SHIFT

MetamorphoSis of cultural Heritage
Into augmented hypermedia assets
For enhanced accessibiliTy
and inclusion

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Document info

Document ID:	D3.4 - Accessible framework of inclusive museum exhibits for 3D digital asset perception
Version date:	31/03/2025
Total number of pages:	70
Abstract:	This deliverable presents the SHIFT Extended Reality (XR) Accessibility Framework, developed in the context of T3.5. The framework provides ready-to-use components and features, to enhance the accessibility of XR environments. The accessibility features of the framework have been evaluated with 20 users with visual impairments, highlighting the framework's strengths and weaknesses. A series of refinements were implemented, leading to the development of the final version of the framework. Additionally, all the technologies developed in the context of WP3, are harnessed into the framework, providing multimodal interaction and multifaceted personalized information to the end-users, considering their accessibility needs and individual characteristics. This deliverable concludes T3.5, demonstrating a comprehensive approach to inclusive and accessible XR experiences.
Keywords:	Extended Reality, Extended Reality Accessibility, Multimodal Interaction, Cultural Heritage, User-Centered Design, User-based Evaluation

Authors

Name	Organisation	Role
Katerina Valakou	FORTH	Senior RTD Engineer
George Margetis	FORTH	Postdoctoral Researcher

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

REVIEWERS

Name	Organisation	Role
Anika Spiesberger	TUM-MED	Research Assistant
Ioana Crihana	ANBPR	Reviewer
Stefania Stanica	ANBPR	Reviewer
Andreas Bienert	SMB-SPK	Researcher
Beatrice Aretz	TUM-MED	Research Assistant
Moritz Maier	DBSV	Researcher

VERSION HISTORY

Version	Description	Date
0.1	Initial deliverable structure and table of contents	13/01/2025
0.2	50% of the content	18/02/2025
0.3	80% of the content	25/02/2025
0.4	Content for refinements and additions to the framework	02/03/2025
1.0	First complete draft for internal review	10/03/2025
1.1	Version with suggested revisions	23/03/2025
2.2	Final version for submission	31/03/2025

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Executive Summary

The deliverable D3.4 presents the SHIFT Extended Reality (XR) Accessibility Framework, a comprehensive solution designed to enhance accessibility in XR applications, particularly for blind and visually impaired users. The framework follows an Accessible by Design approach, ensuring that Cultural Heritage (CH) experiences in immersive environments are inclusive and adaptable. The framework includes a wide range of customizable accessibility adaptations, such as alternative text for visual elements, hierarchical audio descriptions, interactive hotspots, 3D spatialized sound, and scene adaptations (brightness adjustment, magnification lenses, and recoloring tools). These features allow users to explore 3D digital artefacts with greater clarity and independence, supporting various interaction modalities that align with individual accessibility needs.

To assess the effectiveness of the first version of the framework, a user-based evaluation was conducted with 20 participants with visual impairments. The results demonstrated high effectiveness, with users successfully interacting with virtual museum artefacts. However, feedback identified areas for improvement, particularly in artefact findability, navigation between hotspots, and multimodal feedback clarity. Based on user feedback, multiple refinements were implemented in the final version of the framework to address these issues. Additionally, all work package (WP)3 tools were fully integrated into the framework, allowing personalized accessibility adaptations.

The SHIFT XR Accessibility Framework establishes a solution for inclusive CH experiences in XR environments. By enabling multimodal accessibility, the framework ensures that diverse users can explore and interact with 3D digital assets in an intuitive, immersive, and accessible manner. The outcomes of this work will be evaluated further in the SHIFT pilots. This deliverable concludes T3.5 *Accessible framework of inclusive museum exhibits for 3D digital asset perception*.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Contents

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

LIST OF FIGURES

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

LIST OF TABLES

Abbreviations and Acronyms

Abbreviation / Acronym	Description
alt text	Alternative Text
AR	Augmented Reality
CH	Cultural Heritage

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

DBSV	Deutscher Blinden- und Sehbehindertenverband
HMD	Head-Mounted Display
MR	Mixed Reality
NASA-TLX	NASA Task Load Index
NVDA	Non-Visual Desktop Access
SSQ	Simulator Sickness Questionnaire
TS	Total Simulator Sickness
TTS	Text-To-Speech
UAP	Unity Accessibility Plugin
UEQ	User Experience Questionnaire
UI(s)	User Interface(s)
UX	User Experience
VE	Virtual Environment
WCAG	Web Content Accessibility Guidelines
VR	Virtual Reality
XR	Extended Reality

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

1. Introduction

Extended Reality (XR) refers to the wide range of technologies along the spectrum of reality and virtuality, including Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR) technologies. It involves the fusion of virtual objects into the real world or immersive digital environments [1]. XR technologies hold a transformative potential to revolutionize the way we interact with technology and extend across various sectors [2], such as education, healthcare, and cultural heritage (CH) preservation. Recently, XR has gained recognition as a technology set to revolutionize both daily life and business practices. As XR blurs the lines between physical and digital realms, its significance in shaping the future of human-computer interaction becomes increasingly more prominent. Despite the uptake of XR technologies by the general public, they impose serious interaction challenges for persons with disabilities. The current rapidly evolving technological landscape raises the imperative to address accessibility challenges to ensure that these advancements are accessible by design to all individuals. Accessibility by design is a fundamental principle that emphasizes the proactive integration of accessibility features into the core design and development processes of technological innovations, aligned with the notions of Universal Access and Design for All [3]. While the importance of creating inclusive XR environments is widely acknowledged, the path to achieving this goal remains intricate. At the same time, there is a growing recognition that different categories of disabilities require different approaches to address their specific accessibility issues.

This deliverable introduces the first and final version of the SHIFT XR Accessibility Framework. The developed framework provides multiple ready-to-use software tools enhancing accessibility adaptations in XR applications, following the 'Accessible by Design' approach. It aims to simplify the process of adjusting accessibility settings, tailored to the user's accessibility needs, without burdening developers with multiple disparate tools. Focusing on supporting the development of accessible XR applications for blind, partially sighted users, and people with visual impairments in general, the framework offers customizable text settings, alternative text for visual elements, audio description of the visual objects, integration of hotspots, and multiple controlling mechanisms for user interaction. It also includes features such as edge enhancement for 3D artefacts, hierarchical navigation within the XR environment, foreground positioning of active objects, and scene adaptations like brightness adjustment, magnified lenses, and recoloring tools to cater to specific visual needs. To explore the effectiveness of the accessibility features of the first version of the framework, and to identify any limitations, a user-based evaluation was conducted. The evaluation involved 20 participants with vision impairments who provided feedback on the framework's effectiveness, evaluating how well it met their accessibility needs, and the overall usability regarding the ease of navigation and interaction within the VR museum application. Additionally, the mental workload and the VR-induced discomfort were measured in order to ensure that the system provides a comfortable and enjoyable experience. The results of the evaluation indicated that the integration of the framework into a VR application

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

significantly enhanced the exploration of the VR environment for users with vision impairments. However, multiple refinements were necessary to address the challenges and limitations identified through user feedback.

In response to these findings, several refinements were made to enhance artefact findability, improve navigation, and provide clearer multimodal guidance. A method for locating the artefacts within the virtual environment (VE) was developed, offering precise positioning of the first interaction point with the artefact, combined with audio feedback to guide exploration. Additionally, hotspot-to-hotspot navigation was improved by integrating 3D sound, complementing the existing haptic guidance system (D3.7). To ensure a fully multimodal and adaptable experience, the framework integrates all tools developed in WP3, allowing for customized user experiences (UX) tailored to different audience needs. With dynamic text descriptions (T3.2), personalized text-to-speech narration (T3.3), and haptic exploration of digital artefacts (T3.4), the system provides adaptations for diverse user groups.

1.1 Scope and Objectives

The SHIFT XR Accessibility Framework has been developed to enhance the accessibility of XR applications, particularly for blind and visually impaired users, ensuring that CH experiences in immersive environments are inclusive and engaging. This deliverable outlines the development, evaluation, and refinements of the framework, detailing how it facilitates multimodal interactions and supports diverse user needs through a combination of haptic, auditory, and visual adaptations. The primary objective of the framework is to provide ready-to-use accessibility solutions that developers can easily integrate into XR applications without requiring extensive customization. Key functionalities include customizable text settings, alternative text for visual elements, hierarchical audio descriptions, interactive hotspots, 3D spatialized sound, and haptic feedback mechanisms. Additionally, the framework incorporates scene adaptations such as brightness adjustments, magnification lenses, and recoloring tools to support users with different levels of visual impairment. The system dynamically adapts content based on the selected user profile, ensuring that each user receives an experience tailored to their abilities and preferences. To evaluate the framework's effectiveness, a user-based evaluation was conducted with 20 participants with visual impairments, focusing on usability, task completion, cognitive workload, and overall UX. The feedback gathered from this evaluation informed a series of refinements.

The final version of the framework fully integrates tools developed within WP3, including the contemporary asset description tool (T3.2), the text-to-speech (TTS) tool (T3.3), and the haptics tool (T3.4). These integrations allow for personalized accessibility adaptations, ensuring that users can explore CH assets using a combination of text, audio, and haptic feedback. Ultimately, the SHIFT XR Accessibility Framework aims to establish a flexible, and scalable solution for inclusive CH experiences in XR environments. By enabling multimodal accessibility, the framework empowers a wide range of

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

users to engage with 3D digital assets, fostering greater inclusivity in virtual museum spaces and beyond.

