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Virtual reality in astronomy education: reflecting on design principles through a dialogue between researchers and practitioners

Magdalena Kersting [a,b], Jackie Bondell [c,d], Rolf Steier [e] and Mark Myers[c]

[a]Department of Teacher Education and School Research, University of Oslo, Oslo, Norway; [b]Department of Science Education, University of Copenhagen, Copenhagen, Denmark; [c]The Australian Research Council Centre of Excellence for Gravitational Wave Discovery OzGrav, Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Australia; [d]The Australian Research Council Centre of Excellence for Dark Matter Particle Physics, School of Physics, The University of Melbourne, Melbourne, Australia; [e]Department of Primary and Secondary Teacher Education, Oslo Metropolitan University, Oslo, Norway

ABSTRACT
Virtual reality (VR) technologies have the potential to transform astronomy education practices profoundly: new forms of visual representations, perceptual engagement and embodied participation promise authentic learning experiences in formal and informal learning spaces. While a growing body of research studies the educational needs and opportunities of VR astronomy education from the learner's perspective, relatively few studies have explored the perspectives of education and public outreach (EPO) professionals. This study aims to turn our attention to these complementary perspectives and shed light on design considerations for using VR in astronomy education. We unpack design principles as a dialogue between researchers and practitioners, framing this dialogue as an act of reflective practice. The findings and the ensuing dialogue draw on data from two focus group interviews with EPO professionals and scientists from the Australian Research Council Centre of Excellence for Gravitational Wave Discovery. Our design principles centre on aspects of immersion, visualisation, facilitation, and collaboration and can guide astronomy educators who wish to use VR in formal and informal learning environments. Besides, our study contributes to a deeper understanding of the new learning contexts VR technologies can create in astronomy education.

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Introduction

Virtual reality (VR) technologies present exciting opportunities to transform astronomy education because they offer immersive and embodied learning experiences that make abstract concepts more accessible. By their very nature, astronomical objects are challenging to represent because they are far removed from our everyday experiences and sensory perceptions (Azevedo & Mann, 2018; Eriksson, 2019; Kersting, 2020; Salimpour et al., 2021). The vast scale of the universe challenges our imaginative faculties, and many astronomical phenomena, such as the phases of the moon or the cause of the seasons on Earth, confuse learners (Chastenay, 2016; Madden et al., 2019; Yu et al., 2015). Besides, concepts of cutting-edge astronomy, including black holes or

CONTACT Magdalena Kersting mkersting@ind.ku.dk, magdak@uio.no

gravitational waves, seem counterintuitive or even contradictory to our knowledge of the world (Bondell & Myers, 2021; Steier & Kersting, 2019; Ubben et al., 2022), often 'involving complex temporal and spatial scale relations' (Salimpour et al., 2021, pp. 013104–2). Therefore, astronomy provides educators with an ideal proving ground for putting the educational promises of VR to use.

These promises rely on features that characterise the affordances of VR to create new learning contexts in astronomy: immersion, visualisation, collaboration, and facilitation (Kersting, Steier, et al., 2021). Immersion and a sense of presence have been shown to promote inquiry learning, practical skills, spatial abilities, and conceptual understanding of abstract concepts (Hurtado-Bermúdez & Romero-Abrio, 2020; Matovu et al., 2022; Potkonjak et al., 2016). When engaged through the immersive features of VR, learners are not merely external observers of scientific concepts: they become embodied participants who navigate and manipulate the representation from within. In astronomy, immersion may take the form of going on virtual trips to stars and making measurements of the star's temperature and composition (Bondell & Myers, 2021) or taking on the role of an astronaut who navigates microgravity outside of the International Space Station (Tamaddon & Stiefs, 2017). Common to these immersive forms of engagement is their tapping into learners' embodiment, that is, into the experiences that arise from bodily interactions with the material world (Kersting, Haglund, et al., 2021).

Visualisation features of VR offer unique opportunities for learners to explore abstract concepts and phenomena that are beyond the visual limitations of reality (Matovu et al., 2022). For example, by dynamically manipulating the scale, rotation, and viewpoint of virtual planetary objects, learners can actively engage with visual representations from an egocentric point of view (Detlefsen, 2014; Yang et al., 2020). Such visual representations support learners' discovery that the same basic physical laws govern all objects in the solar system (Yair et al., 2003). Besides, students can gain a deeper understanding of the complex processes involved in stellar evolution through visualisations of the otherwise invisible life cycle of stars, including nuclear fusion, supernova explosions, and the formation of black holes (Bondell & Myers, 2021).

Collaboration in VR can take the form of collaborative learning activities distributed within and across virtual spaces. Researchers have started to develop a metric of shared viewing across multiple virtual reality devices and have found that a higher level of shared views and joint attention might be related to increased conceptual discussions in astronomy education (Diederich et al., 2021). Designing VR technologies such that sharing and communicating astronomy concepts becomes integral to the experience is a promising route to foster engagement (Kersting, Steier, et al., 2021).

Facilitation is a core aspect of learning. In astronomy education, facilitation can take various forms, including human-led instruction and integrated interactive features within the learning environment (Lindgren et al., 2014; Tscholl & Lindgren, 2016). Human-led instruction often consists of the expertise and guidance of astronomers and astronomy educators who can maintain and enhance learners' interest and guide them towards meaningful experiences in the VR environment (Kersting, Steier, et al., 2021).

In summary, VR technologies hold great potential for transforming astronomy education by offering immersive and visually innovative learning environments that foster collaboration and communication among learners. In response, researchers have started to study if VR lives up to its potential. There is a growing body of literature on whether and how these technologies can increase knowledge, skills, and motivation in astronomy (e.g. Atta et al., 2022; Bedregal-Alpaca et al., 2020; Lindgren et al., 2016; Madden et al., 2020; Severson et al., 2020; Yang et al., 2020). However, few studies have explored the complementary perspectives of education and public outreach (EPO) professionals, including their experience with and motivation to use VR in astronomy education. This study provides a novel perspective by turning our attention to those who develop VR experiences in astronomy education. Since the educational value of VR depends on how these technologies are integrated into specific learning contexts (Makransky et al., 2020), EPO professionals can provide valuable insights into design considerations. These insights, in turn, can support astronomers, educators, teachers, and researchers who wish to use or study VR in formal and informal astronomy education.

Research questions

To shed light on design considerations for VR in astronomy education, we ask:

- RQ1. What characterises the motivation of EPO professionals to use VR in astronomy education?
- RQ2. Which opportunities and challenges of VR astronomy education guide the development and facilitation of VR astronomy experiences?
- RQ3. Reflecting on the findings from RQ1 & RQ2, what design principles can be formulated to develop and use VR in astronomy education?

Extended and embodied realities – a clarification of our terminology

This study acknowledges that VR is but one of several related technologies that create new learning contexts in astronomy. By blurring the line between real and virtual worlds, such technologies provide learners with a technologically mediated embodied reality, i.e. an embodied sense of ‘being there’ (Lindgren & Johnson-Glenberg, 2013; Matovu et al., 2022; Southgate et al., 2018). Extended reality (XR) is the collective term for these technologies, which comprise virtual reality (VR), augmented reality (AR), and mixed reality (MR) (Lee et al., 2020). These technologies share common features but also possesses central differences.

