible approach. In this paper, we report the findings from semi-structured interviews with 27 participants from three domains: aviation, architecture, and wayfinding. The choice of the domains was based on the arguments that there are certain professions with high importance of complex 3D spatial information in their professional activities (aviation and architecture) and that the general public in some non-professional activities can also benefit from the 3D approach (wayfinding). The results of our study show that the concept of 3D sketch mapping was perceived as an intuitive way to represent 3D spatial information but there are certain situations where the existing 2D approach would be more effective. With these findings, we identified potential use cases of 3D sketch mapping that are domain-specific and also general across the domains. Among these use cases, we found that 3D sketch mapping is especially useful in communication when users hold asymmetrical knowledge/information (e.g., expert vs. non-expert, a person who is familiar vs. unfamiliar with the space). The findings presented in this paper serve as a basis for developing 3D sketch mapping as an effective tool to study spatial understanding that will complement the traditional 2D sketch mapping.

2 Background

2.1 Sketch mapping

Sketch maps have been one of the commonly used methods to study people's perceptions of environments. Since it was introduced by Lynch in the 1960s [15], sketch mapping has been used in various research studies for externalizing and studying mental models of spatial

information [24, 26, 21]. One of the main characteristics of sketch mapping as a research tool is that it is truly open-ended and the drawers are free to include anything in any form [17]. This results in ease and simplicity in terms of collecting data, but it also produces some challenges. The main limitation of sketch mapping is the abstraction and distortion of the collected information [10, 2], and therefore it is challenging to interpret the collected data [5]. One of the reasons for the abstraction and distortion of information is the medium used for sketch mapping that forces drawers to represent mental models on a 2D surface regardless of the spatial dimension to be externalized [6]. The traditional approach to sketch mapping uses a pen and paper, which is a two-dimensional interface, and it can be difficult to effectively express mental models, especially when the information to be externalized is 3D. Converting 3D information to 2D in order to represent it on paper can cause unnecessary cognitive demand, and it is prone to distortion [27]. Based on this limitation, the concept of 3D sketch mapping adds another dimension to the conventional 2D approach. It may already seem intuitive to represent the 3D aspect of spatial information with 3D interfaces, however, it requires careful consideration from different perspectives to validate it as an effective method to study human spatial understanding.

2.2 3D sketching with XR

3D sketching is an interesting activity in fields other than spatial cognition research and for different purposes than mapping, especially with a focus on the aesthetical expression of an object or a confined area (e.g., in product and interior design [11], and arts [13]). However, creating 3D sketches in general has been a challenging task also in those fields. One of the main reasons has been the lack of 3D display technologies that enable visualizing 3D [3]. Early systems for 3D sketching were forced to use 2D displays, and to create 3D lines on a 2D display, the drawers had to go through an unintuitive and tedious process of specifying a set of constraints to define a curve [20, 9]. What made 3D sketching more accessible recently is the development of XR technologies. With XR devices commercially available these days, users can create 3D lines and objects directly in 3D space through freehand mid-air drawing, enabled by head-mounted 3D displays together with motion-tracking technologies. XR-enabled 3D sketching greatly changes the way we express and interact with 3D information [23, 4]. From the sketch mapping point of view, the intuitive interface of XR for creating 3D sketches is a promising opportunity to be explored. Fig. 1 shows a user creating a 3D sketch with an XR device.

Technological developments in 3D sketch mapping may be profoundly influenced by research in 3D sketching, as both topics stand to gain from advancements in hardware technology for XR and 3D display as well as knowledge in spatial cognition, but it also requires a more extensive understanding of how larger-scale spatial information (e.g., the topography of a terrain and layout of a multi-story building with distinct interior design per room/floor area) can be externalized and communicated. Such connections and distinctions between 3D sketching and 3D sketch mapping in the research scope of spatial information also motivate our domains of interest and interview question design in our study.