1.2 Structure of the Report

The remainder of this document is organized as follows:

- Section 2 provides a review of existing literature for systems and methodologies applied to enhance accessibility in XR, specifically for visually impaired individuals.
- Section 3 describes the methodology followed for the implementation of the proposed approach for developing the SHIFT XR Accessibility Framework.
- Section 4 provides a taxonomy for the classification of accessibility solutions for XR environments.
- Sections 5, 6, and 7 explain in depth the accessibility features of the framework, the implementation, and its integration to XR applications.
- Section 8 outlines the steps taken and the outcomes obtained in evaluating the effectiveness of the first version of the framework, through a user-based evaluation.
- Section 9 explains in detail the refinements based on the insights gathered from the user-based and presents the final version of the SHIFT XR Accessibility Framework.
- Section 10 concludes the deliverables highlighting its outcomes.

2. Accessibility in Extended Reality

Accessibility in XR pertains to creating interfaces and interactions that are usable and meaningful for individuals with various abilities. Turning attention to users with visual impairments, research has demonstrated the transformative potential of XR technologies in bolstering accessibility. These technologies serve as visual aids [4], [5], offering multimodal and alternative ways for input and output [7], amplifying environmental awareness [8], and facilitating sensory substitution [23]. Novel user interaction techniques have also emerged, combining concepts such as object localization and spatial audio [9]. Although these early endeavors, the hurdles in engaging with digital content within the context of XR persist. Persons with visual impairments grapple with barriers in perceiving visual information within XR environments, including text, images, videos, and 3D objects.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

2.1 Interaction Problems in Extended Reality for people with visual impairments

Users with low vision, general visual impairments, or the blind encounter several interaction problems in XR environments. One of the main issues is the limited visual acuity of individuals with low vision which hinders their ability to perceive objects, text, and other important visual details in VEs. Specifically, small font sizes, low-contrast color schemes, or colors that are difficult to distinguish from one another, and other factors that impact legibility can create significant difficulties [5], [10]. Besides barriers to perceiving the XR environment and the information provided therein, additional barriers have been reported in terms of interaction. Users with visual impairments, are confronted with insurmountable obstacles when trying to interact with virtual elements, such as selecting menu items with a laser pointer or picking up virtual objects, due to issues in judging distance and low contrast with the background [4]. While some applications have implemented alternative interaction techniques for navigating in the application or in menus such as voice recognition, the number of such applications remains limited. In addition, applications that use screen reader or magnification software, which is widely used by people with low vision, may cause loss of content [11].

Furthermore, another category of barriers refers to the devices and input methods employed. Using traditional buttons on a motion controller to perform functions can be difficult for users who may struggle to see small visual elements or find it difficult to navigate complex menus, further limiting the accessibility of these virtual interfaces [11]. Some systems rely heavily on visual and auditory cues or facial expressions, as input methods, which can be difficult for blind people to perceive [9]. While haptic feedback can provide an additional sensory output, the current technology used for haptic feedback in VR applications may not be sufficient or accessible for people who are blind.

2.2 Accessible Extended Reality Solutions

Recent research has focused on hybrid interaction techniques that integrate multiple sensory modalities as a more robust and effective solution for visually impaired individuals in VR. These approaches, which often incorporate haptic, auditory, or motion-based feedback, aim to enhance the immersive experience for blind users and improve their ability to interact with VEs in a more natural and intuitive manner. Racing in the Dark [7] is a VR game for blind individuals that combines haptic feedback for instant decision-making and auditory feedback to provide information about the surrounding environment, with the goal of reducing cognitive workload. The game leverages the built-in haptic, tracking, auditory, and voice systems of the VR headset to provide a non-visual car racing experience for players. By exploring commercial VR interfaces to provide critical information in real-time, Racing in the Dark tackles the development challenge of providing useful information to players in time to make split-second decisions.

Funded by the European Union
This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

A method that facilitates navigation in large virtual environments (VEs) with intricate architecture involves the use of a white cane controller—an assistive device inspired by the traditional white cane used by visually impaired individuals. In the VR context, this controller mimics the physical act of tapping and sweeping, allowing users to explore the shape and layout of virtual spaces through haptic feedback. It employs a lightweight three-axis brake mechanism to convey the overall structure of virtual objects, while a voice coil actuator simulates surface textures through subtle vibrations. Spatialized audio, generated based on how sound propagates through the virtual geometry, further enhances spatial awareness and orientation within the VE [12]. Another technique involves the replacement of vision in a VR art museum, whereby audio and haptic feedback are utilized to help users navigate and locate objects of interest [13]. Audio cues are played at the location of historical figures to draw attention, while the vibration of the controller is used when the player looks in the direction of a virtual object. VR's audio cues allow visually impaired individuals to orient themselves and move towards a target without visual information. Soundspace VR, a project focused on enhancing audio-based navigation in VEs, provides diverse types of sounds to represent different objects [14]. For example, the sound of running water could indicate the presence of a river, while the sound of footsteps could indicate the presence of a walking path. By listening to the sounds, users can infer the location and distance of objects in the VE. A similar approach was VStroll, an audio-based virtual exploration tool that encourages walking among people with vision impairments by using spatial audio [15]. The system had multiple points of interest to which a short description was attached. When the user passed by any of these points, the description of the hotspot was announced. To make the user spatially aware of the location of the hotspots, these were played using binary spatial audio, such that the announcement would be audible only in left/right ear.

Visual display configuration and customization: Individuals with visual impairments benefit from tools that adjust colors, brightness, and magnification [5], [11]. In many systems, adjustments are automated and tailored to user needs. CueSee, an AR application for Head-Mounted Displays (HMDs), assists visually impaired individuals in product searches by automatically recognizing items and guiding attention with five customizable visual cues: Guideline, Spotlight, Flash, Movement, and Sunrays [16]. A study with twelve low-vision participants confirmed the effectiveness of these cues in enhancing search performance. ChromaGlasses, a wearable HMD, enhances color perception by modifying the environment in real time at the pixel level, offering a more natural viewing experience [17]. Similar techniques also support colorblind individuals by overlaying adjustments onto the real world.

Interaction techniques: In XR environments designed for individuals with visual impairments, a variety of interaction techniques are applied to support them. Many techniques have been implemented to leverage auditory cues to augment UX. AIMuseum, a Unity application that integrates technologies

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

with local museums, artworks, and exhibitions, is an example of such an approach [18]. By using AR and screen reader technology, AIMuseum projects virtual information on real environments, and QR codes link to predefined databases, facilitating access to and interaction with cultural environments. The application uses embedded screen readers to provide additional information about art pieces and 3D modeling to accurately reproduce artworks, such as a rapier. The results of a user-based study showed that the use of AIMuseum improved users' interest in artworks and their getting additional information. Participants found the interaction to be easy and relaxing, with some indicating that the screen reader helped them to focus or understand the artwork in a new way.

Many systems adopt an auto-reading strategy which is activated when users point at interactive elements within the VE. This means that users can freely move the pointer into the VE and when it hovers over an interactive element the audio description is triggered. There are applications that use the headset controllers as the pointer. An alternative technique involves a haptic glove and a set of gestures that allow for the interactive triggering of verbal object descriptions. For example, pointing with one finger towards an object triggers a general description of the object, while pointing with two adjacent fingers triggers a more detailed description. The user can also control the flow of audio feedback by performing gestures such as waving from left to right or making a fist and moving it up or down to raise or lower the speed of speech. Additionally, the gloves provide force feedback to complement the audio feedback and allow for a more holistic and accessible experience in VR.

However, a major challenge for users with visual impairments is the point-and-select paradigm, which is often ineffective for non-visual interaction. Instead, these users benefit more from sequential access to the interactive elements of a User Interface (UI). A common technique employed in this respect is scanning, which sequentially highlights and gives focus to the interactive elements of a UI [19]. When the user initiates a switch or input command, the highlighted element becomes activated, allowing for interaction. To facilitate text input within this scanning paradigm, on-screen keyboards are often integrated, offering a means of selecting characters or commands. Various scanning techniques have been developed, each presenting distinct strategies for accessing individual interactive elements within the UI.

Development Tools: Recognizing the urgent need to create accessible XR environments, researchers have proposed several tools to support accessibility by design. These tools aim to streamline and automate common development tasks, making it easier to build XR experiences that consider accessibility from the beginning. An illustrative example is the XR Interaction Toolkit [20], specifically designed to simplify the implementation process by offering preconfigured components that ensure seamless compatibility across various VR devices. Moreover, the toolkit incorporates scripts that facilitate fundamental interactions within VR environments. Gear VR Accessibility is an alternative toolkit offering developers some tools to create inclusive XR environments. Among its functionalities

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

are adaptations like zoom, inverted colors, auto-reading (screen reader), and caption features, all tailored for VR settings. This framework not only focuses on visual enhancements but also integrates features that cater to users with hearing impairments, cognitive differences, and other accessibility requirements [21]. SeeingVR is a similar approach for Unity 3D, which can be used as a plugin by developers, to enhance the visual display settings of VR applications and offers 14 distinct tools to optimize visual accessibility for individuals with low vision [5]. Despite the progress achieved, many of these efforts remain in the prototype stage within the research field, lacking integration into mainstream applications or platforms, while developers identify that they need better integration of accessibility guidelines, alongside code examples of specific accessibility features.

3. Methodology

The SHIFT XR Accessibility Framework is designed to empower developers to create inclusive and user-friendly games and applications. It enables seamless integration of accessibility features, making content accessible to a wider audience, including users with various disabilities and impairments. The foundation of our accessibility framework lies in our commitment to the following design goals and principles:

- Inclusivity: Ensure that users with diverse abilities can fully engage with the content by providing customizable options and support for assistive technologies.
- Flexibility: Offer developers a range of accessibility features that can be easily integrated into their projects while allowing for customization and extensibility.
- Modularity: Organize the framework into distinct components to enable efficient maintenance and scalability.

The methodology for developing the framework adopted the Human-Centered Design approach [22], aiming to thoroughly understand the context of use, acquire user requirements, design and develop prototypes, and evaluate them, in an iterative approach. By adhering to this approach, a solution design becomes genuinely centered around the human experience, taking into careful consideration the needs, preferences, and behaviors of users, as well as the specific context in which the system will be utilized. As a result, a high-quality UX can be achieved, tailored to the needs of the target users, fostering the intuitiveness, unobtrusiveness, adaptivity, usability, and appeal of the developed system as well as its overall acceptance by users.

