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Mestrado em Gestão e Tecnologia Industrial

## Dissertação de mestrado

# Design guidelines for intuitive virtual reality authoring tools

Apresentada por: Iolanda Lima Chamusca
Orientador: Prof. Dr. Ingrid Winkler
Coorientador: Prof. Dr. Antônio Lopes Apolinário Junior

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**CENTRO UNIVERSITÁRIO SENAI CIMATEC**
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Iolanda Lima Chamusca

# Design guidelines for intuitive virtual reality authoring tools

Salvador, 2023

Iolanda Lima Chamusca

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*Centro Universitário SENAI CIMATEC*

Coorientador: Prof. Dr. Antônio Lopes Apolinário Junior
*Universidade Federal da Bahia*

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Assinado eletronicamente por:
INGRID Winkler
CPF: ***.486.968-**
Data: 30/03/2023 10:52:46 -03:00

Orientadora: **Profa. Dra. Ingrid Winkler**
SENAI CIMATEC

Electronically signed by:
Antônio Lopes Apolinário
CPF: ***.659.867-**
Date: 3/21/2023 3:58:41 PM -03:00

Coorientador: **Prof. Dr. Antônio Lopes Apolinário Junior**
UFBA

Assinado eletronicamente por:
Marcio Fontana Catapan
CPF: ***.829.269-**
Data: 21/03/2023 16:26:52 -03:00

Membro Externo: **Prof. Dr. Marcio Fontana Catapan**
UFPR

Electronically signed by:
PEDRO MARIO CRUZ E SILVA
CPF: ***.276.774-**
Date: 3/21/2023 4:40:59 PM -03:00

Membro Externo: **Prof. Dr. Pedro Mário Cruz e Silva**
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Abstract

Virtual reality (VR) experiences are frequently developed using game engines, which are difficult for unskilled professionals who lack programming and 3D modeling skills. Concurrently, there is a knowledge gap in software project design for intuitive VR authoring tools, which were intended to be more user-friendly. Frequently, these authoring tools are inadequate due to a lack of standardized operating procedures. This study contributes to the development of more intuitive VR authoring tools and the evaluation of existing ones by proposing design guidelines. We adopted the Design Science Research paradigm, which consists of the following six steps: (1) problem identification, (2) solution objective definition, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication. Following these steps the study identified the complexity in VR authoring tools due to the lack of ontologies, defined the solution of proposing design guidelines, developed a Systematic Literature Review following PRISMA, demonstrated a guidelines' proof-of-concept to experts, evaluated the guidelines by experimenting an example authoring tool and communicated the findings as a review and an article. As results, fourteen papers were reviewed and fourteen design guidelines were compiled for requirements and features, including Visual Programming, Immersive Authoring, Sharing and Collaboration, and Movement Freedom, among others. Next, we evaluated the validity of the design guidelines, and the results indicated that they may be useful for assisting with the evaluation of intuitiveness in VR authoring tools and promoting the creation of other intuitive tools. In addition, they can support the growth of the metaverse, as virtual content creation is one of its pillars, as well as contribute to the creation of standard concepts for the area, creating in another words, ontologies.
**Keywords**: Virtual reality, Authoring tools, Design guidelines, Human-computer interaction, Metaverse.

# Sumário

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# Lista de Siglas

AI ......... Artificial Intelligence
APIs ....... Application Programming Interface
ASQ ....... After-Scenario Questionnaire
CNN ....... Convolutional Neural Network
DSR ....... Design Science Research
DG ........ Design Guidelines
GAN ...... Generative Adversarial Networks
HCI ........ Human-Computer Interaction
HMD ...... Head-Mounted Displays
IoT ........ Internet of Things
ISMAR .... IEEE International Symposium on Mixed and Augmented Reality
IVWPs .... Integrated Virtual World Platforms
PCC ....... Pearson Correlation Coefficient
PRISMA ... Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SGD ....... Sustainable Development Goal
SLR ....... Systematic Literature Review
SUS ....... System Usability Scale
VPL ....... Visual Programming Languages
VR ........ Virtual Reality
XR ........ Extended Reality
WYSIWYG what you see is what you get

# 1. Introduction

This chapter describes the study's *Problem definition*, *Research relevance*, *General* and *Specific objectives*, and *Document organization.*

## 1.1 Problem definition

Creating virtual reality (VR) experiences is not widespread and requires expensive and lengthy development processes using game engines such as Unreal[1] and Unity[2], which demand expert professionals in programming languages and/or 3D modeling (CASSOLA et al., 2021; NEBELING; SPEICHER, 2018; ZHANG; ONEY, 2020; IPSITA et al., 2021; KRAUSS et al., 2021; YIGITBAS et al., 2021). This is because of the unusual input and output devices used in virtual reality, as well as the complexity of the software architecture of VR systems. These devices include head-mounted displays (HMD), tracking systems, 3D mice, and others (SHERMAN; CRAIG, 2018).

Therefore, making interactive scenes in virtual reality is hard and uncomfortable for people who have not done it before, which include people who come from high level creator groups, such as digital artists and designers, and developers who come from other technology fields, that are not immersive (KRAUSS et al., 2021; YIGITBAS et al., 2021). This group also includes professionals who only want to use virtual reality as a supplement to their day-to-day work, such as professors, doctors and engineers (BERNS; SÁNCHEZ; RUBE, 2020; VELEV; ZLATEVA, 2017; VERGARA et al., 2019).

Authoring tools are an alternative to the lengthy learning curve, as they aim to facilitate the creation of content with minimal iterations. The term *authoring tool* refers to software structures that include the most important tools and features of content creation while making product maintenance

[1]https://unity.com/pt
[2]https://www.unrealengine.com/en-US

faster and better (COELHO et al., 2022; ZIKAS et al., 2020). In contrast to high-fidelity prototypes, which necessitate sophisticated programming and 3D modeling skills, these technologies are used for low-fidelity creation, which requires fewer skills (KRAUSS et al., 2021).

Virtual reality experiences can presently be created using a variety of authoring tools, many of which are free-source programs (LYNCH; GHERGULESCU, 2017). But these tools usually lack ontologies, standardized processes, documentation and tutorials in addition to functionality, which makes them unsuitable for supporting the complete development cycle and difficult to define best practices for multiple user applications (KRAUSS et al., 2021; O'CONNOR; DOMINGO, 2017; CASSOLA et al., 2021; VELEV; ZLATEVA, 2017; ZIKAS et al., 2020; COELHO et al., 2022). This occurs because these authoring tools are often developed as proof-of-concept, to help test the user's acceptance and identify main features they might enjoy to see on the final product, but not with an application field in mind (COELHO et al., 2022).

Furthermore, software or platforms in the form of authoring tools are very hard to make because every feature becomes a priority. They aim to give creators creative freedom while standardizing underlying technologies, making everything as interconnected as possible, and minimizing the need for creators to be trained or know how to program (BALL, 2022). Combined with the complexity of virtual reality systems architecture, these barriers contribute to the persistence of novices' learning difficulties, requiring good prior knowledge to utilize the full potential of the tool (YIGITBAS et al., 2021).

Previous studies have addressed various aspects of using authoring tools for the creation of virtual reality experiences, complementing one another. (KRAUSS et al., 2021; COELHO et al., 2022; ASHTARI et al., 2020). One introduced eight key barriers to creating virtual and augmented reality experiences, such as *Difficult to know where to start*, *Lack of concrete design guidelines and examples*, *Difficult to design for the physical aspect of immersive experiences* and *User testing and evaluation challenges* (ASHTARI et al., 2020). Other investigated the challenges that virtual and augmented reality creators face when using authoring tools for collaborative teamwork, such as *Lack of tool support* and *Missing a common language and shared concepts* (KRAUSS et al., 2021). Another systematically reviewed studies on authoring tool development to analyze their usability evaluation methods (COELHO et al., 2022).

These studies have concentrated on analyzing how authoring tools were used after they were developed and made available to users rather than on how the development process affected the final product. Therefore, there is a knowledge gap regarding the design of virtual reality authoring tool software, which needs to be mitigated by assisting software developers in defining good project design and evaluating existing tools according to their intuitiveness, getting into the root cause of the problem. They need to wisely choose and create the features and requirements that these tools must have to be considered intuitive, as well as understand why existing tools do not meet this purpose (PRESSMAN, 2021).

## 1.2 Research relevance

Effective human-machine communication is needed to understand probable interactions, what is happening in the present, and what can happen next. Human-centered design prioritizes human needs, skills, and behaviors, and then designs to meet them. Following design guidelines, people can understand how to create well-designed virtual reality experiences; similarly, creating design guidelines can support the development of intuitive authoring tools to create the VR experience. The results will contribute to structure the discussion about how beginners can accomplish their goals with a more user-friendly and inclusive authoring tool, in a more sustainable VR (JERALD, 2015).

Professionals of all skill levels would benefit from authoring tools that are intuitive, helping them reach their virtual reality goals more quickly. The accelerated growth of immersive technology can benefit concepts such as the metaverse, in which users can seamlessly experience a digital life and make digital creations supported by the metaverse engine, especially with the support of extended reality (XR) and human-computer interaction (HCI) (WANG et al., 2022). Similar to authoring tools, integrated virtual world platforms (IVWPs) are used to create games (such as Roblox, Minecraft, and Fortnite Creative) that use graphical interfaces, symbols, and objectives instead of code and have a simpler interface, enabling users to create virtual worlds for the metaverse with less support, money, expertise, and skills (BALL, 2022).

There are still a lot of open questions on what is the easiest and best way to build the metaverse, facilitating exchanges of information, virtual goods, and currencies between these virtual worlds. Organizations worldwide have been conducting a variety of initiatives to explore new technological solutions and to exploit their benefits, including transformations of business operations, products, processes, structures and management concepts (MATT; HESS; BENLIAN, 2015). Digital transformation is about adopting these disruptive technological solutions, such as virtual reality, to increase productivity, changing how people interact with it, either as consumers or professionals (EBERT; DUARTE, 2018).

Metaverses are a major digital transformation that has already been impacting the work format in the technology area, encouraging the need for vacancies for people specialized in using the metaverse in conjunction with a company's strategy. For that, people and easier-to-use virtual reality authoring tools will be required to enable the creation of new digital content, and the more people collaborating to build these worlds, the bigger and more diverse it will be. Virtual world engines will become a standard feature of the metaverse as the global economy continues to shift to virtual worlds (BALL, 2022).

In addition, virtual reality has helped organizations to achieve several Sustainable Development Goals (SDG), such as SDG 8 (Decent work for all) and SDG 9 (Industry, Innovation, and Infrastructure), by replacing physical products or real-world interactions with virtual ones, therefore reducing carbon emissions (FREITAS; GOMES; WINKLER, 2022), and foreseeing ergonomic risks, protecting workers from risk of harm and improving workplace well-being (SILVA; GOMES; WINKLER, 2022). Therefore, increasing the use of sustainable experiences by adding virtual reality technologies, contributes directly to a more sustainable future.

Finally, proposing design guidelines for the development of more intuitive virtual reality authoring tools and the evaluation of existing ones can serve as a starting point for addressing the previously mentioned challenges and barriers in the industry. Contributing to demonstrating how to start utilizing VR by providing concrete guidelines and examples, proposing a way to test and evaluate tools, as well as bring a common language and shared concepts, developing ontologies (ASHTARI et al., 2020; KRAUSS et al., 2021; COELHO et al., 2022).

## 1.3 General Objective

Given the above, the objective of this work is to contribute to the development of more intuitive virtual reality authoring tools and the evaluation of existing ones by proposing design guidelines.

## 1.4 Specific Objectives

To achieve the general objective of this research and in accordance with the Design Science Research (DSR) steps, the following specific objectives were proposed:

1. To refine the problem research on virtual reality authoring tools;
2. To define solution objectives;
3. To develop the design guidelines for intuitive virtual reality authoring tools;
4. To demonstrate a proof-of-concept of the developed design guidelines;
5. To evaluate the validity of the developed design guidelines;
6. To communicate the study results.

The DSR processes are covered in full in Chapter 2.

## 1.5 Questions and hypotheses

Despite the fact that previous studies of aspects related to the use of authoring tools addressed challenges associated with the development of both

Augmented Reality and Virtual Reality experiences, each technology has its own requirements, primarily involving different development processes and hardware, even though game engines serve as the foundational software the majority of the time (ASHTARI et al., 2020; KRAUSS et al., 2021; COELHO et al., 2022). In light of this, the research sought to investigate the nuances of Virtual Reality development without addressing Augmented Reality.

In addition, it is vital to note that the design guidelines are not designed to directly help authors in the creation of virtual reality experiences, which would be the final result obtained by using an authoring tool. The guidelines are intended for the software developers who develop the authoring tools utilized by the experiment's authors later on, indirectly making the entire creative process more intuitive. Authors can use them to evaluate existing authoring tools, as demonstrated in the experiment described in Chapter 4, but it is not appropriate for them to use the guidelines during the creation of the final experience, as the guidelines are focused on making the authoring tool more intuitive, so they should be used in earlier phases.

## 1.6 Document Organization

This work is divided into the following five chapters:

- **Chapter 1 - Introduction**: Constitutes the problem definition, research relevance, objectives, questions and hypothesis, and the organization of the presented document. In this chapter, the general context that supports the importance of the development of the study is discussed, highlighting the main scientific contributions;
- **Chapter 2 - Methodological aspects**: Constitutes the general method and the specific methods utilize in each paper presented in Chapter 3 and Chapter 4 to achieve the final results of the study;
- **Chapter 3 - Towards sustainable virtual reality: gathering design guidelines for intuitive authoring tools**: Presented in the format of a paper submitted to the Sustainability journal on 10/Dec/2022 and published on 6/Feb/2023 (CHAMUSCA et al., 2023), as part of the development of the Specific Objectives 1, 2 and 3 of

this work, namely *to refine the problem research on virtual reality authoring tools*, *to define solution objectives*, and *to develop the design guidelines for intuitive virtual reality authoring tools*. It consists of a prospective and review study to identify virtual reality authoring tools whose authors classify as intuitive, aiming at the development of design guidelines according to their main characteristics through analysis of articles based on scientific and technological prospecting;

- **Chapter 4 - Evaluating design guidelines for intuitive virtual reality authoring tools: a NVIDIA Omniverse's experiment**: Presented in the format of a paper, submitted as an article on the Preprint.org platform on 29/Sep/2023, generated from the Metaverse and Application workshop held in IEEE International Symposium on Mixed and Augmented Reality (ISMAR) in 2022 (CHAMUSCA et al., 2022). The publication of six pages for the ISMAR 2022 workshop was part of the development of the Specific Objective 4, namely *to demonstrate a proof-of-concept of the developed design guidelines*, testing and revising them through expert reviews, with a preliminary version exposed to researchers. At the same time, the article contributes to the development of Specific Objectives 5 and 6, which are, respectively, *to evaluate the validity of the developed design guidelines* and *to communicate the study results*. The Specific Objective 6 can be met not only by this chapter, but also by all other publications produced during the study's implementation;

- **Chapter 5 - Final Considerations**: The final considerations of the work are offered, which include discussions of the findings presented in the preceding chapters, limitations, and recommendations for further research.

# 2. Methodological aspects

## 2.1 General Method

This research has an exploratory character, which has as its main objective to develop, clarify and modify concepts and ideas (GIL, 2015). Exploratory research is used in cases where it is necessary to define the problem with greater precision, providing criteria and understanding of facts and data (MALHOTRA, 2001). In this perspective, this study is characterized by identifying which design guidelines can support the development process of more intuitive VR authoring tools and their application in an experiment in order to bring more evidence of their contributions in the development process of these tools.

As for the type, this research is characterized as Qualitative, which is a way to explore and understand the meaning that individuals or groups attribute to a social or human problem. The research process involves the questions and procedures that emerge, the data typically collected in the participant's environment, the analysis of the data inductively built from the particularities to the general themes and the interpretations made by the researcher about the meaning of the data (CRESWELL J. W. & CRESWELL, 2017).

As for the research strategy, the study adopt Design Science Research, which proposes to be a way of producing scientific knowledge that involves the development of an innovation, with the intention of solving real-world problems and, at the same time, make a scientific contribution. Design Science Research proposes bringing theory and practice together in order to unite the rigor of scientific research with the relevance of applied research developed within organizations. Knowledge is produced in the context of the application, which can be industry, government or society (DRESCH; LACERDA; JUNIOR, 2015).

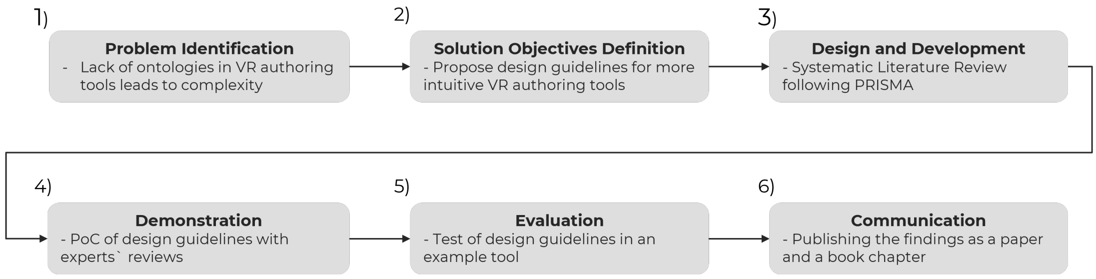
A fundamental concept in the DSR research paradigm is that of an *artifact*, something that is artificial, or constructed by humans, as opposed to something that occurs naturally. In this context, a designer answers questions relevant to human problems through the creation of innovative artifacts, thus contributing new knowledge to the body of scientific evidence. The designed artifacts should improve existing solutions to a problem or provide a first solution to an important problem, proposing to be useful and fundamental to understanding this problem (LACERDA et al., 2013). The artifact produced in this study was the list of the fourteen design guidelines.

To achieve the specific objectives of this research and in line with the Design Science Research steps, the following methods were applied, which are similar to those employed in prior studies (GREGOR; HEVNER, 2013; PEFFERS et al., 2007):

- To achieve the Objectives 1, 2 and 3, a literature review was undertaken following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles (PAGE et al., 2021; BOOTH et al., 2021);
- To meet the Objective 4, a proof-of-concept of the applicability of the developed design guidelines was demonstrated, testing and revising them through expert reviews, with preliminary versions exposed to researchers in seminars and workshops (CHAMUSCA et al., 2022);
- To achieve the Objective 5, the validity criteria of the developed design guidelines was evaluated by putting them to the test on an example tool;
- To achieve the Objective 6, the study's findings were communicated by publishing three publications and delivering this document.

The general set of methodological aspects that make up the development of this research were divided into the steps shown in Figure 2.1. In the subsequent sections, a summary of the methodology employed at each of these stages is described.

Figura 2.1: *Design Science Research* flow, adapted from (PEFFERS et al., 2007)




## 2.2 Methods of Chapter 3

The review paper submitted to the Sustainability journal, and presented in Chapter 3, applied the PRISMA guidelines, followed by a process of seven steps: planning, defining the scope, searching the published research, assessing the evidence base, synthesizing, analyzing, and writing (BOOTH et al., 2021). The Design Science Research is not mentioned in the published material, because presenting this paper as part of a larger study would bring too much complexity for a literature review, but the work is still considered as part of the first three steps of the paradigm.

An expert in virtual reality-based design testing of product development defined the initial search strategy (FREITAS; GOMES; WINKLER, 2022), which was then qualitatively assessed by three senior researchers with strong background and experience with 3D visualization tools. Three main questions defined the scope of this review, related to the characteristics of VR authoring tools, the definition of intuitiveness in this context and the guidelines for designing more intuitive ones. The investigation was carried out using the scientific databases Scopus and Web of Science, where a particular string was used to search the literature based on the research questions previously presented (BOOTH et al., 2021).

Inclusion and exclusion criteria filters were applied to reduce the number of documents found by selecting those that were relevant to the research questions (BOOTH et al., 2021). One of these criteria, the research period between 2018 and 2021, was chosen for being equivalent to the fast progression of this technology through these years, not only academically but also in virtual reality hardware releases. All the criteria were compiled in a Systematic review flow diagram, adapted from PRISMA, and presented as Figure 1 of the article.

In terms of data analysis steps and procedures used for interpreting and validating collected data, a text non-numerical analysis was employed, with the type of interpretation consisting of themes and patterns to identify design guidelines, and peer experts debriefing strategy for validating findings (CRESWELL J. W. & CRESWELL, 2017). The retrieved articles were read through Mendeley Desktop and the characteristics of virtual reality authoring tools in terms of which *artifact* was developed in the study were compiled. Then, using Microsoft Excel, the text data gathered were arranged by bracketing segments into categories and labeled them with a title, creating the design guidelines, which were grouped into *requirements* or *features*.

Finally, each identified design guideline was discussed in depth by a qualitative narrative, along with quotations from the reviewed works from which that guideline was interpretated, to support the categorized themes (CRESWELL J. W. & CRESWELL, 2017). Using the authors' qualitative understanding, a list of *related terms* for each guideline was also compiled, which is primarily made up of synonyms, not being connected to the frequency with which they appear in the reviewed articles. This process led to the fourteen design guidelines presented in the Chapter 3, which were also compiled in a visual depiction, shown as Figure 4 in the article.

## 2.3 Methods of Chapter 4

The preprint article generated from the ISMAR Metaverse and Application Workshop, and presented in Chapter 4, unlike the previous chapter, declares to adopt the Design Science Research paradigm (GREGOR; HEVNER, 2013; PEFFERS et al., 2007). The first three steps were completed in Chapter 3. To cover step 4, it was demonstrated a proof-of-concept of the applicability of the proposed design guidelines, testing and revising them through expert reviews, with preliminary versions exposed to researchers in seminars and workshops, such as the Metaverse and Applications Workshop, held in ISMAR 2022 (CHAMUSCA et al., 2022). Chapter 4 carry out the remaining step 5 and part of the step 6, which is covered by all publications communicating the findings of this work.

In step 5, the validity criteria of using the fourteen developed design guidelines to verify the intuitiveness of existing VR authoring tools were evaluated by putting them to the test on an example tool. The evaluation started by applying the Pearson Correlation Coefficient (PCC) to the Chapter 3 results to find out how often two guidelines were found together in the studies that were looked at during the SLR, serving later as an indicator to compare with the later results.

Then, an experiment with six engineering students was conducted. They were tasked with qualitatively examining the design guidelines while using the NVIDIA Omniverse Enterprise package as an exemplary use case of an authoring tool. Before using NVIDIA LaunchPad to get into Omniverse, the participants read a document that explained each design guideline in detail. Then, the participants' insights about the design guidelines were captured using two methods. The first method was a Likert-scale questionnaire comprising fifteen questions. The scale had a numeric scale that ranged from *totally disagree* (1 point) to *totally agree* (5 points) which should be marked according to their agreement about the existence of a design guideline in Omniverse.

Two equations were used as a first proposal of how to estimate a punctuation to an authoring tool's intuitiveness using the guidelines. It was assumed that a percentage lower than 50% of the maximum punctuation value would characterize authoring tools that are not very intuitive, while a higher percentage would indicate greater intuitiveness. The questionnaire results were also matched to the correlation analysis results to confirm the similarities, which were determined by examining the score of the guidelines with strongest positive and negative correlation obtained on the questionnaire.

The second method was a focus group interview, in which participants answered eighteen questions on their understanding of the design guidelines and their experience using them to evaluate the exemplary use case. Finally, a pipeline was provided including a compilation of all the steps carried out in this study, as a guide for anybody wishing to replicate the experiment using different VR authoring tools. Step 6 entails communicating the findings not only from this article, but all the publications derived from this study, presenting the validity of the design guidelines as an artifact.

In the subsequent chapters, the methodology employed at each of the publications is described in further detail.

# 3. Towards sustainable virtual reality: gathering design guidelines for intuitive authoring tools

The development of the Specific Objectives 1, 2 and 3 of this work, namely *to refine the problem research on virtual reality authoring tools*, *to define solution objectives*, and *to develop the design guidelines for intuitive virtual reality authoring tools* is presented below in the format of a paper submitted to the Sustainability journal on 10/Dec/2022 and published on 6/Feb/2023 (CHAMUSCA et al., 2023). This study compiles design guidelines derived from a systematic literature review to contribute to the development of more intuitive virtual reality authoring tools.

We searched the Scopus and Web of Science knowledge databases for studies published between 2018 and 2021 and discovered fourteen articles, which develop virtual reality authoring tools whose authors classify as intuitive. Fourteen requirement and feature design guidelines were compiled, such as Visual Programming, Immersive Authoring, Reutilization, Sharing and Collaboration, Metaphors, and Movement Freedom, among others. The gathered guidelines have the potential to either guide the development of new authoring tools or to evaluate the intuitiveness of existing tools. Furthermore, they can also support the development of the metaverse since virtual content creation is one of its bases.