2.3 Research questions

With the concept of 3D sketch mapping and the technology available to implement it, our interest is to explore how it is perceived from a user point of view. To make it a valid approach to studying human spatial understanding and validate its applicability as a research technique, it is important to understand how users feel about its feasibility and usability. The research questions to be addressed in this paper are as follows:

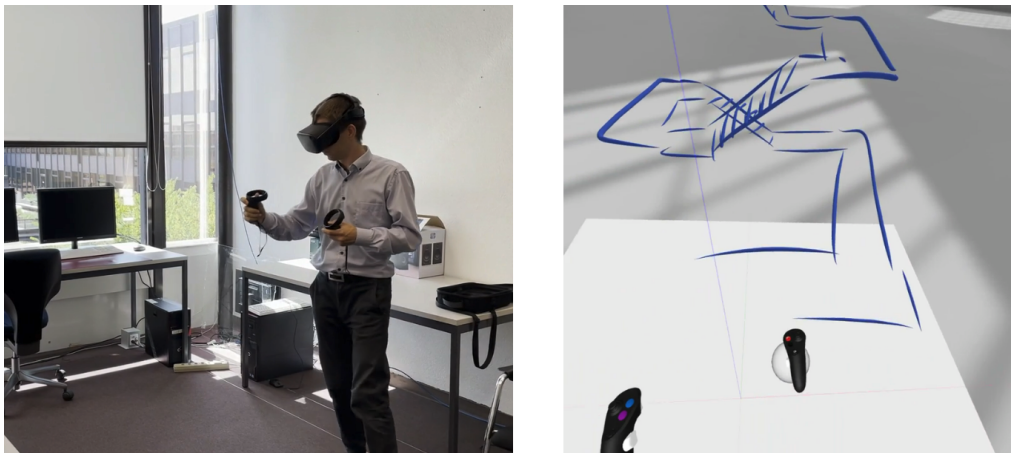

Figure 1 A user performing a 3D sketch mapping task using a VR headset (left) and the 3D interface that he sees (right). The task was to sketch the shape of the stairs in a multi-floor building.

- How is the concept of 3D sketch mapping using XR technology perceived in terms of its feasibility in different domains?
- How do 3D sketch maps differ from conventional 2D sketch maps in terms of their applicability?
- What are the potential use cases of 3D sketch maps in different domains?

3 Study design

With the purpose of investigating the perceived feasibility of 3D sketch maps and exploring the potential use cases, we followed a qualitative approach and conducted semi-structured interviews with participants from three domains. The domains were selected after considering the importance of 3D information and the potential generalizability of the findings to non-professional applications. We chose two professional domains: aviation and architecture, where 3D information is expected to be important for carrying out different tasks. Another domain we investigated in this paper is wayfinding. We decided to include it in our study because wayfinding was the most commonly applied domain for the sketch mapping technique and we wanted to identify the gap that 3D sketch maps can address. It is a non-professional domain where we can explore the generalizability of the concept beyond people with specific professions.

3.1 Participants

We interviewed 27 participants in total (8 females and 19 males), nine participants per each of the three domains. For the aviation domain, we recruited pilots in either the commercial or private sector. We had three commercial pilots and six private pilots participated in the interviews. For the architecture domain, we recruited architects who had a Bachelor's degree in architecture and at least one year of work experience in the industry. In the wayfinding domain, we recruited students at a university who have been taking courses in multi-level buildings. The interviews focused on their experience in wayfinding inside complex multi-level buildings. All interviews were conducted in person and audio-recorded.

3.2 Procedure

The interview with each participant started by introducing ourselves and the research project that the current study was part of. We explained the purpose and the procedure of the interview to the participants and asked them to sign a consent form if they agreed to take part in it. Then we started recording the audio. The interview was semi-structured and we followed a list of guiding questions. The guiding questions concerned four topics: the importance of 3D information in the domain, how 3D information is represented in their tasks, the potential use of 3D sketch mapping, and the potential challenges. The full list of the guiding questions is attached in Appendix A. The interviewer used these questions to structure the interview but did not exactly follow them, i.e., we asked ad-hoc follow-up questions to interesting responses and also changed the order of the questions when necessary. After the first two topics, we introduced the concept of 3D sketch mapping. Once the concept was introduced and before continuing with the remaining topics, participants were also asked to try a 3D sketching tool available in the market so that they become familiarized with the concept of mid-air 3D sketching. For this, we used an existing app called Gravity Sketch[1] on the Oculus Quest VR headset[2]. Upon the completion of the interview, the participants were compensated with 25 Swiss Francs for their participation. The study design including the procedure, interview questions, and monetary compensation has been approved by the ethics commission of ETH Zürich.

3.3 Data analysis

We adopted an open coding approach to analyze the interview transcripts due to the exploratory manner of the study [22]. Two authors of this paper developed and evaluated the coding schema, first individually and then discussed together to merge them into the final one.

4 Results

In this section, we report the findings from the interviews. As a result of analyzing the transcripts, we grouped the findings into five categories: (1) importance of 3D information in their domain, (2) limitations of the current 2D approach to dealing with 3D information, (3) potential advantages of 3D sketch mapping, (4) use cases, and (5) challenges. For each of the findings, we provide one or two example quotes from the interviews. The summary of the findings across categories is shown in Table 1.