Understanding and Specification of the Context of Use: The initial phase of our methodology involves comprehending the technological environment, the target users, and the accessibility challenges imposed, as well as the overall context of use. This was achieved through the analysis of the user requirements (D1.1 and expanded in D1.4), followed with a systematic literature review. The target users have been identified as people with visual impairments, including persons who are blind, with

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

low vision, or with visual impairments in general. Blindness, low vision, and general vision impairments encompass a range of visual disabilities, each with distinct characteristics and prevalence rates. The impact of vision impairment depends on how much and in what way someone's vision is impaired. Visual impairment may cause the individual difficulties with normal daily tasks including reading and walking. According to the World Health Organization (WHO), the global estimates as of 2020 indicate:

Blindness: A person is considered blind if their best-corrected visual acuity is less than 3/60 (or 20/400) in their better eye. Causes of blindness can vary, with cataracts, uncorrected refractive errors, and age-related macular degeneration being some of the leading factors. [23]

Low Vision: Low vision refers to individuals with significant visual impairment that cannot be fully corrected by conventional glasses, contact lenses, or medical treatments[1]. Conditions causing low vision include glaucoma, diabetic retinopathy, and various retinal disorders. People with low vision often require specialized aids, such as magnifiers or electronic devices, to assist with daily activities [23].

General Vision Impairments: General vision impairments include impairments that can be corrected with conventional glasses, like myopia[2]. Colorblindness is also referred to in this category based on the fact that it affects the perception of color, but not necessarily visual acuity [24]. Colorblindness, a genetic condition that primarily affects men, is estimated to impact roughly 1 in 12 men and 1 in 200 women of Northern European descent. In these individuals, specific cone cells responsible for detecting certain colors do not function correctly [23].

Based on the systematic literature review, the key interaction problems faced by persons with visual impairments when interacting with XR environments are summarized below:

- Lighting and Contrast – Brightness and darkness effects make it difficult to judge distances and contrast when interacting with virtual elements. Low-contrast backgrounds on text elements further hinder readability.
- Limited Accessibility Settings – Few options for adjusting display settings, modifying visual elements, or using alternative inputs like voice commands.
- Restricted Field of View and Content Positioning – Users require adjustments in the positioning of VE and content to accommodate limited visual perception.
- Navigation and Menu Interaction Challenges – Difficulty selecting menu items using laser pointers, navigating complex menus, and dealing with small fonts or inaccessible instructions.

[1] https://en.wikipedia.org/wiki/Visual_impairment
[2] https://www.mayoclinic.org/diseases-conditions/nearsightedness/symptoms-causes/syc-20375556

Funded by the European Union
This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

- Lack of Screen Reader and Magnification Support – Absence of proper screen reader integration, which may also cause content loss. Magnification software can interfere with navigation.
- Insufficient Haptic Feedback – Current VR haptic feedback technology does not provide adequate tactile cues for users with visual impairments.
- Absence of Natural Object Descriptions – Lack of intuitive ways to request object descriptions in VEs.
- Uncontrolled Auditory Information – No proper control over auditory cues, which can overwhelm or confuse users.
- Customization Limitations – Difficulty in modifying display settings, configuring functionalities, or adapting features to individual needs.
- Reliance on Visual Cues – Many interactions depend on facial expressions or visual feedback, making them inaccessible to blind users.

User Requirements: The foundation of the methodology was established based on the user requirements defined in D1.1 "SHIFT requirements, user evaluation guidelines, and acceptance metrics", which provided a comprehensive baseline for ensuring accessibility across SHIFT's technological solutions. These initial requirements were later expanded and refined in D1.4 "SHIFT requirements, user evaluation guidelines and acceptance metrics – final version", incorporating insights gathered through workshops and direct engagement with visually impaired users.

Design and Development: The design and development process of the framework was informed by XR accessibility guidelines reported in the literature, The XR Association[3] founded by Google, HTC Vive, Microsoft, Meta, and Sony Interactive Entertainment has produced a set of best practices for developers with an emphasis on accessible and inclusive design of immersive experiences [18]. In this respect, general guidelines for promoting inclusive design have been formulated, as well as technical guidelines. More particularly, the guidelines applicable to the design of XR for persons with visual impairments are summarized below:

General

- Deliver your narrative through multiple methods including spoken dialogue or narration, text, in-application events, etc.
- Ensure that all areas of the UI can be accessed using the same input method.
- Allow multiple input methods to be used at the same time.
- Enable the functionality to bring objects closer to the users.

[3] https://xra.org/about/

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

- Provide clear audio landmarks.
- Controller-based locomotion is imperative to providing a comfortable UX for people with physical disabilities and visual impairments and also accommodates the largest audience for your application. Start by exploring joystick locomotion, teleportation, or a combination of the two but also consider others as well.
- As much as possible, implement vibrations/haptics so they're easily distinguishable when they need to communicate different things. Use timing, duration, and intensity to create differentiation.

Visual Accessibility

- Allow users to magnify or reduce objects and text to make them larger or smaller.
- Allow users to change font type and size for more easily readable text.
- Use sans serif fonts.
- Avoid relying on the use of color to differentiate between user options and communicate important information. Allow users to recolor the interface and objects, provide shapes or symbols alongside meaningful colors, or provide textures on objects or elements to help distinguish color-based information.
- Provide customized high-contrast skins for the environment to suit luminosity and color contrast requirements.
- Support audio augmentation and text-to-speech. Using a virtual menu system - enable a self-voicing option and have each category, or item description, spoken as they receive focus via a gesture or other input.
- Support overlays to help ensure all users can read and understand the text display.
- Spatialize text about an arm's length away from the user in virtual space. If you would prefer to avoid placing your captions at a fixed distance from the user, you can explore other options like speech bubbles, placing the text above or below characters who are speaking.

Interaction Accessibility

- Allow users to map several actions to a single controller button or action to be able to complete complex multi-step actions or choices in a sequence.
- Ensure hit targets are large enough with suitable spacing around them.
- Ensure Navigation and interaction can be controlled by voice activation. Voice activation should preferably use native screen readers or voice assistants rather than external devices to eliminate the additional step needed to pair devices.
- Consider supporting hand tracking.
- Minimize the complexity of your controller scheme.

Design and development of the proposed framework was conducted iteratively, incorporating expert feedback through interim prototype versions and user-based feedback for the final framework implementation. The design phase entailed the development of mock-ups for accessible XR scenarios, to illustrate the visual UX, keeping also in mind that additional modalities addressing alternative

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

sensory channels would be integrated. Figure 1 below illustrates initial mockups of accessible XR solutions for color blind individuals, whereas Figure 2 illustrates a mockup for CH artefact with active point of interest, a solution for low vision individuals.

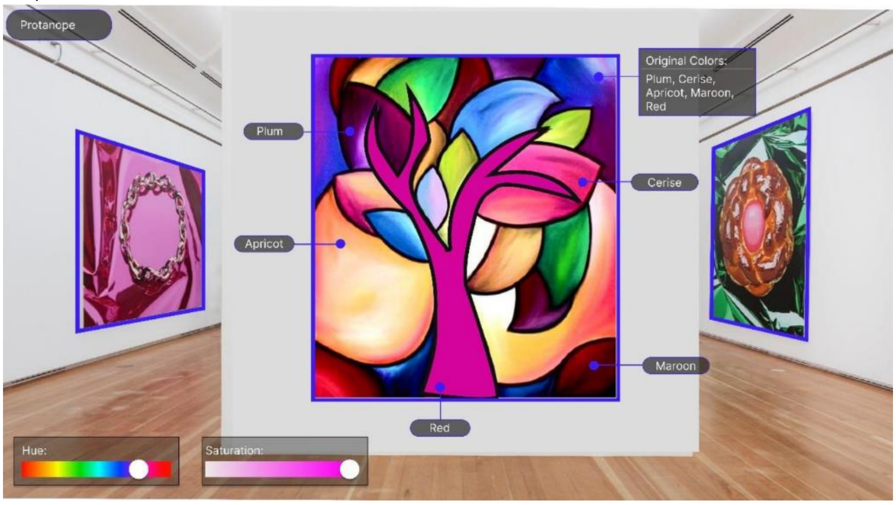

Figure 1: Mock-up for color blind users, with protanope. A colored overlay is placed over the red colors that the user can not distiquish. Points of interest are highlighted and there is a description of the original colors

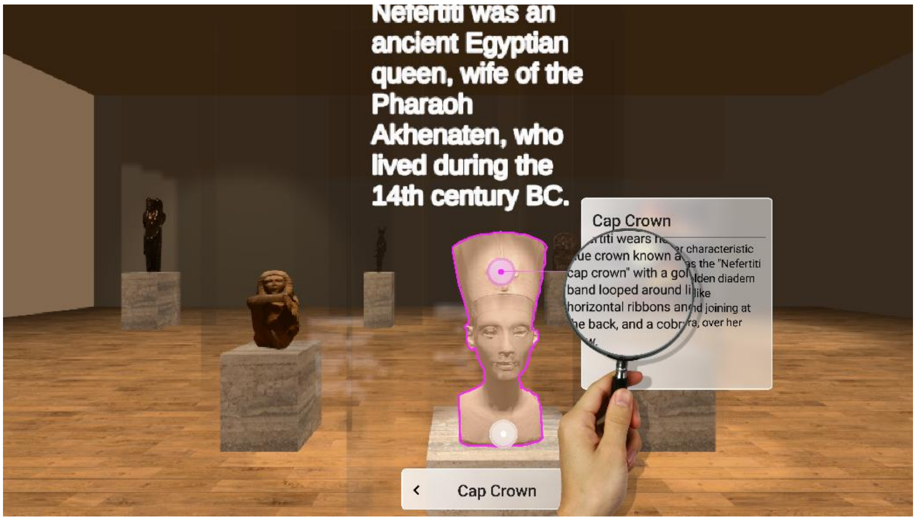

Figure 2: Mock-up for CH artefact with active hotspot

Evaluation: Evaluation plays a pivotal role in Human-Centered Design, ensuring that a prototype addresses user requirements and is suitable for the intended context of use. In the context of the XR accessibility framework, two evaluation methods were employed, namely expert-based reviews and

Funded by the European Union
This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

user-based assessments. The goal of expert-based evaluation is to identify potential usability issues before they become problems for the end user. This method can be highly cost-effective, allowing a large proportion of usability flaws to be detected ahead of full development with limited resource investment, ensuring user-friendly and inclusive results.