*sustainability*

MDPI

*Review*

# Towards Sustainable Virtual Reality: Gathering Design Guidelines for Intuitive Authoring Tools

**Iolanda L. Chamusca [1,*], Cristiano V. Ferreira [2], Thiago B. Murari [3], Antonio L. Apolinario, Jr. [4] and Ingrid Winkler [3,*]**

[1] Ford Motor Company, Camaçari 42831-710, Brazil
[2] Technological Center of Joinville, Federal University of Santa Catarina, Rua Dona Francisca, 8300, Zona Industrial Norte, Joinville 89219-600, Brazil
[3] Department of Management and Industrial Technology, SENAI CIMATEC University Center, Salvador 41650-010, Brazil
[4] Department of Computer Science, Federal University of Bahia, Salvador 40170-110, Brazil
* Correspondence: ichamusc@ford.com (I.L.C.); ingrid.winkler@doc.senaicimatec.edu.br (I.W.)

**Abstract:** Virtual reality experiences are frequently created using game engines, yet they are not simple for novices and unskilled professionals who do not have programming and 3D modeling skills. Concurrently, there is a knowledge gap in software project design for intuitive virtual reality authoring tools, which were supposed to be easier to use. This study compiles design guidelines derived from a systematic literature review to contribute to the development of more intuitive virtual reality authoring tools. We searched the Scopus and Web of Science knowledge databases for studies published between 2018 and 2021 and discovered fourteen articles. We compiled fourteen requirement and feature design guidelines, such as Visual Programming, Immersive Authoring, Reutilization, Sharing and Collaboration, Metaphors, and Movement Freedom, among others. The gathered guidelines have the potential to either guide the development of new authoring tools or to evaluate the intuitiveness of existing tools. Furthermore, they can also support the development of the metaverse since virtual content creation is one of its bases.

**Keywords:** virtual reality; authoring tools; intuitiveness; digitization; sustainability; user-centered design; human–computer interaction; metaverse



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## 1. Introduction

Organizations worldwide have been conducting a variety of initiatives to explore new technological solutions and to exploit their benefits, including transformations of business operations, products, processes, structures, and management concepts [1]. Digital transformation is about adopting these disruptive technological solutions, such as virtual reality (VR), to increase productivity, changing how people interact with it, either as consumers or professionals [2].

Virtual reality has helped organizations to achieve several Sustainable Development Goals (SGD). Immersive experiences improve education, raise citizen awareness, and support behavior change toward more sustainable choices, from plastic pollution to building design, as well as sustainable mobility, tourism, and water management [3], contributing to achieving SDG 5 (Gender Equality), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Accuracy). In product development, VR has been essential to a more sustainable process, reducing carbon emissions by replacing physical products or real-world interactions with virtual ones [4], and foreseeing ergonomic risks, protecting workers from the risk of harm and improving workplace well-being [5]. As a result, it is a critical contribution to achieving SDG 8 (Decent work for all) and SDG 9 (Industry, Innovation, and Infrastructure), which calls for more sustainable industrialization, resource efficiency, and clean, environmentally sound technology and industrial processes. Therefore, a more sustainable virtual reality contributes directly to a more sustainable future.

On the other hand, creating virtual reality experiences is not widespread and requires expensive and lengthy development processes using game engines such as Unreal (https://unity.com/pt, accessed on 7 December 2022) and Unity (https://www.unrealengine.com/en-US, accessed on 7 December 2022), which demand expert professionals [6–8]. This is due to the complexity of the software architecture of virtual reality systems, which involves a great diversity of resources including unusual input and output devices, such as head-mounted displays (HMD), tracking systems, 3D mouses, and others [9]. In addition, for a true digital transformation to take place in the economy and society we live in, it is necessary to ensure that more people are able not only to use virtual reality experiences but also to have the skill to create them.

This complex nature of immersive technology requires a multidisciplinary profile from professionals, which includes considerable technical knowledge in programming languages and/or 3D modeling [8,10–12]. Therefore, developing interactive scenes in VR is challenging and uncomfortable for novices, which include people who come from high-level creator groups, such as digital artists and designers, and developers who come from other technology fields that are not immersive [11,12]. Beginners also include professionals such as teachers, doctors, engineers, and other professionals who only want to use virtual reality as a supplement to their day-to-day work [13–15].

An alternative to the long learning curve is to adopt authoring tools, as they aim to enable efficient content creation through minimal changes. The term authoring toolrefers to software structures that include the most important tools and features of content creation while making product maintenance faster and better [16,17]. These tools are used for low-fidelity authoring, which requires less programming skills, as opposed to high-fidelity prototyping, which requires advanced programming skills [11].

There is currently a range of authoring tools for creating virtual reality experiences, with many of them available as open-source software [18]. These tools, however, are frequently limited not only in functionality but also in documentation and tutorials, making them unsuitable for supporting the entire development cycle [11,19]. This occurs because these authoring tools are often developed as proof-of-concept, to help test the user's acceptance and identify the main features they might enjoy seeing on the final product, but not with an application field in mind [16].

These factors contribute to the technology's lack of maturity, making it difficult to define best practices for multiple user applications, leading to the lack of standardized processes, the lack of recommended practices, the lack of a common language, and the lack of interoperability between virtual reality tools and between pre-existing data such as 3D assets and codes [6,11,14,17]. Combined with the complexity of virtual reality systems architecture, these barriers contribute to the persistence of novices' learning difficulties, requiring good prior knowledge to utilize the full potential of the tool [12].

Previous studies have addressed various aspects of using authoring tools for the creation of virtual reality experiences [11,16,20]. These studies complement one another, while one study introduced eight key barriers to creating virtual and augmented reality experiences [20], another investigated the challenges that virtual reality creators face when using authoring tools for collaborative teamwork [11], and another systematically reviewed studies on authoring tool development to analyze their usability evaluation methods [16].

These studies have concentrated on analyzing how authoring tools were used after they were developed and made available to users rather than on how the development process affected the final product. Therefore, there is a knowledge gap regarding the design of authoring tool software, which we seek to mitigate by listing design guidelines to assist software developers during the project definition phase. The guidelines will help them choose and create the features and requirements that these tools must have to be considered intuitive [21].

Effective human–machine communication is needed to understand probable interactions, what is happening in the present, and what can happen next [22]. The human-centered design prioritizes human needs, skills, and behaviors, and then designs to meet them. Following design guidelines [22], people can understand how to create well-designed virtual reality experiences; similarly, the guidelines of this study support the development of intuitive authoring tools to create the VR experience, but not the experience itself. The results will contribute to structuring the discussion about how beginners can accomplish their goals with a more user-friendly and inclusive authoring tool in a more sustainable VR.

The faster expansion of immersive technology can also bring a huge advantage to concepts such as the metaverse, a major digital transformation that has already been impacting the work format in the technology area, encouraging the need for vacancies for people specialized in using the metaverse in conjunction with a company's strategy. In the metaverse, users can seamlessly experience a digital life as well as make digital creations supported by the metaverse engine, particularly with the assistance of extended reality and human–computer interaction [23]. The virtual worlds that will compose the metaverse need to be created. For that, people and authoring tools will be required to enable the creation of new digital content, and the more people collaborating to build these worlds, the bigger and more diverse it will be.

Thus, the goal of the present study is to compile design guidelines derived from a systematic literature review to contribute to the development of more intuitive virtual reality authoring tools. This document is organized as follows: Section 2 describes the materials and methods utilized, Section 3 presents and analyzes the results, and Section 4 provides conclusions and suggestions for further research.

## 2. Materials and Methods

This systematic literature review adopted a qualitative approach to identify the central issues in the field, i.e., summarize the literature by pointing out the central issues [24]. The study is exploratory, which means that there has been little research on intuitive virtual reality authoring tools. This concept must be explored and comprehended, and qualitative research is particularly useful when the researcher does not know the important variables to examine [24].

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which was designed to "help systematic reviewers transparently report why the review was done, what the authors did, and what they found" [25]. Additionally, it followed a process comprising the following seven steps: planning, defining the scope, searching the published research, assessing the evidence base, synthesizing, analyzing, and writing [26]. This systematic literature review is registered on Open Science Framework, number https://osf.io/u3q7m, accessed on 7 December 2022.

As preceded by the authors of Ref. [4], an expert in virtual reality-based design testing of product development defined the initial search strategy, which was then assessed individually by three senior researchers. Qualitative research is interpretative research [24]; therefore, it is relevant to the outcomes of this study that the authors have a strong background and experience with 3D visualization tools, graphical design, computer-aided design, and software such as SolidWorks, Adobe Photshop, CATIA, and Autodesk, among others.

The strategy resulting from this validation process is described in the sections that follow.

### 2.1. Planning

The knowledge bases that will be investigated are determined during the planning step [26]. The investigation was carried out using the scientific databases Scopus and Web of Science. These databases were chosen because they are reliable, multi-disciplinary scientific databases of international scope with comprehensive coverage of citation indexing, providing the best data from scientific publications. Scopus now includes 87 million curated documents [27], whereas the Web of Science covers more than 82 million entries [28].

### 2.2. Defining the Scope

Defining the scope means presenting proper research questions; therefore, three main questions were selected for this systematic review:

Q1: What are the characteristics of the virtual reality authoring tools reviewed? Q2: What is the definition of intuitiveness in virtual reality authoring tools? Q3: What are the guidelines for designing intuitive virtual reality authoring tools?

### 2.3. Literature Search

In the literature search step, a particular string is used to search the database set up in the planning step, based on the research questions asked in the defining the scope step [26]. The first keywords utilized were *virtual reality* and *VR* to specify the search for this specific cut from immersive technology; therefore, not considering augmented reality, with the goal of defining, at the end of this study, design guidelines more focused on virtual reality experiences. The exploratory search was based on articles focused on describing the process to develop *authoring tools*, specifically oriented to create virtual reality experiences, followed by complementary keywords, *system* and *frameworks*, added to the string to cover other types of software tools.

Because virtual reality experiences can be difficult for novice users to create, the focus is on keywords linked to intuitiveness. From the word *intuitive*, other synonyms were gathered: *flexible*, *democratize*, *adaptable*, *usable*, *facilitate*, *simplify*, *easy* and *user-friendly*. Thus was formed the final search phrase: TITLE-ABS ((*virtual reality* OR *VR*) AND (*authoring tools* OR *system* OR *framework* AND (*intuitive* OR *flexible* OR *democratize* OR *adaptable* OR *usable* OR *facilitate* OR *simplify* OR *easy* OR *user-friendly*)).

### 2.4. Assessing the Evidence Base

The assessing step uses inclusion and exclusion criteria filters to reduce the number of documents found in the searching the literature step—selecting those that are relevant to the research questions [26]. These criteria were applied to the researched articles in three phases, as follows:

Phase 1: exclusions through filter options provided by the database used in the research.

- E1.1.: The entry title or abstract did not have one or more of the terms described in the search phrase;
- E1.2.: Published before 2018;
- E1.3.: Entry not written in the English language;
- E1.4.: Virtual reality is not a keyword;
- E1.5.: Duplicate entry.

Phase 2: exclusions through screening of the abstract of publications.

- E2.1.: Entry is theoretical work (e.g., information system proposal, literature review, poster);
- E2.2.: Entry does not consider the development of authoring tools for virtual reality immersive experiences creation;
- E2.3.: Entry focus on augmented reality;
- E2.4.: Entry develops authoring tools for virtual reality experience creation not based on the use of HMD on virtual environments (e.g., CAVE, 360 video).

Phase 3: exclusion through screening of the entire article, using the tool Mendeley Desktop for organizing and classifying the publications.

- E3.1.: Entry with less than 5 pages;
- E3.2.: Entry related to the development of authoring tools not directly defined as intuitive and easy to use for beginners and unskilled professionals;

- E3.3.: Entry limited on the development of authoring tools specific to an area of application (e.g., health, engineering, education, and culture).

The research period chosen was between 2018 and 2021, the last four years before the development of this study; a period equivalent to the fast progression of this technology through these years, not only academically but also in virtual reality hardware releases. For example, the advent of technologically advanced virtual reality headsets in 2016 represented a breakthrough for virtual reality applications and practitioners with the release of the HTC Vive Steam VR headset, the first commercial release of sensor-based tracking [29,30]. Another significant event in the evolution of virtual reality headsets occurred in 2018, with Oculus launched the Oculus Go, the first commercially available wireless virtual reality headset with an affordable built-in screen [31].

*2.5. Synthesizing and Analyzing*

Figure 1 depicts the flow of the systematic review from searching the published research to synthesizing processes.

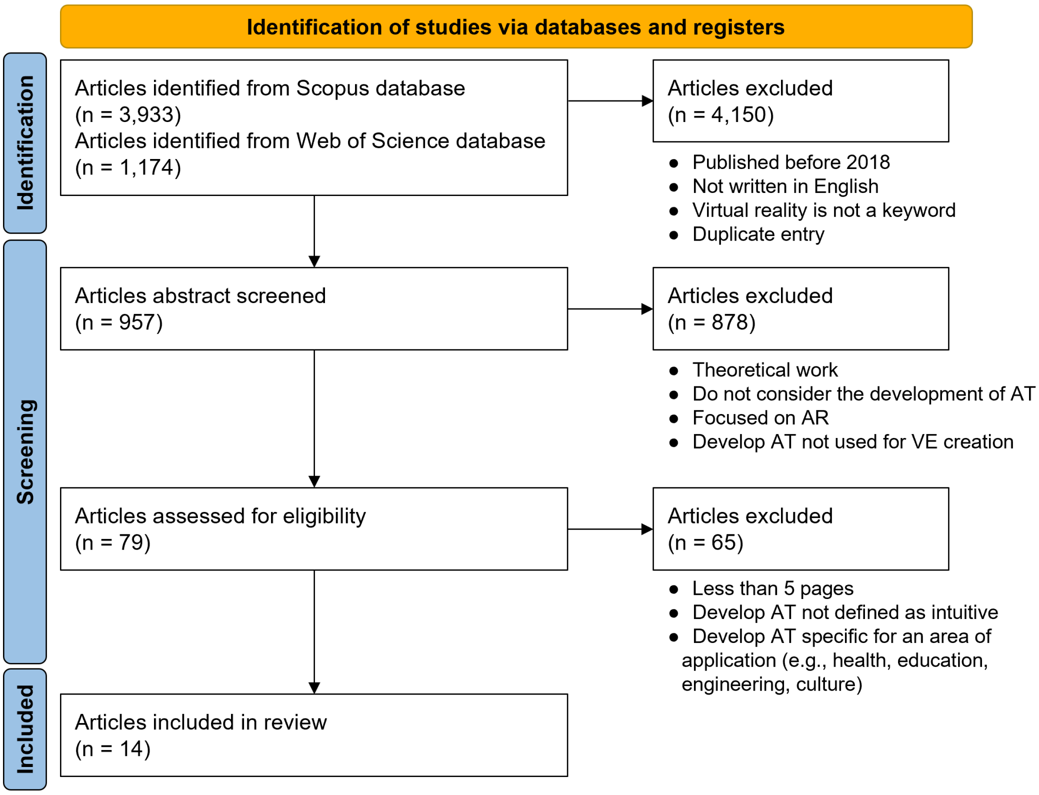


**Figure 1.** Systematic review flow diagram, adapted from PRISMA [25].

Textual information is analyzed in qualitative research designs, allowing researchers to interpret themes or patterns that emerge from the data [24]. The procedures for data analysis aim to extract meaning from the text; they entail segmenting, deconstructing, and reconstructing the data [24]. In terms of data analysis steps and procedures used for interpreting and validating collected data, we employed text non-numerical analysis, with the type of interpretation consisting of themes and patterns to identify design guidelines, and peer experts debriefing strategy for validating findings.

Regarding the non-numeric analysis and interpretation of themes and patterns, we began by reading the retrieved articles through Mendeley Desktop and describing the characteristics of virtual reality authoring tools (Table 1) in terms of which *artifact* was developed in the study, the *software* and *hardware* used and *plugin* or *standalone* type, where a plugin is "software developed to work over other software to facilitate processes" and a standalone is "a software that works without any other software and is designed specifically for a purpose" [16].

**Table 1.** Characteristics of the virtual reality authoring tools.

| Ref | Artifact | Hardware | Software | Type |
|---|---|---|---|---|
| [32] | Tool for 3D assets search through immersive handmaid sketch in VR | Oculus Consumer Version 1 (HMD) and Oculus Touch Controllers | Unity3D Engine and Convolutional Neural Network (CNN) | Plugin |
| [33] | Tool for visual feedback of haptic properties in VR | HTC Vive Kit (HMD) | Unity3D Engine | Plugin |
| [34] | Collaborative web-based authoring tool for creating virtual environments in VR | Oculus Rift Consumer version and HTC Vive (HMD) | Node.js/EasyRTC, Socket.IO, WebRTC and A-FRAME (Three.js + WebVR) | Standalone |
| [35] | Architecture for a collaborative immersive tool for multisensory experiences creation in VR | HTC Vive (HMD), Bose QuietComfort 25 headphones, Sensory Co SmX-4D for Smell, Buttkickers LFE kit and wind simulator | Unity3D Engine | Plugin |
| [36] | Immersive authoring tool that allows applying reaction behaviors to objects using visual programming | Oculus Rift (HMD) | NOT INFORMED | Standalone |
| [37] | Tool for 3D assets editing and application of behaviors to objects | HTC Vive Pro Eye (HMD) and controllers | Unity3D Engine (C#) and SteamVR | Plugin |
| [38] | Authoring tool for developing interactive agents for VR applications | NOT INFORMED | Unity3D Engine and Cortana for speech recognition | Plugin |
| [8] | Immersive authoring tool that allows applying reaction behaviors to objects using visual programming | NOT INFORMED | A-FRAME (Three.js and WebVR), Node.js and RxJS | Standalone |
| [17] | Immersive authoring tool with visual programming to reproduce gamified training scenarios through modular architecture | Oculus Quest 2 (HMD), HTC Vive (HMD), Microsoft Hololens (HMD) and Magic Leap | Unity3D Engine and CodeDOM (.NET Framework) | Plugin |
| [39] | Authoring tool that uses "nugget tiles" (blocks) so authors can create reduced learning experiences in VR | HTC Vive (HMD) | Unity3D Engine and Virtual Reality Tool-kit (VRTK) | Plugin |
| [10] | Platform for interactive virtual objects creation in VR through physical objects presented in the real world, using AI | Oculus Quest (HMD), Oculus Link, Touch controllers and iPad Pro | Unity3D Engine and AppScanner | Plugin |
| [40] | Authoring tool that allows flexible control of work spaces for data analysis during collaborative activities in groups inside an immersive space in VR | HTC Vive Pro (HMD), Backpack | Unity3D Engine, Immersive Analytics Toolkit (IATK) and Oculus Avatar SDK (body) | Plugin |
| [41] | Web-based authoring tool with better graphic quality | NOT INFORMED | Unity3D Engine and WordPress/MySQL | Plugin |
| [12] | Web-based intuitive authoring tool for interactive 3D scenes creation in VR | NOT INFORMED | A-FRAME (Three.js), React and JavaScript | Standalone |

Then, using Microsoft Excel, we hand-coded the data collected in the studies to generate the design guidelines, i.e., we arranged the text data gathered by bracketing segments into categories and labeled them with a title. The coding process was then utilized to provide a description of the categories for analysis, which are the themes that often arise as major findings in qualitative investigations.

Based on the authors' interpretation, a method inspired by the agile methodologies artifacts [42] was used. The product backlog, one of the artifacts produced by the scrum process, is a prioritized list of product requirements or features that provide business value for the customer [21]. In this study, the virtual reality authoring tools were considered as *products*, and the non-expert users as *customers*. Therefore, the identified design guidelines were also grouped into *requirements* (generic concepts that delimit the major characteristics of a product by understanding the user's needs before the development starts and will help define the product's features), or *features* (tools one uses within a system to complete a set of tasks or actions, the functionality of a feature provide the user a desired outcome).

Finally, we discussed each identified design guideline in depth in a qualitative narrative, along with quotations from the reviewed works from which we interpreted that guideline, to support the categorized themes [24]. Although we recognized numerous quotations for each identified design guideline, we highlighted just three quotations as illustrative instances of each design guideline for the purpose of this article's writing flow; the entire list of quotations is accessible as Supplementary Materials. Using the authors' qualitative understanding, a list of *related terms* for each guideline was also compiled, which is primarily made up of synonyms. However, these terms are not connected to the frequency with which they appear in the reviewed articles, since having a higher frequency of appearance in the articles does not make them more important in the context of our analysis, as well as all the guidelines have the same weight in terms of relevance. The information flow summarizing all the steps covered in this section is presented in Figure 2.

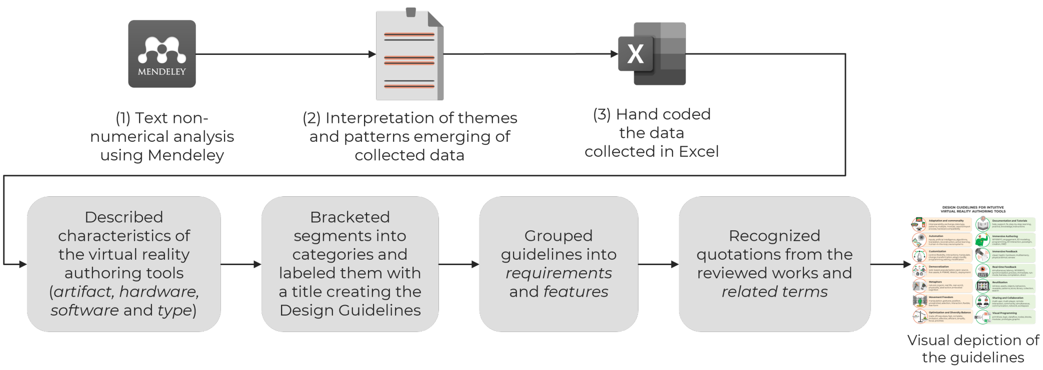


**Figure 2.** Synthesizing flow diagram.

Many qualitative studies include visuals, figures, or tables as adjuncts to the discussions [24], so we generated a visual depiction of the developed design guidelines, as shown in Section 3).

Qualitative validity means that the researcher checks for the accuracy of the findings by employing certain procedures; is based on determining whether the findings are accurate from the standpoint of the researcher or the readers of an account [24]. We used the peer debriefing strategy to assess the validity of the identified design guidelines, which involved peer debriefs reviewing and asking questions about the qualitative study at field conferences such as the IEEE International Symposium on Mixed and Augmented Reality (ISMAR) so that the account would resonate with researchers other than the authors. This strategy, which involves an interpretation beyond the authors' view, adds validity to an account.

This process led to the fourteen design guidelines presented in the following section.

## 3. Results

In the following sections, the research questions Q1, Q2, and Q3 are addressed.

### 3.1. Characteristics of the Virtual Reality Authoring Tools

The fourteen studies were reviewed to analyze the research question *Q1: What are the characteristics of the virtual reality authoring tools reviewed?*, and the results are presented in this section. The following is a summary of the main characteristics of the virtual reality authoring tools developed by the reviewed studies:

1. Virtual environment creation, where everything that the user sees is a 3D model, also containing collaborative interaction, visual programming, and immersive authoring [16];
2. Generic purpose, not developed for the use in a specific field, such as Mechanical Engineering or Medicine [16];
3. Manipulating and importing 3D objects by searching online, either by text or with an immersive sketch in VR mode, editing assets, and adding behaviors;
4. Facilitating interaction between software and hardware through haptic feedback visualization and multisensory stimuli;
5. Interactive human characters development, giving the user pre-setted behaviors such as mouth movements to speak;
6. Artificial intelligence automation using different types of networks to help the user achieve their goals with more efficiency.

Item 1 also represents an exclusion criterion described in Section 2.4, which was defined by the fact that most of the authoring tools developed in the field today are aimed at creating 360º videos [16]. The 360º experiences allow users to look around freely and are very simple to create, only requiring the application of one or more video files in a virtual reality context to work, nonetheless valuable information can be lost. All the potential interactivity with elements in virtual reality is wasted in a 360º experience, which is why it is a major limitation that the authoring tool only supports 360º videos. In addition, as the authoring tools for creating virtual environments are more complex to use, the present study will have greater value in its contribution towards the intuitiveness of creating VR experiences in virtual environments.