While VR fully immerses users in a computer-generated environment, typically through headsets (Matovu et al., 2022), AR enhances the user’s perception of the real world by overlaying digital information, such as images, text or sounds, on top of the physical environment (Salmi et al., 2017; Sirakaya & Alsancak Sirakaya, 2018). MR is a more advanced form of AR that allows digital content to interact with the real world more seamlessly, inviting users to engage with and manipulate virtual objects while remaining grounded in the real world (Lindgren & Johnson-Glenberg, 2013). The common denominator among XR technologies is their tapping into learners’ embodiment and taking advantage of our natural tendencies for physical interaction with the environment (Johnson-Glenberg & Megowan-Romanowicz, 2017). While our study focuses on VR, we acknowledge that all XR technologies have great potential for transforming astronomy education.

Theoretical background

Our study aims to investigate the motivation of education and outreach professionals to use VR in astronomy education (RQ1), identify opportunities and challenges of VR astronomy experiences (RQ2), and formulate and reflect on design principles (RQ3). This section briefly presents the theoretical background of motivational theory and reflective practice that supports our investigation.

Motivation

Motivation is a complex psychological construct that drives individuals to engage in activities and pursue goals. Over the years, numerous theories and frameworks have been developed to understand and explain motivation in various educational contexts, including informal science education (e.g. Salmi et al., 2017; Salmi & Thuneberg, 2019; Staus et al., 2021; Woithe et al., 2022). Some of the most influential and relevant theories include intrinsic motivation, achievement motivation, and situational motivation: intrinsic motivation is the drive to engage in an activity for its own sake, driven by personal interest, curiosity, or enjoyment (Hidi & Renninger, 2006; Ryan & Deci, 2000). Achievement motivation focuses on the drive to achieve success and avoid failure, often concerning personal goals or societal standards (McClelland et al., 1953; Renninger & Hidi, 2019). Situational motivation pertains to the motivational state that emerges from the specific context or environment in which learning occurs (Renninger & Hidi, 2019). In our study, we are interested in the motivation of science educators and outreach practitioners to use VR in astronomy education. We expect these professionals to be driven by various intrinsic, achievement, and situational motivation factors.

Reflective practice

This study is an interdisciplinary effort drawing on various types of expertise ranging from technical design expertise to astronomy knowledge and education research perspectives. In formulating our third research question, we tasked ourselves with stepping back from direct educational practices to articulate broader design principles. This stepping back requires articulating some of the tacit knowledge that goes into designing VR educational experiences as well as analysing and making sense of them. To this end, we took inspiration from Schön's (1983) well-known concept of reflective practice. Schön (1983) distinguishes between reflection *in* action and reflection *on* action. Reflection in action includes the kinds of in-the-moment thinking and knowing that occur during an event. In contrast, reflection on action entails looking back on the event after it has occurred.

Reflective practice has been adapted in many disciplines, including informal science education. Recent studies have leveraged Schön's notion of reflection in and on action as their analytical lens, demonstrating its continued relevance and applicability across domains (Ash & Lombana, 2012; Patrick, 2017; Roedema et al., 2022). These studies and our own highlight the value of reflective practice as a means to inform and refine the design and implementation of educational experiences in informal contexts.

In our study, we drew on a general understanding of reflective practice as 'the process of learning through and from experience towards gaining new insights of self and/ or practice' (Finlay, 2008, p. 1). This understanding guided our inquiries of RQ3, which we framed as an act of reflective practice through dialogues between education researchers and practitioners.

Research design

Educational background

This study is grounded in the EPO programme of OzGrav, the Australian Research Council Centre of Excellence for Gravitational Wave Discovery. The programme's vision[1] is 'to inspire young people to take up careers in science & technology' and 'to inspire and educate the general population about the nature of our Universe and explain how the scientific method works and can be trusted'.

Black holes, neutron stars, and gravitational waves are abstract astronomy concepts. Through its educational programmes, the project embraces the opportunities of VR technologies to make these concepts more accessible and elevate EPO practices in astronomy.[2] The EPO team comprises science educators, VR developers, digital artists, and astrophysicists who develop and deliver astronomy programmes. Besides, scientists often participate in outreach activities and act as tour guides at public outreach events. Two major VR programmes of the project that rely on wireless head-mounted VR headsets of the type Lenovo Mirage Solos are *Bigger Than Big* and *Mission Gravity*.

Bigger Than Big takes users on a journey through the vastness of space, exploring the solar system and beyond. The experience aims to educate the general public about the relative sizes and distances of celestial objects in an engaging and accessible way. *Mission Gravity* is an immersive educational programme designed for lower- and upper-secondary students, focusing on teaching stellar evolution through scientific modelling and VR technology (Bondell & Myers, 2021). Students work in teams to collect and analyse data from a virtual trip to nearby stars, using the laws of physics to understand how stars change over time. The immersive VR environment enables students to interact with stars, make measurements using virtual tools, and investigate stellar remnants.

Data collection and analysis

This study follows a two-step analytical approach based on a thematic analysis of focus group interviews and subsequent reflective dialogues.

Step 1: addressing RQ1 & RQ2 through focus group interviews

Building off prior work with an evaluation of the project's EPO activities (Kersting, Steier, et al., 2021), we drew on two semi-structured focus group interviews to characterise the motivation of practitioners (RQ1) and identify opportunities and challenges (RQ2) with regards to VR astronomy education. The first author conducted interviews with the EPO team (four participants, 45 min) and a group of scientists who had previously volunteered as VR guides at public outreach events (eight participants, 60 min). All participants gave informed consent to be interviewed, and as a project-internal evaluation, additional approval by an ethics committee was not required.

The interview guide focused on designing and delivering VR astronomy experiences and how learners engage with astronomy through VR. After transcription, the first author used the Atlas.ti software to analyse the transcripts through thematic analysis a few days after the interviews were conducted. Coding started deductively with four themes (EPO activities, motivation, challenges, opportunities), for which the codes were then developed inductively. The first author did the first coding round before iteratively discussing and cross-checking the codes with the second and fourth authors (members of the EPO team). These discussions functioned as an extended member-checking process to verify the first authors' initial interpretations and agree on the themes and codes.

Based on these discussions, the original themes were revised to provide a more nuanced overview: challenges and opportunities were further subdivided into challenges and opportunities regarding the format and content of the VR experiences. Later on, aspects of motivation were further categorised in line with three relevant types of motivation (intrinsic, achievement, and situational). Tables 1 and 2 map the final themes and codes to the first two research questions. Selected quotes illustrate each code.

Step 2: addressing RQ3 through reflective dialogues

To address RQ3, i.e. formulating design principles for developing and using VR in astronomy education, we invited two of the interviewed outreach professionals to join the second analysis stage. We chose the Public Outreach Coordinator and Education and Outreach Content Developer because both had been involved in planning, designing, and implementing the VR programmes and had participated actively in the focus group interview. Taking the findings of the thematic analysis as our starting point, we engaged in two reflective dialogues between two educational researchers (first and third author) and two practitioners (second and fourth author), each of which lasted 60 min and was audiotaped and transcribed.