Two usability and one accessibility experts were involved throughout the design and development of the proposed framework. To facilitate the review, a scene from a VR museum was developed as a demonstrator of the proposed framework and its application for the development of accessible XR environments. Reviews were conducted based on well-established guidelines, including the Heuristic Guidelines, Guidelines for the Design of VR environments, as well as the WCAG 2.1 guidelines. Furthermore, accessibility audits involved manual checks and empathic modeling techniques [25], simulating the experience of persons with visual impairments, namely blind and low-vision users. The results of these assessments produced valuable findings which were directly addressed in the next prototype iteration.

Despite the significant contributions of expert-based reviews, especially in the context of systems addressing persons with disabilities, the value of user-based assessments is immeasurable, as it is the most appropriate way of ensuring that the system is useful and usable by its target users. The process and results of the first user-based evaluation are described in detail in Section 8. After analyzing the results from this evaluation, many refinements and new features were added to the SHIFT XR Accessibility Framework, as detailed in Section 9.

4. Taxonomy

Derived from the analysis of the relevant literature on the accessibility on XR solutions and the user requirements, we developed a taxonomy, aiming to consolidate this analysis to an easy-to-understand classification (see Figure 3). The taxonomy delineating technologies for accessibility within XR environments served as a blueprint of the technological solutions reported in the literature in the field of XR accessibility, but also as a roadmap for the development of the proposed framework. Key lessons learned from the literature review, which are also evident in the produced taxonomy and on which the proposed framework aims to address, are the following:

- **Multi-Faceted Input and Output Considerations:** The taxonomy underscores the importance of incorporating diverse avenues for input and output within XR applications. Developers and researchers should recognize the value of accommodating various sensory modalities and interaction techniques. More specifically, instead of relying on singular modes, such as visual or audio cues alone, the taxonomy encourages the exploration of innovative combinations that encompass visuals, haptics, audio descriptions, and 3D sounds. By harnessing the synergies

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

between these modalities, XR experiences can transcend limitations and cater to a broader range of user needs.

- **Sensory Substitution and Synergy:** Incorporating lessons from the taxonomy, endeavors should embrace the concept of sensory substitution. Instead of solely relying on a single sensory channel, the fusion of sensory inputs can lead to enhanced UXs. The taxonomy's insights suggest that the integration of visuals, haptics, audio, and 3D sounds can collectively substitute for the absence of one sense, compensating for the limitations faced by individuals with visual impairments. Solutions should explore how various sensory inputs can be optimally combined to address this challenge and make XR environments more user-friendly.
- **Meaningful Labeling and Enhanced Scene Comprehension:** One of the taxonomy's key takeaways is the emphasis on meaningful labeling within XR scenes. The importance of appropriately labeling objects, images, and essential assets within the VE becomes apparent. Meaningful labeling not only aids in scene comprehension but also enables users with visual impairments to interact effectively with the virtual world. Developers should consider strategies to provide context-rich descriptions that facilitate accurate and intuitive navigation, aligning with the taxonomy's insights on enhancing the accessibility of XR scenes.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

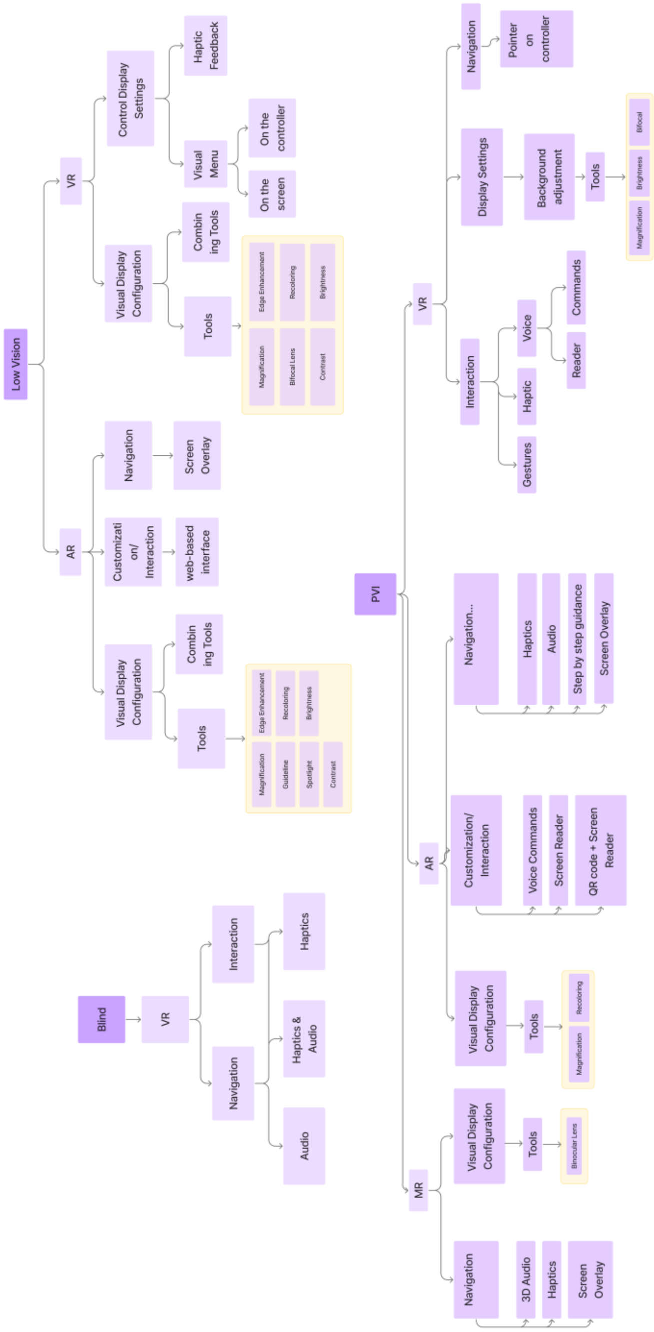

Figure 3: Taxonomy diagram

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

5. The SHIFT Extended Reality Accessibility Framework

The SHIFT XR Accessibility Framework is a comprehensive solution that provides multiple accessibility features for XR projects. This section presents an overview of the framework's key components and their objectives, followed by a detailed explanation of the implementation process.

5.1 Framework Overview

The XR Accessibility Framework aims to foster a cohesive and inclusive XR experience for users with varying abilities, empowering them to engage with XR content seamlessly. The first version of the XR Accessibility Framework supports a range of content adaptations, focusing mainly on people with vision impairments, to enhance accessibility for text, images, videos, and 3D artefacts. However, it is worth mentioning that the design and implementation approach of the framework allows the employment of more accessibility features aiming to assist persons with other disabilities as well. For textual information, developers can customize font size, color, outline thickness, and text background, facilitating improved legibility and contrast, which are particularly beneficial for individuals with low vision. Images are enriched with alternative text (alt text) to provide textual descriptions, and multimedia content is equipped with user-friendly controls, such as resizing, play, and pause options. For 3D artefacts, developers can define points of interest with additional information that can be delivered in accessible ways. Furthermore, developers can activate the edge enhancement tool, offering greater control over line colors and thickness, ultimately improving object visibility for enhanced UX.

The XR Accessibility Framework also emphasizes interactive element identification, integrating widgets with supplementary information, such as text, images, videos, haptics, and 3D sound to support users with disabilities in comprehending XR content effectively. Moreover, the framework incorporates a scanning feature, enabling users with visual impairments to navigate through interactive elements in a customizable hierarchical order, enhancing accessibility based on individual user requirements. Additionally, the framework enhances user interactions for individuals with visual impairments by bringing specific interactive objects forward in the scene, ensuring improved visibility and ease of interaction. This feature also reduces cognitive burden for users with cognitive impairments, enabling a more focused and engaging XR experience.

In addition, the framework enables the enhancement of the XR elements with haptics, by incorporating the SHIFT haptic tool (T3.4) and with audio descriptions and 3D sound. Overall, the integration of haptics with audio descriptions and 3D sound elevates the UX by providing a multi-sensory immersion and improved artifact localization.

Furthermore, the framework offers scene adaptations, providing functionalities like brightness adjustment, a magnified lens for enlarged viewing, and a recoloring tool catering to the needs of color-

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

blind individuals. Users can select a color profile to customize the scene, addressing specific visual requirements and preferences, further enhancing the overall XR experience.