Examining Table 1, the *standalone* authoring tools on the reviewed works were always the web-based ones, using A-FRAME to be built, which is easier to use for proof-of-concept platforms, while the *plugin* authoring tools were always based on Unity3D Engine, a mainstream non-paid game engine. This shows that the authoring tools (standalone and plugins) made in the reviewed works are not ready for the market yet because they have not been released as final products. Table 1 summarizes the variables described in each article:

### 3.2. Definition of Intuitiveness in Virtual Reality Authoring Tools

The fourteen studies were examined in regard to the research question *Q2: What is the definition of intuitiveness in virtual reality authoring tools?*. The reviewed articles highlight intuitiveness as *easy-to-use*, *quickly*, *high usability*, *for non-experts*, *short training*, *simple*, *facilitate* and *reduce complexity*. In these studies, intuitiveness is related to completing tasks quickly, requiring minimal learning, lowering the entry barrier, reducing information, time, and steps, being appropriate for both expert and non-expert users, being aware of and feeling present in virtual reality, feeling comfortable with the tool, making few mistakes, and using natural movements in virtual reality.

It is not possible to evaluate or measure intuitiveness, but we may measure it with usability, effectiveness, efficiency, and satisfaction, using well-established questionnaires and methods (some of them listed in Table 2). For example, usability can be measured with System Usability Scale (SUS), effectiveness can be measured by tasks completed successfully, the number of errors, and the number of help requests, efficiency can be measured by time spent to complete a task and perceived workload, and satisfaction can be measured with the After-Scenario Questionnaire (ASQ) [16,43]. Other measures can be taken into account, such as learnability (time to learn a tool) and recommendations to others.

High-technology products need to exhibit good usability, a qualitative measure of the ease with which a human can employ the functions and features offered [21]. In this study, *intuitive* refers to the quality of an easy-to-use authoring tool whose usability, effectiveness, efficiency, and satisfaction evaluation showed positive results.

In terms of usability evaluation methods, nine studies adopted Likert-scale surveys [8,10,12,17,32,33,37,40,41], three used SUS [10,12,35], four adopted other types of questionnaires such as ASQ and NASA TLX [35,37,39,41], three used qualitative retrospective interviews [8,10,36], two implemented other methods such as the thinking-aloud method or measured the number of errors and time taken to complete the activity [38,39], and only one did not use any evaluation methods [34]. Table 2 shows how almost all of the authoring tools, using various methods of evaluation, presented similar conclusions, which are often described in terms of being intuitive.

**Table 2.** Detecting *intuitiveness* in the virtual reality authoring tools.

| Ref. | Intuitiveness Quote |
|---|---|
| [32] | "[...] users can perform search more quickly and intuitively [...]" |
| [33] | "[...] rapidly create haptic feedback after a short training session." |
| [34] | "The tool features an intuitive and easy to use graphical user interface appropriate for non-expert users." |
| [35] | "[...] positive feedback from users regarding ease of use and acceptability." "[...] an authoring tool that is intuitive and easy to use." |
| [36] | "[...] most participants commented positively on this application and [...] expressed that the application is easier for beginners." |
| [37] | "AffordIt! offers an intuitive solution [...], show high usability with low workload ratings." |
| [38] | "[...] people with little or even no experience [...] can install VAIF and build interaction scenes from scratch, with relatively low rates of encountering problem episodes." |
| [8] | "FlowMatic introduces [...] intuitive interactions, [...], reducing complexity, and programmatically creating/destroying objects in a scene." |
| [17] | "[...] efficient data structure, for simple creation, easy maintenance and fast traversal [...] users can create VR training scenarios without advanced programming knowledge." |
| [39] | "[...] An immersive nugget-based approach is facilitating the authoring of VR learning content for laymen authors." |
| [10] | "The interaction procedures are simple, easy to understand and use, and don't demand any specific skill expertise from users." |
| [40] | "We choose user interface elements [...] to minimize learning time [...]" "it was useful to see each others' work in real time to improve workspace awareness, and it was easy to share findings with one another." |
| [41] | "Evaluation results indicate the positive adoption of non-experts in programming [...] participants felt somewhat comfortable using the system, considering it also as simple to use." |
| [12] | "[...] we have analyzed the effectiveness, efficiency, and user satisfaction of VREUD which shows promising results to empower novices in creating their interactive VR scenes." |

### 3.3. Defining the Design Guidelines

The fourteen studies were examined in regard to the research question *Q3: What are the guidelines for designing intuitive virtual reality authoring tools?* and the results are presented in the following section.

Getting the proper virtual reality specifications is difficult, and a creator's first few projects often fail [22]. Well-designed virtual reality experiences may increase performance and save costs, give new worlds to explore, boost education, and develop deeper comprehension by letting users walk in someone else's shoes. However, even virtual reality professionals cannot always effectively define a new project from the start since good virtual reality design combines technology and human perception. Trying to mitigate this challenge, design guidelines help authors to create better virtual reality experiences [22], which is the same strategy we use in the present study but in a different context. As well as Pressman [21] design guidelines were gathered to help software developers, specifically aiming to support the development of intuitive virtual reality authoring tools.

Thereafter, the design guidelines will help beginner authors break the barrier of starting to create in virtual reality. Moreover, since most of the authoring tools found in the reviewed works are only proof-of-concept, the guidelines can encourage the development of mainstream platforms with fewer limitations, democratizing the technology and increasing its maturity. Figure 3 shows how software developers can use design guidelines during the development process of authoring tools:

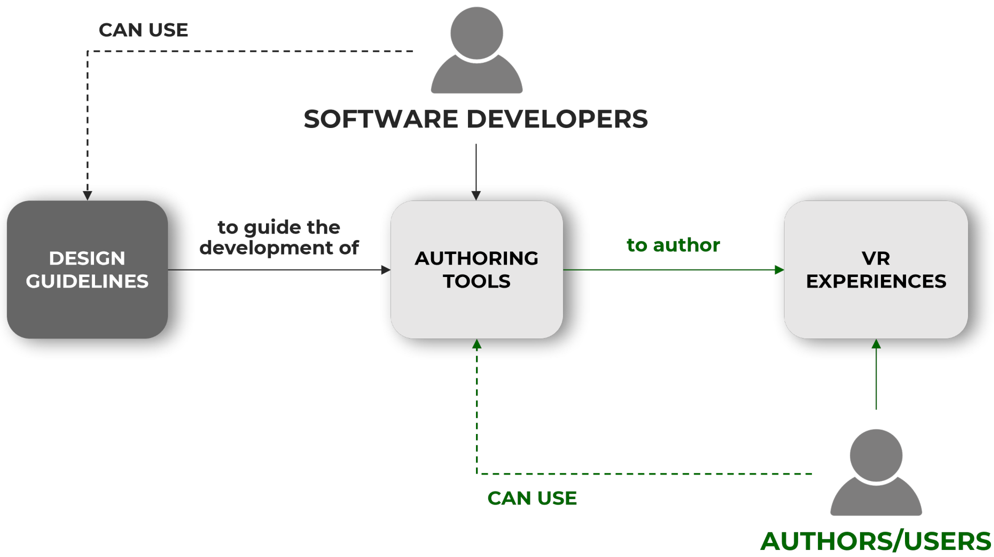


**Figure 3.** Information flow of the design guideline application in the authoring tool life cycle.

The lack of ontologies related to the concepts of virtual reality authoring tools is examined [16], indicating that there are few connected standards for the development of these platforms. In other words, concepts, methods, and nomenclature are not well-established, resulting in the development of authoring tools with vastly different formats and the application of diverse evaluation techniques to determine their usability. Similarly, the need for a taxonomy proposal for the metaverse was addressed since the wide scope of this concept causes a lack of understanding about how it works [44]. Between the proposed taxonomies, we can point out the *components* that are thought to be necessary for the realization of the metaverse, namely hardware, software, and contents. Many similarities were found between the design guidelines suggested in the current study and technologies that have recently become issues and interests to the metaverse and were mapped as hardware, software, and content [44]. This adds to the belief that the guidelines can positively contribute to the creation of the metaverse, through their influence in facilitating the use of the components that form them.

Moreover, our findings also contribute to advancing the creation of ontologies for the development of virtual reality authoring tools in relation to the current gaps [16]. Due to the lack of ontologies for authoring tools, the concepts, and common functions among the authoring tools analyzed, often used different terms to refer to the same element. It is important to highlight that the guidelines obtained complement each other, and were never presented in isolation. The non-identification of a guideline in a given work does not mean that the authoring tool does not use it, it only means that it was not mentioned in the article description. Moreover, the identification of a guideline in the article is not necessarily linked to its presence in the tool, but it may have been cited as an application of previous work or an intention to improve the tool in the future. Table 3 summarizes the design guidelines and their application.

**Table 3.** Design Guidelines list, classification, articles, and related terms.

| N | Design Guidelines | Classif. | Articles | Related Terms |
|---|---|---|---|---|
| 1 | Adaptation and commonality | Requirement | [8,12,17,34,35,38–41] | interoperability, exchange, data type, patterns, multiple, modular, export/import process, hardware compatibility |
| 2 | Automation | | [10,12,17,32,37,38,41] | inputs, artificial intelligence, algorithms, translation, reconstruction, active learning, human-in-the-loop, neural systems |
| 3 | Customization | | [8,10,12,34–41] | control, flexibility, interactions, manipulate, change, transformation, adapt, modify, programming, editing, modification |
| 4 | Democratization | | [8,12,34,38–41] | web-based, popularization, open-source, free assets, A-FRAME, WebGL, deployment |
| 5 | Metaphors | | [8,10,12,17,32–34,36,37,39,40] | natural, organic, real life, real-world, physicality, abstraction; embodied cognition |
| 6 | Movement Freedom | | [8,10,32,34,36,37,39,40] | manipulation, gestures, position, unrestricted, selection, interaction, flexible, free-form |
| 7 | Optimization and Diversity Balance | | [8,10,12,17,32,35,37,39–41] | trade-off, less steps, fast, complete, limitation, effective, efficient, simplify, focus, priorities |
| 8 | Documentation and Tutorials | Feature | [8,12,17,37,38,41] | help, support, fix, step-by-step, learning, practice, knowledge, instructions |
| 9 | Immersive Authoring | | [8,10,12,17,32,34–37,39,40] | WYSIWYG, engagement, 3D modeling, programming, 3D interaction, paradigm, creation, HMD |
| 10 | Immersive Feedback | | [33,35–37] | visual, haptic, hardware, multisensory, physical stimuli, senses |
| 11 | Real-time Feedback | | [8,12,17,32–37,39,40] | simultaneous, latency, WYSIWYG, synchronization, preview, immediate, run-mode, liveness, compilation, direct |
| 12 | Reutilization | | [8,10,12,17,32,34,36,38,39,41] | retrieve, assets, objects, behaviors, reusable, patterns, store, library, collection, search |
| 13 | Sharing and Collaboration | | [12,34,35,40,41] | multi-user, multi-player, remote interaction, community, simultaneous, communication, network, workspace |
| 14 | Visual Programming | | [8,17,36,39,41] | primitives, logic, dataflow, nodes, blocks, modular, prototype, graphic |

The next sections describe the design guidelines classified as requirements.

#### 3.3.1. Adaptation and Commonality

This guideline relates to *interoperability* [44], to enable the integration of different data acquisition sources (hardware or software), adaptable to a wide variety of cases and purposes; being usable for any application field (education, science, history, business, culture, and design); allowing communication with different types of virtual reality hardware, such as different head-mounted displays, controllers, and wearables such as haptic gloves and clothes; use of patterns, blocks, nodes, or modules to organize functionalities; allowing content creators to set up different modules by turning on and off plugins, which can also change the tool's user interface; use of the same tool to create for different platforms, such as personal computers, head-mounted displays, and mobile smartphones; use of common programming languages and/or have the ability to use a known language of the user's choice; acceptance of different file extensions for the same type of data, such as .fbx, .catpart, and .igs, which are all extensions for 3D data from different types of 3D modeling; having a unique file extension that could retain all kinds of information and be used by all software would be the perfect scenario, which is performed by Universal Scene Description (USD) files, an extension created by Pixar. The following examples illustrate the guideline:

- "To ensure a proper multisensory delivery, the authoring tool must communicate effectively with the output devices" [35];
- "using semantically data from heterogeneous resources" [17];
- "Establishing an exchange format and standardizing the concept of VR nuggets is a next step that can help to make it accessible for a greater community" [39].

#### 3.3.2. Automation

This guideline concerns automatic processing of activities that would require human interference, where algorithms must complement the human creative work to avoid non-productive activities; the use of an artificial intelligence network such as CNN or GAN to create systems that can analyze inputs and come up with better results; the use of simple sketch drawings to search for equivalent 3D models; scanning the physical world through complementary hardware such as LiDARs or smartphones and use a raw point cloud to retrieve better virtual models; production of 3D models out of 2D images; provide autonomous tools to segment the 3D mesh into minor parts; triangle reduction on high polygon objects; follow human repetitive activities to create codes to reproduce them (human-in-the-loop); prediction of actions with smart suggestions, such as adding functions and behaviors to objects; artificial intelligence assistant to provide tutorials and help as needed; use various inputs, such as voice commands, to activate a functionality [44]; translation into different languages; using cameras to track the authors' bodies so that the movements can be analyzed and behaviors can be made automatically. The following examples illustrate the guideline:

- "The number of triangles on high polygon objects were reduced to optimize the cutting time to an order of magnitude of seconds" [37];
- "In other words, the interaction manager enables developers to create events that are easy to configure and are applied automatically to the characters" [38];
- "The idea is to provide users with a modeling tool that intuitively uses the reality scene as a modeling reference for derivative scene reconstruction with added interactive functionalities" [10].

#### 3.3.3. Customization

This guideline refers to giving the author enough control over changes; application of 3D content anywhere in the virtual environment; alignment of 3D virtual models to scale, position and orientation; appearance configuration of 2D and 3D elements, changing color, size and shape; assigning behaviors and animations to a 3D mesh; assigning and combining functions and interactions between objects; modifying scene lighting, cameras, and environments; set timing, duration, start/end point, intensity, and direction of virtual reality multisensory stimuli; create more expressive interactivity through action specification for VR hardware, such as controllers and/or haptic gloves; applying emotional state and personality to a virtual agent; specifying behaviors to react to discrete events such as user actions, system timers or collisions; customization of the virtual reality hardware while the software is always in an executable state; add annotations; edit texts; set pattern-specific parameters on software that uses them; organize the workspace layout by changing tools, tabs, and windows of the software. The following examples illustrate the guideline:

- "While the state-of-the-art immersive authoring tools allow users to define the behaviors of existing objects in the scene, they cannot dynamically operate on 3D objects, which means that users are not able to author scenes that can programmatically create or destroy objects, react to system events, or perform discrete actions" [8]—missing customization;
- "The system workflow design of VRFromX that enables creation of interactive VR scenes [. . . ] establishing functionalities and logical connections among virtual contents" [10];
- "Some requests were [. . . ] more freedom to change the parameters of the experience, i.e., to right click on 3D models and change the parameters of the assets on the fly" [41].

#### 3.3.4. Democratization

This guideline relates to providing people with access to technical expertise via a radically simplified experience; authoring tools that can be accessed via a web browser (web-based) to make it easier for people to get started because they do not require the download of a special program and can be used for a variety of cases and purposes; web-browser application that can also be used through mobile devices that support virtual reality, bringing more accessibility and knowledge about virtual reality development; open-source and publicly available tools that can reach multiple researchers to build and evaluate them; the use of platforms such as GitHub to share resources and encourage users to contribute their own assets; empowerment of the citizen-developer model, with no-code procedures to design and develop virtual reality applications; hardware popularization with lower costs and better quality; the use of free stores for the distribution of applications and plug-ins at no cost; the use of libraries and frameworks such as Three.js and A-FRAME for web-browser development. The following examples illustrate the guideline:

- "[. . . ] the advances of WebVR have also given rise to libraries and frameworks such as Three.js and A-FRAME, which enable developers to build VR scenes as web applications that can be loaded by web browsers" [8];
- "FlowMatic is open source and publicly available for other researchers to build on and evaluate" [8];
- "[. . . ] democratization is focused on providing people with access to technical expertise (application development) via a radically simplified experience and without requiring extensive and costly training" [41].

#### 3.3.5. Metaphors

This guideline refers to turning abstract concepts into tangible tools; use of visual resources and gestures to execute actions in the virtual world in a similar way to the real world, which improves the author's immersion; beginning actions with natural interactions and manipulation, for example, inserting a virtual disk into a virtual player as a start trigger to play music; move and position objects as if they were in the real world; use of buttons on the controllers to reproduce actions similar to what we would do in real life, such as pulling the trigger button to grab an item and releasing it to drop; use of miniatures to localize things at a glance on the interface; connection of objects distant from each other by making the physical movement of drawing visible lines between them; the use of visual icons, such as fire and ice, to represent haptic feedback, such as warm and cold, to the user, inducing a multisensory experience; the use of different shapes and colors to represent different types of data; the use of numbers to indicate sequences; the use of hologram overlays to show the content of a pattern or object before interacting with it; real-world and virtual events that can be linked using IoT-enabled devices, for example, starting an object print in a virtual printer can start the process on a physical 3D printer; not using the correct metaphor can sometimes lead to a user misinterpreting the tool or action; in different contexts such as collaborative work, metaphors can naturally appear, such as the formation of individual territories when working in groups in the same space. The following examples illustrate the guideline:

- "They can draw edges to and from these abstract models to specify dependencies and behaviors (for example, to specify the dynamics of where it should appear in the scene when it shows up)" [8];
- "Similar to Alice in Wonderland, the users will gradually shrink as they trigger the entry procedure. Authors can access the world in miniature model and experience it in full scale to make changes to the content" [39];
- "Compared to the logic used in the construction of interactions, the task construction uses generic activities which should be also clear to novices without a technical background since they are comparable to actions in the real world" [12].

#### 3.3.6. Movement Freedom

This guideline concerns using body movements to simplify creation and interaction while authoring in virtual reality immersion; use of 3D hand drawing (not only 2D) to retrieve 3D models, even with non-perfect sketches; freedom to explore the space, touch objects, manipulate elements, and encounter other users in a flexible virtual space; having the ability to move freely and safely in the virtual world, zooming in and out without needing to change positions in the physical world; immersive editing of programming elements through direct manipulation; manipulation of virtual objects using movements similar to those in the physical world, which can also be interpreted as a metaphor; free arrangement of elements anywhere in the virtual space; interacting with and editing 3D elements through simple hand gestures in a free-form manner, for example, by selecting an area of the 3D to be cut; creation of organic 3D shapes through immersive modeling; organization of a workspace using all the extensions of a virtual environment; having not only the option to work individually but also access another user by moving toward them to share items or communicate; having different options to visualize all the extensions of an element, either by rotating it, physically moving around it, or even going through it to have different points of view. The following examples illustrate the guideline:

- "One reason is that through direct manipulation users can feel more immersed—as if the wire is in their hands" [36];
- "A brush tool was developed which enables users to select regions on point cloud or sketch in mid-air in a free-form manner" [10];
- "Users can also perform simple hand gestures to grab and alter the position, orientation and scale of the virtual models based on their requirements" [10].

#### 3.3.7. Optimization and Diversity Balance

This guideline relates to the reduction in steps to authoring experiences without limiting creative freedom, which can often be achieved with the application of other guidelines such as automation, visual programming, and reuse; giving the authors the feeling of completing more activities in less time, by reducing the number of inputs to obtain a result; reduction in ambiguity between views in 2D and 3D by authoring in immersion, so the user does not have to spend a lot of time imagining projections; improving the efficiency of the editing process through collaborative work with many users; use of a programming language that is easy to use and has free codes available from outside libraries; positioning of priority items physically close to the user, such as keeping a set of tools always attached to the author's hand; avoid complexity and unnecessary actions, which can lead to incomprehension, impatience, and fatigue for authors; not showing all training materials at once to reduce cognitive load; organization of functionalities in patterns and categories to focus attention during development; the use of the right rendering modes and making the best use of the hardware to always obtain good graphics and performance; combination of simple elements to create others that are more complex. The following examples illustrate the guideline:

- "To make our system more efficient, we have to limit the capabilities of the Action entity targeting simple but commonly used tasks in training" [17];
- "The construction uses two dialogs to create the task and the activities so that the novice only needs to focus on the current task or activity" [12];
- "We decreased further the complexity by using wizards to focus the user on smaller steps in the development" [12].

The following sections describe the design guidelines classified as features.

#### 3.3.8. Documentation and Tutorials

This guideline refers to educating the user while using a tool, demonstrating the step-by-step process in real time; using diversified resources to present how to execute a function, such as images, animations, recorded videos, text, audio guidance, holographic icons, and virtual embodied characters; creating specific initial tasks to teach basic tools on practice; publish tutorials in a variety of places, including YouTube, software documentation, and online forums; making sure to include missing information reported by users to complement the materials; encouraging online communities to create more knowledge about the tool; inclusion of error messages to help the user understand what not to do and how to recover activities; making sure that help buttons are visible and easily accessible; avoiding the presentation of too many steps at once, keeping enough details and a logical structure to follow; the use of automation to detect when the user is having difficulties to move on with a task and provide an insight to solve that. The following examples illustrate the guideline:

- "For each step, instructions are visualized as text in the menu to help participants remember which step they are performing" [37];
- "We believe that more visual aid in the form of animations showing the movement path can help ease the thinking process of participants" [37];
- "Documentation would be another interesting direction in the future, as two participants said they preferred A-FRAME in the sense that the APIs documentation was detailed and easy to understand" [8].

#### 3.3.9. Immersive Authoring

This guideline relates to avoiding 2D-display or projections while creating a virtual world; performing multiple activities while immersed and use the immersion to improve the author's creation experience by, for example, executing a sketch in 3D to start a search for assets, 3D modeling, programming, building scenes or environments, reading documentation, and interacting with other authors; enjoying an immersive experience that has been deployed is not the same as creating this experience using virtual reality as a development tool, as the first option is only available to the final user; when applied with real-time feedback, immersive authoring creates a *what you see is what you get* (WYSWYG) experience; reducing the abstraction needed to convert 2D information to 3D; allowing users to share information and resources while they are in the same space and working with other people; a good immersive authoring interaction in virtual reality is heavily influenced by movement freedom and haptic feedback; to fit with the user view extension and avoid visual pollution or confusion, the immersive user interface must be simplified; avoidance of switching back and forth between the 2D and 3D screens to check how things are displayed in immersion; well applied to testing virtual reality functions in real-time and debugging; one issue is that wearing a head-mounted display for an extended period of time can be exhausting. The following examples illustrate the guideline:

- "[. . . ] expedites the process of creating immersive multisensory content, with real-time calibration of the stimuli, creating a "what you see is what you get (WYSWYG)" experience" [35];
- "[. . . ] immersive authoring tools can leverage our natural spatial reasoning capabilities" [36];
- "With the lack of additional spatial information and the disconnection between developing environments (2D displays) and testing environments (3D worlds), users have to mentally translate between 3D objects and their 2D projections and predict how their code will execute in VR" [8]—(missing immersive authoring).

### 3.3.10. Immersive Feedback

This guideline relates that, in virtual reality, action feedback is both visual and haptic/physical, using hardware parts, such as head-mounted displays, controllers, and wearable as an extra interaction source; immersive experience feedback can have multiple formats, from rendered icons and symbols to haptic stimuli such as controller vibrations. It is possible to accurately represent physical stimuli such as thermal, vibrotactile, and airflow, which require different hardware to reproduce and can be costly or inflexible, but would increase immersion [44]; users accept creative solutions such as animations, sounds, and icons representing physical stimuli as feedback; visual and haptic feedback must occur in real-time to be accurately felt, or the user will not engage with the application if the stimuli arrive at the wrong time; the tool must allow the author to apply immersive feedback and preview the results before releasing them; associating behaviors from virtual elements to the tracking of hardware (head-mounted displays and controllers); configuring controller buttons to start logical operations to facilitate the development, such as activating a virtual menu attached to the hand or a frequently used function. The following examples illustrate the guideline:

- "Rendering haptic feedback in virtual reality is a common approach to enhancing the immersion of virtual reality content" [33];
- "[. . . ] various types of haptic feedback, such as thermal, vibrotactile, and airflow, are included; each was presented with a 2D iconic pattern. According to the type of haptic feedback, different properties, such as the intensity and frequency of the vibrotactile feedback, and the direction of the airflow feedback, are considered" [33];
- "The use of multisensory support is justified by the fact that the more the senses engaged in a VR application, the better and more effective is the experience" [35].

