

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

Supplementary Materials

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

S1. Adaptation and Commonality

1. “[...] will make available Open APIs and Graphical User Interfaces to enable the integration of different artifacts from different 3D data acquisition sources” [34].
2. “To ensure a proper multisensory delivery, the authoring tool must communicate effectively with the output devices” [35].
3. “[...] 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” [35].
4. “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” [17].
5. “using semantically data from heterogeneous resources” [17].
6. “Authors can easily adapt existing lessons by rearranging nuggets, for example, to adapt to the prior knowledge of the audience” [39].
7. “Existing nuggets that may be implemented in another medium, such as a video or a graphic, can easily be exchanged” [39].
8. “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].
9. “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” [39].
10. “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” [41].
11. “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” [41].

S2. Automation

1. “A neural net system can analyze this sketch and retrieve a set of matching models from a database” [32].
2. “The algorithm clips the mesh using each face from the mesh cutter primitive using a brute force method” [37].

3. "The number of triangles on high polygon objects were reduced to optimize the cutting time to an order of magnitude of seconds" [37].
4. "In other words, the interaction manager enables developers to create events that are easy to configure and are applied automatically to the characters" [38].
5. "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" [17].
6. "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" [17].
7. "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].
8. "Recent works in artificial intelligence (AI) have used deep learning to automatically reconstruct the digital scene from 3D scans" [10].
9. "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" [10].
10. "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" [10].
11. "We also plan to consider usage of other modalities such as voice input to enhance user interaction" [10].
12. "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" [41].

S3. Customization

1. "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" [34].
2. "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" [35].
3. "Objects have several attributes listed next to them that can be modified" [36].
4. "[...] 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" [8].

5. "By using basic dataflow programming, these immersive authoring tools can only express a limited set of static relationships among pre-defined objects in a scene" [8] - missing customization.
6. "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.
7. "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 360° image)" [39].
8. "The system workflow design of VRFromX that enables creation of interactive VR scenes [...] establishing functionalities and logical connections among virtual contents" [7 - rev].
9. "[...] 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" [40].
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].

S4. Democratization

1. "The purpose is a multi-user collaboration platform for the web browser adaptable to a wide variety of cases and purposes" [34].
2. "[...] the synchronization of the 3D scene among the clients takes place in real-time, minimizing latency as much as possible" [34].
3. "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" [38].
4. "Other developers may want to create new characters, and we encourage users of VAIF to contribute their characters to the library" [38].
5. "[...] 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].
6. "FlowMatic is open source and publicly available for other researchers to build on and evaluate" [8].
7. "These stores also support the distribution of applications/plugin-ins free of charge" [39].
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].

9. ““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” [41].
10. “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)” [41].
11. “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” [41].

S5. Metaphors

1. “Sketching represents a natural way for people to convey information” [32].
2. “[...] 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].
3. “[...] enables users to reach out, grab, and manipulate objects just as they would in real life” [34].
4. “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” [36].
5. “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].
6. “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” [8].
7. “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].
8. “To facilitate the selection tiles, we used hologram overlays to give insights on the content it provides” [39].
9. “They could relate the virtual interactions to real world interactions” [10].
10. “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” [40].
11. “[...] 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” [40].

12. “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].

S6. Movement Freedom

1. “Critically these methods have generally used 2D sketches. Our system allows the user to sketch in 3D” [32].
2. “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” [34].
3. “One reason is that through direct manipulation users can feel more immersed—as if the wire is in their hands” [36].
4. “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” [36].
5. “The authors can arrange the VR nugget widgets freely within the space of the assembly room” [39].
6. “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].
7. “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].
8. “FIESTA allows users to freely position authoring interfaces and visualization artifacts anywhere in the virtual environment” [40].
9. “[...] 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” [40].
10. “We saw no instances of participants orbiting around 3D visualizations when working independently, instead rotating them on the spot by clutching” [40].

S7. Optimization and Diversity Balance

1. “[...] we avoided to include complex functionalities during sketch phase to study the effectiveness of pure sketch interaction” [32].
2. “[...] this work suggests to implement interactions that can be easily extendable by combining them or attaching them to one or more objects” [37].
3. “FRP fits within the dataflow model but also provides more expressive functionality, such as the abstractions of event streams” [8].
4. “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].
5. “[...] cognitive applications lack of realism, but they offer intuitive and easy to follow mechanics” [17].

6. “[...] a nugget system is restricted to only have one nugget in an active state to simplify their usage for laymen” [39].
7. “[...] we choose an approach that balances user interaction with AI automation” [10].
8. “Although the evaluators were partially satisfied from the features available, they suggested that the number of features should significantly increase” [41] - missing optimization.
9. “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” [12].
10. “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].
11. “We decreased further the complexity by using wizards to focus the user on smaller steps in the development” [12].