We framed these dialogues as an act of reflective practice, which we understand both as a process of reflecting *on* and *in* action. On the one hand, the design work and the events of the EPO activities had already occurred and served as the primary objects of investigation. We reflected together *on* these activities through joint analysis in the context of this research project.

On the other hand, the task of developing and articulating design principles was also in the foreground. In these dialogues, we were developing principles and figuring out how to express our ideas to one another so that new understandings would emerge. From this perspective, the second analysis stage moved beyond synthesising prior work to engaging and reflecting *in* dialogues to develop design principles that drew on our different forms of expertise. These kinds of scientific learning conversations are themselves an important form of practice for outreach professionals, designers, and researchers, and the development of these design principles depends on this dialogic framing (Roedema et al., 2022).

Table 1. Four themes of the thematic analysis help characterise the motivation of EPO professionals to use VR in astronomy education (RQ1).

Themes	Codes	Example quotes
EPO activities	Developing	**Practitioner 3:** And our job at the moment is to take new technologies that are emerging in the market and to adapt them to teach astrophysics and science. And to use them not only for entertainment but for education. **Practitioner 4:** We are really lucky to have content developers in-house because there are a lot of things that look cool in virtual reality out there, but to be able to tailor the content of what we need, as well as the new things that we're discovering, so we can be close to that cutting edge of content. I think we're in a really lucky position for that.
	Delivering	**Practitioner 4:** We have really great volunteers that anytime we want to run something, I think partly because it's a cool content, and we have cool stuff to show off, so there's never a shortage of people who will come and help us do all of those events.
	Training	**Practitioner 1:** So it's the train-the-trainer model so that they [teachers] can ideally use content that we develop or be inspired by our content to deliver science in their classrooms. **Practitioner 1**: I think that we've done a good job trying (…) to engage our members and our specialty, our early-career scientists, try to get them to be confident in science communication and then turn that into them facing outward, whether it's through videos, whether it's through engaging with the public.
Achievement motivation	Impact	**Practitioner 1:** When we are developing content, we ensure that it has scalability options. I think it is really important to ensure that what we spend time on can get as broad a reach as possible. **Practitioner 3:** The mobile VR headset is especially powerful because children can take that home and they become the educator. Then they share it with their friends, and then we don't just inspire one child with science. If it inspires one child so that the child then goes on to be empowered to be a mini-science communicator themselves, that's awesome.
	Relevance	**Practitioner 1**: I think that we have developed a very solid school incursion programme, which has received good feedback, especially from teachers, regarding its relevance to the curriculum and its collaborative nature. And that it brings cool VR into the classroom and doesn't require them to provide a lot or bring that experience to the students. (…) Letting teachers and students see that VR can be used as an educational tool in which they learn relevant science in a way that wouldn't otherwise be accessible.
Intrinsic motivation	Enjoyment	**Scientist 1:** I just like to tell people about science and what I'm doing and convey my passion to them. **Practitioner 3**: I love VR. If I could be in VR right now, I would be.
Situational motivation	Excitement	**Practitioner 4:** Most of my job is sitting at a desk typing. So any time we get to have those festival events, I really look forward to it, and I always hope it's going to be fun, and I'm excited to chat with people, and I think it is really great when you have a self-selected science audience, and they already are engaged, interested. **Scientist 4:** They [science festival visitors] clearly were having lots of fun, like little kids. Yeah, and it's fun; you feel that fun as well. So, because they're so excited, you feel it too.
	Confidence	**Scientist 3:** I think it's awesome, gives me a little bit of confidence. Because all week long I enjoy my work and everything. But then, when one plot is not doing what it's supposed to do, it's the end of my work. I don't know anything, imposter syndrome. Nothing's working. Am I going to figure it out? But then, when interacting with the public or at least others, you have the conversation about, wow, how big the star is (…). It just gives you a little bit of confidence, I guess.

Quality standards

Given the direct involvement of two outreach professionals in the second stage of our analysis, we chose the quality standards of trustworthiness and authenticity to discuss the strengths and limitations of our research design (Taylor, 2014). To ensure that we arrived at findings with a high degree of trustworthiness, we collected data in the social environment of the EPO team at their workplace. The first author conducted the focus group interviews a few days after the practitioners and scientists had delivered a VR programme at a science festival in the greater Melbourne area. The recent experiences at the festival allowed the interviewees to provide rich insights into the challenges and opportunities of VR astronomy education.

Besides, ongoing conversations with the practitioners before, during, and after the science festival allowed the first author to understand the research context better. In particular, the

Table 2. Four themes of the thematic analysis help characterise opportunities and challenges of VR astronomy education (RQ2).

Theme	Codes	Example quotes
Content challenges	scientific accuracy	**Practitioner 3**: I think we have a very fact-based approach, so we do try and keep things to the right size if we can and the right colours. **Practitioner 2**: Scientific accuracy, you mean? **Practitioner 3**: That's really important to us. I think also scale is very tricky. When you first get in that solar system [in *Bigger Than Big*], and you want to see all the planets, that's not what it looks like. Yes, the scale is correct in terms of size, but the distances between them are ridiculous. In that case, you have to think about what you're going to sacrifice. Because if you fit them all into scale, then they're just tiny dots off in the distance when you're that close to the Sun. (…) It's tricky, but it's a good pursuit to be in.
	science phenomena	**Practitioner 1:** (…) astrophysics has a lot of challenges due to distances and scales of objects that are still a challenge that scientists deal with.
	prior knowledge of audience	**Scientist 1**: I mean, we can have two levels. Those who know too much or those who don't know or don't want to know. They can be going through: just put on a headset, do whatever you want. And then people who want to listen, who want to ask, 'Okay what's this going on? Okay what's this?'
Format challenges	people's needs	**Practitioner 1**: When we work with people in VR, we have to be cognizant that the experience may be different and may not always be good for everyone. When we are working with groups, we have to remind them, 'you don't have to do this'. And that's why we have the screencasting, so people can still get the experience without being in it. Ideally, we provide a safe space for it, and we sort of have this risk assessment that we do: tell them that if they don't feel well, they can just lift it off their heads or raise their hands. All that VR safety stuff. I think those are useful reminders that everyone will have a different experience in VR.
	delivery	**Scientist 2**: You had so many different people all trying to share the headsets, and the headsets maybe had something go wrong with them. Just trying to balance keeping everyone's attention and instructing them and keeping everything technically working properly was, yeah, challenging doesn't really capsulate it. But, it forced you to step up to the challenge in order to keep it engaging for everyone
	practical concerns	**Practitioner 4**: I guess another slightly different aspect is that when we're developing new content, we always have to be aware of what we can achieve within the time. So is there time pressure on, say, an event coming up or something, and what can be realistically achieved within that time? It's kind of the boring extra, but it's important.
Content opportunities	observation	**Practitioner 3**: As soon as you put those VR glasses on, it looks like they're looking at the night sky. (…) You start in the solar system with things that you're familiar with. And you build on that until you get to the thing that we actually want to talk about, which is black holes and gravitational waves.
	curiosity	**Practitioner 3**: I guess you would want to engage kids because they are naturally curious. But I think there's also a place for VR and outreach and things for non-kids as well as for non-scientists. And also science enthusiasts. There would have been quite a few parents at that event who were super keen and were like, 'Yes, we're going to take our kids to a science kind of festival '.
	scientists	**Practitioner 3**: I think there is definitely a space for the science we want to share. And particularly the things about the research of our helpers, that's why we pick them to be our outreaches. And people do want to ask those questions. There's a lot of knowledge our outreaches have behind the knowledge of the things that they explained, so we're really lucky to have them on the team.
Format opportunities	collaboration	**Practitioner 4:** I think personally, I would like them to experience it as a group event, not as an individual isolated thing. So I'd be more interested in people getting together like we have with the big events and having a shared experience than somebody sitting at home just looking and stuff.
	visualisation	**Practitioner 2:** I love the fact that virtual reality frees you from the limitations of actual reality. For our purposes, because we teach astrophysics, we get to play with micro-gravity experiences, and we get to throw things into orbit around objects with a lot of mass. And it makes those concepts quite easy to understand. And even visualising warped spacetime, we're trying different ways of doing that in VR. And flying up close to a star and then watching it evolve, and then being in a spaceship, man, what's more exciting than that?
	versatility	**Practitioner 4**: I like VR because it's very easy to set up and pack up. And it's not messy. It is a really elegant solution to lots of experiences in a short amount of