### 3.3.11. Real-Time Feedback

This guideline relates to a real-time visualization or physical perception of what is being authored, related either to 3D editing, code compilation, animation preview, or hardware set-up used for a scene; help avoid making mistakes while creating, as you do not need to wait until the end to see the result; minimizing latency [44]; it allows non-experts to spot mistakes much more quickly; visual representation of actions performed on objects, such as a wireframe highlight to describe the geometry selection and an animation preview to show if the behaviors attached to an object really work; view the editing actions of other users in collaborative sessions as they occur simultaneously; preview of multisensory physical stimuli, such as wind, heat, or vibration, while applying them to objects, despite the fact that they are frequently created through code in a 2D screen; available either for conventional 2D monitors or head-mounted display devices; allows better fine-tuning of the experience; when associated with immersive authoring, real-time feedback enables content creators to have a *what you see is what you get* experience, which means the user has a real view of the virtual environment while composing the scene; the authoring tool must allow the author to choose between turning on or off this feature as it can often cause issues and delay during the initialization of complex scenarios due to the quantity of information. The following examples illustrate the guideline:

- "AffordIt! offers an intuitive solution that allows a user to select a region of interest for the mesh cutter tool, assign an intrinsic behavior, and view an animation preview of their work" [37];
- "We believe that more visual aid in the form of animations showing the movement path can help ease the thinking process of participants" [37];
- "The novices are supported in the construction by visualizing the interactive VR scene in the development. This ensures direct feedback of added entities to the scene and modified representative parameters of the entities inside the scene. This enables the novice to spot mistakes immediately" [12].

#### 3.3.12. Reutilization

This guideline concerns optimizing the development time by retrieving relevant elements from a collection or library, such as 2D/3D objects, audio files, codes to set behaviors and interactions, animations, lighting, and so on, so the author does not always need to have advanced knowledge in 3D modeling or programming [44]; libraries and collections must be integrated into the software so the user does not need to access external sources and go through different processes to import different formats of files to the authoring tool, facilitating scene creation; integrating popular libraries into the tool leads to a bigger variety of models, considering that more authors are collaborating with these libraries; it is difficult to find the right element in large libraries; automation processes, such as artificial intelligence networks trained to search for 3D assets in the virtual world using free-hand sketches, can help; saving author's creations for later is another form of reusing things; having templates helps start content creation in authoring tools; photogrammetry is an automated way to retrieve objects from the real world using cameras. The following examples illustrate the guideline:

- "We propose that by utilizing recent advances in virtual reality and by providing a guided experience, a user will more easily be able to retrieve relevant items from a collection of objects" [32];
- "[...] we propose intuitive interaction mechanisms for controlling programming primitives, abstracting and re-using behaviors" [8];
- "Users can also save the abstraction in the toolbox for future use by pressing a button on the controller" [8].

#### 3.3.13. Sharing and Collaboration

This guideline relates to the creation and manipulation of virtual space via collaborative works in which multiple and disparate stakeholders can use their imaginations while working with multisensory immersion from a local or remote network; following each other's activities in real-time; present ideas, products, and services to stakeholders, executives, or buyers in a business context; speeding up the creation process with more workers dealing with different tasks at once; enabling virtual round-tables for creative works, improving prototyping processes; combining the knowledge of different professionals in the same experience; edit of different objects at the same time by different users; people with more immersive technology experience can better assist and guide beginners while sharing the same space; users can change how others perceive them by customizing the color and shape of their avatars [44]; in sharing activities, tasks can be assigned and materials can be switched between users, such as 3D and 2D assets, text documents, textures, etc; create specific tools to enable a better experience in collaborative mode, such as setting mechanisms to lock the editing of an object by a user while it is being edited by another person; different groups of people will interact in different ways and at different levels and frequencies, changing the format of the discussions and also establishing social protocols such as owning objects and claiming territory in virtual space. The following examples illustrate the guideline:

- "[. . . ] directly transmitted to others, and they can observe the doings of others in real time. The users work together on a virtual scene where they can add, remove, and update 3D models" [34];
- "This is useful because multisensory VR experiences might require multiple features that are produced by different professionals, and a collaborative feature will enable the entire team to work simultaneously" [35];
- "Each user is uniquely identified by a floating nameplate and avatar color. The same color is also used for shared brush selections. This allows users to see the actions of others to support collaborative tasks and information sharing, as well as to avoid physical collisions" [40].

#### 3.3.14. Visual Programming

This guideline concerns programming through dataflow instead of creating text lines of code to create behaviors and reactions for the scene components, characters, and objects, which leads to a reduction in text inputs; the use of geometrical formats as nodes that already have a function applied to them, so the author does not need to re-write the text or even know how to do it; all the functions and connections can be presented in a graphic and optimized way; the Blueprint from Unreal Engine, applied through 2D interaction, is a well-known and well-implemented visual programming format in the world of game engines; there are already a variety of formats for the Visual Programming Languages, and they can be implemented in both desktop editing mode (2D screen) and immersive authoring mode (using head-mounted display); the nodes containing preset functions can be called *primitives*; the connection between primitives is also visual, being usually represented by edges going from one node to the other; still, this format can have problems becoming too complex when the codes get too big; it helps with reutilization as the abstraction of functions as groups of nodes can be saved, duplicated, and united to create more complex functions; it can speed up the process of prototyping behaviors. The following examples illustrate the guideline:

- "FlowMatic uses novel visual representations to allow these primitives to be represented directly in VR" [8];
- "Unreal Blueprint, a mainstream platform for developing 3D applications, also uses event graphs and function calls to assist novices in programming interactive behaviors related to system events" [8];
- "The development of a visual scripting system as an assistive tool aimed to visualize the VR training scenario in a convenient way, if possible fit everything into one window. The simplicity of this tool was carefully measured to provide tools used also from non-programmers. From the beginning of the project, one of the main design principles was to strategically abstract the software building blocks into basic elements" [17].

Figure 4 brings a visual depiction of the developed design guidelines.

#### 3.3.15. Additional Considerations

Other factors were frequently mentioned in the reviewed works, such as engagement, fun-to-use, immersiveness, physical comfort, graphical quality, and the acquisition cost of equipment. These factors are not directly involved with intuitiveness, as the guidelines are, because they could be considered as consequences or even challenges related to the democratization of virtual reality technology. Therefore, there is a distance from the design guidelines proposal for the development of more intuitive virtual reality authoring tools, but they are related to the general structure of the technology in our society, aiming for a more popular use among people with various levels of knowledge.

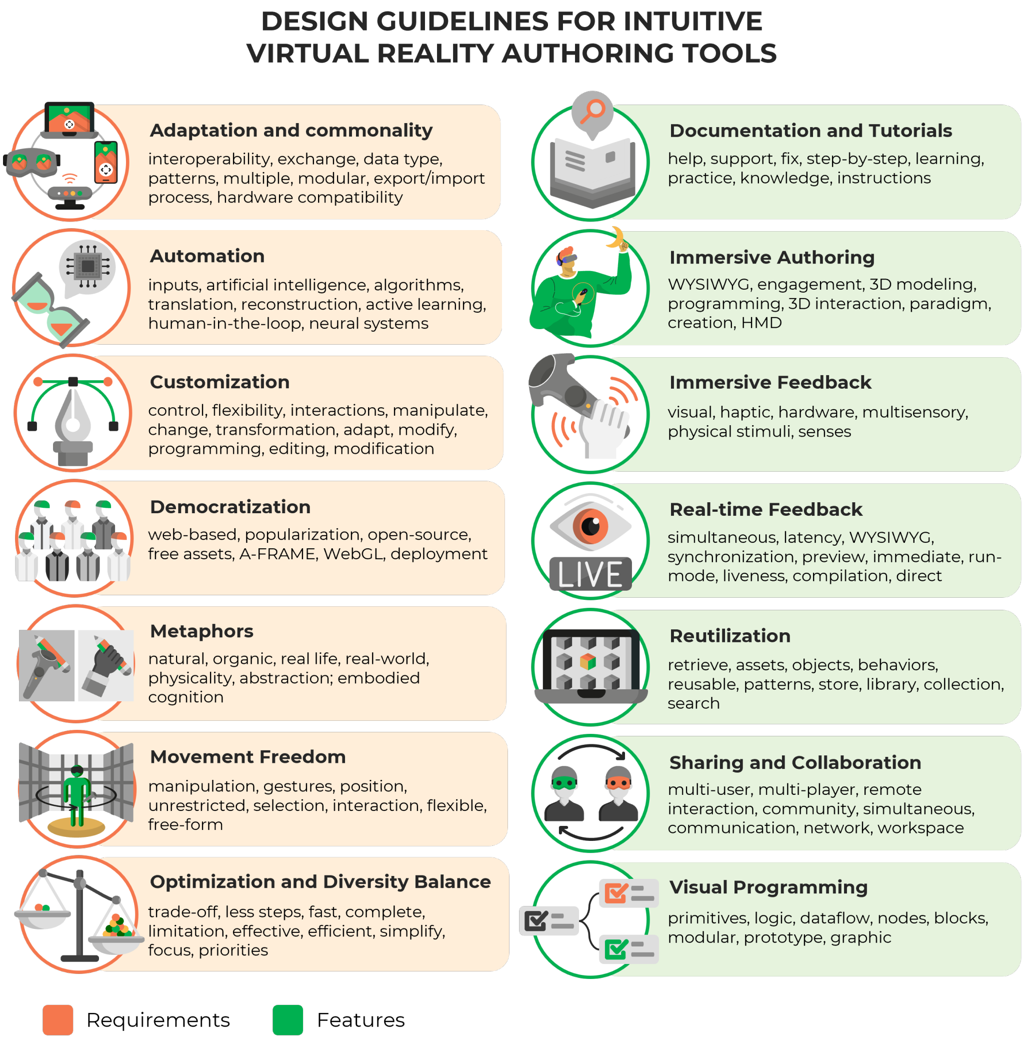


**Figure 4.** The fourteen developed design guidelines.

Concerning the term's definition, *engagement* stands for the active participation and involvement of the user with the tool, indicating that the users have a high level of engagement with the experience provided. As a complement to engagement, the term *fun-to-use* is used to describe the tools with which the users were not only focused on completing the tasks but also having a good time doing it, being frequently related to the concept of gamification. *Immersiveness* is the quality of an experience that provides the user with deep absorption and makes them feel like they have been transported to another world through multisensory feedback, not just based on images and sounds.

The lack of *physical comfort* is frequently mentioned since virtual reality equipment is heavy, meaning that spending a lot of time with it can be exhausting and cause motion sickness in some people. *Graphical quality* is another factor pointed out as being missing from virtual reality experiences due to the geometry optimization necessary to be processed by the head-mounted display. *Graphical quality* has a direct effect on how immersed you feel in an experience, since the better the graphics, the more immersed you feel. Finally, the high *cost* of good virtual reality equipment acquisition is pointed out as one of the main reasons why the technology has not been well popularized so far. The following are quotations from the reviewed works that used the terms:

- Engagement: "The system also provides an engaging and immersive experience inside VR through spatial and embodied interactions" [10];
- Fun-to-use: "[. . . ] the results of the statement if the participant had fun constructing the interactive VR scene suggests that VREUD supplies novices with a playful construction

of interactive VR scenes, which could motivate them to develop their first interactive VR scene" [12];

- Immersiveness: "[. . . ] the majority of VR applications rely essentially on audio and video stimuli supported by desktop-like setups that do not allow to fully exploit all known VR benefits" [35];
- Physical comfort: "[. . . ] some participants commented that navigating the virtual world could cause slight motion sickness" [8]/"[. . . ] we could observe impatience and fatigue when the participants had to type in the text for the callouts using the immersive technology (a virtual keyboard) or had to connect the nuggets to bring them in chronological order" [39];
- Graphical quality: "One disadvantage of these tools is that they do not support highly photorealistic graphics and first person view edits which are achievable only by Unreal Engine and professional CAD software in runtime environments" [41];
- Cost: "It lowers the cost as the templates and the abstractions replace the Application Designer and Programmer by standardizing" [41]/"These wider application areas of VR require, besides affordable devices, a usable process of authoring to reach the full potential" [12].

Another key consideration is how, in practice, the design guidelines should positively contribute to the growth of the metaverse through their impact on the development of easier-to-use authoring tools and, consequently, the increase in the volume of virtual world creation.

The computing power and programming required to create virtual worlds and the accurate physical behavior of related objects are discussed [45]. In a metaverse architecture, the concept of *metaverse engine* is presented, which includes software technologies used in the creation of virtual worlds, such as immersive technologies (virtual reality, augmented reality, mixed reality), brain–computer interaction, artificial intelligence, digital twins (3D creation), and blockchain [23]. Ideally, the *metaverse engine* would use big data coming from the real world in an automatic way to create, maintain, and update the virtual world. The virtual economy would come from virtual avatars doing things on their own, such as trading personalized content made by AI to improve the metaverse ecology.

Contrasting these ideas, human developers are still in charge of making virtual worlds for the metaverse. Because of that, *virtual world engines* will become a standard feature of the metaverse, much like English is a standard language in the world, as the global economy continues to shift to virtual worlds [45]. Besides the many advantages presented by mainstream game engines such as Unreal and Unity, there is still a lot of discussion on what is the easiest and best way to build the metaverse, including how to facilitate the exchange of information, virtual goods, and currencies between these virtual worlds.

The *integrated virtual world platforms* (IVWPs) are a new approach to dealing with the creation of virtual worlds that "are designed so that no actual coding is required. Instead, games, experiences, and virtual worlds are built using graphical interfaces, symbols, and objectives [. . . ] The IVWPs interface enables users to create more easily and with fewer people, less investment, and less expertise and skill [45]".

This definition is very similar to those used to refer to authoring tools in several of the works analyzed here, but a difference can be seen by looking at the context in which each idea is used. While some work delves into game development, bringing examples such as Roblox, Minecraft, and Fortnite Creative [45], which are platforms that reach thousands of users and make thousands of dollars, authoring tools developed in the academic context are seen as proof-of-concepts with non-profit goals and are most often applied in the professional environment, not entertainment. Furthermore, it is interesting to see how both integrated virtual world platforms and authoring tools share not only concepts but also challenges, such as the fact that both "wants to enable creators' creative flexibility while standardizing underlying technologies, maximizing interconnectivity among everything that's built, and minimizing the need for training or programming knowledge on the part of creators" [45]. Therefore, these platforms are more difficult to develop than the Game Engines mentioned above, as every feature becomes a priority.

Facilitating virtual reality development is also not a priority in the mainstream when it comes to integrated virtual world platforms, since one of today's biggest platforms, focused on virtual reality and augmented reality, Facebook's Horizon World remains small when compared to Roblox, which provides immersive virtual reality but prioritizes traditional screens [44].

As for which platform to use for the metaverse, due to the diversity of potential applications, the high technical level of difficulty to unite all of them in something unique, and given the speed at which new platforms are emerging, the best solution would be to handle all existing tooling options simultaneously, also avoiding market monopolization by a single corporation [45]. That is why gathering design guidelines could also affect the development of metaverses since it should help make authoring tools, or even integrated virtual world platforms, that are more intuitive for the people who make virtual worlds to use.

## 4. Conclusions

The fourteen gathered design guidelines can support the development of more intuitive authoring tools focused on authors with limited prior knowledge of 3D modeling and programming, resulting in a more sustainable virtual reality. With the evolution of immersive technologies, many of these guidelines are becoming easier to implement. However, it is also important to understand the intended audience and demand so the priority guidelines for that context can be defined. Even so, the main contribution of this research is the systematic organization and classification of widely used themes and concepts in virtual reality since none of them were invented in this research, creating, in other words, ontologies.

In this study, three research questions were satisfactorily addressed. To answer the *Q1: What are the characteristics of the virtual reality authoring tools reviewed?*, we extract important information related to the VR authoring tools developed in the reviewed articles, such as the artifact definition, software, and hardware tools used in the development process, as well as their plugin or standalone type classifications. In addition, we highlight important general characteristics of these tools, such as their ability to create virtual environments, incorporate 3D models, and serve a general purpose, as they can be used to create VR experiences for a variety of fields. To answer *Q2: What is the definition of intuitiveness in virtual reality authoring tools?*, we compiled key quotes from the reviewed articles that exemplified intuitiveness. As we have seen, it is not yet possible to evaluate or measure intuitiveness objectively, but other metrics such as usability, effectiveness, efficiency, and user satisfaction can be used to indicate a tool's intuitiveness. Such techniques were employed in the reviewed articles, indicating that the authoring tools developed were intuitive, according to our qualitative interpretation of the definition of intuitiveness. Thus, we hypothesized that by evaluating the characteristics of such intuitive tools, we would be able to respond to *Q3: What are the guidelines for designing intuitive virtual reality authoring tools?*, which was accomplished based on the fourteen design guidelines presented.

In practice, these guidelines can be used as a starting point for software developers during the project exploration phase, assisting them in defining the requirements and features of their virtual reality authoring tool. The guidelines can also be used to evaluate the intuitiveness of existing virtual reality authoring tools when applied to a research methodology. Other findings and contributions of this study included discussions about the lack of ontologies and taxonomies related to virtual reality authoring tools and how the guidelines can aid in the development of the metaverse. We discovered that the guidelines themselves may become ontologies and/or taxonomies, while the influence of the creation of more intuitive virtual reality authoring tools should increase the number of people capable of creating their own content to compose the virtual worlds and VR experiences of the metaverse since non-experts would also be able to use them.

As a limitation of this study, the design guidelines were derived from the reviewed articles, which means other guidelines may not be identified by our literature search. In addition, many of the guidelines are also connected to software development principles in general; therefore, some of them could be applied to applications not related to virtual reality. Moreover, our categorization of the guidelines is subjective; they could be organized into different categories.

Concerning future research, each guideline provides the opportunity to delve deeper into the definition of a technical software development approach, even to the point of creating a subclass. Since the guidelines are never presented in isolation, it would be interesting to analyze the correlation level between them, to better understand how to apply them in a project. In addition, it is necessary to conduct actual tests in the context of application development using the guidelines in order to comprehend their impact on the project definition. Finally, it is possible to test the use of the guidelines as a system for evaluating existing authoring tools from the perspective of novice professionals or individuals with no background in 3D modeling or programming.

Above all, this research focused on the democratization of tools for creating virtual worlds, which directly impacts the faster and more sustainable advance and dissemination of trends such as the metaverse. Because of this, virtual reality technology will keep helping to reach the UN Sustainable Development Goals by giving more people the chance and independence to create immersive experiences and develop skills for the digital transformations of society.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10.3390/su15042924/s1.

**Author Contributions:** Conceptualization, I.L.C. and I.W.; methodology, I.L.C. and I.W.; validation, I.W., A.L.A.J., T.B.M. and C.V.F.; formal analysis, I.W. and A.L.A.J.; investigation, I.L.C.; resources, I.W., A.L.A.J. and T.B.M.; data curation, I.L.C.; writing—original draft preparation, I.L.C.; writing—review and editing, I.W., A.L.A.J., T.B.M. and C.V.F.; visualization, I.L.C.; supervision, I.W., A.L.A.J. and T.B.M.; project administration, I.L.C. and I.W. All authors have read and agreed to the published version of the manuscript.

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# 4. Evaluating design guidelines for intuitive virtual reality authoring tools: a NVIDIA Omniverse's experiment

The publication of six pages for the Metaverse and Applications ISMAR 2022 workshop was part of the development of the Specific Objective 4, namely *to demonstrate a proof-of-concept of the developed design guidelines*, testing and revising them through expert reviews, with a preliminary version exposed to researchers (CHAMUSCA et al., 2022).

The development of Specific Objectives 5, which is *to evaluate the validity of the developed design guidelines* is presented in the format of a paper, submitted as an article on the Preprint.org platform on 29/Sep/2023, generated from the Metaverse and Application workshop held in IEEE International Symposium on Mixed and Augmented Reality (ISMAR) in 2022 (CHAMUSCA et al., 2022). At the same time, the article contributes to the Specific Objective 6, namely *to communicate the study results*, which can be met not only by this chapter, but also by all other publications produced during the study's implementation. Adopting the Design Science Research paradigm, this study aims to evaluate the validity of fourteen design guidelines for the development of intuitive virtual reality authoring tools as an artifact.

While a previous study completed the first steps of the Design Science Research, by identifying problems, defining solution objectives, and developing and demonstrating the design guidelines, this work seeks to qualitatively evaluate their application in a practical experiment. A group of engineering students with no prior experience in creating virtual worlds were tasked with examining the design guidelines while using the NVIDIA Omniverse Enterprise as an exemplary use case and responding to a questionnaire and a focus group interview about how they perceived these guidelines. A correlation analysis confirmed that most guidelines scores behaved as expected and were ranked according to the use-case functionality. The participants understood the guidelines' definition and could decide if they agreed or disagreed with their presence during the experiment. In conclusion, according the Design Science Research paradigm, the proposed artifact is useful, i.e., the design guidelines for virtual reality authoring tools perform what they are designed to do and are operationally reliable in accomplishing their goals.

*Article*

# Evaluating design guidelines for intuitive virtual reality authoring tools: a NVIDIA Omniverse's experiment

**Iolanda L. Chamusca [1,*], Cristiano V. Ferreira [2], Thiago B. Murari [3,4], Antonio L. Apolinario Jr. [5] and Ingrid Winkler [3,4*]**

1 Ford Motor Company, Camaçari 42831-710, Brazil
2 Technological Center of Joinville, Federal University of Santa Catarina, Rua Dona Francisca, 8300, Zona Industrial Norte, Joinville 89219-600, Brazil; cristiano.v.ferreira@ufsc.br
3 Department of Industrial Management and Technology, SENAI CIMATEC University Center, Salvador 41650-010, Brazil; thiago.murari@fieb.org.br
4 Institute for Science, Innovation and Technology in Industry 4.0/ INCITE INDUSTRIA 4.0, Salvador, BA, 41650-010, Brazil
5 Department of Computer Science, Federal University of Bahia, Salvador 40170-110, Brazil; antonio.apolinario@ufba.br
* Correspondence: ichamusc@ford.com (I.L.C.); ingrid.winkler@doc.senaicimatec.edu.br (I.W.)

**Abstract:** Virtual reality software might be challenging to utilize for beginners and unskilled professionals who do not have a programming or 3D modeling background. Concurrently, there is a knowledge gap in software project design for intuitive virtual reality authoring tools, which were supposed to be easier to use. These tools are frequently insufficient due to a lack of support and standard operating procedures. Adopting the Design Science Research paradigm, this study aims to evaluate the validity of fourteen design guidelines for the development of intuitive virtual reality authoring tools as an artifact. While a previous study completed the first steps of the Design Science Research, by identifying problems, defining solution objectives, and developing and demonstrating the design guidelines, this work seeks to qualitatively evaluate their application in a practical experiment. A group of engineering students with no prior experience in creating virtual worlds were tasked with examining the design guidelines while using the NVIDIA Omniverse Enterprise as an exemplary use case and responding to a questionnaire and a focus group interview about how they perceived these guidelines. A correlation analysis confirmed that most guidelines scores behaved as expected and were ranked according to the use-case functionality. The participants understood the guidelines' definition and could decide if they agreed or disagreed with their presence during the experiment. We conclude that, in accordance with the Design Science Research, the proposed artifact is useful, i.e., the design guidelines for virtual reality authoring tools perform what they are designed to do and are operationally reliable in accomplishing their goals.

**Keywords:** virtual reality; authoring tools; NVIDIA Omniverse; intuitiveness; user-centered design; human-computer interaction; design guidelines

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## 1. Introduction

The creation of virtual reality (VR) content and experiences is not widespread and still demands costly and time-consuming development processes employing game engines such as Unreal[1] and Unity[2], which require the services of skilled professionals [1–3]. This is because of the unusual input and output devices used in virtual reality, as well as the complexity of the hardware and software architecture of VR systems. These devices include head-mounted displays (HMD), tracking systems, 3D mice, and others [4,5]. Because

1 https://www.unrealengine.com/en-US
2 https://unity.com/pt

immersive technology is complicated, professionals need to have a wide range of skills, including a lot of technical knowledge in programming languages and/or 3D modeling [3,6–8]. So, making interactive scenes in virtual reality is hard and uncomfortable for people who have never done it before [7,8].

Authoring tools are an alternative to the lengthy learning curve, as they aim to facilitate the creation of content with minimal iterations. The term *authoring tool* refers to software structures that include only the most relevant tools and features for content creation while enhancing and speeding up product maintenance [9,10]. In contrast to high-fidelity prototypes, which necessitate sophisticated programming skills, these technologies are used for low-fidelity writing, which requires fewer programming skills [7]. Virtual reality experiences can presently be created using a variety of authoring tools, many of which are free-source programs [11]. But these tools usually lack documentation and tutorials in addition to functionality, which makes them unsuitable for supporting the complete development cycle [7,12].