4.1 Aviation

"The 3D aspect is crucial in the aviation industry." The importance of 3D information in the domain of aviation was highly acknowledged by multiple participants. Four out of nine participants mentioned how 3D information is important in carrying out their tasks:

> *You have to think three-dimensional as soon as you are in the air. I have to think of where I am in terms of not only longitude and latitude but also altitude. (P9)*
> *You have to put the information in your mental picture and it is automatically 3D because the environment we are flying in is 3D. (P4)*

[1] Gravity Sketch: `https://www.gravitysketch.com/`. See `https://www.youtube.com/watch?v=a93kTXPHdn8` for a demonstration of 3D sketching in VR. Accessed: June 11, 2024.
[2] Oculus Quest by Meta: `https://www.meta.com/gb/en/quest/`. Accessed: June 11, 2024.

Two participants reported that the information along the vertical dimension is particularly important in the private sector:

> *In private aviation, the altitude, or height information is very important. One thing you have to consider for private flights, and less for commercial flights, is the height of the terrain. There is always a safety altitude that you must maintain and you want to know how high the terrain is at the place you want to go. (P5)*

"We always use 2D to communicate 3D information and it creates some problems." While the participants perceived the importance of 3D information, they reported limitations in showing 3D information in 2D representations that they use currently. First of all, one limitation of presenting 3D information on a 2D representation is that the information is flattened, and therefore, it is often too densely displayed and hard to read:

> *The representations we use are top-down views. Then you have a lot of information about the airspace, heights, and limits. Everything is displayed in such a manner that sometimes it's unreadable, to be honest. (P7)*

While the participants perceived the importance of 3D information, they reported limitations in showing 3D information in 2D representations that they use currently.

> *The visualizations that we have are typically always 2D projections of 3D environments. So it's always up to pilots for interpretation. (P1)*
> *So you build a mental model in your mind that is 3D, but then during the flight, you still have to use your 2D representations to look for where you need to go and where you can't go. There is the potential to get confused. (P5)*

"I can imagine 3D sketch maps to be useful." Although making a sketch was not normally part of the professional activities of a pilot, they saw the potential advantage of sketch mapping in 3D, especially in terms of the ability to represent 3D information directly in 3D. Three participants reported that 3D representations could be more intuitive and clear than 2D ones when creating them as well as reading them:

> *For three-dimensional sketching, I would have an easier time sketching it than having it on paper. (P8)*
> *If you have a way to show the same information but in 3D, it will be very useful and a lot more intuitive to understand. (P6)*

Another interesting point mentioned by three participants regarding the potential advantages of 3D sketch mapping was the possibility of building a better mental model through the process of sketch mapping in 3D:

> *If planning were made in three dimensions using 3D sketch maps, I think also in your mind, you would remember and think of your flight like this. I might have a more 3D mental model of a path if the planning were in 3D. (P8)*
> *What I can imagine is that doing the 3D sketching in the planning phase could help you during the flight because you planned it in a different way. I can build a better representation of the space which could help me during the actual flight. (P5)*

Table 1 Summary of the main findings from the interviews. The numbers in brackets show the number of participants who mentioned the point.

	Benefits of 3D sketch maps over 2D	Use cases	Potential challenges
Aviation	▬ Information is not compressed, therefore easier to read (6) ▬ More intuitive when creating (3) ▬ Possibility of building a better mental model (3)	▬ Flight route planning (4) ▬ Communication with non-experts (4) ▬ Training new pilots (3)	▬ Learnability of the tool compared to pen and paper (1) ▬ Fail safety of the tool to be used in the domain (1)
Architecture	▬ Intuitive to sketch, without 3D to 2D transformation (7) ▬ No abstraction or compression of information (3) ▬ Ability to show all information in a single representation (2)	▬ Communication with non-experts (5) ▬ Allowing non-experts to sketch themselves (2) ▬ Replacing physical model building (3) ▬ Complementing existing 2D sketches and model building (3)	▬ Less directness when sketching a concept compared to pen and paper (5) ▬ Consideration on how the tool might affect the sketched outcome (3)
Wayfinding	▬ Ability to show 3D information directly in 3D (3) ▬ Easier to understand the sketched information (5)	▬ Communication (3) ▬ Route planning for navigation (3) ▬ Wayfinding in indoor multi-level buildings rather than outdoor (3)	▬ Availability of hardware (3) ▬ Unfamiliarity of 3D representations compared to 2D (2) ▬ Impact on information selection process when sketching in 3D (1)