(*Continued*)

Table 2. Continued.

Theme	Codes	Example quotes
		time. It’s highly reusable; it doesn’t cost us anything additional to run. You don’t have to restock things. **Practitioner 3:** I like the versatility of virtual reality because we can show lots of different things with just one piece of equipment. And we can use it for lots of people (…). From that initial investment, the number of people that we can use that for scales well.

conversations after the festival helped clarify observations and verify the findings of the thematic analysis through member checking (Taylor, 2014). The reflective dialogues in the second stage of analyses constituted an extension of the member-checking practice, as they allowed the practitioners to challenge and nuance the researchers’ interpretations.

To ensure that our findings displayed a high degree of authenticity, the first author focused on establishing relationships of mutual understanding and benefit with the EPO team. As a visiting research fellow at the OzGrav headquarters, the first author immersed herself in the social and professional environment, thereby understanding the complexities of the team’s daily tasks. To counter potential biases and strengthen the quality of the analysis, the third author joined as an educational researcher who was ‘outside’ of the social context of the programme.

Findings RQ 1: what characterises the motivation of EPO professionals to use VR in astronomy education?

For the interviewees, their primary education and outreach activities encompass three tasks: developing, delivering, and training. Developing involves creating education and public outreach programmes, adapting new technologies for educational use, and establishing networks with key stakeholders like education and industry partners. Delivering refers to various settings where the team actively runs and delivers VR programmes, including formal school incursions and informal public outreach. Training encompasses activities that educate others in educational endeavours, such as teacher professional development workshops and science communication training for scientists. Jointly, these activities serve as the backdrop to understand the motivation of the EPO team to use VR in astronomy education.

We unpack this motivation through achievement, intrinsic, and situational motivation. Achievement motivation is driven by the desire to accomplish goals. For the practitioners, such goals align with the programme’s vision to inspire and educate young people and the general population about the nature of our universe. Creating impact was one major goal that drove the use of VR. The interviewees expressed the wish to reach many people and increase the impact of their resources by training others. In this context, the education and outreach professionals appreciated that VR-facilitated experiences are easily scalable. Closely related to impact is the goal to develop VR activities that are relevant to the intended audiences and can elevate instructional practices. Relevance is crucial in the school context because teachers follow the science curriculum and need resources tailored to the curriculum.

Intrinsic motivation refers to the desire to engage in an activity for its own sake, and we found public outreach to be such a motivating factor in and of itself. The interviewees felt motivated to do VR outreach activities because they enjoy sharing their passion for science, feel a sense of satisfaction from inspiring children to pursue careers in science, and have a great liking for VR technology.

The final theme, situational motivation, captures aspects of the specific learning contexts the interviewees found motivating. The scientists and practitioners mentioned that outreach events are exciting and fun, contributing to a positive atmosphere and helping motivate them and the participants to engage with the content. The scientists also mentioned that sharing their knowledge with others gave a boost to their confidence. In this context, the VR tour provided a natural setting for the scientists to become involved and take on the role of tour guides.

Findings RQ 2: which opportunities and challenges of VR astronomy education guide the development and facilitation of VR astronomy experiences?

Opportunities for developing and facilitating VR astronomy education

The format of VR technologies offers unique opportunities for astronomy education in terms of versatility, visualisation, and collaboration. Versatility refers to designing VR environments that utilise the flexible setup of VR equipment, allowing for reusable and adaptable experiences. The interviewees described the advantages of having no extra costs after the initial investment in equipment: VR headsets are easy to set up, reusable, and robust. Here, the corresponding design considerations concern the initial investment of VR equipment connected with the motivation to have an educational impact. The team can run many science events or school incursions with a few headsets. Another aspect of versatility is the flexibility that comes with running VR tours. Based on the audience, the guides can facilitate longer or shorter experiences or guide different participants through the tour at different paces. This flexibility is another aspect that outreach professionals consider when delivering their programmes.

Visualisation captures the opportunities of VR to visualise astronomical phenomena. The team described how the development of their VR experiences is guided by the wish to turn abstract science into visually memorable experiences. Here, the consideration of visually striking designs ties in with the overarching motivation to create an educational impact. VR technologies overcome visual limitations while connecting learners to their embodied reality, serving as a powerful tool for visualising otherwise inaccessible phenomena. However, the interviewees felt that they still needed to make full use of all visualisation possibilities and that the blending of real and virtual elements could be further utilised in their programmes.

Collaboration describes how VR technologies can be used and experienced collaboratively. This aspect was a key consideration for the outreach team, who tried to enhance the visual and immersive features of VR by creating collaborative settings in which learners can interact with each other or with the tour guide. Shared screens and shared task allocation serve as means to turn VR experiences into collaborative activities that have received good feedback from participants.

In addition to these opportunities, the astronomy content itself presents further possibilities for education and outreach that we capture through the codes of observation, curiosity, and scientists. Observation allows for accessible VR experiences featuring familiar celestial objects, while curiosity is inspired by exotic and unexplained astronomical phenomena. For example, *Bigger Than Big* features the night sky and the Sun, the Earth and the Moon to evoke recognition and excitement before moving on to more exotic phenomena, such as pulsars and gravitational waves that cannot be observed with the naked eye. Finally, the involvement of scientists in VR activities adds an authentic dimension to the learning experience. The outreach team explained how they wanted to leverage the expertise of their scientists in outreach activities and, thus, designed VR activities accordingly.

Challenges of developing and facilitating VR astronomy education

The challenges of developing and facilitating VR astronomy education experiences can be broadly divided into two categories: those related to the format of VR experiences and those related to discipline-specific content challenges of astronomy.

Format-related challenges include addressing people’s needs, finding suitable delivery formats, and overcoming practical concerns. People’s needs encompass that different people react differently to VR and that not everybody experiences these technologies in a positive way: reactions may vary from overexcitement to discomfort. Therefore, safety issues were an essential design consideration for the team. Accessibility is another critical factor that must be considered when designing VR experiences. Delivery challenges involve finding suitable formats for different audiences and learning contexts while considering the limitations of VR hardware. For example, the scientists found it challenging to accommodate groups of people because different people often spend different amounts of time in the VR experience. This socially active setting of informal learning contexts constrains the facilitation of VR experiences, which, in turn, feeds into design considerations on how to run such tours.