Professionals of all skill levels would benefit from mature and mainstream authoring tools that are intuitive, helping them reach their virtual reality goals more quickly. Furthermore, the accelerated growth of immersive technology can benefit concepts such as the metaverse, in which users can seamlessly experience a digital life and make digital creations supported by the metaverse engine, especially with the support of extended reality (XR) and human-computer interaction (HCI) [13]. Similar to authoring tools, integrated virtual world platforms (IVWPs), such as Roblox, Minecraft, and Fortnite Creative, are used to create games through graphical symbols and objectives instead of code and have a simpler interface, enabling users to create virtual worlds for the metaverse with less support, money, expertise, and skills [14].

On the other hand, software or platforms in the form of authoring tools are very hard to develop because they aim to give creators creative freedom while standardizing underlying technologies, making everything as interconnected as possible, and minimizing the need for creators to be trained or know how to program [14]. In the end, every feature becomes a priority.

This issue has previously been addressed, and design guidelines have been compiled to assist software developers in defining authoring tool projects [15]. The guidelines were meant to help these developers in choosing and creating the *requirements* and *features* that the authoring tools must fulfill in order to be considered intuitive [16], as well as provide a way for virtual reality authors to evaluate the intuitiveness of previously developed tools. Fig. 1 illustrates the information flow when using design guidelines in these two scenarios.

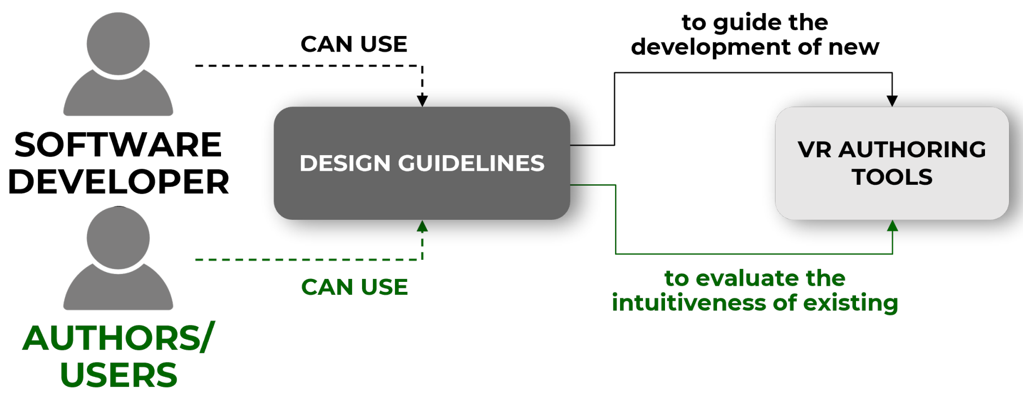



**Figure 1.** The design guidelines' artifact may be used at two stages of the life cycle of a VR authoring tool (adapted from Chamusca et al. [15])

Chamusca et al. [15] developed and demonstrated the design guidelines as an artifact, but they have not yet been assessed. According to the Design Science Research (DSR) paradigm, it is important to collect evidence that a proposed artifact is useful. This means showing that the proposed artifact works and does what it is supposed to do, i.e., that it is operationally reliable in achieving its goals [17].

There are still a lot of open questions on what is the easiest and best way to build the metaverse, facilitating exchanges of information, virtual goods, and currencies between these virtual worlds. However, such design guidelines contribute to the growth of the metaverse through their impact on the development of easier-to-use virtual reality authoring tools and, consequently, the increase in the volume of virtual world creation. Virtual world engines will become a standard feature of the metaverse as the global economy continues to shift to virtual worlds [14].

This study aims to evaluate the validity of the design guidelines for intuitive virtual reality authoring tools [15] by putting them to the test on an example tool: the NVIDIA Omniverse Enterprise. Therefore, verifying qualitatively the use of this artifact in the stage depicted in green on Fig. 1. Developed by NVIDIA, the Omniverse intends to impact the open metaverse and 3D internet, by becoming a foundation for the creation of industrial metaverse applications in architecture, engineering, manufacturing, scientific computing, robotics and industrial digital twins [18].

This document is organized as follows: Sect. 2 describes the materials and methods utilized, Sect. 3 presents and analyzes the results, and Sect. 4 provides our conclusions and suggestions for further research.

## 2. Materials and Methods

This study adopted the Design Science Research paradigm. In addition to a knowledge contribution, effective DSR should make clear contributions to the real-world application environment from which the research problem or opportunity is drawn [17], i.e., an important practical contribution by the DSR's artifact.

Similar to the method used in prior DSR investigations [17,19], we followed the six following steps: (1) identify the problem; (2) define the solution objectives; (3) design and development; (4) demonstration; (5) evaluation; and (6) communication.

The first four steps were completed by Chamusca et al. [15]. In steps 1 and 2, the problem was identified and the solution objectives were set, which were to propose design guidelines to support the project process of intuitive virtual reality authoring tools. Step 3 was a literature review that followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles [20] and was done using a method that includes planning, scoping, searching, assessing, and synthesizing [21]. The outcomes of the literature review were synthesized, and the authors developed an artifact: the fourteen design guidelines described in Table 1.

In step 4, the authors demonstrated a proof-of-concept of the applicability of the proposed design guidelines, testing and revising them through expert reviews, with preliminary versions exposed to researchers in seminars and workshops, such as the Metaverse and Applications Workshop, held in the IEEE International Symposium on Mixed and Augmented Reality (ISMAR) [22]. The methods employed to carry out the remaining 5 and 6 steps in this study are described below.

In step 5, we evaluated the validity criteria of using the fourteen developed design guidelines to verify the intuitiveness of existing VR authoring tools by putting them to the test on an example tool. We started this evaluation by applying the Pearson Correlation Coefficient (PCC) to the Chamusca et al. [15] results to find out how often two guidelines were found together in the studies that were looked at during the SLR (Sect. 3.1). In a later step of this study, this analysis was used along with the Likert-scale questionnaire as another indicator to evaluate the validity of the design guidelines (Sect. 3.2).

Then, we conducted an experiment with six engineering students from our Virtual and Augmented Reality for Industrial Innovation Lab (referred to as participants P1–P6). They had no background in programming, no prior experience using the exemplary authoring tool or creating virtual worlds in any form of game engine, and no prior awareness of the

**Table 1.** Design guidelines (DG) list, Abbreviation code (AC), and Frequent terms [15]

| DG | AC | Frequent terms |
|---|---|---|
| Adaptation and commonality | DG1 | interoperability, exchange, data type, patterns, multiple, modular, export/import process, hardware compatibility |
| Automation | DG2 | inputs, artificial intelligence, algorithms, translation, reconstruction, active learning, human-in-the-loop, neural systems |
| Customization | DG3 | control, flexibility, interactions, manipulate, change, transformation, adapt, modify, programming, editing, modification |
| Democratization | DG4 | web-based, popularization, open-source, free assets, A-FRAME, WebGL, deployment |
| Metaphors | DG5 | natural, organic, real life, real-world, physicality, abstraction; embodied cognition |
| Movement freedom | DG6 | manipulation, gestures, position, unrestricted, selection, interaction, flexible, free-form |
| Optimization and diversity balance | DG7 | trade-off, less steps, fast, complete, limitation, effective, efficient, simplify, focus, priorities |
| Documentation and tutorials | DG8 | help, support, fix, step-by-step, learning, practice, knowledge, instructions |
| Immersive authoring | DG9 | what-you-see-is-what-you-get (WYSIWYG), engagement, 3D modeling, programming, 3D interaction, paradigm, creation, HMD |
| Immersive feedback | DG10 | visual, haptic, hardware, multi-sensory, physical stimuli, senses |
| Real-time feedback | DG11 | simultaneous, latency, WYSIWYG, synchronization, preview, immediate, run-mode, liveness, compilation, direct |
| Reutilization | DG12 | retrieve, assets, objects, behaviors, reusable, patterns, store, library, collection, search |
| Sharing and collaboration | DG13 | multi-user, multi-player, remote interaction, community, simultaneous, communication, network, workspace |
| Visual programming | DG14 | primitives, logic, data-flow, nodes, blocks, modular, prototype, graphic |

fourteen design guidelines. However, some of them mentioned a basic understanding of 3D modeling and/or navigation.

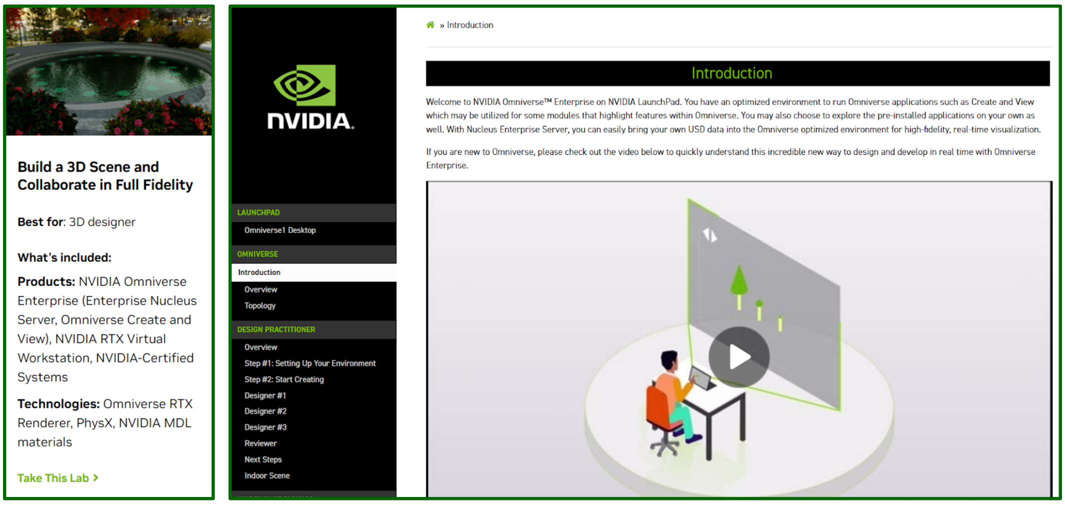
The experiment's participants were tasked with qualitatively examining the design guidelines while using the NVIDIA Omniverse Enterprise[3] package as an exemplary use case of an authoring tool. Although NVIDIA has not specifically indicated so, for the purposes of this study, the Omniverse components are regarded as an authoring tool, as just a subset of its available tools were utilized in our experiment, including only the most relevant features for content creation. The evaluation of a tool is part of its life cycle and, consequently, enters the process of product design and may generate improvements to be implemented. Therefore, the design guidelines must work as a reference for the whole software product design process, including their evaluation ( 1).

We chose NVIDIA Omniverse as an use case because it helps create virtual worlds and the metaverse through virtual collaboration, 3D simulation, modeling, and architectural design [13,23]. Omniverse's main features include virtual reality, artificial intelligence to analyze audio samples and match them with meta-humans' facial animation, 3D market-places and digital asset libraries, connectors to outside applications like Autodesk Maya[4] and Unreal Engine, and integration of 3D workflows like digital twins [24]. The platform was used, for example, to build a digital twin for BMW that improved the precision of its in-

[3] https://www.nvidia.com/en-us/omniverse/
[4] https://www.autodesk.com/products/maya

dustrial work by combining real-world auto factories with VR, AI, and robotics experiences [25].

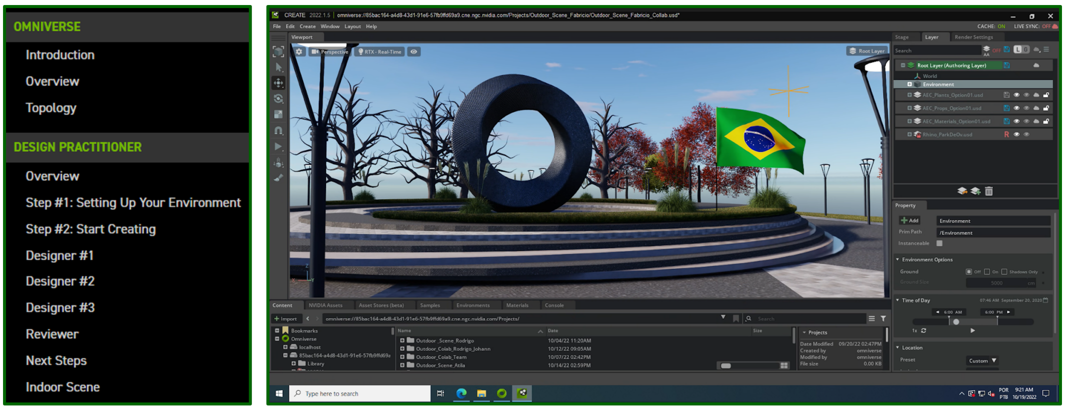
Industrial concerns are gaining a lot from the engineering simulation available on this tool, even though it was the creative sector that gave virtual worlds their initial impetus through game development and entertainment studios [26]. For professional teams, NVIDIA Omniverse Enterprise can develop comprehensive and photo-realistic design platforms that enable better designs with fewer expensive mistakes in less time. Teams of designers, engineers, marketers, and manufacturers can work together through the Omniverse Nucleus Cloud. This lets creators in different places share and collaborate in real time on designing 3D scenes for industrial applications, like car design [13,24,26]. However, even similar to VR authoring tools in the professional context, Omniverse can be seen as complex for having many sub-products, requiring some time to learn the user interface, presenting a challenge to find the most efficient way to use it, and requiring research in its documentation [27].




(a) (b)

**Figure 2.** (a) Hands-on lab; (b) NVIDIA LaunchPad interface for Omniverse Enterprise

The six participants experimented the hands-on lab *Build a 3D Scene and Collaborate in Full Fidelity* (Fig. 2(a)) taking turns with three NVIDIA LaunchPad free tryout accounts for Omniverse Enterprise (Fig. 2(b)). LaunchPad gave users access to NVIDIA virtual machines with graphics capabilities that they could use to run Omniverse apps like Create and View.




(a) (b)

**Figure 3.** (a) Tutorial steps for the Create platform; (b) Screenshot of the Create interface

Fig. 3(a) illustrates the experiment scope, limited to the activities described on the topics *Overview*, *Step #1: Setting Up Your Environment*, *Step #2: Start Creating*, *Designer #1*, *Designer* #2 and *Designer* #3. The goal was to install the application needed to access the virtual machine, learn how to install and run the Create application, and work together to build a 3D scene of a park, as shown in Fig. 3(b). The same scene could be seen by three people at the same time, each using one of the three accounts that had been requested before. Each participant should execute the activity described by one of the *Designers*. The activities included adding an environment, adjusting lighting, adding 3D assets from a library, adding or changing textures from a library, and organizing the work layers to guarantee the organization of the space while also avoiding the conflict of more than one person editing the same object at once.

Before using LaunchPad to get into Omniverse, the participants read a document that explained each design guideline in detail (Supplementary Materials) [15]. Then, we answered questions for further clarification on the design guidelines definitions. After that, the participants took turns using the accounts. All Omniverse LaunchPad sessions were done through online remote meetings.

Then, we captured the participants' insights about the design guidelines using two methods. The first method was a Likert-scale questionnaire comprising fifteen questions (Supplementary Materials). The scale had a numeric scale that ranged from *totally disagree* (1 point) to *totally agree* (5 points). which should be marked according to their agreement about the existence of a design guideline in Omniverse. Additionally, the participants were questioned about significant observations made throughout the execution of the tutorials, which could include system errors, challenges, and interesting functionalities. The equations shown in Fig. 4 are a first proposal of how to estimate a punctuation to an authoring tool's intuitiveness using the guidelines, where the *guideline score* corresponds to the average of participants' answers on the Likert-scale questionnaire (1-5) and the *final score of the tool* evaluated stands for the sum of all guideline scores. These equations were applied to the experiment realized in this study so the answers obtained with the second method could be compared to other indicator.

$$\overline{G} = \frac{\sum_{i=1}^{p} G_i}{p} \quad (a)$$

$$F = \sum \overline{G} \quad (b)$$

$\overline{G}$ = *guideline score*
$G$ = *participant answer in Likert−scale*
$p$ = *number of participants*
$F$ = *final score of the tool*

**Figure 4.** (a) Average of participants' answers on the Likert-scale questionnaire (1–5); (b) Sum of all guidelines scores

The number obtained as the final score was compared to the maximum score value in the questionnaire, which is equal to 70, considering the product between fourteen guidelines and five points for *totally agree*. It was assumed that a percentage lower than 50% of this total value would characterize authoring tools that are not very intuitive, while a higher percentage would indicate greater intuitiveness. The questionnaire results (Sect. 3.2) were also matched to the correlation analysis results (Sect. 3.1) to confirm the similarities, which were determined by examining the score of the guidelines with strongest positive and negative correlation obtained on the questionnaire. However, these values where obtained to serve as a demonstration of how the guidelines could be used to evaluate a VR authoring tool and to be compared with the results obtained with the second method.

The second method was a focus group interview (Sect. 3.3), in which participants answered eighteen questions on their understanding of the design guidelines and their experience using them to evaluate the exemplary use case (Supplementary Materials). The answers were recorded in audios and converted to text using an online tool, which was then analyzed in the results session. Finally, we provide a pipeline including a compilation of all the steps carried out in this study, as a guide for anybody wishing to replicate the experiment using different VR authoring tools.

Step 6 entails communicating our findings from this work, in which we demonstrate how an evaluation experiment using a VR authoring tool may be undertaken from the perspective of the design guidelines, therefore assessing the validity of the guidelines as an artifact.

## 3. Results

In the following sessions, we describe our findings.

### *3.1. Reviewing the design guidelines*

Most of the authoring tools found in the systematic review are just proof-of-concept, but the design guidelines can encourage the development of mainstream platforms with fewer limitations, democratizing the technology and increasing its maturity. Moreover, the findings in Chamusca et al. [15] contribute to initiating or advancing the creation of ontologies for the development of virtual reality authoring tools in relation to the gap previously identified [9]. The lack of ontologies related to the concepts of virtual reality authoring tools has been discussed, indicating that there are few connected standards for the development of these platforms [9].

Furthermore, the guidelines can positively contribute to the creation of the metaverse through their influence in facilitating the use of the components that make it up. The wide scope of this concept causes a lack of understanding about how it works, leading to the need for a taxonomy proposal for the metaverse [28]. Between the proposed taxonomies, the components thought to be necessary for the realization of the metaverse were: hardware, software, and contents. Many similarities were found between the design guidelines developed by Chamusca et al. [15] and the technologies that have recently become issues and interests in the metaverse and were mapped as hardware, software, and content [28].

The works reviewed by Chamusca et al. [15] define intuitiveness as related to completing tasks quickly, requiring minimal learning, lowering the entry barrier, reducing information, time, and steps, being appropriate for both expert and non-expert users, being aware of and feeling present in virtual reality, feeling comfortable with the tool, making few mistakes, and using natural movements in virtual reality. Although there is no standard method to evaluate or measure intuitiveness, aspects such as usability, effectiveness, efficiency, and satisfaction may be quantified using well-established questionnaires and methods like the System Usability Scale (SUS) and the After-Scenario Questionnaire (ASQ) [9,29].

The utilization of questionnaires as a well-established method to evaluate software tools was the source of the idea of using the guidelines artifact in association with a questionnaire to help the process of evaluating virtual reality authoring tools. This is also supported by the contribution of the guidelines to the creation of ontologies and taxonomies in the field. There is a lack of standard concepts, methods, and nomenclature not only during the development of VR authoring tools with vastly different formats but also in the application of diverse evaluation techniques to determine their usability [9].

The developed guidelines complement one another and were not given separately [15]. Fig. 5 shows the correlation analysis that was done with the fourteen design guidelines. It shows which pairs of guidelines show up together more or less often in the works that were reviewed. The three strongest negative and positive correlation values (CV) in Fig. 5 were captured, and from that, the pairs of design guidelines that presented these values were highlighted in Tables 2 and 3. The columns related to questionnaire scores (QS) link the scores for each guideline presented in Fig. 6, which will be explained in more detail in Sect. 3.2, to the correlation analysis.

Examining the cases of Democratization (DG4) and Adaptation and commonality (DG1), the strong positive correlation can be associated with the fact that multiple elements related to DG1 can, consequently, lead to DG4. For example, using the same authoring tool on different devices and accepting different file extensions for the same type of data can help simplify and provide access to a tool for more users. Movement freedom (DG6)

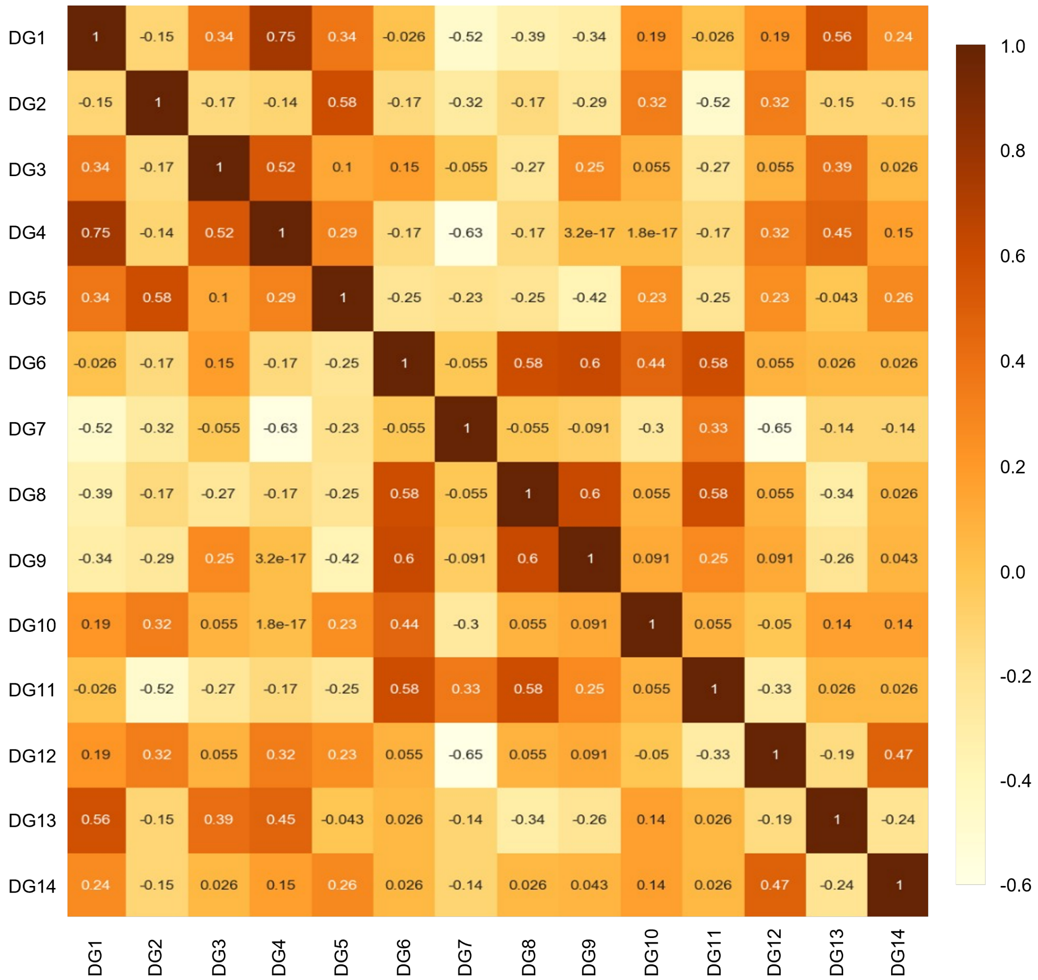



**Figure 5.** Applying the Pearson Correlation Coefficient (PCC) to the fourteen design guidelines

**Table 2.** Design guideline pairs with the strongest positive correlation

| CV | Design guidelines pairs | QS | QS Dif. |
|---|---|---|---|
| 0.75 | Democratization (DG4) and Adaptation and commonality (DG1) | 1.5 (DG4) and 4 (DG1) | 2.5 |
| 0.60 | Movement freedom (DG6) and Immersive authoring (DG9) | 1.5 (DG6) and 2.5 (DG9) | 1 |
| | Movement freedom (DG6) and Metaphors (DG5) | 1.5 (DG6) and 3.5 (DG5) | 2 |
| 0.58 | Documentation and tutorials (DG8) and Automation (DG2) | 4.5 (DG8) and 3 (DG2) | 1.5 |
| | Metaphors (DG5) and Immersive authoring (DG9) | 3.5 (DG5) and 2.5 (DG9) | 1 |
| | Real-time feedback (DG11) and Immersive authoring (DG9) | 4 (DG11) and 2.5 (DG9) | 1.5 |
| | Real-time feedback (DG11) and Metaphors (DG5) | 4 (DG11) and 3.5 (DG5) | 0.5 |

and Immersive authoring (DG9) are codependent, since DG6 can not exist without DG9, but the inverse can happen. Actually, DG6 complements DG9, literally highlighting the importance of having movement freedom during an immersive authoring experience. Movement freedom (DG6) can be composed by Metaphors (DG5), for example, by moving and positioning objects as if they were in the real world and connecting objects distant from each other by making the physical movement of drawing visible lines between them.