5.2 Core Components and Features

The architecture of the framework is organized into several core components, each serving a specific purpose to facilitate accessibility adjustments seamlessly. The following sections describe the key components and their functionalities:

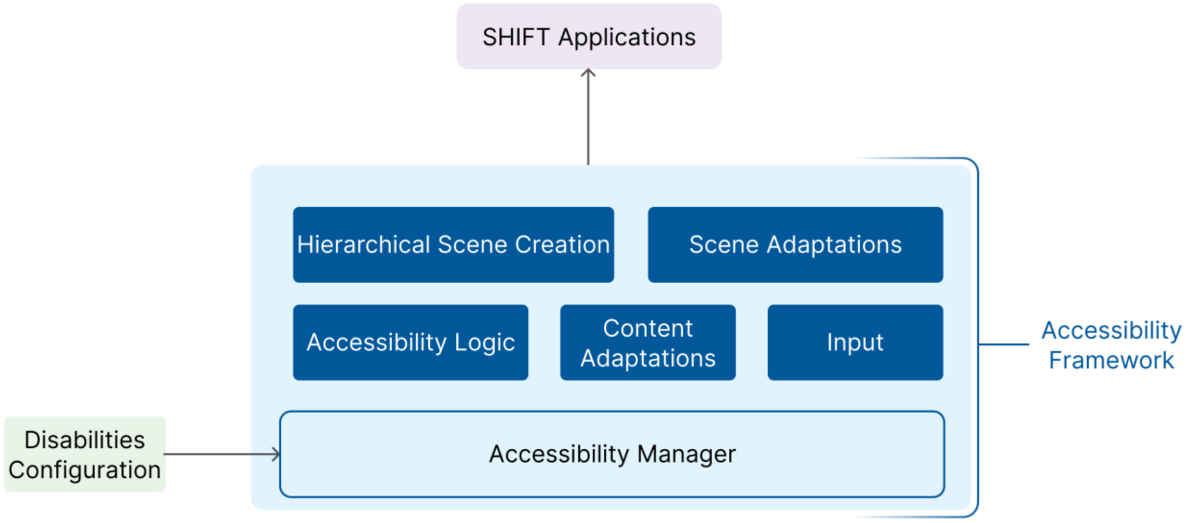

Figure 4: Core Components of the Accessibility Framework

- The **Accessibility Manager** is the core component of the XR Accessibility Framework. This component serves as a fundamental enabler for incorporating various accessibility features into XR applications, ensuring a cohesive and inclusive XR experience for users with diverse abilities and disabilities. In this context, the Accessibility Manager plays a pivotal role as the central hub, orchestrating communication and data flow between the diverse accessibility features offered by the framework and the game/application components. The manager facilitates the dynamic enabling and disabling of accessibility features based on user preferences and requirements.
- The **Content Adaptation Components** optimize accessibility for text, images, videos, and 3D artefacts. For text, it provides customization options for font, color, outline, and background. Images and videos include alt text for visual descriptions. Multimedia content is enriched with controlling features such as resizing, play, and pause options. Customizable video subtitles allow adjustments to font styles and sizes. The framework also introduces an edge enhancement tool for 3D artefacts, enhancing object visibility.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

- The **Hierarchical Scene Creation** component consists of three components, namely Interactive Element Definition, Hierarchical Structure Specification, and Active Object Forwarding. This component takes as input the interactive elements, identified by the developer. Each interactive element is associated with a widget that provides supplementary information to aid users with disabilities in understanding the content. The Hierarchical Structure Specification assists users with visual impairments in effective navigation through interactive elements within the XR scene. The elements are activated and read in a hierarchical order as they are visually displayed in the XR scene from top to bottom and from left to right, however, this order can be customized by developers. Furthermore, the framework caters that all the active elements are brought in front of the user one by one upon selection.
- The **Scene Adaptation Components** offer functionalities such as brightness adjustment, a magnified lens for enlarged viewing, and a recoloring tool to modify the color scheme, thus catering to the needs of color-blind individuals.
- **Input Components** are responsible to handle user input supporting multiple ways of input such as keyboard, headset controller, and gestures. These components serve as the interface between users and the XR application, facilitating seamless communication and interpretation of user commands.
- The **Accessibility Logic Component** serves as a fundamental and integral module within the XR Accessibility Framework. Its primary role revolves around dynamically deciding to enable or disable accessibility features in response to user-specific requirements. This component operates based on a JSON-like element, received by the Accessibility Manager, which encapsulates the chosen disabilities of the user. By utilizing this information, the Accessibility Logic Component reconfigures the XR scene, through the Accessibility Manager, to align with the user's accessibility needs.

In summary, the flow of information is as follows: The Accessibility Logic Component updates the state based on the user's selected disability, which determines the enabled accessibility features. This state information is passed to the Accessibility Manager, which coordinates and activates the accessibility components. The Content Adaptation Components, which is activated by the Accessibility Manager if needed, optimize the XR content for accessibility, while the Hierarchical Scene Creation component aids users in understanding and navigating the XR scene in a sequential manner. The Scene Adaptation Components enhance scene viewing for specific user needs. In parallel, the Input Components handle user interactions, enabling users to engage with the XR application effectively. Further details of each component are discussed in the following sections.

5.2.1 Accessibility Manager

As already mentioned, this component serves as a central hub to the architecture of the framework, managing the activation of the appropriate components, based on the input received from the Accessibility Logic Component. The Accessibility Manager serves as an enabler in the XR Accessibility Framework, facilitating a cohesive and inclusive XR experience via an effective coordination of the

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

diverse accessibility features provided by the framework. This is essential in harmonizing the functionalities of different components, ensuring a seamless integration of accessibility adjustments within XR applications. By centralizing the communication and data flow between the various accessibility features and game/application components, the Accessibility Manager streamlines the process of enabling or disabling specific accessibility functionalities based on user preferences and requirements. Through the Accessibility Manager developers can select and adjust the accessibility feature they want to add to their game/application. The framework, through the Accessibility Manager, offers intuitive controls for adjusting font sizes, colors, contrast, and other visual elements, through the Content Adaptation Component. The Accessibility Manager receives as input the Disabilities Configurator and applies the Accessibility Logic as described in Section 5.2.4. By managing feature activation, the manager minimizes computational overhead and ensures a smooth and responsive XR experience.

5.2.2 Hierarchical Scene Creation

The XR Accessibility Framework empowers developers to enhance the accessibility of their XR scenes by identifying and designating specific interactive elements within the VE. These interactive elements serve as the focal points for the integration of various accessibility features, ensuring a more inclusive XR experience for users with disabilities.

Interactive Element Definition

The process begins with developers indicating the interactive elements they wish to apply accessibility features. These elements may include 3D artifacts, buttons, menus, or any other components that play a pivotal role in the XR application's functionality and user interactions. By selecting and designating these elements, developers lay the foundation for providing supplementary information and customizations tailored to users with disabilities. Every specific interactive element is associated with a widget which acts as an information portal for users. The widget provides users with supplementary content, such as text descriptions, images, videos, 3D sound, and haptics, offering valuable insights into the interactive element's purpose, characteristics, and functionalities. For example, a 3D artifact within an XR museum application can be designated as an interactive element and linked to a widget containing textual descriptions about the artifact's historical context, significance, and cultural relevance. The widget's content is meticulously curated to cater to the specific needs of users with disabilities, providing them with multiple ways of accessing information. For instance, users with visual impairments may rely on the embedded screen reader to audibly read the textual descriptions provided in the widget.

Hierarchical Structure Specification

In addition to the interactive element and its associated widget, the XR Accessibility Framework incorporates a mechanism for hierarchical order scanning to further enhance the accessibility and comprehension of the XR scene. This mechanism requires developers to identify the hierarchical

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

structure of ‘scannable’ elements, that is elements that will be accessed by users. In this regard, it is noted that for users with visual impairments, elements that should be added in the hierarchical structure include not only the interactive elements of the scene, but textual elements as well. As a result, this feature of the framework enables developers to create more detailed and informative XR experiences, particularly when dealing with complex 3D artifacts or scenes. At the top level of the hierarchy, developers designate the main interactive element, which serves as the primary focus of user interaction. For instance, in the context of an XR museum exhibit featuring a statue, the statue itself is the main interactive element. Within the main interactive element, developers can embed hotspots which represent specific points of interest or sub-elements of the main artifact. For example, in the statue case, a necklace worn by the statue could be identified as a hotspot. The necklace automatically becomes an interactive element internally within the framework, facilitating interactions related to the specific hotspot. Each hotspot, like the main interactive element, may also be associated with its own widget. This widget contains supplementary information specific to the hotspot, such as for instance details about the necklace's craftsmanship, material, or cultural significance.

This hierarchical structure is used by blind users to effectively navigate the XR environment using the embedded screen reader. Each element in the hierarchical structure that contains other interactive elements acts as a container for the screen reader, such as a 3D artifact containing one or more specific points of interest within the XR scene. The framework incorporates a set of navigation options specifically designed to facilitate exploration by blind users. Users can easily move through the hierarchical order of interactive elements by utilizing commands such as “enter container”, “go to next container”, “go to previous container”, and “exit container”, mapped to specific input events (e.g. a keyboard key, a controller key, etc.) These commands allow users to sequentially access and explore different interactive elements within the XR scene. With the option “enter container”, users can select a specific container and access its child containers. With the commands “go to next container” and “go to previous container” users can switch between sibling containers, and finally with the command “exit container” users can return to the parent container. The hierarchical system consists of various levels, including root containers, which represent the main interactive elements within the XR scene, and sibling containers, which are interactive elements at the same hierarchical level (see Figure 1Figure 5). Furthermore, child containers represent interactive elements nested within their parent containers. The developer can change the order of the containers through the Accessibility Manager. This functionality grants users the ability to delve deeper into the XR scene, gaining access to more detailed information about specific aspects of the scene. By providing this hierarchical structure, the framework empowers blind users to navigate the XR environment with greater ease and efficiency.

Funded by the European Union

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement no 101060660.