Use cases: Flight route planning, communications, and training. With these potential advantages, the participants could come up with a number of use cases in the aviation domain. A use case that was mentioned by four participants was for sketching the flight routes in the planning phase:

> *I think flight planning could be really interesting, especially for places that I am not familiar with. (P9)*
> *So I can imagine you actually look at a base map on 2D paper, and you can draw flight routes in 3D over the map, and then the information gets flattened down to the piece of paper. And whenever you need to see the 3D, it pops out of the paper. (P5)*

Another use case that four of the participants could anticipate was for communication purposes. They emphasized how it could be more useful for communication with non-experts compared to experts:

> *Making 3D information accessible also in 3D would make it easy to understand for people who are not professionals. For the professionals, we have a common language and we don't have to think a lot about it when it's represented in 2D. However, sketching in 3D would be beneficial for non-professionals who don't know the language of the domain. (P4)*

If it's a long flight, that would be something I could see myself doing, just to have all crew members involved in the flight plan. I can see myself just sketching it out because then you probably will have a common idea of what I was trying to say. (P3)

Another potential use case of 3D sketch mapping was for training. Three participants expected that it could be useful for training new pilots:

For training new pilots on vehicle dynamics, it usually helps to sketch it ... and doing it in 3D would be easier to understand. (P1)
For an instructor to assess the decision-making of the students, I think that would also increase their efficiency. In aviation, you need to be able to visualize it in 3D and we are still using 2D representations for that. (P3)

Challenges: Learnability and adoption of new technologies. There were also challenges anticipated by the participants for the use cases to be realized in the field. A participant mentioned the learnability of the tool as a factor that could affect the adoption of 3D sketch mapping:

With pen and paper, it's just very easy and there's no learning involved at all because we all have learned it since kindergarten. So learning, especially getting familiar with depth perception and getting used to it might take some time. (P1)

Another challenge mentioned by another participant that is related to the nature of the aviation domain was the difficulty in introducing new technologies to an environment where safety is the biggest concern:

I don't think this kind of technology will completely replace the current way of doing it, that is in 2D. It is safety that is the most important and when everything fails, all we have is the 2D representations on paper. So the position of this kind of tool is not to replace the 2D ways but to give additional value to it. (P9)

4.2 Architecture

"3D is important but 2D is as important." In the architecture domain, four out of nine participants reported that 3D information is important for their work, but in terms of the representation, the 2D way of doing it is as important as the 3D approach:

We deal with 3D information all the time, but we often use 2D representations for it. It's partially because in some cases, it is sufficient to use 2D representation. (P19)

While both 2D and 3D representations are important for architects, what is crucial after creating a sketch is to be able to visualize the information in 3D and get a feeling for it. For this, architects often build physical models. Four participants agreed on the importance of realizing the sketch in 3D through model building, however, they also reported that it is a time-consuming process:

You need to see what it looks like and what we need is to build a model. And sometimes it takes a lot of time. (P14)
Building a working model is important because you always find out what you did not see when it's just a sketch in 2D. But it is very time-consuming. (P19)

"Sketching 3D information on a 2D plane is difficult and we often lose information." Regarding the current practice related to 3D information, architecture was an interesting domain since sketching was already a very important part of their work as mentioned by a participant:

> *Sketching happens all the time. From the beginning to the end. Drawing is the way we are thinking. We discuss with the other architects also with our sketches. (P11)*

Although architects were already using sketches in their professional activities, there were some limitations of the current 2D-based approaches. One limitation which was reported by three participants was the difficulty in expressing 3D information on 2D surfaces. The difficulty was related to the transformation that they had to do when converting 3D information to a 2D representation:

> *With the currently available methods, it's difficult to express all the 3D information that I need to show. You always have to think about how to represent it in 2D. (P13)*

Three participants commented on the abstraction and compression of information that happens when representing 3D information on a 2D surface:

> *You have to translate what you have in your head into a drawing, and when you draw in 2D, it's always a compression of what you are thinking. I think you lose quite a lot of information when you do it. (P16)*
> *The problem is that when working with 2D representations, it does not give you the complete image straight away. It is always a reduction or an abstraction of what is really in 3D space. (P19)*

Two participants mentioned that, when the information is represented in 2D, there is also potential for wrong interpretation due to the abstraction:

> *It always depends on how much imagination you have or how much 3D information you can implement in your head from 2D sketches. And it can be dangerous because it has a lot of potential to be interpreted in the wrong way. (P14)*

"3D sketch mapping is a direct and intuitive way to express 3D information." Most of the participants saw the potential usefulness of the 3D approach to sketch mapping. seven out of nine participants agreed that sketch mapping in 3D would be a more direct and intuitive way to represent 3D information in their mind compared to 2D:

> *If you have a complex form, sometimes it's easier to directly draw in 3D and see how it looks. If I can do it in 3D, then I don't have to worry about drawing 2D perspectives. (P12)*
> *If I imagine a space, it's always 3D. It's not looking down from the top. Maybe it's really just the way we have been taught, just the way we do it. (P14)*

Another benefit of 3D sketch mapping mentioned by two participants was that all the information can be shown within a single representation and there is no need to create multiple sketches in order to include all the information:

> *If you sketch on paper, you really have to do many different drawings to show one space. I think this 3D approach can be very useful because you just need to think about one thing instead of multiple subparts. (P17)*

Another two participants saw 3D sketch mapping as a new way to express a concept effectively and efficiently:

> *I think 3D sketching can be another language that we can use to express and communicate. I think it's quite strong. When using 2D sketches, often you are quite limited. I think 3D sketching can be a more powerful language than 2D. (P16)*

Use cases: Communications and replacing/complementing existing practices. Similar to the aviation domain, one of the use cases reported by multiple participants was for communication purposes. Five participants said 3D sketch mapping would facilitate communication, particularly when talking with non-experts:

> *It can be useful for communication with clients. Especially when you talk to non-professionals, it will be a very appropriate tool to make them understand what your concept is. (P19)*
> *For communication with non-architects, it can be interesting because they can see better with 3D than with 2D plans. (P15)*

Another interesting point raised by two participants regarding the communication with non-experts was that they could be the ones who are sketching to express their ideas:

> *I think this tool can be interesting for clients when they want to show you something. It can be easier for them to express what they think or have in their minds. (P12)*
> *When talking with your landlords, if they can sketch directly in 3D and see it right away in 3D, it will be much better. You have this really direct three-dimensional transfer and it would make misunderstanding much smaller. (P14)*

Another use case in the architecture domain was related to physical model building. Three participants said that it can be replaced by 3D sketch mapping:

> *The physical quick models would be, I think, almost completely replaced by this 3D sketching because it's more or less doing the same job. And it's a lot faster than gluing two cardboard pieces just to show to another person. (P15)*

Three participants saw 3D sketch mapping not as a tool that would replace something they use now, but more as a tool that could complement the existing practices:

> *We might still start with a simple sketch on paper, but as soon as you have it, then we can switch to a tool like this to see how it looks in 3D. There is room for this there. I don't think it will replace existing steps, but probably complement them. (P16)*
> *Maybe there is room for this between traditional 2D sketching and physical model building. If you can directly sketch something in 3D and communicate before building a physical model which can take a lot of time, it can really improve efficiency. (P11)*

Challenges: New technology adding complications to the process. Regarding the potential challenges for 3D sketch mapping to be adopted, five out of nine participants mentioned the connection between your brain and what you sketch. They reported that when you introduce technology to express what you have in your mind onto a medium, the connection becomes less direct compared to using a pen and paper:

> *We always start by sketching on paper because the connection between your head and your hand is direct. But if you use a device, the connection is not very direct. It's hard to translate the idea in your mind or your thoughts into a sketch if the connection is not direct. (P11)*

Another interesting point raised by three participants regarding the adoption of 3D sketch mapping in the domain was how the tool can affect the way architects do their jobs:

> *I don't think it's really that I have something very concrete in my mind before sketching it out. You have something in your mind, but it only becomes concrete as you sketch it and you also get feedback from what you sketch. That's why the tool I use is very important. It affects the whole process. (P18)*
> *In architecture, we are so used to drawing two-dimensional plans. I think it affects the sketches we create, like all buildings you see, they are just flat floors and straight walls. I think if you have another tool for working on architecture, that might change what we create. (P16)*

4.3 Wayfinding

"The importance of 3D depends on multiple factors." In the wayfinding domain, the participants showed different opinions on the importance of 3D information. For wayfinding in multi-level buildings, two participants reported that the importance of 3D information depends on the complexity of the space:

> *The importance of the third dimension depends on the complexity of the building. And the complexity of the building is not exactly about its height, but more about the different floor plans for each floor and the complicated connections between them. And I think the 3D information is more important when the complexity is higher. (P29)*