Documentation and tutorials (DG8) are often created using Automation (DG2), for example, through AI assistants that detect when the user is having difficulties moving on with a task and provide smart suggestions to solve that. The use of Metaphors (DG5) can help make Immersive authoring (DG9) easier by turning abstract concepts into tangible tools, such as using buttons on the controllers to reproduce actions similar to what we would do in real life, like pulling the trigger button to grab an item and releasing it to drop it. Finally, Immersive authoring (DG9) and Metaphors (DG5) must have Real-time feedback (DG11) to work properly, enabling content creators to have a *what you see is what you get experience*, meaning the user has a real view of the virtual environment while composing the scene [15].

**Table 3.** Design guideline pairs with the strongest negative correlation

| CV | Design guidelines pairs | QS | QS Dif. |
|---|---|---|---|
| -0.65 | Immersive feedback (DG10) and Reutilization (DG12) | 1.5 (DG10) and 4.5 (DG12) | 3 |
| -0.63 | Immersive feedback (DG10) and Democratization (DG4) | 1.5 (DG10) and 1.5 (DG4) | 0 |
| -0.52 | Immersive feedback (DG10) and Adaptation and commonality (DG1) | 1.5 (DG10) and 4 (DG1) | 2.5 |
| | Real-time feedback (DG11) and Automation (DG2) | 4 (DG11) and 3 (DG2) | 1 |

Regarding the design guidelines with strong negative correlation, it is remarkable that Immersive feedback (DG10) appears on three of the four correlations. This makes sense, because the definitions brought by DG10 are really unique for the immersive context, making the use of some kind of virtual reality device mandatory. Reutilization (DG12), Democratization (DG4), and Adaptation and commonality (DG1) are not guidelines limited by the use of devices, being more generalist to the virtual world creation. Safe conduct, Adaptation and commonality (DG1) could indirectly contribute to Immersive feedback (DG10), considering that allowing communication with different types of VR hardware is one of its definitions. Real-time feedback (DG11) and Automation (DG2) are two guidelines connected to a good system infrastructure, and automated functions should have real-time feedback but nothing more than that.

These results illustrate that it is possible to assess the existence of guidelines on a tool by understanding how they relate to one another, resulting in an indicator evaluate the design guidelines artifact, which were done in Sect. 3.2.

### *3.2. Likert-scale questionnaire*

After executing the tutorial described in the NVIDIA LaunchPad, the participants answered the Likert-scale questionnaire, followed by the detailed document about the design guidelines. Fig. 6 presents these answers, with the design guidelines ranked by the average value of their scores, as determined by the equation provided in Fig. 4(a).

The five guidelines with higher scores are shown in the following topics with examples of where the guidelines were seen by the participants, according to their comments:

1. Sharing and collaboration (DG13): the participants could see in real time the updates made by the others, and they finished the activities quicker by splitting the job between more people;
2. Customization (DG3): the participants could easily change the color and texture of the assets imported from the libraries;
3. Documentation and tutorials (DG8): the LaunchPad itself promotes a good step-by-step for a first try of the tool, giving an enough number of activities so the person can get to know the tool without being lost in numerous tutorials;
4. Reutilization (DG12): Omniverse Create has libraries of assets with many 3D models and textures available, so the participants did not need to look for them outside the software;
5. Adaptation and commonality (DG1): the participants could see the same file being updated in real time on the Omniverse View, while the scene was being created on Omniverse Create; also, the asset libraries were integrated with the software interface, so they did not need to worry about file extension compatibility or do an extra process to import them.

The five guidelines with lower scores were: Immersive authoring (DG9), Democratization (DG4), Immersive feedback (DG10), Movement freedom (DG6), and Visual programming (DG14). We could not run a test using virtual reality during the experiment

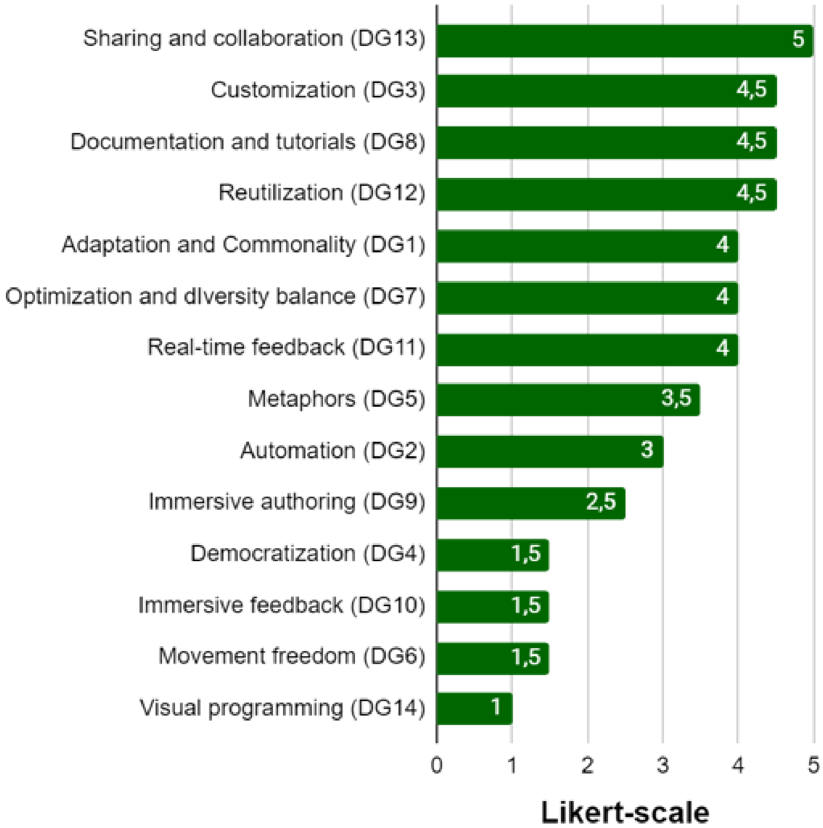



**Figure 6.** Average value of each guideline's determined score for the exemplary use case

with the exemplary use case because the NVIDIA LaunchPad did not provide the tool Omniverse XR, which certainly caused the decrease in the score given to the guidelines related to immersiveness, which are Immersive authoring, Immersive feedback, Movement freedom, and Visual programming. This demonstrates that the participants understood the design guidelines' definitions since, even though they are not specialists, they were able to understand that the experience did not fit their descriptions and disagreed with the presence of these guidelines.

We also observed that, similar to the complex game engines frequently used for VR development today, such as Unreal and Unity, in the version of Omniverse Enterprise experimented as the exemplary use case, virtual worlds for VR experiences are still developed primarily using 2D screens, not HMDs and other wearables. This is different from what Chamusca et al. [15] saw during the development of the guidelines, since the reviewed works showed that adding virtual reality equipment to the process of creating an VR experience can make it easier to understand and do it correctly. This indicates that the guidelines were comprehensible and the participants did not perceive intuitiveness in creating an immersive experience without being allowed to test it along the way.

Democratization (DG4) was at the bottom of the list, probably because Omniverse Enterprise is not free and can only be used with paid NVIDIA accounts or limited free tryout accounts, which were the case in this study. Also, technical problems related to the high latency of the virtual machines faced by some participants probably affected the results, which will be discussed in the next Sect. 3.3. On the other hand, all the participants could complete the activities proposed in the exemplary use case, even though they had never used similar software before.

Using the equation shown in Fig. 4(b) to calculate the sum of all guidelines scores and comparing them to the maximum score value in the questionnaire, we obtained a total score of 45 out of a maximum of 70, or 64%. This percentage represents the global level of intuitiveness of a VR authoring tool from the guidelines' perspective, as experienced by the participants while executing the experiment. This average score is aligned with the declaration that the Omniverse tool can be seen as complex, requiring time to understand the user interface, presenting a challenge to find the most efficient way to use it, and requiring research in its documentation [27]. This contributes to the validity of the design guidelines since the medium score of 64% obtained from their perspective, matches past feedback about the software.

Regarding the correlation between the guidelines, most of them were in line with the results shown in Sect. 3.1 when the difference between their scores was checked. It was assumed that guidelines with strong positive correlation values would have lower difference values, while those with strong negative correlation values should have high difference values. Table 2 and Table 3 show that the design guidelines pairs with strong positive correlation values had a score difference of around 0.5 and 1.5, while the pairs with strong negative correlation values had a score difference of around 2.5 and 3, which matched the expectation. However, an unexpected score difference of 2.5 in Table 2 and 0 in Table 3 draws attention, having the guideline Democratization (DG4) as a common factor.

This indicates that some unexpected occurrence connected to the Omniverse experience produced a mismatch between this guideline and the others, most likely the same incident that led to this guideline's low score on the Likert-scale questionnaire. During the focus group interview, which will be discussed in Sect. 3.3, participants talked about problems like *the program taking too long to respond to commands* and *difficulty installing the virtual machine*. Such problems are not directly related to the usability of the tool, but rather to the specific circumstances of each participant, such as an incompatible internet connection. This may have caused a decrease in the Democratization (DG4) score to 1.5, not following the expectation of having a higher score such as Adaptation and Commonality (DG1) with 4 points, with which has a strong positive correlation of 0.75, leading to the high score difference of 2.5. Technical issues in conjunction with the absence of Omniverse XR approximated the Democratization (DG4) score with the low results of the immersiveness-related guidelines, Immersive feedback (DG10) being one of them with 1.5 points, with which DG4 has a low correlation level of -0.63, but a low difference score of 0 in this experiment.

### *3.3. Focus group interview*

The participants' responses obtained with the focus group interview are examined in the following section.

#### 3.3.1. The exemplary use case Omniverse tool

During the execution of the experiment, the participants encountered both obstacles and opportunities associated with the activities proposed in Omniverse LaunchPad. Four of the participants said that applying textures to small areas was the hardest part. This includes actions applying grass on a small piece of the 3D ground mesh. Three participants said that the software took too long to respond to commands, which could be caused by technical problems like incompatible internet connection.

Only one participant mentioned difficulty starting the program and following the LaunchPad step-by-step instructions for installing the virtual machine. Two participants had difficulties understanding how to navigate inside the 3D environment, which includes rotating the camera and zooming in and out on objects, while two other participants considered this an easy and intuitive task.

> *"There was a step where it was asked to apply grass to a specific area, and I was not able to select it. That step really stuck with me. I did not know if it was because I was not using the right tool, if I had skipped a step, or if the tutorial was not able to instruct me to reach my goal."* - P2

Omniverse LaunchPad provided links to external videos along the tutorial with more details on some features, such as applying textures to meshes. Possibly, participants who had difficulty with this function did not notice these links in the explanation or limited themselves to only follow the instructions on the main page with the activities. Four participants said that importing 3D assets from the Sketchfab[5] library and placing them in the scene was one of the easiest things to do. Another participant highlighted how easy was to set the environment's illumination for the skybox using a slide button that changed the position of the sun in real time.

> *"For me, the most intuitive part was adding and removing objects such as trees, vases, benches, and tables. It was very intuitive because it has an illustrative icon of what you were going to place, and when you select and drag it into the scene, the software tells you where that object will be, and you can even see it from different perspectives."* - P4

When asked if they had already used a tool similar to the exemplary use case Omniverse, three participants mentioned they had already had contact with parametric 3D modeling software (Solidworks[6]), three cited games like The Sims and Minecraft as facilitators, and only one had already had a brief contact with a game engine (Unity) but with the intention of create a 2D mobile application. We found that participants who had previous experiences with software or games that required interaction and movement in a 3D environment found Omniverse easier to use because the controls are usually very similar.

> *"I had not used a tool like Omniverse before, but something that might have made it easier was my experience with games like The Sims, as you created an environment and inserted objects."* - P3

### 3.3.2. Guidelines identification

Along with the activity to be carried out for the exemplary use case Omniverse, participants were provided with a detailed document describing the fourteen design guidelines' definitions and a Likert-scale questionnaire that asked if they agreed, or disagreed, with the presence of the guidelines in association with the software functions used in the activity. To efficiently answer the questionnaire, most of the participants (four) chose to take notes as they followed LaunchPad tutorials, using the guidelines' document as a support during this process. Only two participants did not take notes, although they did consult the guidelines' definitions in order to be able to answer to the questionnaire coherently.

Despite being instructed to identify the presence or absence of the design guidelines in the tool under test, the participants were not told how to do it. When asked about their method for associating the guidelines with Omniverse, the participants answered that they focused on identifying the steps they found complex or easy to accomplish and connecting them with the definitions of the guidelines. Most did it in a segmented way, i.e., after completing each step instructed by LaunchPad, so that all the details were clear in their memories. Another way of highlighting the presence or absence of a guideline in the experimental tool was the association with the examples given in the definitions of the guidelines; if an example was directly found, positive points were given to the guideline.

Participants also mentioned that some guidelines were obvious while others required more reflection, particularly on whether their presence or absence would be limited to a specific stage of the activity or was truly part of the Omniverse's characterization as a tool. Among the guidelines that were easier to identify were: Automation, Customization (cited three times), Democratization, Movement freedom, Documentation and tutorials (cited

5 https://sketchfab.com/
6 https://www.solidworks.com/

twice), Real-time feedback (cited twice), Reutilization, Sharing and collaboration, and Visual programming (cited twice). Listed below are statements from participants that demonstrate their reasons for identifying these guidelines as easy to identify:

- *"In group dynamics and collaboration, I could see the almost instantaneous change of material, color, or movement made by other people"* - (P1, about Real-time feedback);
- *"This guideline did not exist, and because of that, I had a lot of difficulty with the slowness to perform some actions"* - (P2, about Real-time feedback);
- *"I pointed out this guideline because I could not find it during the experiment, so it was very easy to identify"* - (P3 and P6, about Visual programming);
- *"I was impressed with what a person is able to do using Omniverse through a virtual machine accessed by a mere notebook, since even using a computer with a good GPU, the graphics processing of programs like this takes a long time"* - (P6, about Democratization);
- *"The tool has a library with assets you can place and reuse in the environment"* - (P3, about Reutilization).

Among the guidelines considered more difficult to identify, the following were mentioned: Metaphors, Movement freedom (cited twice), Optimization and diversity balance, Immersive authoring (cited twice), Immersive feedback, Sharing and collaboration, and Visual programming. Below are some of the participants' statements that show their motivations for pointing out these guidelines as difficult to identify:

- *"I had a lot of difficulty answering the question about this guideline. I had to read its description several times to find out if the LaunchPad would apply with the definition"* - (P1, about Immersive authoring);
- *"Even interacting with an open environment, I felt a little limited, so I kept questioning whether I really had this movement freedom or if it was a freedom within the limitation of using the software through a 2D screen"* - (P1, about Movement freedom);
- *"I found it a little subjective; I could not say to what extent we can consider that the process was optimized or not, and whether it was complex or not"* - (P2, about Optimization and diversity balance);
- *"The most difficult for me were the two that involved immersion, because I believe it is subjective to identify if I am immersed in that environment; what may be immersive for me may not be immersive for someone else, and vice versa"* - (P3, about Immersive authoring and Immersive feedback);
- *"I had to read the guideline a few times to have a better understanding when answering, due to my lack of knowledge in the area"* - (P4, about Visual programming);
- *"I could not say if that was easy or not, because I did not have much experience with collaboration in other similar applications and software, so Omniverse collaboration might not be efficient in front of the guideline"* - (P5, about Sharing and collaboration).

Guidelines classified as features or requirements were equally mentioned as easy or difficult to identify, so no discussion can be given on that. However, the Movement freedom, Sharing and collaboration, and Visual programming guidelines were mentioned both as easy and difficult to identify by different participants, which may represent ambiguity in the definitions given to them and, consequently, a lack of standards to determine situations in which these guidelines apply or not. This was clear from what the participants said, since they were not sure about the meaning of some of the terms used in the guidelines' definition. Immersiveness, for example, was not directly linked to virtual reality experiences by the participants, but all of the examples in the definition of the guidelines are linked to this aspect. This can also be attributed to the participants' lack of experience with the area and its technical terms.

The lack of experience may also be the reason why the guidelines with highest scores on the Likert-scale questionnaire (Sharing and collaboration, Customization, Documentation and tutorials and Reutilization) were presented as easy to identify, while four of the guidelines with the lowest scores (Immersive authoring, Immersive feedback, Movement freedom and Visual programming) were presented as difficult to identify. This suggests that even though the participants were able to discern that the low score guidelines were not featured in the tool, they still had doubts when responding to the questionnaire, indicating that they were challenging to recognize. The inverse is true of the guidelines with the highest scores, which were easily observable throughout the execution of the experiment and could, thus, be better evaluated. This raises the question of whether the difficult-to-identify guidelines had subjective descriptions, as many of the participants claimed, or whether the fact that the tool did not present the examples stated by its definitions led to a lack of clarity for the interpretation of the participants, who were unable to implement the concepts illustrated in the examples.

In this perspective, the Democratization guideline stands out because, unlike the others with low scores on the questionnaire, it was presented as easy to identify, preserving the history of inconsistencies revealed throughout the experiment. Comparing Democratization's score to the correlation analysis revealed unexpected findings, which could be attributed to the fact that the tool is not free and that technical issues occurred throughout the test. Given that not all participants experienced technical difficulties during the experiment, P6's generally positive comment in this Section may add to the prior claims. In addition, the fact that a guideline is considered easy to identify should not be correlated with its presence, as participants P3 and P6 made evident in their comments regarding the absence of Visual Programming.

#### 3.3.3. Guidelines strengths and weaknesses

Then, the participants were asked about the strengths and weaknesses related to the use of guidelines for evaluating the intuitiveness of existing authoring tools for experiences in virtual reality (Fig. 1). Three participants said that the inclusion of practical examples to the description of the guidelines was the greatest strength. This was due to the fact that the examples made it feasible to compare the assessed tool functionalities to those of other software or apps throughout the experiment, despite the fact that part of the general description was not very clear. Moreover, titles were cited as strengths, since they allowed for rapid reference to what the guideline defines.

> *"I think the titles were very striking and helped us understand what that guideline meant. See Real-time feedback, for example. Just reading the title, I can easily associate it with the definition without necessarily having to read it."* - P2

Participants pointed out that one of the weaknesses was the use of unusual words like *haptic*, that were derived from the field's technical terminology. Other examples were the subjectivity of some of the definitions, the lack of visual references, such as pictures, to compose the definitions of the guidelines, and the lack of delimitation to make more clear the difference between guidelines with similar names.

> *"Some guidelines, such as Metaphors, are very subjective, which could be solved using images, for example."* - P6

Concerning the presented set of guidelines, all participants agreed that it was appropriate and complete. They did not suggest any additional guidelines to be added to the list, although some believe that as technology evolves, new guidelines may be necessary.

According to all participants, the guidelines have different weights in terms of intuitiveness. This indicates that the presence of guidelines with a higher weight makes a tool more intuitive, whereas those with a lower weight have less of an effect. However, there was no consensus among the participants about which guideline would have higher or lower weights, so this topic should be treated as a future research. Three of the participants stated that the relevance of the guidelines varies based on the context in which a tool is being assessed. For instance, if the experience is collaborative or individual, or if the technology includes head-mounted displays and other VR peripherals, the relevance of certain guidelines changes.

> *"I believe the guidelines have different weights. For example, I consider Democratization to have a high weight in terms of intuitiveness, whereas Visual programming I consider to have a lower weight when analyzing a tool."* - P6

All participants believed that most of the guidelines were self-explanatory. However, some of them are subjective, making it difficult to use them to evaluate VR authoring tools, as their existence or absence can be understood differently by each individual. Nevertheless , all participants indicated they would utilize the guidelines to evaluate the intuitiveness of other VR authoring tools. This is due to the fact that the guidelines helped them comprehend the potential of using Omniverse, and how it could be implemented. One of the participants believes that using the guidelines to evaluate other authoring tools will also contribute to the improvement of their definitions. Two others said that the guidelines can assist them in finding a tool that satisfies the requirements for the development of a particular project.

> *"The idea is to use the guidelines to find the tool that best meets the requirements of your project."* - P5 and P6

#### 3.3.4. Changing suggestions for the guidelines' future

In an effort to improve the concept of the guidelines, participants were requested to suggest changes and future applications. The majority of proposed modifications involved rearranging and categorizing the guidelines, including, for instance, a reduction in their number and convergence of those with comparable concepts. In order to guide the evaluators to assess an authoring tool through a certain sequence of the guidelines list, it was suggested that the guidelines be reorganized into those to be judged before testing with a tool and those to be judged during the experiment. Moreover, the parameters might be categorized as applicable to the evaluation of 2D experiences, virtual reality immersion, or both. In the end, one participant disagreed with the suggestions to make modifications because he believed it was essential to analyze each guideline as it is now written.

> *"I believe you can reduce the number of guidelines by grouping concepts that are similar together; for example, Metaphor and Movement freedom are very similar in my interpretation."* - P1
> *"I believe Democratization should be one of the first guidelines to look for before experimenting with a tool because, if the tool does not have it, a much smaller audience will be able to access it and really evaluate the following guidelines."* - P2

For future implementations of the guidelines, the participants proposed replicating this experience, primarily by altering the composition of the evaluation group and the software tools evaluated. For instance, the application might be conducted with a group of industry specialists, such as programmers and VR experience designers, in order to obtain more technical input, since they are also the target audience for the guidelines application as a development guide for new VR authoring tools. The present investigation selected a group of participants with different degrees of experience, which may have led to variations in scores and interpretations of the guidelines' principles. The same test can be administered to individuals of different generations, such as children, teenagers, and the elderly, in order to compare their findings based on their technological experiences.

Participants also suggested conducting more extensive testing with each of the guidelines individually, examining specific experiences to identify them in tools, and then returning to the test collectively. About altering the software tools evaluated, identifying those that are recognized as intuitive on the market can help to confirm whether or not the guidelines are effective, since high scores would be expected. Reproducing the experiment using a tool that serves a different purpose or in a situation that enables the experience not only on 2D screens but also on head-mounted displays may illustrate that the guidelines are applicable to a wide range of authoring tools.

> *"I think the next step would be to test other authoring tools, especially those that allow authoring in virtual reality. We tested a tool mainly for 2D editing during this experiment, perhaps immersed in virtual reality we will have other insights that we have not noticed yet."* - P6

This leads to a discussion of the consequences of not being able to utilize head-mounted displays during the current experiment. Even though they knew what the immersiveness guidelines meant, all of the participants reported that it was difficult for them to evaluate the tool based on these guidelines. If everyone had tested the tool in virtual reality, their responses about Immersive authoring, Immersive feedback, Movement freedom, and Metaphors would be different. Nonetheless, the majority of them took this into account when answering the questions. Figure 6 demonstrates that these recommendations earned low scores.

All participants were aware that, in the context of the experiment, the example use case Omniverse lacked immersive elements, which resulted in a lower score. This demonstrates the effectiveness of the guidelines for the evaluation of existing VR authoring tools. In addition, even though the intuitive creation of virtual reality experiences is the final objective of the design guidelines, a significant portion of this creative process consists of developing the virtual world on 2D screens. Yet, the literature review indicates that the incorporation of virtual reality devices throughout the creation of the experience makes the process more intuitive and straightforward to implement, since the author will have the same experience as their audience along the way.

> *"Although not having had the experience of immersion in VR, it was not difficult to judge Omniverse in compliance with the guidelines. However, I disagreed with the existence of the guidelines related to immersion because I did not live the experience and hence did not recognize it in comparison to what I saw in Omniverse."* - P5

#### 3.3.5. Further considerations

Throughout the experiment, the Internet connection, the configuration of the virtual machine, and the execution of some software operations presented technical issues or took too long for certain participants. The participants were asked if these concerns affected their overall impressions of the experiment. Three participants claimed that they did not encounter any technical issues or that the issues were minor and had no effect on their performance during the experiment. Two more participants reported relevant issues during the experiment, but they did not believe they were related to the program's adherence to the guidelines. Instead, they believed the difficulties were due to their own circumstances. For instance, P4's poor internet connection made the access to the virtual machine unstable and impacted the video call communication with the interviewers.

On the other hand, P6 mentioned a delay in the software's response to his actions, such as zooming in and out and updating reflections and shadows when adding objects to the scene, which we believe may have affected his perceptions of the Real-time feedback guideline, although he did not specifically mention this connection.