Practical concerns, such as time, money, infrastructure, and available personnel, must also be considered when developing and facilitating VR programmes. According to the interviewees, the regular charging of headsets is one example of how practical concerns significantly constrain the facilitation of VR experiences.

Discipline-specific content challenges in astronomy include addressing scientific phenomena, prior knowledge of the audience, and maintaining scientific accuracy. As already noted in the introduction, astronomy is a domain that presents learners with many conceptual challenges. While science phenomena and prior knowledge represent known challenges in astronomy education, scientific accuracy is a new aspect when visualising astronomical concepts through VR. Practitioners must balance visual accuracy, oversimplification, and artistic choices to create compelling VR experiences. The interviewees felt a tension in trying to strike this balance, and in the next section, we give examples of how the team has solved some of these tensions.

Findings RQ 3: reflecting on the findings from RQ1 & RQ2, what design principles can be formulated to develop and use VR in astronomy education?

In this section, we present design principles for developing and using VR in astronomy education. We have arrived at these design principles through reflective dialogues that encompassed a dual approach of reflection *on* and *in* action: by creating a space for open communication and collaborative thinking, the dialogues allowed us to reflect on past events and experiences (reflection on action) while actively engaging in developing design principles in a process that unfolded through real-time reflections as we engaged with one another and responded to the ongoing conversation (reflection in action). We structure the presentation of the design principles in line with the four features of VR engagement presented in the introduction: immersion, visualisation, collaboration, and facilitation. For each VR feature, we present a set of design principles (Table 3) and illustrate the principles with examples from the VR programmes *Bigger Than Big* and *Mission Gravity* and excerpts from the reflective dialogues.

Designing for immersion

The design principles for immersion (DPI) in Table 3 highlight the importance of leveraging the immersive nature of VR to create a realistic and engaging experience without overwhelming participants. The design of *Bigger Than Big* and *Mission Gravity* is grounded in principles that

Table 3. Design principles for developing and using VR in astronomy education.

Design principles for immersion	Design principles for visualisation	Design principles for collaboration	Design principles for facilitation
DPI 1. Take advantage of bodily immersion in VR environments. **DPI 2.** Take advantage of narrative immersion through storytelling. **DPI 3.** Avoid overwhelming participants with sensory input and use movement deliberately.	**DPV 1.** Visualise astronomical scales through different representations. **DPV 2.** Make clear when representations are scientifically accurate and when artistic freedom is required to communicate an idea. **DPV 3.** Use visualisations to evoke emotional experiences.	**DPC 1.** Use screencasting to foster collaboration. **DPC 2.** Treat VR experiences as group activities.	**DPF 1.** Prioritise VR safety and build trust. **DPF 2.** Put people at the centre of the experience. **DPF 3.** Create flexible rather than static VR experiences. **PDF 4.** Create opportunities for interactions with scientists.

prioritise both bodily and narrative immersion, ensuring that participants are fully engaged in exploring astronomical phenomena.

One key design principle underlying both VR experiences is the emphasis on bodily immersion (DPI 1). Participants can look and move around the virtual environment from a first-person perspective that closely resembles real-life exploration. For example, wireless headsets enable unrestricted movement, allowing users to lean into or away from scenes as they would in a physical setting. This intuitive navigation system ensures that tour guides can concentrate on delivering engaging astronomy content without spending time instructing participants on navigating the virtual environment:

Researcher 2 : Intuitively I would think that in any kind of VR, you're using your body in a way that more closely resembles how you experience physical phenomenon. And there has to be something meaningful there, even if we don't know exactly what.
Practitioner 1 : Yeah, fewer mental hoops to jump through to enjoy it.
Researcher 1: It's a really good point that you're making: there are fewer hurdles when we can just tap into this way of conceptualising the world immediately without having to translate which button do I have to press.
Practitioner 1 : I think by taking away some of those mental hurdles and having them in this environment straight away, it gives you space for, no pun intended, for other things such as the storytelling and bringing them along for this journey. You take away all those barriers and then it makes that path to let them enjoy the experience and think about the science and ask questions about the science and not have to ask questions about how to do I do XYZ?

Besides, involving participants in bodily ways instead of letting them be mere onlookers of scenes further creates the illusion of an embodied reality. In *Mission Gravity*, students can engage with stars, evolve them, employ virtual instruments to make measurements, navigate space as stars alter in size, and examine stellar remnants. The educational possibilities of this immersive format contrast with merely viewing flat objects or passively watching a 360-degree video (Bondell & Myers, 2021).

Narrative immersion through storytelling is another crucial design principle for *Bigger Than Big* and *Mission Gravity* (DPI 2). By developing the story path before designing the environment, the EPO team ensured that the narratives were compelling and cohesive. In *Mission Gravity,* participants find themselves in a spaceship on a mission to study distant stars. In *Bigger Than Big,* the experience begins with an exploration of the relative sizes of familiar objects such as the Sun, Earth, and Moon. After introducing these familiar objects, the story eases participants into the more exotic and unfamiliar astronomical phenomena, like black holes and gravitational waves. This approach provides an engaging journey that is tailored to the prior knowledge of the audience.

To avoid making people feel sick or unstable, the design of both VR tours places careful limits on the sensory features of the environment, avoiding too much sensory input that is not connected to the physical reality of users (DPI 3). In particular, the environments tie back the virtual experiences to the reality of participants by making clear how movement connects to the visual content (i.e. is the person getting a sense of moving, or is the object moving further away, or is the object getting smaller?).

Designing for visualisation

The design principles for visualisation (DPV) in Table 3 suggest utilising various representations to depict astronomical scales, finding a balance between scientific accuracy and visual accessibility, and evoking emotional responses through striking visualisations.

One of the fundamental design principles in *Bigger Than Big* is using different representations to visualise the vast scales and distances of astronomical phenomena (DPV 1). By illustrating both long and short scales in various ways, such as comparing stellar evolution to the fleeting existence of a supernova or showing the transformation of a massive star into a tiny neutron star, the VR environment helps participants grasp the enormity of the universe:

Practitioner 2: I was thinking about the problem with scale in astronomy. I think that comes in a number of different forms. There's the problem of scale and distance but also the scaling of energy (…). If someone's looking at a star in VR, you can't really have it pumping out as much energy as the previous one because you have to be conscious, obviously, not to make something too bright. And then also the scale of time, like the evolutionary lifetime of the star, billions of years. Not much changes, then it goes supernova and changes very, very fast, so there's those aspects. What are the challenges with unobservable phenomena? Things like magnetic radiation that's outside the visual range, radio, X-Ray, and then gravitational waves. How do you portray that? Are you getting a true sense of the scale, or is it a distorted sense? And I suspect that's the case because in the *Bigger Than Big* scene where you've got Jupiter, the Sun and then the blue supergiant, they're all scaled. Their relative scales, the blue supergiants had to be further away; you don't get a sense that it's that much bigger.