S8. Documentation and Tutorials

1. “For each step, instructions are visualized as text in the menu to help participants remember which step they are performing” [37].
2. “We believe that more visual aid in the form of animations showing the movement path can help ease the thinking process of participants” [37].
3. “[...] 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” [38].
4. “[...] 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” [38].
5. “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].
6. “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” [17].
7. “[...] the contextual helping mechanisms of the tool were not efficient. Further developments toward this direction should be done [...]” [41].
8. “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” [41].
9. “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” [41].
10. “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” [12].

11. “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” [12].

S9. Immersive Authoring

1. “[...] users remain immersed within the environment without relying on textual queries or 2D projections which can disconnect the user from the environment” [32].
2. “[...] 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].
3. “Content Creator could have a real feel of the immersive experience being created instead of imagining the VE in a desktop interface” [35].
4. “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” [35].
5. “[...] immersive authoring tools can leverage our natural spatial reasoning capabilities” [36].
6. “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” [8].
7. “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).
8. “[...] 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”” [8].
9. “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” [17].
10. “Immersive authoring technologies can be utilized for seamlessly supporting a WYSIWYG (what you see is what you get) authoring approach” [39].
11. “It allows VR authoring without the need to step outside a virtual environment during the content creation process” [39].
12. “[...] 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” [39] - (missing immersive authoring).

13. "We presume that it may be beneficial to use both desktop and immersive technologies within the VR nugget authoring workflow" [39].
14. "In VRFromX, we designed a system for users to interact with scanned point cloud in an embodied manner inside a virtual environment" [10].
15. "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" [12] - (missing immersive authoring).
16. "Head Mounted Display (HMD) is required to construct the scene and long developing sessions are tiring for the user" [12].

S10. Immersive Feedback

1. "Rendering haptic feedback in virtual reality is a common approach to enhancing the immersion of virtual reality content" [33].
2. "[...] 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].
3. "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" [35].
4. "[...] main goal of having a collaborative multisensory VR authoring tool that supports various stimuli: sound, haptic feedback and smell" [35].
5. "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"" [35].
6. "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].
7. "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)" [36].
8. "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" [37].
9. "The user interface involved the use of menu buttons fixed to the left controller and placing points to define four different operations" [37].

S11. Real-time Feedback

1. “[...] the synchronization of the 3D scene among the clients takes place in real-time, minimizing latency as much as possible” [34].
2. “[...] expedites the process of creating immersive multisensory content, with real-time calibration of the stimuli” [35].
3. “Different virtual elements can be edited simultaneously in real-time by different Content Creators” [35].
4. “[...] 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” [35].
5. “[...] immersive authoring environments allow users to evaluate their code as they write it in the VR environment” [36].
6. “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].
7. “We believe that more visual aid in the form of animations showing the movement path can help ease the thinking process of participants” [37].
8. “Programmers manipulate programming primitives through direct manipulation and get immediate feedback on their program’s state and output” [8].
9. “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” [8].
10. “Another participant also mentioned that the liveness gave her “more sense of accomplishment”” [8].
11. “[...] real-time compilation process may cause performance issues in complex training scenarios and delay the initialization of scenegraph” [17].
12. “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” [39].
13. “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].

S12. Reutilization

1. “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].
2. “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” [38].

3. "[...] we propose intuitive interaction mechanisms for controlling programming primitives, abstracting and re-using behaviors" [8].
4. "FlowMatic allows users to import both primitive models (e.g. cubes, spheres) and models from Sketchfab2, a popular library of 3D models" [8].
5. "Users can also save the abstraction in the toolbox for future use by pressing a button on the controller" [8].
6. "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" [17].
7. "Action prototypes: We designed reusable prototypes based on VR software design patterns to transfer behaviors from the real to the virtual world" [17].
8. "[...] 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" [39].
9. "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/plugin-ins free of charge" [39].
10. "Using the segmented point cloud as the input query, AI algorithms assist user in retrieving corresponding 3D models" [10].
11. "Another important feature is the support of templates that modify the capabilities of the authoring interface and the resulting experience" [41].

S13. Sharing and Collaboration

1. "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" [34].
2. "[...] 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].
3. "[...] it is of utmost importance to develop mechanisms that allow for the expeditious creation of multisensory VR experiences in a collaborative manner" [35].
4. "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" [35].
5. "Different virtual elements can be edited simultaneously in real-time by different Content Creators" [35].
6. "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" [40].
7. "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” [40].

8. “Users see each other as virtual avatars aligned to their real-world positions [40].
9. “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].
10. “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” [40].

S14. Visual Programming

1. “FlowMatic uses novel visual representations to allow these primitives to be represented directly in VR” [8].
2. “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” [8].
3. “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].
4. “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” [8].
5. “[...] 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” [8].
6. “In this project, we propose a visual scripting system capable of generating VR training scenarios following a modular Rapid Prototyping architecture” [17].
7. “[...] two categories according to their visual appearance and basic functionalities: a) block-based and b) node-based scripting languages” [17].
8. “On the other hand, node-based visual languages represent structures and dataflow using logical nodes to reflect a visual overview of dataflow” [17].
9. “Visual scripting encapsulates all the functionalities from the base model while offering high visualization capabilities” [17].
10. “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].

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