> *"As I created various reflective elements, such as the fountain with water, there were some issues with the application. The tool would occasionally freeze and go for a while without responding; other times, it would stop responding and close, causing me to lose all of my work."* - P6

Only one participant made the connection between the technical issues and their perceptions of the guidelines. P3 had problems installing the virtual machine to access the Omniverse, which impacted his analysis of the Democratization guideline. For him, this meant that LaunchPad might not function properly on all computers, and that the instruction lacked sufficient information to assist him fix the issue. Even P1, who indicated minor difficulty with this step, stated that he "self-taught" himself how to accomplish it.

At the conclusion, the participants offered additional observations about the entire experience, from utilizing Ominiverse and reading the list of guidelines to responding to the Likert-scale questionnaire and taking part in the focus group interview. Throughout the experiment in collaborative mode, one participant missed seeing who was working with him since the tool did not display the person's name, number of coworkers in the same environment, position in the scene, or the object they were modifying at the moment. We speculate that this indirectly affected his opinion of the Sharing and collaboration guideline.

> *"When I was in collaborative mode, I did not know who was editing an object or which object was being edited; things just changed. For example, the tree's color suddenly changed, but I only knew that someone else had done it because I was also connected with them on a video call."* - P1

The participants also stated that there was little information about errors in LaunchPad and that it was difficult to determine their causes. Some of them were unable to perform simple operations such as undo (ctrl+z) but could not explain why. Before beginning the activity, the training also neglected to offer users with fundamental information about how to use the program, such as where to alter the camera speed and screen size for navigating in the scene. Such information would have increased user comfort.

### *3.4. The pipeline of using Design Guidelines for evaluating existing VR authoring tools*

Fig. 7 illustrates a pipeline containing a compilation of all the steps taken in this study to evaluate the intuitiveness of an existing VR authoring tool in accordance with the Design Science Research paradigm [17], whereas Fig. 8 illustrates how these steps are applied as a guide for anyone who wishes to replicate the experiment using different VR authoring tools.

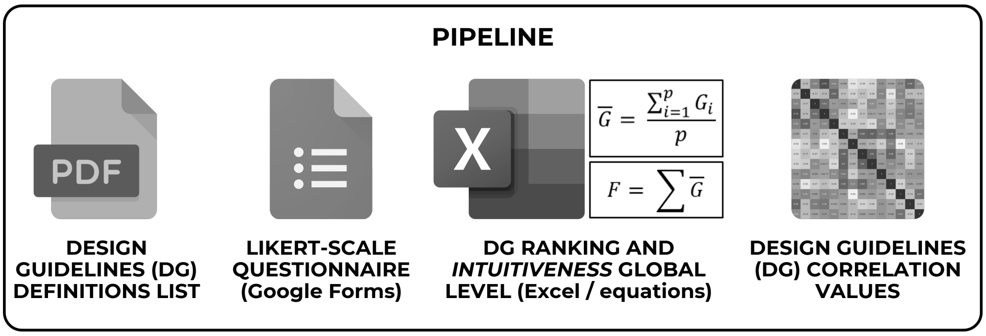



**Figure 7.** The pipeline and the elements that compose it (Supplementary Materials)

Fig. 8 illustrates the step-by-step process for evaluating the intuitiveness of an existing VR authoring tool using the design guidelines artifact. Different evaluators may use different-sized groups to test the to-be-evaluated tool; in the present study, six participants were utilized (1). The fourteen design guidelines definitions list should be distributed to the

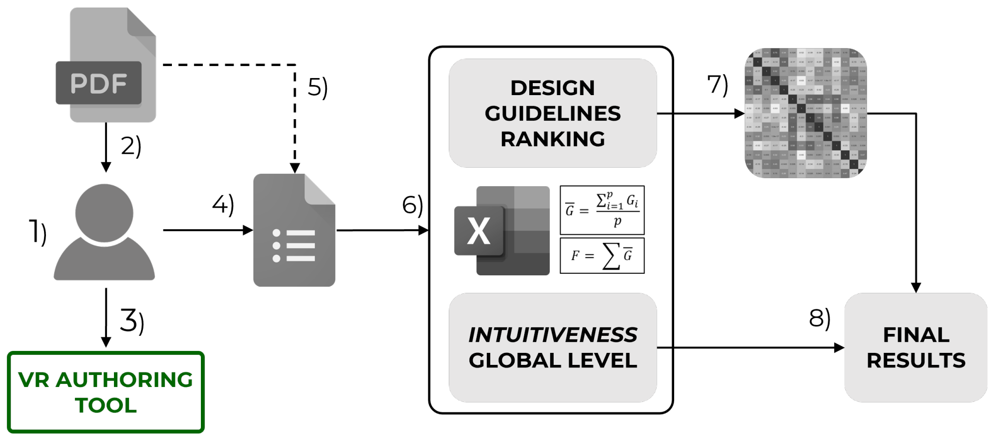



**Figure 8.** Process flow of the pipeline application

participants, as done here and described at the Sect. 2, so that they get familiar with them (2). Participants must have access to the authoring tool that will be tested and evaluated in order to complete an activity or series of tasks that demonstrate the tool's functionality (3). Hence, the Likert-Scale questionnaire can be filled independently by each participant based on their opinions of the tool's features (4). Participants must consult the design guidelines anytime they are uncertain about how to complete the questionnaire (5).

The questionnaire responses must then be analyzed so that a ranking of the scores for the design guidelines and an global level of intuitiveness may be determined. To obtain these products, he answers from the Google Forms must be exported to an Excel spreadsheet and then run through the equations in Fig. 4 (6). The scores of the guidelines that form pairs of strong positive or negative correlations with others should be highlighted, as shown in Tables 3 and 4, and compared to see if the tool exhibits expected behavior (7). The final findings of the evaluation should include the ranking, the comparison with the correlation values and the intuitiveness global level, which, when combined, should reflect the intuitiveness of the evaluated VR authoring tool (8).

As the primary objective of this study was to assess the validity of the design guidelines, we utilized the focus group interview to obtain more in-depth qualitative data on them. Future experiments utilizing different VR authoring tools do not require focus group interviews into their process flow.

## 4. Conclusions

We demonstrated how to conduct an evaluation experiment from the perspective of the design guidelines using an existing VR authoring tool, thereby analyzing the guidelines' validity as an artifact. The proposed artifact is valuable, according to Design Science Research, because the design guidelines for virtual reality authoring tools created by Chamusca et al. [15] perform what they are supposed to do and are operationally reliable in completing their goals. As a significant contribution to the field, we produced a pipeline encapsulating all of the steps taken in this study, which may be used as a guide for anyone desiring to recreate the experiment using the artifact in a different VR authoring tool.

The study concentrated on illustrating *how to* use the design guidelines rather than offering a wide range of quantitative data analysis. Despite the fact that the primary goal of the experiment was to qualitatively assess the validity of the design guidelines in evaluating existing VR authoring tools, the quantitative results showed that the exemplary use case does not have a high level of intuitiveness, receiving a score of 64%, which was supported by previous feedback from users who tested the NVIDIA Omniverse Enterprise tool [27].

The correlation analysis between the guidelines sought to determine the level of interdependence between the guidelines under review, as they did not exist in isolation in any of the VR authoring tools which has the potential to be evaluated. As a result, the correlations were employed as a cross-check indicator when analyzing the findings of the

Likert-scale questionnaire and focus group interviews. The cross-check confirmed that the majority of the guidelines scores behaved as predicted and that the ranking obtained using the Likert-scale questionnaire was consistent with the Omniverse functionalities.

The participants understood the definition of the guidelines and could correctly identify their existence during the experiment. The Likert-scale questionnaire provided a simple method of gathering participants' perspectives on which guidelines they agreed or disagreed about having found in the tool. Later in the focus group session, they were asked to reaffirm their viewpoint on which guidelines were easier or more difficult to identify. Comparing the responses, the easy-to-identify guidelines were connected with those that obtained the highest scores, and the difficult-to-identify guidelines with those that received low scores. This outcome was consistent with the profile of the group used in this experiment, which lacked technical capabilities and indicated that the participants' evaluation was carried out mostly using the practical examples supplied by the guidelines' definitions as direct references.

As a result, everything that the participants observed in the tool and was presented in the definition as a practical example acted as a motivator for a rise in score, while the opposite also occurred. Therefore , when an example was not displayed in Omniverse, the definition of the guidelines became more subjective in the participants' eyes, because it could not be viewed in an illustrated and practical manner. This is supported by the participants' statement highlighting the guidelines' weakness of not offering illustrated examples with figures.

The choice of a use case that is not particularly regarded as a VR authoring tool by its developers is a limitation of this experiment, although it is crucial to account for the lack of ontologies and taxonomies in this domain. While many programs have all of the qualities of an authoring tool, such as the IVWPs, they are not frequently declared as such. Participants' inability to experiment with creating virtual worlds using VR devices also influenced their perceptions and was a limitation of this study. The participants' profile of the group used to judge the guidelines can also be viewed as a limitation, because while the participants' lack of knowledge allows for testing how well defined the guidelines are to the point of being clear to professionals who are not in the VR area, it can also lead to feedback on subjectivity in the definition of guidelines that contains more technical terms.

The experiment's goal was to create a pipeline through a qualitative review of the steps performed during the experiment, rather than to provide robust quantitative data. Given the reduced sample of participants (six) and the fact we assessed only one authoring tool, the numerical data offered in the study can be viewed as a limitation. In any case, it should not be interpreted as an invalidation of the experiment, but rather as a chance for further research.

In terms of future research, we propose altering the group of evaluators with VR industry players, such as expert programmers and designers of virtual reality experiences, to gather additional technical input. Furthermore, we recommend experimenting with various VR authoring tools or in a context that enables the experience to be enjoyed not only on 2D screens but also on head-mounted displays. Comparing the findings of the evaluation through design guidelines with common methods for measuring usability, such as the System Usability Scale (SUS) and the After-Scenario Questionnaire (ASQ), can be used to demonstrate their efficacy as a method. The Omniverse tool can be assessed again to test if the score given for the design guidelines is restricted to the activity outlined in the LaunchPad, as well as to examine its potential for metaverse creation and industrial applications.

In the future, the guidelines' definitions could be improved by reorganizing the list format, using pictures to explain the definitions in text, and including more explanation for the technical terms. Further tests with the design guidelines are recommended in order to propose an organization of these by different weights, resulting in different relevance among the fourteen listed today in terms of intuitiveness. In addition to reinforcing Chamusca et al. [15] suggestion as future research, guidelines must be adopted to guide the development of new VR authoring tools at the start of a software project, which can also bring input for their use in the evaluation of existing ones. Furthermore, since immersive technologies will improve in terms of hardware and software, as well as product and service, the design guidelines definition and practical examples must evolve over time.

The use of design guidelines worked successfully even for guiding professionals outside the field in their initial contact with tools like Omniverse. This study revealed that the design guidelines might be effective in assisting not only the development of new intuitive VR authoring tools but also the evaluation of the intuitiveness of existing ones. As a result, the design guidelines contribute to the democratization of tools for authoring virtual worlds to be experienced in virtual reality, which has a direct impact on the creation of ontologies and the faster dissemination of technology trends such as the metaverse, as more people from various professional backgrounds become capable of creating it.

**Supplementary Materials:** The following supporting information can be downloaded at: https://bityli.com/I45G2, (1) Design Guidelines for Intuitive Virtual Reality Authoring Tools - definitions list; (2) Likert-scale questionnaire; (3) Design guidelines ranking and intuitiveness global level; (4) Focus group interview questions.

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# 5. Final considerations

We found that, in accordance with the Design Science Research, the proposed artifact is useful, i.e, the design guidelines for virtual reality authoring tools developed perform what they are designed to do and are operationally reliable in accomplishing their goals.

## 5.1 Discussions

The design guidelines might be effective in assisting not only the development of new intuitive VR authoring tools focused on authors with limited prior knowledge of 3D modeling and programming, but also to evaluate the intuitiveness in existing ones. Moreover, in accordance with the Design Science Research paradigm, an pipeline was obtained, so other VR authoring tools can be properly evaluated by using this process flow. With the evolution of immersive technologies, many of these guidelines are becoming easier to implement. However, it is also important to understand the intended audience and demand so the priority guidelines for that context can be defined. Even so, the main contribution of this research is the systematic organization and classification of widely used themes and concepts in virtual reality, since none of them were invented in this research, creating, in other words, ontologies.

In this study, six specific objectives were satisfactorily addressed. The Specific Objectives 1, 2 and 3 of this work, namely *to refine the problem research on virtual reality authoring tools*, *to define solution objectives*, and *to develop the design guidelines for intuitive virtual reality authoring tools* were addressed in the paper *Towards sustainable virtual reality: gathering design guidelines for intuitive authoring tools.* Important information related to the VR authoring tools developed in the reviewed articles are extracted, such as the artifact definition, software, and hardware tools used in the development process, as well as their plugin or standalone type classifications. In addition, important general characteristics of these tools are highlighted, such as their ability to create virtual environments, incorporating 3D models, and serve a general purpose, as they can be used to create VR experiences for a variety of fields. Key quotes were compiled from the reviewed articles that exemplified intuitiveness. As seen, it is not yet possible to evaluate or measure intuitiveness objectively, but other metrics such as usability, effectiveness, efficiency, and user satisfaction can be used to indicate a tool's intuitiveness. Such techniques were employed in the reviewed articles, indicating that the authoring tools developed were intuitive, according to qualitative interpretation of the definition of intuitiveness. Thus, it was hypothesized that by evaluating the characteristics of such intuitive tools, it would be possible to accomplish based on the fourteen design guidelines presented.

In practice, these guidelines can be used as a starting point for software developers during the project exploration phase, assisting them in defining the requirements and features of their virtual reality authoring tool. The guidelines can also be used to evaluate the intuitiveness of existing virtual reality authoring tools when applied to a research methodology as pipeline. Other findings and contributions of this study included discussions about the lack of ontologies and taxonomies related to virtual reality authoring tools and how the guidelines can aid in the development of the metaverse. It was discovered that the guidelines themselves may become ontologies and/or taxonomies, while the influence for the creation of more intuitive virtual reality authoring tools should increase the number of people capable of creating their own content to compose the virtual worlds and VR experiences of the metaverse, since non-experts would also be able to use them.

The Specific Objectives 4, *to demonstrate a proof-of-concept of the developed design guidelines*, was achieved by testing and revising the guidelines through expert reviews, with preliminary versions exposed to researchers in seminars and workshops, such as the Metaverse and Applications ISMAR 2022 workshop (CHAMUSCA et al., 2022). The Specific Objective 5, namely *to evaluate the validity of the developed design guidelines* were addressed in the article *Evaluating design guidelines for intuitive virtual reality authoring tools: a NVIDIA Omniverse's experiment*. Here, the correlation analysis confirmed that the majority of the guidelines scores behaved as expected and their ranking was coherent with the functionalities provided by the exemplary use case. The participants had good understanding about the guidelines definition and could properly recognize their presence during the experiment.

Later in the focus group session, they were asked to reaffirm their viewpoint on which guidelines were easier or more difficult to identify. Comparing the responses, the easy-to-identify guidelines were connected with those that obtained the highest scores, and the difficult-to-identify guidelines with those that received low scores. This outcome was consistent with the profile of the group used in this experiment, which lacked technical capabilities and indicated that the participants' evaluation was carried out mostly using the practical examples supplied by the guidelines' definitions as direct references. As a result, everything that the participants observed in the tool and was presented in the definition as a practical example acted as a motivator for a rise in score, while the opposite also occurred.

Also, using the guidelines as an evaluation method indicated that the exemplary use case does not present a high level of intuitiveness, receiving a score of 64%, which was indicated by previous feedback of users that tested the tool.

## 5.2 Limitations

As a limitation of this study, the design guidelines were derived from the reviewed articles, which means other guidelines may not be identified by literature search. In addition, many of the guidelines are also connected to software development principles in general, therefore, some of them could be applied to applications not related to virtual reality. Also, the categorization of the guidelines is subjective; they could be organized in different categories. Regarding the experiment, a limitation is the selection of a use case that is not particularly addressed as a VR authoring tool by their developers, although it is crucial to account for the lack of ontologies and taxonomy in this domain. Even though they feature all the properties of an authoring tool, such as the IVWPs, authoring tools are usually not declared as such.

Participants' inability to experiment with creating virtual worlds using VR devices also influenced their perceptions and was a limitation of this study. The participants' profile of the group used to judge the guidelines can also be viewed as a limitation, because while the participants' lack of knowledge allows for testing how well defined the guidelines are to the point of being clear to professionals who are not in the VR area, it can also lead to feedback on subjectivity in the definition of guidelines that contains more technical terms.

The experiment's goal was to create a pipeline through a qualitative review of the steps performed during the experiment, rather than to provide robust quantitative data. Given the reduced sample of participants (six) and the fact that only one authoring tool was assessed, the numerical data offered in the study can be viewed as a limitation. In any case, it should not be interpreted as an invalidation of the experiment, but rather as a chance for further research.

## 5.3 Future work suggestions

Concerning future research, each guideline provides the opportunity to delve deeper into the definition in a technical software development approach, even to the point of creating subclass. In addition, it is necessary to conduct actual tests in the context of application development using the guidelines in order to comprehend their impact on the project definition, which can also bring input for their use in the evaluation of existing ones. Further research may vary the organization of the group of evaluators or the used software tools, such as skilled specialists in the industry like programmers and designers of virtual reality experiences, to obtain more technical input.

In addition, future experiment authoring tools may be executed with a different purpose or in a context that allows the experience not only on 2D screens but also on head-mounted displays, or comparing the results using the evaluation through design guidelines with standard methods for measuring usability, such as the System Usability Scale (SUS) and the After-Scenario Questionnaire (ASQ). One could also experiment with the Omniverse tool in contexts such as the creation of experiences for specific industries, such as the automotive industry, to determine if the score received is limited to the activity outlined in the example use case, as well as to determine if Omniverse is suitable for use by beginners and to analyze its potential for metaverse creation and industrial applications.

Additionally, in the course of time, the design guidelines list must evolve as immersive technologies advance, both in terms of hardware and software, as well as product and service. In the future, the guidelines' definitions could be improved by reorganizing the list format, using pictures to explain the definitions in text, and including more explanation for the technical terms. Further tests with the design guidelines are recommended in order to propose an organization of these by different weights, resulting in different relevance among the fourteen listed today in terms of intuitiveness.

The use of design guidelines worked successfully even for guiding professionals outside the field in their initial contact with tools like Omniverse. This study revealed that the design guidelines might be effective in assisting not only the development of new intuitive VR authoring tools but also the evaluation of the intuitiveness of existing ones. As a result, the design guidelines contribute to the democratization of tools for authoring virtual worlds to be experienced in virtual reality, which has a direct impact on the creation of ontologies and the faster dissemination of technology trends such as the metaverse, as more people from various professional backgrounds become capable of creating it.

# A. Supplementary Materials

The following sections contains the Supplementary Materials quoted in Chapter 3 and 4.

## A.1 Towards sustainable virtual reality: gathering design guidelines for intuitive authoring tools

The sections that follow provide illustrations that demonstrate each specified design guideline:

### A.1.1 Adaptation and Commonality

- "[...] will make available Open APIs and Graphical User Interfaces to enable the integration of different artifacts from different 3D data acquisition sources" (CAPECE et al., 2019).
- "To ensure a proper multisensory delivery, the authoring tool must communicate effectively with the output devices" (COELHO et al., 2019).
- "[...] the CB is designed to be modular and flexible allowing Content Creators to configure the different stimuli modules and to deactivate a given module if required" (COELHO et al., 2019).
- "Modular architecture: To support a wide variety of interactions and different behaviors within the virtual environment, we want our system to integrate a modular architecture of different components linked into a common structure" (ZIKAS et al., 2020).
- "using semantically data from heterogeneous resources" (ZIKAS et al., 2020).
- "Authors can easily adapt existing lessons by rearranging nuggets, for example, to adapt to the prior knowledge of the audience" (HORST

et al., 2020).

- "Existing nuggets that may be implemented in another medium, such as a video or a graphic, can easily be exchanged" (HORST et al., 2020).
- "Establishing an exchange format and standardizing the concept of VR nuggets is a next step that can help to make it accessible for a greater community" (HORST et al., 2020).
- "For example, this could be done comparable to the .unitypackage format for exchanging Unity project files. With such an exchange format, a platform for VR nuggets could be built" (HORST et al., 2020).
- "Some authoring tools support multiple application fields either through the use of templates that simplify the editing procedure or through low-level editors that allow the explicit combination of assets toward the targeted application field" (VERVERIDIS et al., 2022).
- "The export format is also an important feature. The proposed tool is taking advantage of Unity3D to export in all formats, whereas all the other tools export only in WebGL" (VERVERIDIS et al., 2022).

### A.1.2 Automation

- "A neural net system can analyze this sketch and retrieve a set of matching models from a database" (GIUNCHI; JAMES; STEED, 2018).
- "The algorithm clips the mesh using each face from the mesh cutter primitive using a brute force method" (MASNADI et al., 2020).
- "The number of triangles on high polygon objects were reduced to optimize the cutting time to an order of magnitude of seconds" (MASNADI et al., 2020).
- "In other words, the interaction manager enables developers to create events that are easy to configure and are applied automatically to the characters" (NOVICK et al., 2020).
- "Another idea is to collect this data through video from a real-life scenario by monitoring the trainer and afterward processing the data

using machine learning to extract important key features and construct a template of the training scenario" (ZIKAS et al., 2020).

- "In the future, we aim to utilize computer vision to capture the trainer's movements from external cameras or directly from within the virtual environment to automatically generate interactive behaviors in VR" (ZIKAS et al., 2020).
- "The idea is to provide users with a modeling tool that intuitively uses the reality scene as a modeling reference for derivative scene reconstruction with added interactive functionalities" (IPSITA et al., 2021).
- "Recent works in artificial intelligence (AI) have used deep learning to automatically reconstruct the digital scene from 3D scans" (IPSITA et al., 2021).
- "An embodied user interaction design that supports point cloud segmentation and editing, the AI assistant that guides object retrieval and alignment, and the spatial and visual interface for functionality and logic authoring" (IPSITA et al., 2021).
- "Khurana et al. highlighted the importance and breakthroughs that AI and VR can make when combined together and concluded that by the combination of AI, the virtual world will be more than a realistic world" (IPSITA et al., 2021).
- "We also plan to consider usage of other modalities such as voice input to enhance user interaction" (IPSITA et al., 2021).
- "Amazon's Sumerian can be used for training purposes with the additional feature that exploits speech recognition and synthesis technologies from Amazon Web Services (AWS) to give intelligence to its virtual avatars" (VERVERIDIS et al., 2022).

### A.1.3 Customization

- "In this virtual space, the users have more degrees of control over the communication with others (free to explore, touch objects, and encounter users) and more types of interactions with digital objects inside a flexible virtual space" (CAPECE et al., 2019).

- "Content Creators and editors can now be fully immersed in the multisensory virtual reality experience while editing it and adjusting all necessary features, parameters and stimuli to maximize its immersiveness and sense of presence" (COELHO et al., 2019).

- "Objects have several attributes listed next to them that can be modified" (ZHANG; ONEY, 2019).

- "[...] FlowMatic, an immersive authoring tool that raises the ceiling of expressiveness by allowing programmers to specify reactive behaviors [...] that react to discrete events such as user actions, system timers, or collisions" (ZHANG; ONEY, 2020).

- "By using basic dataflow programming, these immersive authoring tools can only express a limited set of static relationships among predefined objects in a scene" (ZHANG; ONEY, 2020) - missing customization.

- "While the state-of-the-art immersive authoring tools allow users to define the behaviors of existing objects in the scene, they cannot dynamically operate on 3D objects, which means that users are not able to author scenes that can programmatically create or destroy objects, react to system events, or perform discrete actions" (ZHANG; ONEY, 2020) - missing customization.

- "These can either be included by the initial authors of IN-Tiles or defined as a parameter of the system so that laymen authors can input their own environment skin (e.g., as 360º image)" (HORST et al., 2020).

- "The system workflow design of VRFromX that enables creation of interactive VR scenes [...] establishing functionalities and logical connections among virtual contents" (IPSITA et al., 2021).

- "[...] teams of three colocated participants are given flexible visualization authoring tools to allow a great deal of control in how they structure their shared workspace" (LEE et al., 2020).

- "Some requests were [...] more freedom to change the parameters of the experience, i.e., to right click on 3D models and change the parameters of the assets on the fly" (VERVERIDIS et al., 2022).