Researcher 1: Just one quick question because you just said the true sense versus the distorted sense of the scale. Can we really expect visitors to take away an understanding of the true sense? I mean, I'm not an astronomer (…) I wouldn't claim that I have a true sense of scale. Is this something that we can expect? Or what kind of expectations do you have when you put the participant into this environment? What should they learn?

Practitioner 2: I agree. It's hard to get a sense of that scale. Like even something that's 10 times bigger than something else, that's a big difference. And then when you're talking about a thousand times bigger, yeah.

Researcher 2: Well, I'm just wondering how much of a problem you view it as the sense of scale might not be what we think of as correct. There's an emotional basic understanding that we're dealing with scales that are really difficult to understand. So, you could come away with that understanding that the level of scale we're talking about from the participant's perspective is humongous. Does it need to be a model in the way that a scientist would use to have all the pieces accurate? Or are you emphasising the emotional experience of just getting an understanding, 'Okay, this is way bigger than I thought'?

Figures 1 and 2 illustrate design decisions related to the tension between astronomical scales regarding sizes and distances. This tension came up as a particularly tricky challenge in depicting the solar system in *Bigger Than Big*: if both scales of size and distance were correct, the planets would be tiny dots off in the distance.[3] Figure 3 exemplifies artistic choices that were made to visualise otherwise invisible aspects of pulsars and binary star systems (DPV 2). The reflective dialogues also suggested that evoking emotional experiences through visualisations can be a worthwhile goal in VR astronomy education (DPV 3). Although it may not be possible for users to comprehend the true scale of celestial objects fully, designers can focus on creating experiences that elicit emotional reactions, such as awe or wonder and convey the vastness of the universe.

Designing for collaboration

The design principles for collaboration (DPC) in Table 3 promote teamwork, communication, and shared learning to enhance the overall educational experience for participants in the VR environment. One approach to encouraging collaboration is using screencasting (DPC 1). Screencasting is the wireless projection of the internal view in virtual reality to an external flat computer screen, allowing an external viewer to see what the person in VR is viewing in real time. The OzGrav system allows the images from up to nine separate VR headsets to be wirelessly projected onto one computer screen. Screencasting allows participants outside the virtual environment to join the experience without becoming immersed themselves and, crucially, to communicate with the person in the virtual world. By preparing people for the VR experience through screencasting, the designers encourage organic conversations where participants help each other navigate the virtual environment.

Mission Gravity is designed as a group activity, thereby exemplifying several design features focused on collaboration and social interaction in VR experiences (DPC 2). One example of fostering collaboration is the design of different roles within the VR activity. For instance, in *Mission Gravity*, students work in teams, with different students gathering, verbally communicating, and recording

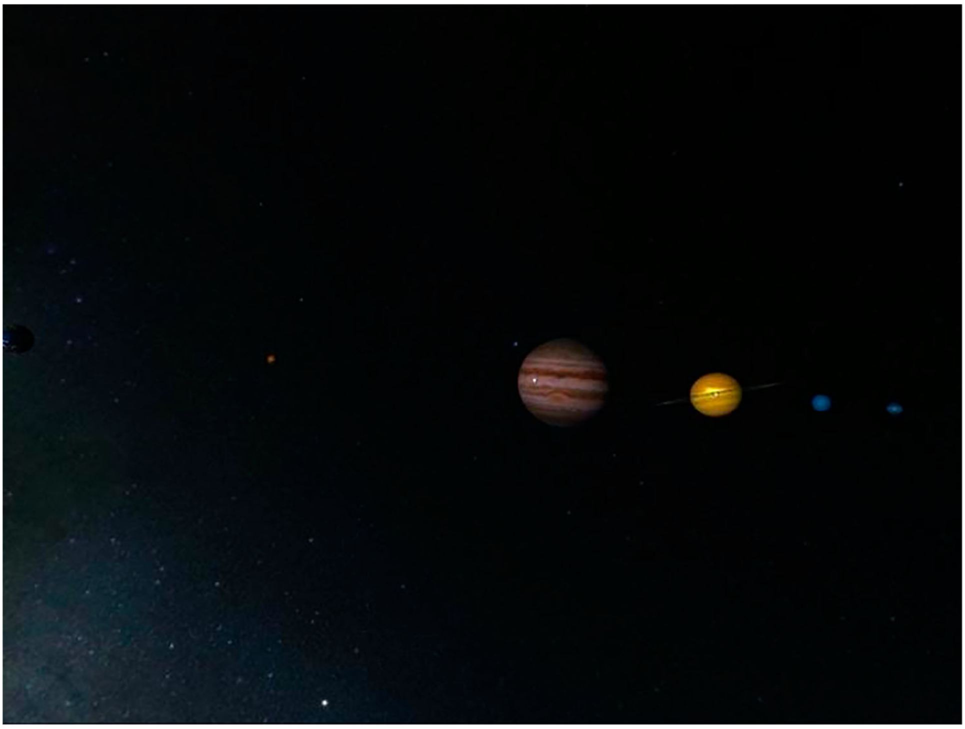

Figure 1. This screenshot of the VR tour Bigger Than Big illustrates the scale of the outer planets of the solar system. Note that the scale of the planets is accurate, but the distance is not.

data of the stars (e.g. temperature, wavelength, mass) in the virtual space. This division of responsibilities promotes teamwork and communication between students. The reflective dialogues emphasised the deliberate choice to design for conversational partners across the XR environment, the screencasting, and the physical space to prompt conversations where participants help each other.

Additionally, *Mission Gravity* allows participants to revisit the experience through others' perspectives. When students take turns in the VR environment, those who have already completed the activity often turn into experts or leader who can guide their peers. This setup empowers the students who have already encountered the VR experience and fosters a sense of collaboration and expertise within the group:

> Practitioner 2: For example, with the Mission Gravity school incursion, students are working in teams. One of them has to write down what the other person is collecting, the data that they're gathering. There's that communication where one is gathering the information and seeing it, and then verbally relaying it; the other one needs to record it.
>
> Practitioner 1: And then it's kind of funny what happens when they work in groups with the Mission Gravity. You sometimes see it if kids are taking turns with the guided tour, then one who has already been in the VR, they become a leader for the next person. They take over, telling them what they're seeing or guiding them on how to do it. So, it's that collaboration piece which, I think, is the first person to go empowers them within their little social group to be the new expert.