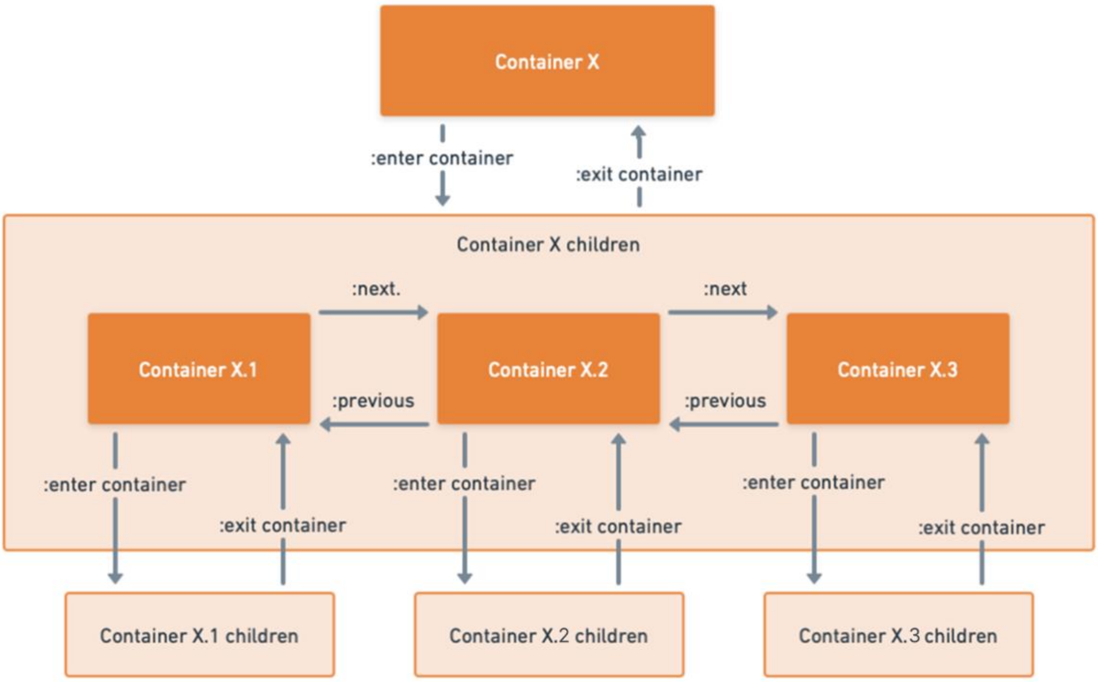

Figure 5: Screen reader commands flow

5.2.3 Active Object Forwarding

This feature is specifically designed to enhance the navigation experience for individuals with disabilities within the XR environment. It streamlines the user's interaction by automatically bringing specific interactive objects, selected by the developer, to the forefront of the scene, closer to the user's current viewpoint. By dynamically adjusting the positioning of these active objects, the framework aims to improve their visibility, making it easier for users with visual impairments to identify and engage with the relevant elements. The incorporation of this feature into the framework aims to significantly enhance user comfort and facilitate intuitive interactions. Leveraging the haptic attributes of each artifact, the framework allows users to physically touch the objects. Therefore, by bringing the object closer to the user's hands, the framework streamlines the interaction process, making it easier and more convenient for users to engage with the artifacts. This feature eliminates the need for users to make unnecessary hand movements to locate desired artifacts, resulting in a seamless and efficient interaction process. Users can confidently and effortlessly explore the XR scene, as the relevant interactive elements are brought within easy reach.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

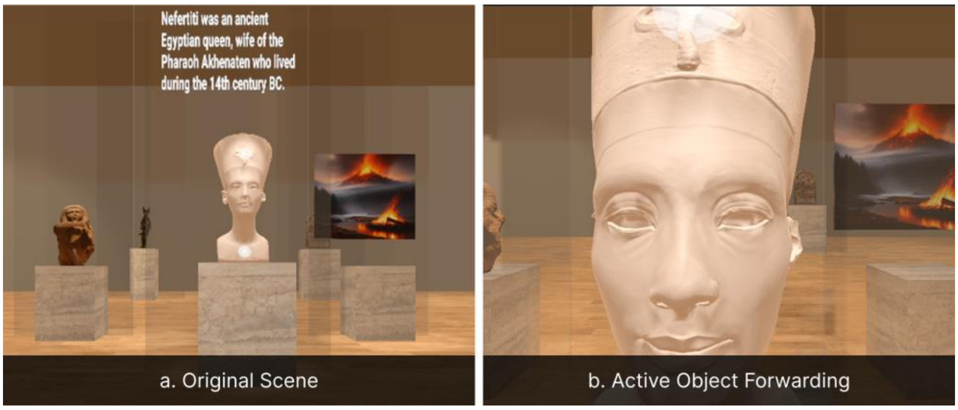

Figure 6: Active Object Forwarding feature

The above-mentioned hierarchical scene creation mechanism is a generic hierarchical approach which can support different assistive devices that require the structured provision of an application content, such as screen readers or scanning devices (e.g. binary switches). To this extent, our solution can be easily generalized to address the needs of persons with diverse disabilities.

5.2.4 Accessibility Logic

The Accessibility Game Logic in the XR Accessibility Framework offers a user-friendly and customizable approach to address various categories of disabilities within XR applications. Developers can specify the disabilities their application aims to accommodate using the "AMConfigurationEditor" menu, located in the Unity top bar. This menu provides a comprehensive set of disability categories, including blindness, low vision, color blindness, hearing impairment, and upper limb motor disabilities. For instance, when developers select the color blindness option, a dropdown menu appears, offering different types of color blindness, such as protanope, deuteranope, and tritanope. Developers can easily toggle between different disability options based on their target audience or user preferences. Once the specific disability types are chosen, the Accessibility Game Logic, sends this input to Accessibility Manager in order to orchestrate the adjustments within the XR scene accordingly. For example, if the application is designed for blind users, any assisting videos or images will be hidden, and the screen reader will be activated to provide auditory feedback. Similarly, for users with low vision, the framework can apply magnification lenses and brightness adjustments to enhance the visibility of visual elements. Moreover, for individuals with color blindness, the recoloring tool will adapt the color scheme to better suit their visual perception.

5.2.5 Content Adaptation Components

Text Accessibility Component: The Text Accessibility Component serves as a tool for enhancing the accessibility of textual information within XR applications. Developers utilizing the Text Accessibility

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Component gain access to a comprehensive set of customization options, including font size, color, outline thickness, and background color adjustments. These granular controls allow developers to fine-tune the presentation of text, catering to the specific needs and preferences of individual users. For instance, individuals with low vision can benefit from increased font size and high-contrast color schemes, enhancing text legibility and readability. A feature of the Text Accessibility Component lies in its dynamic search capability. Upon integration into an XR application and activation, the component automatically scans and identifies all *<Text>* objects within the scene. This automated process ensures that accessibility adjustments are universally applied throughout the application, maintaining consistency and coherence in the presentation of textual information. Importantly, this feature extends its inclusivity to *<Text>* GameObjects that may not currently be active within the scene, ensuring that accessibility enhancements persist across various states of the XR application/game.

The Text Adjustment Component in the Accessibility Framework offers a notable feature to address situations where the text content exceeds the predefined space allocated by developers, either due to the length of the text or the chosen font size. When such an overflow occurs, the text is automatically adapted by overlapping and splitting it into multiple pages to ensure it remains within the designated area. To facilitate user interaction with the multi-page text, a 3D button is prominently displayed at the bottom of the text section, as shown in Figure 7c. By pressing this button, users can easily navigate to the next page of the text, thereby accessing the continuation of the content. Correspondingly, a "back" button is also presented, enabling users to revert to the previous page, enhancing the user's ability to navigate and comprehend the text without any constraints.

Figure 7: Accessibility Framework Text Adjustments

Media Accessibility Component: The Media Accessibility Component enriches images and videos by adding alt text descriptions, enabling screen readers to convey textual information about the visual content. Furthermore, this component incorporates various controlling mechanisms for multimedia content, encompassing options like resizing which facilitates a user-friendly and interactive experience.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

3D Artefact Enhancement: The 3D Artefact Enhancement component offers developers a way to enhance the visualization of 3D objects, thereby enhance the overall UX. By enabling the edge enhancement feature, developers can effectively improve the visibility of object edges, thereby facilitating a better perception of the shapes and boundaries of 3D artifacts within the XR environment, as depicted in Figure 8. This enhancement is of particular significance for individuals with visual impairments, as it aids in their comprehension of the spatial layout and relationships between different objects within the virtual scene. Furthermore, the 3D Artefact Enhancement component provides developers with essential customization options, granting them greater control over the visual representation of 3D artefacts. This level of flexibility empowers developers to tailor the visual aesthetics of their XR applications to suit users' preferences and specific accessibility requirements. By fine-tuning line colors and thickness, developers can adapt the rendering of 3D artefacts to optimize contrast, by adding edges to the virtual scene based on depth and surface normal changes and visibility for individuals with diverse visual needs.

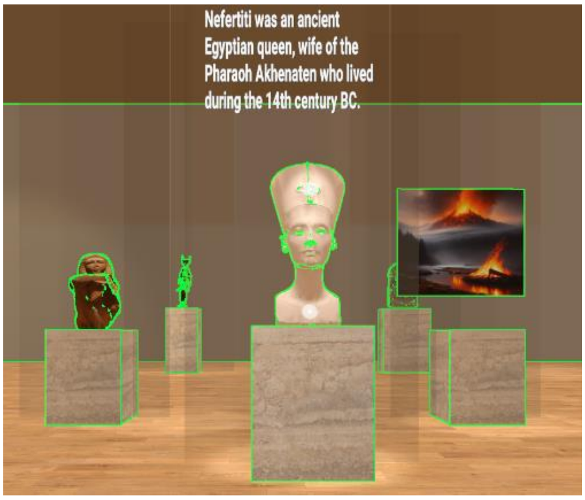

Figure 8: Edge Enhancement Tool

5.2.6 Scene Adaptation Components

Scene adaptations within the XR Accessibility Framework play a pivotal role in tailoring the XR environment to meet the specific needs of users with diverse abilities. The framework incorporates a set of features that allow for the customization of visual elements, ensuring an inclusive and accessible XR experience. By providing functionalities like brightness adjustment, magnification lens, and a recoloring tool with multiple color profiles, the scene adaptations empower users to optimize the visual representation of the XR content according to their individual requirements. The framework not only allows developers to easily configure these settings but also provides the flexibility for developers to enable users to adjust them through function calls. This user-centric approach fosters a more meaningful and immersive XR experience, promoting inclusivity and ensuring that users with various visual impairments can confidently engage with and comprehend the XR environment.