### A.1.4 Democratization

- "The purpose is a multi-user collaboration platform for the web browser adaptable to a wide variety of cases and purposes" (CAPECE et al., 2019).
- "[...] the synchronization of the 3D scene among the clients takes place in real-time, minimizing latency as much as possible" (CAPECE et al., 2019).
- "VAIF is a Unity asset that is publicly available on GitHub and includes resources such as a user guide, tutorial videos published on YouTube, and a README" (NOVICK et al., 2020).
- "Other developers may want to create new characters, and we encourage users of VAIF to contribute their characters to the library" (NOVICK et al., 2020).
- "[...] the advances of WebVR have also given rise to libraries and frameworks such as Three.js and A-FRAME, which enable developers to build VR scenes as web applications that can be loaded by web browsers" (ZHANG; ONEY, 2020).
- "FlowMatic is open source and publicly available for other researchers to build on and evaluate" (ZHANG; ONEY, 2020).
- "These stores also support the distribution of applications/plug-ins free of charge" (HORST et al., 2020).
- "[...] democratization is focused on providing people with access to technical expertise (application development) via a radically simplified experience and without requiring extensive and costly training" (VERVERIDIS et al., 2022).
- "Citizen access" (for example, citizen data scientists, citizen integrators), as well as the evolution of citizen development and no-code models, are examples of democratization" (VERVERIDIS et al., 2022).
- "Through 2023, Gartner expects four key aspects of the democratization trend to accelerate. "One of them is the "democratization of development" (AI tools to leverage in custom-developed applications)" (VERVERIDIS et al., 2022).

- "VR hardware and firmware democratization has been already achieved by the recent cost drops of equipment and the availability of open source libraries (Kuntz et al. 2018). [...] The State-of-the-Art (SoA) methods so far have achieved this democratization by compromising quality through web-based technologies" (VERVERIDIS et al., 2022).

### A.1.5 Metaphors

- "Sketching represents a natural way for people to convey information" (GIUNCHI; JAMES; STEED, 2018).
- "[...] various types of haptic feedback, such as thermal, vibrotactile, and airflow, are included; each was presented with a 2D iconic pattern. According to the type of haptic feedback, different properties, such as the intensity and frequency of the vibrotactile feedback, and the direction of the airflow feedback, are considered" (CHAN et al., 2019).
- "[...] enables users to reach out, grab, and manipulate objects just as they would in real life" (CAPECE et al., 2019).
- "For example, one could imagine a "breadboard" metaphor where users can see their dataflow program on a 2D plane but they can connect the output of their dataflow diagrams to objects in the virtual world" (ZHANG; ONEY, 2019).
- "They can draw edges to and from these abstract models to specify dependencies and behaviors (for example, to specify the dynamics of where it should appear in the scene when it shows up)" (ZHANG; ONEY, 2020).
- "We iterated our design to directly manipulate objects in VR by matching the direct manipulations that people perform physically in real life and preliminary feedback we gathered from user tryouts" (ZHANG; ONEY, 2020).
- "Similar to Alice in Wonderland, the users will gradually shrink as they trigger the entry procedure. Authors can access the world in miniature model and experience it in full scale to make changes to the content" (HORST et al., 2020).

- "To facilitate the selection tiles, we used hologram overlays to give insights on the content it provides" (HORST et al., 2020).
- "They could relate the virtual interactions to real world interactions" (IPSITA et al., 2021).
- "We adapt 3D UI interaction metaphors for data visualization authoring and manipulation: grasping techniques involving direct contact with UI elements at close range, and ranged pointing techniques involving distant interaction with UI elements using a laser pointer" (LEE et al., 2020).
- "[...] our participants generally saw no benefit in using the table in its current state, as it adds an unnecessary constraint (e.g. height in space) in an environment where visualizations can be placed anywhere" (LEE et al., 2020).
- "Compared to the logic used in the construction of interactions, the task construction uses generic activities which should be also clear to novices without a technical background, since they are comparable to actions in the real world" (YIGITBAS et al., 2021).

### A.1.6 Movement Freedom

- "Critically these methods have generally used 2D sketches. Our system allows the user to sketch in 3D" (GIUNCHI; JAMES; STEED, 2018).
- "In this virtual space, the users have more degrees of control over the communication with others (free to explore, touch objects, and encounter users) and more types of interactions with digital objects inside a flexible virtual space" (CAPECE et al., 2019).
- "One reason is that through direct manipulation users can feel more immersed—as if the wire is in their hands" (ZHANG; ONEY, 2019).
- "To cope with this challenge, we propose a 2D map-like dataflow representation design, where users can zoom in, zoom out, and move the whole diagram without changing their positions in the world" (ZHANG; ONEY, 2019).

- “The authors can arrange the VR nugget widgets freely within the space of the assembly room” (HORST et al., 2020).
- “A brush tool was developed which enables users to select regions on point cloud or sketch in mid-air in a free-form manner” (IPSITA et al., 2021).
- “Users can also perform simple hand gestures to grab and alter the position, orientation and scale of the virtual models based on their requirements” (IPSITA et al., 2021).
- “FIESTA allows users to freely position authoring interfaces and visualization artifacts anywhere in the virtual environment” (LEE et al., 2020).
- “[...] we aim to understand how larger groups perform collaborative immersive analytics tasks in an unconstrained immersive environment, whereby users can move freely and are not restricted to tabletops or large displays” (LEE et al., 2020).
- “We saw no instances of participants orbiting around 3D visualizations when working independently, instead rotating them on the spot by clutching” (LEE et al., 2020).

### A.1.7 Optimization and Diversity Balance

- “[...] we avoided to include complex functionalities during sketch phase to study the effectiveness of pure sketch interaction” (GIUNCHI; JAMES; STEED, 2018).
- “[...] this work suggests to implement interactions that can be easily extendable by combining them or attaching them to one or more objects” (MASNADI et al., 2020).
- “FRP fits within the dataflow model but also provides more expressive functionality, such as the abstractions of event streams” (ZHANG; ONEY, 2020).
- “To make our system more efficient, we have to limit the capabilities of the Action entity targeting simple but commonly used tasks in training” (ZIKAS et al., 2020).

- “[...] cognitive applications lack of realism, but they offer intuitive and easy to follow mechanics” (ZIKAS et al., 2020).
- “[...] a nugget system is restricted to only have one nugget in an active state to simplify their usage for laymen” (HORST et al., 2020).
- “[...] we choose an approach that balances user interaction with AI automation” (IPSITA et al., 2021).
- “Although the evaluators were partially satisfied from the features available, they suggested that the number of features should significantly increase” (VERVERIDIS et al., 2022) - missing optimization.
- “A complex interaction is an interaction that can not always be performed by the VR user. Consequently, conditions are applied to the construction of interactions. To not overload the interface, a button is added to the interaction interface [...] to open a wizard that performs the construction of the complex interaction” (YIGITBAS et al., 2021).
- “The construction uses two dialogs to create the task and the activities so that the novice only needs to focus on the current task or activity” (YIGITBAS et al., 2021).
- “We decreased further the complexity by using wizards to focus the user on smaller steps in the development” (YIGITBAS et al., 2021).

### A.1.8 Documentation and Tutorials

- “For each step, instructions are visualized as text in the menu to help participants remember which step they are performing” (MASNADI et al., 2020).
- “We believe that more visual aid in the form of animations showing the movement path can help ease the thinking process of participants” (MASNADI et al., 2020).
- “[...] one novice participant had a hard time knowing how to start building conversations. The user guide does cover this, and the participant later found it” (NOVICK et al., 2020).

- “[...] a participant had trouble with animations and audio files because the participant kept trying to do things on her own instead of following the user’s guide” (NOVICK et al., 2020).
- “Documentation would be another interesting direction in the future, as two participants said they preferred A-FRAME in the sense that the APIs documentation was detailed and easy to understand” (ZHANG; ONEY, 2020).
- “we aim to include a holographic guidance during the VR training scenarios to enhance all Actions with visual information on how to complete each step” (ZIKAS et al., 2020).
- “[...] the contextual helping mechanisms of the tool were not efficient. Further developments toward this direction should be done [...]” (VERVERIDIS et al., 2022).
- “As regards help messages, some participants point out that they have not seen such messages even though tool tips and help buttons have been added” (VERVERIDIS et al., 2022).
- “Error messages are something that were not foreseen in the development as it was believed that error messages with technical details may not be helpful to users. This was proven wrong, and it should be fixed in the future with a mechanism that prompts suggestions on how to fix certain problems” (VERVERIDIS et al., 2022).
- “Since novices usually prefer to learn by exploring or trial and error mechanism, VREUD provides rapid construction and execution that enables the novices to prototype the developed interactive VR scene at each step in the development” (YIGITBAS et al., 2021).
- “In wizard-based development, the user is guided through the development process with a wizard. This requires that the performed task can be split into smaller steps. As a consequence, the user is focused on one step instead of all steps at the same time” (YIGITBAS et al., 2021).

### A.1.9 Immersive Authoring

- “[...] users remain immersed within the environment without relying on textual queries or 2D projections which can disconnect the user from the environment” (GIUNCHI; JAMES; STEED, 2018).

- “[...] expedites the process of creating immersive multisensory content, with real-time calibration of the stimuli, creating a "what you see is what you get (WYSWYG)"experience” (COELHO et al., 2019).
- “Content Creator could have a real feel of the immersive experience being created instead of imagining the VE in a desktop interface” (COELHO et al., 2019).
- “Content Creators and editors can now be fully immersed in the multisensory virtual reality experience while editing it and adjusting all necessary features, parameters and stimuli to maximize its immersiveness and sense of presence” (COELHO et al., 2019).
- “[...] immersive authoring tools can leverage our natural spatial reasoning capabilities” (ZHANG; ONEY, 2019).
- “Previous work has thus explored immersive modeling for building 3D models directly in the immersive virtual environment by proposing intuitive interaction techniques that can leverage users’ spatial reasoning skills” (ZHANG; ONEY, 2020).
- “With the lack of additional spatial information and the disconnection between developing environments (2D displays) and testing environments (3D worlds), users have to mentally translate between 3D objects and their 2D projections and predict how their code will execute in VR” (ZHANG; ONEY, 2020) - (missing immersive authoring).
- “[...] with A-FRAME they had to do “context switch” or “switching back and forth” between the HMD and the IDE. They also preferred FlowMatic for being easier and more convenient, since “everything is in VR”” (ZHANG; ONEY, 2020).
- “With VR editor, users are no longer just observers, they can modify the training scenarios on-the-go, implement new Ideas and fix wrong Action behaviors without specialized programming knowledge” (ZIKAS et al., 2020).
- “Immersive authoring technologies can be utilized for seamlessly supporting a WYSIWYG (what you see is what you get) authoring approach” (HORST et al., 2020).

- “It allows VR authoring without the need to step outside a virtual environment during the content creation process” (HORST et al., 2020).
- “[...] specific authoring actions of the application were not suitable to be performed in VR, such as entering text or connecting VR nuggets to more complex structures” (HORST et al., 2020) - (missing immersive authoring).
- “We presume that it may be beneficial to use both desktop and immersive technologies within the VR nugget authoring workflow” (HORST et al., 2020).
- “In VRFromX, we designed a system for users to interact with scanned point cloud in an embodied manner inside a virtual environment” (IPSITA et al., 2021).
- “The results show that immersive authoring benefits the authoring of VR, however, the current natural interactions in VR lack the accuracy of a desktop solution” (YIGITBAS et al., 2021) - (missing immersive authoring).
- “Head Mounted Display (HMD) is required to construct the scene and long developing sessions are tiring for the user” (YIGITBAS et al., 2021).

### A.1.10 Immersive Feedback

- “Rendering haptic feedback in virtual reality is a common approach to enhancing the immersion of virtual reality content” (CHAN et al., 2019).
- “[...] various types of haptic feedback, such as thermal, vibrotactile, and airflow, are included; each was presented with a 2D iconic pattern. According to the type of haptic feedback, different properties, such as the intensity and frequency of the vibrotactile feedback, and the direction of the airflow feedback, are considered” (CHAN et al., 2019).
- “VR is based upon two principal concepts: Presence and Immersion. Presence can be viewed as a state of consciousness based on the sense of being in the VE; Immersion is more related to the technological aspect of the VR system and the extent to which the technology is

capable of isolating the user from the real world, deceiving their sensations and engaging users with the VE" (COELHO et al., 2019).

- "[...] main goal of having a collaborative multisensory VR authoring tool that supports various stimuli: sound, haptic feedback and smell" (COELHO et al., 2019).
- "The Authoring Tools are designed for Content Creators to create multisensory VR experiences through a GUI that allows adding and configuring the different stimuli that make up the final multisensory VR experience with the possibility of previewing the experience "in-loco"" (COELHO et al., 2019).
- "The use of multisensory support is justified by the fact that the more the senses engaged in a VR application, the better and more effective is the experience" (COELHO et al., 2019).
- "Each avatar can be viewed as a node and by drawing edges between the avatar and other virtual object in the scene, users can create interactive scenes where the attributes of the virtual objects will depend on the the user's tracked devices (i.e. the headset and the controllers)" (ZHANG; ONEY, 2019).
- "The mesh cutters and the interactions to add affordances could be invoked from a menu attached to the left hand controller with the non-dominant hand" (MASNADI et al., 2020).
- "The user interface involved the use of menu buttons fixed to the left controller and placing points to define four different operations" (MASNADI et al., 2020).

### A.1.11 Real-time Feedback

- "[...] the synchronization of the 3D scene among the clients takes place in real-time, minimizing latency as much as possible" (CAPECE et al., 2019).
- "[...] expedites the process of creating immersive multisensory content, with real-time calibration of the stimuli" (COELHO et al., 2019).
- "Different virtual elements can be edited simultaneously in real-time by different Content Creators" (COELHO et al., 2019).

- “[...] the way Content Creators typically produce multisensory content is through the code. This way of creating multisensory content does not give real-time feedback to the Content Creator and additionally requires more iteration” (COELHO et al., 2019).
- “[...] immersive authoring environments allow users to evaluate their code as they write it in the VR environment” (ZHANG; ONEY, 2019).
- “AffordIt! offers an intuitive solution that allows a user to select a region of interest for the mesh cutter tool, assign an intrinsic behavior and view an animation preview of their work” (MASNADI et al., 2020).
- “We believe that more visual aid in the form of animations showing the movement path can help ease the thinking process of participants” (MASNADI et al., 2020).
- “Programmers manipulate programming primitives through direct manipulation and get immediate feedback on their program’s state and output” (ZHANG; ONEY, 2020).
- “Although users enjoy liveness (where they can see the output immediately after they write part of the program), prior work has found that they prefer having a button that allows them to switch between running and editing the program” (ZHANG; ONEY, 2020).
- “Another participant also mentioned that the liveness gave her “more sense of accomplishment” (ZHANG; ONEY, 2020).
- “[...] real-time compilation process may cause performance issues in complex training scenarios and delay the initialization of scenegraph” (ZIKAS et al., 2020).
- “A preview of the editing and preview rooms is displayed in the assembly room as a world in miniature. It is updated during run-time to realize the WYSIWYG paradigm” (HORST et al., 2020).
- “The novices are supported in the construction by visualizing the interactive VR scene in the development. This ensures direct feedback of added entities to the scene and modified representative parameters of the entities inside the scene. This enables the novice to spot mistakes immediately” (YIGITBAS et al., 2021).

### A.1.12 Reutilization

- "We propose that by utilizing recent advances in virtual reality and by providing a guided experience, a user will more easily be able to retrieve relevant items from a collection of objects" (GIUNCHI; JAMES; STEED, 2018).
- "Choosing one or more agent models from VAIF's character gallery. If needed, developers can use tools outside VAIF, such as Fuse and Mixamo from Adobe, to create characters that can be used in VAIF" (NOVICK et al., 2020).
- "[...] we propose intuitive interaction mechanisms for controlling programming primitives, abstracting and re-using behaviors" (ZHANG; ONEY, 2020).
- "FlowMatic allows users to import both primitive models (e.g. cubes, spheres) and models from Sketchfab2, a popular library of 3D models" (ZHANG; ONEY, 2020).
- "Users can also save the abstraction in the toolbox for future use by pressing a button on the controller" (ZHANG; ONEY, 2020).
- "VR software design patterns: We aim to support a large number of interactive behaviors in VR applications to promote new software patterns specially formulated to speed up content creation in VR" (ZIKAS et al., 2020).
- "Action prototypes: We designed reusable prototypes based on VR software design patterns to transfer behaviors from the real to the virtual world" (ZIKAS et al., 2020).
- "[...] in the case of the show and tell VR nugget, authors can replace the main object with their own choice, alter the number of callouts, or change the text on the labels" (HORST et al., 2020).
- "VR nugget stores could be inspired by the 'asset store' for Unity plugins or the app store for mobile apps. These stores also support the distribution of applications/plug-ins free of charge" (HORST et al., 2020).

- “Using the segmented point cloud as the input query, AI algorithms assist user in retrieving corresponding 3D models” (IPSITA et al., 2021).
- “Another important feature is the support of templates that modify the capabilities of the authoring interface and the resulting experience” (VERVERIDIS et al., 2022).

### A.1.13 Sharing and Collaboration

- “The immersive collaborative virtual environment is developing as a convergence of research interests from VR and computer-supported cooperative work communities with its capacity to offer high-level multi-sensory immersion for local and remote networked users” (CAPECE et al., 2019).
- “[...] directly transmitted to others, and they can observe the doings of others in real-time. The users work together on a virtual scene where they can add, remove, and update 3D models” (CAPECE et al., 2019).
- “[...] it is of utmost importance to develop mechanisms that allow for the expeditious creation of multisensory VR experiences in a collaborative manner” (COELHO et al., 2019).
- “This is useful because multisensory VR experiences might require multiple features that are produced by different professionals, and a collaborative feature will enable to the entire team to work simultaneously” (COELHO et al., 2019).
- “Different virtual elements can be edited simultaneously in real-time by different Content Creators” (COELHO et al., 2019).
- “Outside of tightly-coupled collaboration, participants followed social protocols and did not interact with visualizations that did not belong to them even if outside of its owner’s personal workspace” (LEE et al., 2020).
- “Scott et al. observed participants working together on a physical tabletop and identified three types of territories which were implicitly created: personal, shared, and storage territories. These territories

are dynamic, changing depending on the needs of the activity" (LEE et al., 2020).

- "Users see each other as virtual avatars aligned to their real-world positions (LEE et al., 2020).
- "Each user is uniquely identified by a floating nameplate and avatar color. The same color is also used for shared brush selections. This allows users to see the actions of others to support collaborative tasks and information sharing, as well as to avoid physical collisions" (LEE et al., 2020).
- "They explored a data set, authored visualizations, discovered insights, organized visualizations in the space around them, and presented their findings to others — doing so both independently and collaboratively through mixed-focus collaboration depending on the given context" (LEE et al., 2020).

#### A.1.14 Visual Programming

- "FlowMatic uses novel visual representations to allow these primitives to be represented directly in VR" (ZHANG; ONEY, 2020).
- "FlowMatic builds on prior work by integrating concepts from FRP and providing a rich set of programming primitives and intuitive interactions suitable for programmatically creating/destroying objects, defining reactive behaviors, and reducing complexity by abstracting operations" (ZHANG; ONEY, 2020).
- "Unreal Blueprint, a mainstream platform for developing 3D applications, also uses event graphs and function calls to assist novices in programming interactive behaviors related to system events" (ZHANG; ONEY, 2020).
- "The dataflow model is represented by a directed graph, consisting of data sources, data sinks and nodes. The nodes are primitive operations such as arithmetic and comparison operations. The direction of each edge represents the direction of the data propagation across different nodes" (ZHANG; ONEY, 2020).

- "[...] basic dataflow programming has several weaknesses of expressiveness such as visual cluttering when scaling to complex dataflow graphs with lots of nodes and edges, and lack of support" (ZHANG; ONEY, 2020).

- "In this project, we propose a visual scripting system capable of generating VR training scenarios following a modular Rapid Prototyping architecture" (ZIKAS et al., 2020).

- "[...] two categories according to their visual appearance and basic functionalities: a) block-based and b) node-based scripting languages" (ZIKAS et al., 2020).

- "On the other hand, node-based visual languages represent structures and dataflow using logical nodes to reflect a visual overview of dataflow" (ZIKAS et al., 2020).

- "Visual scripting encapsulates all the functionalities from the base model while offering high visualization capabilities" (ZIKAS et al., 2020).

- "The development of a visual scripting system as an assistive tool aimed to visualize the VR training scenario in a convenient way, if possible fit everything into one window. The simplicity of this tool was carefully measured to provide tools used also from non-programmers. From the beginning of the project, one of the main design principles was to strategically abstract the software building blocks into basic elements" (ZIKAS et al., 2020).

## A.2 Evaluating design guidelines for intuitive virtual reality authoring tools

The sections that follow provide the Likert-scale questionnaire, the results obtained with questionnaire's answers and the Focus group interview questions:

### A.2.1 Likert-scale questionnaire

# VR authoring tool experience - Likert-scale questionnaire

E-mail *

Name: *

Through your experience with the authoring tool, does it presented the guideline "Adaptation and commonality"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Automation"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Customization"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Documentation and tutorials"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Immersive authoring"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Immersive feedback"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Metaphors"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Movement freedom"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Optimization and diversity balance"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Democratization"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Real-time feedback"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Reutilization"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Sharing and collaboration"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Through your experience with the authoring tool, does it presented the guideline "Visual programming"?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Totaly disagree | ○ | ○ | ○ | ○ | ○ | Totaly agree |

Place here commentaries and observations done through the execution of the experiment, which may include system errors, challenges and interesting functions:

### A.2.2 Design guidelines ranking and intuitiveness global level

The Figure below shows how the guidelines ranking scores and the intuitiveness global level related to the Omniverse evaluation were obtained. The equations described in Figure 4 were used on the Excel spreadsheet to calculate these values.

Figura A.1: Excel spreadsheet table with the values exported from the Likert-scale questionnaire about NVIDIA Omniverse evaluation

**DESIGN GUIDELINES ($G_i$)**

**PARTICIPANTS OF THE EXPERIMENT ($p$)**

| Px | DG1 | DG2 | DG3 | DG4 | DG5 | DG6 | DG7 | DG8 | DG9 | DG10 | DG11 | DG12 | DG13 | DG14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P1 | 3 | 4 | 5 | 1 | 4 | 2 | 1 | 4 | 1 | 4 | 5 | 3 | 4 | 1 |
| P2 | 4 | 2 | 5 | 4 | 5 | 3 | 1 | 3 | 3 | 2 | 1 | 5 | 3 | 4 |
| P3 | 5 | 4 | 4 | 2 | 3 | 4 | 2 | 3 | 2 | 5 | 5 | 5 | 5 | 1 |
| P4 | 4 | 1 | 3 | 1 | 4 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 5 | 1 |
| P5 | 3 | 4 | 4 | 3 | 5 | 3 | 3 | 4 | 2 | 4 | 4 | 4 | 5 | 1 |
| P6 | 4 | 1 | 5 | 1 | 5 | 2 | 2 | 4 | 1 | 5 | 4 | 5 | 5 | 1 |
| $\overline{G}$ | 4 | 3 | 4,5 | 1,5 | 4,5 | 2,5 | 1,5 | 3,5 | 1,5 | 4 | 4 | 4,5 | 5 | 1 |
| $F$ | 45 | | | | | | | | | | | | | |

### A.2.3 Focus group interview questions

For the focus group interview, eighteen questions were made to the participants:

1. Which were your biggest difficulties during the experiment with Omniverse?
2. In your opinion, which were the most easy-to-use features in Omniverse?
3. Did you already use any tool similar to Omniverse before?
4. How was the process of answering the Likert-scale questionnaire?

5. Which process did you use to identify the guidelines in Omniverse during the experiment?
6. Which guidelines were the most easy to find in Omniverse?
7. Which guidelines were the most difficult to find in Omniverse?
8. In your opinion, which were the strengths of the design guidelines that should be maintained?
9. In your opinion, which were the weaknesses of the design guidelines that should be improved?
10. Do you think the fact that we were unable to use the virtual reality devices in the experiment affected your opinion about the guidelines? How?
11. In your perception, are there other design guidelines to VR authoring tools that are not covered in the list?
12. In your perception, do the guidelines have different weights concerning intuitiveness?
13. Are the design guidelines self-explanatory?
14. Would you use the guidelines to evaluate other similar tools?
15. Would you propose any changes concerning the guidelines organization?
16. Which future research and next steps concerning the design guidelines evolution would you suggest?
17. How much do you think the technical issues influenced your impressions on the experiment?
18. Would you have additional commentaries?

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Iolanda Lima Chamusca

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