Designing for facilitation

The design principles for facilitation (DPF) in Table 3 suggest how educators and content creators can develop safe, engaging, and personalised VR experiences that cater to diverse learning needs

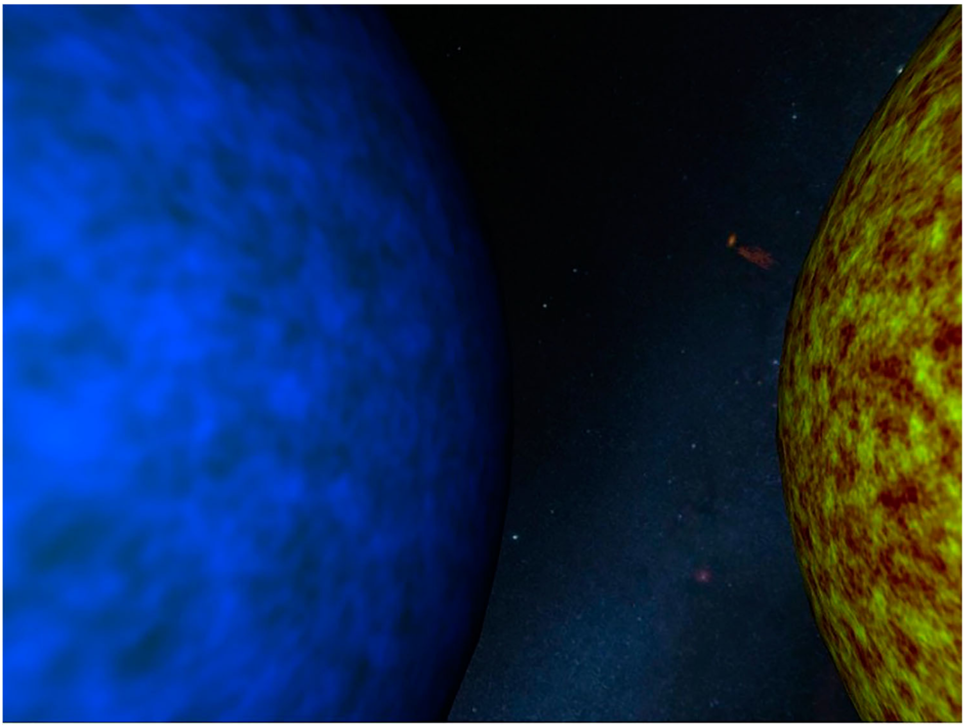

Figure 2. In this scene from Bigger Than Big, the size of a blue supergiant is compared to the size of our Sun. Here, a visual challenge was to convey the enormous size of the blue supergiant while still depicting the Sun and other planets in the solar system.

and promote meaningful interactions with astronomy experts. In *Bigger Than Big,* participants are equipped with wireless, head-mounted VR headsets that are connected to a shared computer. This setup allows groups of users to embark on the tour simultaneously, making each participant feel less on display. Besides, the standalone headsets give users control over the physical device, allowing them to easily remove it if needed, thereby creating a safe learning environment (DPF 1). The scientists act as tour guides and ensure additional participant safety by closely monitoring them during the VR experience and providing clear instructions:

> Researcher 1: I think an important aspect is building trust with the participants. And when you're in VR, you're always on display in a sense. You have to be brave enough to put the headset on, and you're not going to see other people. Do you find that there is a hurdle? How do you invite people to do that and to find the right balance between having people on display and still giving them a good experience?
>
> Practitioner 2: Well, one thing that I did notice, and this kind of just fell out, was when we started doing events where we had multiple people in VR at the same time, we found people were less reluctant. So that's kind of what you were talking about, that on-display thing; when you're the only person, there's more of a focus. But when there are multiple people, you're part of your own little group (…).
>
> Practitioner 1: And I suspect this is another factor in building trust to get people to do the experience: making sure that you've got at least one or a few people watching the people that are in VR and making sure that they're safe. And then the next lot of people see that. Because sometimes, kids want to go up and poke the person in VR, and if you can prevent that from happening and other people see that's not happening, then they feel that when they go there, they'll be looked after.

Moreover, inviting scientists as tour guides has the added benefit of fostering conversations between scientists and participants (DPF 4). By incorporating opportunities for experts to share their

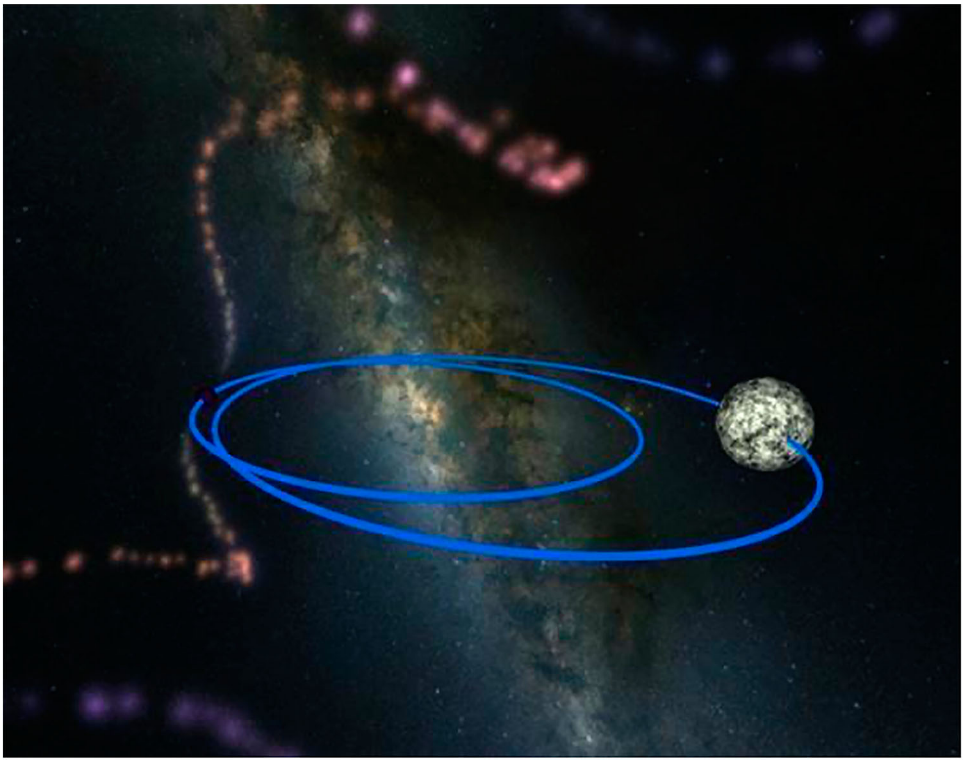

Figure 3. This scene from the virtual reality tour Bigger Than Big demonstrates the orbit of a white dwarf star and a pulsar that emits jets of energy. Adding the blue orbits supports the visualisation of the spiral movement. The jets coming from the pulsars are radio jets, which are not perceptible in the usual visible light spectrum. Here, an artistic choice to visualise this phenomenon was made: the radio jets are represented in a semi-translucent colour that is not continuous but spreads as the distance from the pulsar increases.

research during the experience and by connecting participants with scientists, the VR experience provides an authentic and engaging environment. Finally, facilitators can personalise the VR experience based on participants' interests and current understanding (DPF 2). If facilitators ask participants what they see in the VR environment before providing the information themselves, the facilitators can adapt the experience to match the level of background knowledge or individual interests and preferences (DPF 3). Crucially, the content in the VR environment is created with various levels of explanation, offering additional scenes depending on the depth of understanding desired. This flexibility enables facilitators to tailor the experience to the audience's interests and knowledge:

> Practitioner 2: When creating the content, there's always that thought of different levels or different depths that you can go into. So not having it so that it's an all-or-nothing thing. For example, when we do public sessions and also when we go to schools, one of the first things we do is find out the people's current understanding. And then it's a gauge of what kind of depth they want to go into. Young kids probably just want to have a look at a few things and then move on to the next one. Having the ability to dive deeper if needed, but to be able to skim over without looking like it's skimming, so that they have a sense of, "Oh yes, this thing and then this thing," and not feeling that they're missing something (…).
>
> Practitioner 1: And then with this guided tour, *Bigger Than Big*, we don't go into every detail about every little piece in it. It's designed so there's sort of one level of understanding, but then we can dive deeper depending on who we're talking to. You can kind of go through some things but still have that conversation so people can ask for more depth about something that they see if they're interested. So, I think that's one thing that's really been great in the design of our

experiences is that there are multiple levels in which our visitors or our students can engage with it without feeling like they've seen it all after five minutes.