Brightness Adjustment: The inclusion of the Brightness Adjustment feature in the framework is motivated by the diverse light sensitivity of individuals with low vision. VR scenes can often contain

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

extreme variations in lighting, including dark or bright light effects, which may pose challenges for users with specific visual impairments. To address this issue, the XR Accessibility Framework provides users with the ability to adjust the scene's brightness according to their unique visual preferences and needs as shown in Figure 9.

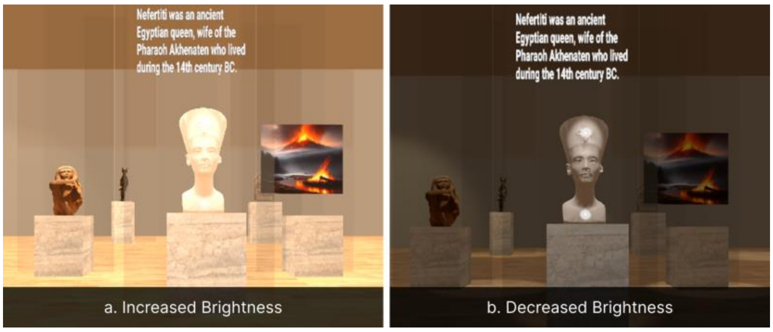

Figure 9: Brightness Adjustment

Magnified Lens: The most prevalent method for enhancing vision and enabling individuals with low vision to perceive details is through magnification. To address this need, the XR Accessibility Framework is providing a Magnification Lens. The Magnification Lens allows users to view the VR scene with up to 10 times magnification, significantly amplifying the visual content. The lens is positioned in front of the user's eyes, covering a 60-degree visual field, ensuring that the majority of the user's focus remains on the magnified content while retaining some spatial awareness in the periphery, as shown in Figure 10. With the Magnification Lens, users can selectively enlarge portions of the XR scene, improving visibility and providing enhanced clarity for individuals with low vision. This feature proves invaluable in enabling users to closely examine and interact with fine details, graphics, or textual information within the XR environment.

Figure 10: Magnified Lens (2 times magnification level)

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Recoloring Tool: The recoloring tool within the XR Accessibility Framework offers a valuable feature to address the needs of color-blind individuals. It provides multiple color profiles, such as protanopia, deuteranopia, and tritanopia, allowing users to modify the color scheme of the XR environment according to their specific type of color blindness. Developers can select the colorblindness type of users and the recoloring tool will automatically apply the chosen color profile to the entire scene, modifying the color representation of various elements, objects, and UI components within the XR application. For instance, a user with protanopia may struggle to distinguish between red and green colors due to the absence of red cones in their eyes. With the recoloring tool, they can opt to replace red with a more distinguishable color, such as magenta, making the XR content more accessible and comprehensible for them Figure 11b.

Figure 11: Recoloring filter for protanopia

5.2.7 Input Component

The Input Component is harmonizing diverse user inputs to a common internal interaction scheme. Presently, the framework incorporates support for two primary input methods: Keyboard input and headset controller input.

Keyboard Input: Keyboard input serves as an accessible means of interaction for users, with a specific focus on facilitating navigation for blind users through the embedded screen reader. The Input Component adeptly interprets and responds to the four fundamental commands used by the screen reader: "enter container," "go to next container," "go to previous container," and "exit container." These commands play a pivotal role in enabling blind users to explore the hierarchical order of interactive elements within the XR scene, providing an essential avenue for comprehensive interaction. The controls are based on popular screen readers such as VoiceOver, NVDA, and TalkBack. By aligning with familiar and widely used screen reader commands, blind users are not required to relearn new control methods. For instance, the "enter container" command is activated by pressing the "Enter" key on the keyboard, while "go to next container" and "go to previous container" commands are seamlessly executed using the "Tab" and "Shift+Tab" keys, respectively. The "exit

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

container" command is triggered by pressing the "Backspace" key. Additionally, the Input Component accommodates supplementary commands for menu interactions, ensuring navigation to the VE.

Headset Controller Input: The XR Accessibility Framework integrates support for headset controller input, further elevating the immersive and interactive experience for users. With headset controllers at their disposal, users can actively engage with the XR environment, leveraging intuitive gestures and interactions. Leveraging the headset controller's left joystick, users can easily navigate through the interactive elements, as illustrated in Figure 12. By pushing the left joystick to the right, users can effortlessly access the next item in the sequence, while pushing it to the left allows for quick access to the previous item. The "left trigger" button serves as the select command, enabling users to interact with the current item and access its detailed information. Additionally, the bottom trigger facilitates the exit from the current active element. The Input Component proficiently interprets a myriad of controller inputs, facilitating seamless navigation and interaction within the XR scene.

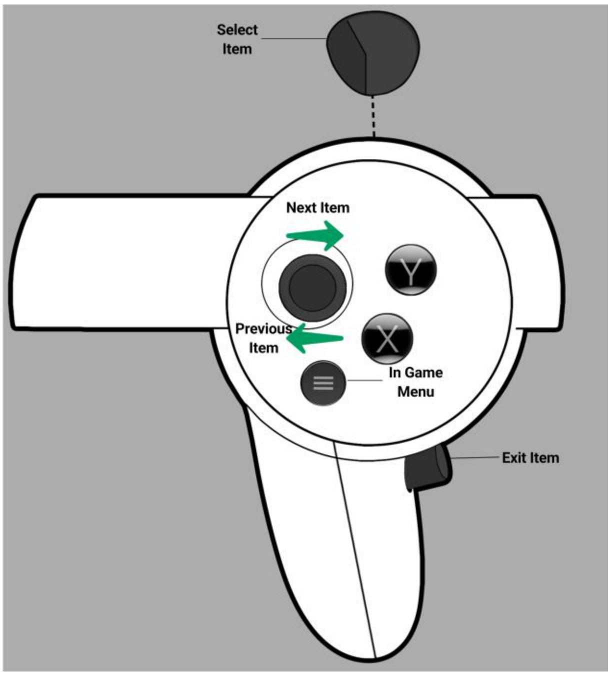

Figure 12: Left controller commands

6. Implementation

This section provides an overview of the framework's component implementations. The framework has been developed using Unity 3D. Each component within the framework functions autonomously, effectively encapsulating the inherent complexity of its specific role. When combined, these components collectively form the complete framework.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Identifying interactive elements in the scene

To identify and enhance interactive elements within the XR scene, the our framework's "InteractiveElement.cs" C# script is utilized by developers. This script is attached to the corresponding Unity GameObjects representing interactive 3D artefacts, and it includes references to the hotspots of the artifact, allowing developers to designate specific interaction points, as shown in Figure 13. If desired, developers can add hotspots to the interactive elements for more precise interaction options. Additionally, the framework provides a Unity 3D tooltip *prefab*[14] for hotspots. Tooltips are graphical overlays that appear when users hover or interact with specific elements in the XR scene. These tooltips can contain supplementary information, such as text, images, or videos, to provide detailed descriptions or explanations about the hotspots of interactive elements. The hotspot prefab provided by the framework is connected to a point of the 3D artefact and follows the camera orientation, in order to be visible from multiple angles, Figure 14. By utilizing the tooltip prefab and attaching the framework's "widget.cs" script to both the interactive 3D artefacts and the hotspots, developers can provide multiple and alternative ways of description for each interactive element. The "widget.cs" script, when used in conjunction with interactive 3D artefacts and hotspots, extends the functionality of the Unity GameObject class, enabling developers to include references to text, image, and video GameObjects. By placing appropriate prefabs within these GameObjects, developers can seamlessly provide supplementary information for users with diverse abilities and disabilities. The script allows for the dynamic customization of the content attached to interactive elements, enhancing the overall accessibility and UX within the XR environment. The framework's "InteractiveElement.cs" script also includes a field called "Order in Hierarchy," which allows developers to modify the order for the hierarchical audio description feature without altering the original order established in the Unity scene. This ensures that the interactive elements are appropriately prioritized and presented to users based on their specific accessibility needs.