There was also a temporal aspect of the importance of 3D information. Three participants reported that the information in the vertical dimension is more important at the beginning of a wayfinding activity and it was mainly due to the fact that they often separate vertical from horizontal wayfinding:

> *When you look for a room in a building, the floor is always the first thing you look for. I would say it is important for me to just first locate a floor, then I think after that, I just use 2D information. (P22)*

"It is challenging to convert 3D information to 2D to sketch." The participants did not have difficulty applying sketch mapping to the activity of wayfinding as most of them had experience with sketches of a path drawn on a piece of paper. One limitation mentioned by four participants in the current 2D approach to sketch mapping for the purpose of wayfinding was the challenge of converting 3D information to 2D so that it can be drawn on a 2D surface:

> *When you are trying to draw something on a 2D plane, it can be quite difficult. We actually live in the 3D world and if we want to draw something that is 3D, we need to first project or transform the 3D information into 2D. (P25)*
> *I think [sketching a 3D space on paper] is demanding for people who draw it. The person who draws it needs better spatial cognition skills to draw this. I think you have to go through some additional steps to think about how to draw on paper. (P22)*

"If sketch maps are in 3D, it will be easier to sketch and also to interpret." The potential advantages of 3D sketch mapping were directly related to the limitation of the current 2D approach. Three participants reported that the main advantage of using a 3D interface for sketch mapping would be the ability to show 3D information directly and intuitively:

> *3D sketching is intuitive. You can just draw how things exist in reality because the building is in 3D naturally so we could just follow what we see every day in reality. (P21)*
> *With that [3D sketching tool], I don't think I need to think about how to represent things in 2D or how to decompose into different 2D planes. I think I can directly start drawing in 3D. (P24)*

Another potential benefit of the 3D approach to sketch mapping was related to the understanding of the sketched information. Five participants said that it would be easier to understand 3D sketch maps compared to 2D ones:

> *It is easy to understand because we are living in 3D spaces. If you are provided with 2D mapping, you first need to transform what is on a 2D plane to build 3D knowledge. But with 3D sketch maps, they are already in 3D space so you can directly get the information. (P27)*

Use cases: Communications and planning routes. Similar to the other two domains, a potential use case of 3D sketch mapping in the wayfinding domain was for communication purposes as mentioned by 3 participants:

> *I think it would be more helpful if I just sketch a map in 3D for those who have never been to the building before. They might find [a paper sketch] harder to understand. (P24)*

Another use case that three participants reported was in the planning phase of wayfinding. They saw the potential in using 3D sketch mapping to plan a route for navigation:

> *I can use a 3D sketch map when I go to a mall to mark the shops that I want to go to because it would save me time. For example, I can draw the shops that I want to go to and find the way so that I don't need to go back and forth. (P22)*

Regarding the use cases, three participants commented on the types of environments that would be more suitable for 3D sketch mapping compared to 2D. In general, they expected better use for indoor multi-level building environments but less for outdoors:

> *I think, especially for buildings with many floors, it would be easier to have 3D representations. But if it is for example, from the train station to the university, you probably don't need 3D. You could do it in 3D, but it's probably not necessary because you are moving on a surface. (P28)*

Challenges: Unfamiliarity of 3D interface and the effect on conveyed information. Regarding the challenges to be addressed, three participants mentioned the availability of hardware to make 3D sketching possible as well as the learnability of the tools:

> *I think probably the drawback is the hardware. You need to use these goggles and you need to get used to how to operate them. But once you understand how to operate it, then the drawing itself is intuitive. (P21)*

Another challenge mentioned by two participants was related to familiarity with 2D representations. They said, even if the environment is 3D, we are still more used to 2D representations than 3D, which makes it challenging to adopt the 3D approach:

I think we are more used to 2D technologies and 2D representations of things. And also, probably people who don't have access to technology or computers, probably prefer to be drawing in 2D because they're just more used to it. (P28)

Lastly, a participant made an interesting comment on the effect of sketching in 2D on the information selection process of sketch mapping:

When you are forced to draw in 2D, you try to not only convert the 3D mental model into 2D but also try to select the information that is more important to do the task. I think it's about when sketching in 2D since you have to be more careful about what to draw and also about how to draw them, you go through more abstraction. But when I am doing it in 3D, I am not forced to do the abstraction because I can actually draw everything as they look. (P29)