Practitioner 2: Well, in terms of design: allowing them to dive deeper. For example, with the guided tour thing, I think it's a case of having extra scenes there that you can go into if you think they need detail. So, for example, there's one bit where we show the stretching and squashing of gravitational waves. There's one wave in front of them but also another one behind them with a different polarity. And if you don't think they're going to be interested, then you don't have to worry about what's behind them, or you can say, "Turn around, and have a look behind you, you'll see something else." So, there's that.

Discussion

This study aimed to explore the design considerations for using VR in informal astronomy education, focusing on the perspectives of education and public outreach professionals. Our findings reveal that various factors motivated EPO professionals to use VR in astronomy education. First, they aimed to create a significant educational impact and develop relevant educational activities for their target audience. This motivation aligns with the overarching goal of formal and informal science education to cultivate a 'citizenry that is educated with respect to science' (Stocklmayer et al., 2010, p. 1).

Second, their passion for science, desire to inspire young learners, and fondness for VR technology also drove their enthusiasm. Additionally, the excitement of outreach events and increased self-confidence from sharing knowledge contributed to their motivation. These motivations align with the broader view of informal science education and public outreach as aspects of our culture, 'as something experiential and emotional – as something that is concerned with the creation of shared meanings' (Davies et al., 2019, p. 2). By highlighting the motivations and experiences of educators and outreach practitioners, our study, thus, contributes to a holistic conceptualisation of astronomy education as an experiential and emotional endeavour of shared meaning-making, an endeavour in which we 'move away from the existing categories of dissemination and dialogue, which focus on directionality of information, and instead move towards the quality and meaning of communication' (Davies et al., 2019, p. 10). In this context, VR technologies serve as a bridge to connect the knowledge and passion of experts to the experiences of learners (Kersting, Steier, et al., 2021).

Versatility, visualisation, and collaboration were among the identified opportunities of VR that can transform astronomy education for the better. The practitioners pointed out that the flexible setup of VR equipment allows for tailored experiences, while vivid visualisations of astronomical phenomena create engaging learning moments. The immersive nature of VR, in particular, stood out as a feature that enables learners to experience astronomical phenomena more tangibly and memorably. These findings resonate with existing literature on the benefits of VR for teaching astronomy. Astronomy learners tend to experience instruction in VR environments as authentic, engaging, and enjoyable (Atta et al., 2022; Madden et al., 2020; Severson et al., 2020). For example, Madden et al. (2020) found that most undergrad students in an introductory astronomy class preferred immersive simulation using a VR headset to a computer-based interactive desktop simulation and an analog hands-on activity when learning about moon phases. In the study, the desktop simulation was designed to mimic the VR activity as closely as possible, and the hands-on activity involved a stationary light that represented the Sun, a small ball that represented the moon, and the participants' heads that stood for the Earth (Madden et al., 2020).

Collaboration further enriches the experience by fostering interaction among participants and between learners and scientists. By capitalising on these opportunities and incorporating the fascinating aspects of astronomy content, VR can transform astronomy education and outreach, creating immersive and impactful experiences for learners. While the literature has previously reported on the motivational effects of authentic interactions between scientists and members of the public, the so-called 'meet-a-scientist' effect (Woithe, 2020), this positive impact had only been explored from the participants' perspective. Our study adds a complementary perspective, showing that personal interactions also benefit scientists. By taking on the role of a VR tour guide, scientists can share their passion for and knowledge of astronomy with others.

However, our study highlights several challenges associated with using VR in astronomy education, including safety concerns and the need to balance visual richness with scientific accuracy. These challenges emphasise the importance of careful design and implementation of VR experiences, informed by pedagogical and technological considerations. Addressing these challenges is crucial for ensuring that VR experiences are engaging and educationally effective.

Limitations of the study

We acknowledge several limitations of our study, which may affect the interpretation of our findings. First, the scope of our research is naturally limited. Although our research design enabled a detailed examination of the motivations and experiences of this programme's education and outreach team, we recognise that our findings may not apply to all astronomy education activities or VR implementations. Outreach professionals in different contexts may encounter additional challenges and opportunities. Further studies with larger samples and quantitative measures would be beneficial in validating and expanding our understanding of VR in astronomy education.

Second, our study focused primarily on the perspectives of outreach professionals, which cannot fully capture the experiences and viewpoints of the learners. While we have previously reported on how science festival participants engaged with the VR experiences of this programme (Kersting, Steier, et al., 2021), future research could further assess learning outcomes and satisfaction to provide a more holistic picture of the use of VR in astronomy education.

Despite these limitations, our study offers valuable observations and design principles that educators and practitioners can use to design and implement VR experiences in informal astronomy education. By understanding the motivations, opportunities, and challenges associated with VR, we can develop better strategies for using VR in these contexts.

Conclusion

In conclusion, this study makes two significant contributions towards bridging the gap between research and practice in VR astronomy education, one empirical and one methodological. Empirically, we have turned our attention to the perspectives of astronomy EPO professionals and contributed to a deeper understanding of the opportunities and challenges that new learning contexts in VR provide for astronomy education. By understanding the motivations of practitioners, we can better appreciate the potential of VR to enhance astronomy education and outreach. Specifically, we have shown how EPO professionals use new forms of embodied engagement, visual representations, collaboration, and facilitation across real and virtual spaces to expand and transform astronomy education practices in formal and informal learning spaces.

Methodologically, we have demonstrated that researchers and practitioners can jointly engage in acts of reflective practice to gain new insights into astronomy education practices. Our dual approach of reflection in and on action, combined with our interdisciplinary backgrounds in design, astronomy, and education research, have enriched the dialogues and facilitated a more comprehensive exploration of the complex interplay between content, pedagogy, and technology in the context of VR education. The dialogue format played a significant role in facilitating both types of reflection.

The dialogues have resulted in design principles for developing and using VR in astronomy education. These principles centre on aspects of immersion, visualisation, collaboration, and facilitation. They can guide astronomers, astronomy educators, teachers, and public outreach professionals who wish to use VR in formal and informal learning contexts. We expect future studies to unpack VR astronomy education opportunities further. As VR technologies continue to evolve, we invite the astronomy education community to engage in more collaborations between researchers and practitioners to realise the full potential of VR.

Notes

1. https://www.ozgrav.org/vision--mission.html
2. https://outreach.ozgrav.org/portal2/
3. This short video clip presents a non-VR version of the depiction of scale in *Bigger Than Big* https://youtu.be/DprhVJHXqwA

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ORCID

Magdalena Kersting http://orcid.org/0000-0003-3568-8397
Jackie Bondell http://orcid.org/0000-0002-8089-5662
Rolf Steier http://orcid.org/0000-0001-9809-3169

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