5 Discussion

While the perceived importance of 3D information differed among the three domains, most of the participants in all domains agreed on the limitations of the current 2D approaches when working with 3D information. They find it challenging to express 3D spatial information in 2D representations, and they feel that it is cognitively demanding to go through the mental conversion that is required to transform 3D into 2D. Moreover, information can be lost in this process and may not be included in the final sketches. The sketched information can therefore be potentially difficult to interpret by others. These findings confirm the results of previous studies on the limitations of the 2D representations of 3D information [6, 11]. On the other hand, the concept of 3D sketch mapping was perceived as positive and potentially useful. The participants reported that it is more intuitive to represent 3D information directly in 3D, that the cognitive demand is less in terms of converting the mental model to an externalized form, and that it can be also effective for communicating 3D information to others. Our findings support the hypothesis on the potential benefit and applicability of the 3D approach to sketch mapping when dealing with 3D spatial information.

While there is consensus in general among the findings in the three domains, the difference in the wayfinding domain from the other two is worth mentioning. Aviation and architecture are professional domains where activities deeply involve communicating and processing 3D information, and the usefulness of 3D sketch maps was well-perceived by the participants. On the other hand, wayfinding is not a professional domain, but rather something that everyone does in their daily lives. In this aspect, the feasibility in the wayfinding domain reflects the generalizability of the concept beyond specific professional domains. Another interesting point about wayfinding is that it is mostly 2D in nature, at least in the conventional way as part of human navigation, i.e., we move on a surface. In this regard, it may be debatable whether the 3D way of sketch mapping would have a significant advantage over 2D. This point is also reflected in our findings of the study – some participants questioned the usefulness of 3D sketching when what they have to draw is a set of 2D flat floor plans of a building. However, there are situations where the information along the vertical dimension is important and of interest from the spatial cognition point of view (e.g., how tall was the ceiling, the height of a sign, or the vertical-horizontal ratio of a space). In such scenarios, 3D sketch maps can provide a way to study how people perceive, understand, and externalize spatial information.

We would like to emphasize that what our findings show is *not* about 3D sketch mapping being superior to 2D and therefore being able to replace the conventional 2D approach. What we find is that there are situations where the 3D approach can be more effective compared to 2D. Using 3D sketch mapping, people can potentially express better in terms of geometric characteristics, and show the relative positions of objects in 3D, which can be difficult using the 2D approach. We also notice that there are cases where 2D sketch maps will do the job, and is likely to be easier for drawers to create. If the environment of interest is mostly 2D or what we as researchers want to study is the 2D aspect of it, then the conventional sketch mapping on 2D interfaces would work well. Although XR technologies are becoming accessible these days, they are still not comparable to the simplicity and the power of using a pen and paper that everyone is already extremely familiar with. The value that 3D sketch mapping offers is about expanding the spectrum of sketch mapping as a research technique. Depending on the situation and the focus of the study, researchers can choose either 2D or 3D sketch maps, whichever suits their purpose better. What is important is to identify those situations where the 3D approach works better compared to 2D, and this paper presented an initial effort in this direction. In this study, we asked the participants to experience 3D sketch mapping in a virtual reality environment. However, acknowledging that 2D sketching within a 3D environment may persist in unique value and objects in the physical world such as tabletop may support this activity, we are exploring augmented reality approaches that enhance the user's tangible interaction with a 2D surface while being able to sketch vertical information of a space in AR. We also envision that 3D sketch mapping could be applicable for training purposes in simulated scenarios (e.g., disaster response planning) where mixed reality can be more suited to transit between virtual scenes (for simulated experiences) and the physical world (for planning based on a 2D base map).

With its potential usefulness discovered in this study, studying 3D sketch maps as a research tool is a promising direction for future research. Will it actually become a valid research tool to study human spatial understanding? This question can be only answered through empirical validation. Regarding this point, one interesting comment from a participant in our study was that forcing them to sketch in 2D made them think more about what to include in the sketch compared to 3D. The selection of information to be drawn, or schematization, is an important aspect of analyzing sketch maps [12]. Is there a difference in terms of the type of information people include in their sketch maps when they have the freedom to draw in a more natural form that is closer to how things appear in the real world? Would that make it a better tool to study what people think of space? This is an interesting and important research direction that will strengthen our ability to study human spatial understanding in our field.

What we also find in our study is that by expanding the sketch mapping technique to 3D, we see its potential as a practical tool to be used in professional activities. Until now, sketch maps have been predominantly used as a research tool, but the concept of sketch mapping is not bound to a research method. The use cases we identified through the interviews with people in different domains show how 3D sketch maps can be used in a practical way and fit in the workflow of specific domains. We identified domain-specific use cases such as flight route planning for pilots or replacing model building for architects (see Fig. 2). We also identified a number of general use cases across multiple domains where 3D sketch maps can be applied such as communicating with non-experts or planning spatial activities. As mentioned by one of the participants, the design of the tool affects and shapes the way people do things. The use cases and the potential challenges discovered in this study should be part of the consideration for implementing the 3D sketch mapping tool.

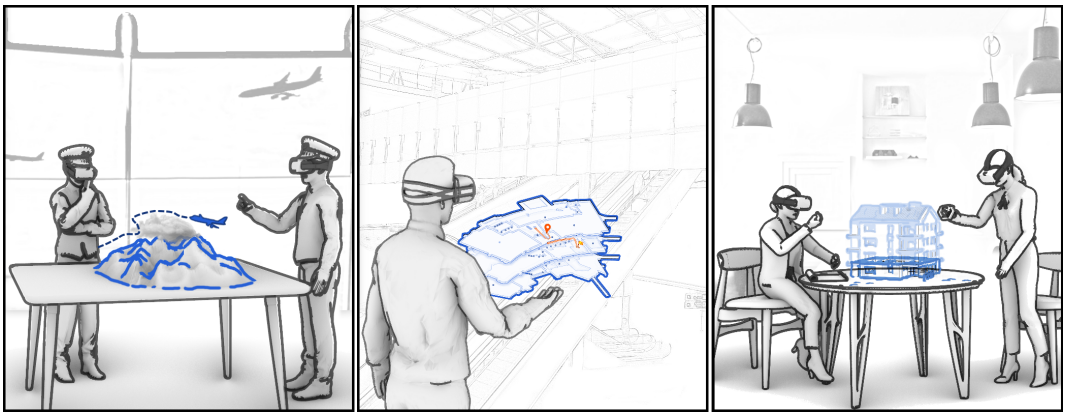

Figure 2 Illustrations of the concept of 3D sketch mapping applied to different domains: Flight route sketching for pilots, wayfinding in complex shopping malls for visitors, and communicating with clients for architects (from left to right).

6 Conclusions

The goal of this study was to understand how the concept of 3D sketch mapping would be perceived by the users from different domains and to explore its potential feasibility. In this paper, we presented the findings from an interview study with participants from three domains. Our findings show that the concept is well perceived by the participants, and it can become a feasible approach to dealing with 3D spatial information that addresses the limitations of the current 2D approaches. Based on these findings, we believe that 3D sketch maps can expand the spectrum of the sketch mapping technique so that it can be applied to a broader range of research scenarios. Furthermore, we also show that by extending sketch mapping from 2D to 3D, there can be more practical use cases in different domains. With the result of this study that provided insights into the feasibility and applicability of the concept from the user's side, future research should include designing and implementing optimal interfaces, followed by validating their effectiveness in empirical studies.

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A Appendix: Interview questions

The following questions were used as guiding questions in the semi-structured interview. The interviewer used these questions to structure the interview but did not exactly follow them, i.e., we asked ad-hoc follow-up questions to interesting responses and also changed the order of the questions when necessary.

Table 2 Guiding questions used in the interviews.

Importance of 3D information in the domain:
▪ Can you describe your job and the tasks you carry out in your professional activities?
▪ Do they involve any 3D spatial information?
▪ How important is 3D information in performing your task?
Representation of 3D information:
▪ How is the 3D information visualized in your domain?
▪ Do you use sketches/drawings/maps in your professional activities? If yes, can you tell us a scenario where it is used?
▪ How are the 3D representations created? Who creates them? What are the tool used?
▪ What interfaces are used to create and visualize them? (e.g., pen and paper, tablets, PCs)?
▪ Do they involve some domain-specific representations? If yes, what are they?
Introduction to sketch mapping and 3D sketch mapping
Potential use of 3D sketch mapping:
▪ Can you think of a situation in your professional activities where 3D sketch mapping can be applied?
▪ What are the benefits and drawbacks of using it compared to how you do it now?
▪ Can you imagine replacing the current ways of doing a task with a 3D sketch mapping tool?
Potential challenges and requirements:
▪ To make it an effective tool, what are the functionalities or features you would like to have?
▪ Can you think of any challenges in applying 3D sketch mapping in your professional activities?
▪ Any other suggestions regarding the development of a 3D sketch mapping tool for the use in your domain?