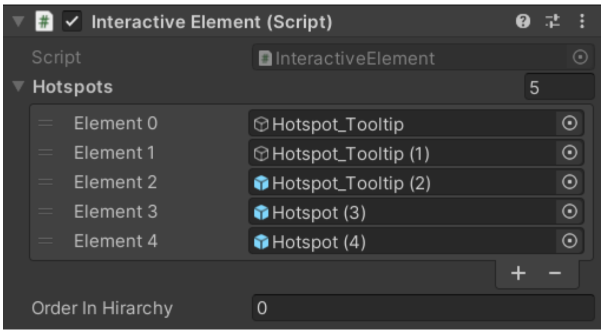

Figure 13: Interactive element script associated with a GameObject, with 5 hotspots GameObjects

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

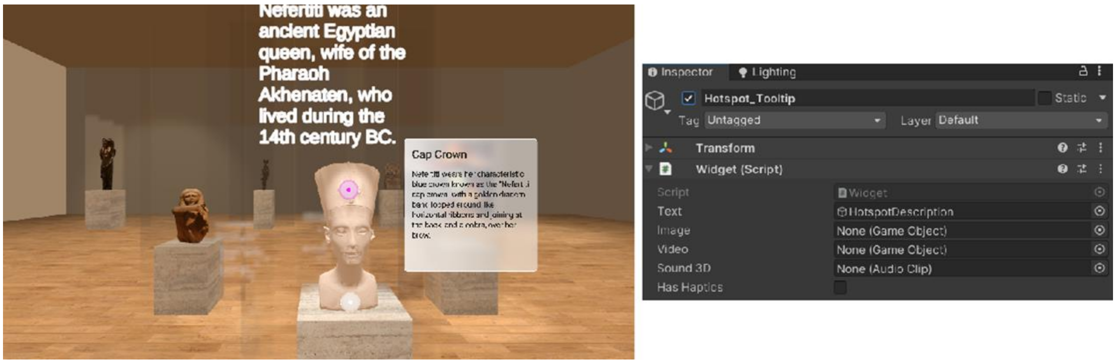

Figure 14: Hotspot with widget attached to it, supplementing information with text

Describing the scene in respect to the hierarchy using screen reader

The XR Accessibility Framework has been bolstered by integrating and building upon the capabilities of the UnityAccessibilityPlugin (UAP)[4], a component that offers essential screen reader features for XR applications. The proposed framework automates the incorporation and configuration of UAP scripts for accessibility, relieving developers from manual setup for GameObjects they wish to be accessible. During runtime, the XR framework actively scans for interactive elements instantiated via the "InteractiveElement.cs" script. For each identified interactive element, the framework searches for an associated widget. Upon finding a widget, the XR framework dynamically adds the necessary components from UAP to make the textual content of the widget accessible to the screen reader, in respect to the "Order in Hierarchy" field from the "InteractiveElement.cs" script. Furthermore, when interactive elements contain hotspots, the XR Accessibility Framework employs an automated search mechanism to locate corresponding widgets linked to these hotspots. Upon identifying the widgets, the framework applies the same accessibility procedure as mentioned above, making the textual information included in hotspot accessible from the screen reader.

In order to preserve the hierarchical order and facilitate the hierarchical audio description feature, the framework maintains a tree structure. This structure organizes the interactive elements within the XR scene, respecting their hierarchical relationships. For each interactive element within the XR scene, the framework establishes a corresponding node in the tree and also adds the interactive element's siblings, parents, and other related elements to the tree structure, progressing upwards in the hierarchy until it reaches the root node, which represents the top-level container of the XR scene. As the user interacts with the XR environment using navigation commands, the framework dynamically

[4] https://github.com/mikrima/UnityAccessibilityPlugin

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

identifies the current interactive element and passes it as input to the UAP, in order to be read by the screen reader. The tree structure serves as a hierarchical map, allowing the framework to precisely determine the user's location and focus within the XR environment. When the user activates specific commands, such as "enter container," "go to next container," "go to previous container," or "exit container," the framework utilizes this tree-based navigation to activate the corresponding container and present the relevant information to the screen reader.

Forwarding active element in front of the user

The XR Accessibility Framework seamlessly integrates with the headset's interactive zone, which is determined and set by the user. This virtual interactive zone encompasses the user's reachable space, allowing them to interact with the XR scene while comfortably seated. Within this zone, the framework actively monitors the user's position and orientation as they explore the VE. When the user selects an interactive element, the framework dynamically positions it in front of the user, ensuring an optimal distance of approximately 40 centimeters from the user's position within the interactive zone. This strategic placement facilitates effortless interaction and visual engagement with the active element, catering to the user's convenience and accessibility needs.

To further enhance navigation and UX, the framework implements a circular ordering mechanism for the active elements within the interactive zone. When the user chooses to navigate to the next element, the current active element smoothly transitions to the position in the scene previously occupied by the last element, as shown in Figure 15. This seamless circular navigation approach ensures a logical and predictable flow of interactive elements, enabling users to efficiently explore the XR content without any unnecessary physical strain or disorientation.

Figure 15: Next and previous element example

Accessibility Logic

The XR Accessibility Framework provides a user-friendly interface for developers to specify the disability types their application aims to address. We have integrated this functionality into the Unity

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

top bar menu, introducing a new <MenuItem> called "AMConfigurationEditor." This menu item inherits the functionalities of the Unity <EditorWindow> and serves as a convenient tool for configuring the scene's accessibility settings. This window and the supported disabilities are depicted in Figure 16. As developers make their selections, a JSON-like element is generated that represents the game/application configuration. The configuration can be easily reviewed and updated through the AMConfigurationEditor, ensuring that developers have precise control over the accessibility features integrated into their application. This JSON object acts as the "Disability Configuration" which is the input for the Accessibility Manager Component.

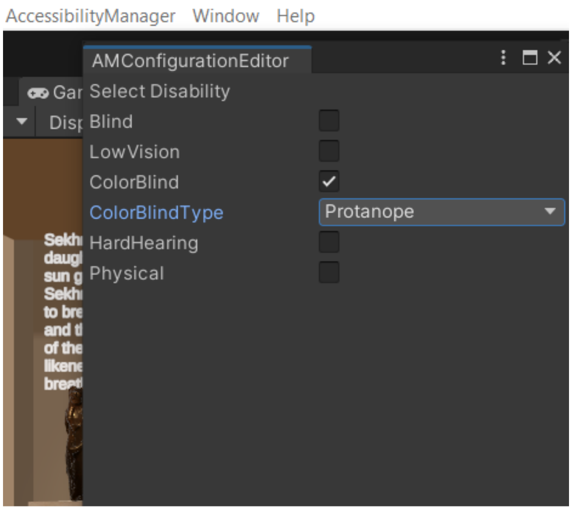

Figure 16: Accessibility Logic Configuration

Adding 3D sound to artifacts

To provide a comprehensive implementation of 3D sound in the XR Accessibility Framework, developers can leverage the widget component to easily add audio to interactive 3D objects. By adding the audio clip, the framework automatically adds the necessary "Audio Source" component to the chosen GameObject, streamlining the setup process for developers. Once the "Audio Source" component is added, the developer can conveniently configure various audio parameters, such as selecting the audio clip, adjusting the volume, setting the pitch, and managing other audio properties through the Unity Inspector. The framework goes beyond basic audio setup, effectively handling the integration of 3D sound with the XR environment. As the user interacts with the scene and their hand approaches or moves away from the bounds of the 3D object, the framework dynamically adjusts the audio volume to create a more immersive experience. This adjustment is achieved through linear interpolation based on the distance between the user's hand and the object, ensuring consistent and natural audio feedback.

Making the content components accessible

Through a scanning process, the component identifies all <Text> objects within the scene and applies adjustments based on the options set by the developer. In the Unity 3D Inspector, developers can access the Accessibility Manager script, where they are presented with a set of parameters for text adjustments. These parameters include:

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

- Font Size Increase: This parameter allows developers to specify the value by which the original font size of the text will be increased.
- Text Color: Developers can set the color of the text through this parameter.
- Outline Thickness and Color: The Text Adjustments component also provides options to control the thickness and color of the text outline.
- Background: To further improve text readability, the framework offers the option to add a high-contrast background to the text object.

Making the scene filters

Magnification Lens: Implemented by adding a 2D plane with a texture rendered from a second virtual camera capturing the VR scene at the same position as the main camera in Unity. The framework adjusts the field of view of this second camera to control the magnification level. This feature enables users with low vision to see details more clearly by enlarging specific areas of interest within the XR scene.

Brightness Adjustment: The framework introduces brightness adjustment to the main camera, allowing developers to modify the intensity field. By setting the intensity value, developers can control the overall brightness level of the XR scene. For instance, a value of 0.1 represents the original brightness, while a higher intensity value will make the scene darker. This tool is particularly useful for users with light sensitivity or low vision who may require custom brightness settings.

Recoloring Tool: The Recoloring component enhances color perception for color-blind users. The framework uses a custom shader to apply recoloring effects. The component uses two colors: The color to be changed and the color to replace it. To cater to different types of color blindness, the XR Accessibility Framework provides predefined color combinations for protanopia, deuteranopia, and tritanopia. For protanopia changes the color red (#FF0000) to magenta (#FF00FF), for deuteranopia changes green (#00FF00) to cyan (#00FFFF), and for tritanopia changes blue (#0000FF) to yellow (#FFFF00).

The Accessibility Manager component offers developers seamless access to these scene adjustment tools, providing an efficient way to configure XR scenes according to various accessibility needs.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

7. Integration to Extended Reality Applications

Integrating the XR Accessibility Framework into applications is a straightforward process, designed to empower developers to enhance their XR experiences with accessibility features seamlessly. The framework is provided as a Unity 3D package, and developers can easily include it in their Unity projects by importing the package. Upon importing the XR Accessibility Framework package, developers need to add the "Accessibility Framework Manager" prefab to their XR scene. This prefab serves as a central control hub, offering public entries that allow developers to configure various accessibility tools and their respective parameters. By incorporating the Accessibility Framework Manager into their XR scene, developers gain access to a standardized and user-friendly way of adjusting accessibility settings, ensuring a coherent and accessible XR experience.

To indicate interactive elements within the scene, developers can utilize the "InteractiveElement.cs" script, which is included in the XR Accessibility Framework. By attaching this script to the corresponding Unity 3D GameObjects representing interactive 3D artifacts, developers identify and designate the specific points of interaction within the XR environment. For each interactive element, developers can further enhance the description by adding the framework's "widget.cs" script. This versatile script extends the functionality of the GameObject class, allowing developers to incorporate diverse methods of description, such as text, images, and videos, thereby ensuring comprehensive accessibility for users.

With the XR Accessibility Framework integrated and interactive elements identified, developers can proceed to customize the XR experience for specific disability categories. The framework provides an intuitive interface, the "AccessibilityManager," which resides as a new menu item of the Unity 3D top bar menu. Through this component, developers can specify the set of disabilities their application aims to address by toggling the corresponding buttons. For example, developers can activate accessibility features for "blindness," "low vision," "color blindness," "hearing impairment," and "upper limb motor disabilities," tailoring their XR experience to meet the diverse needs of users.

In conclusion, integrating the XR Accessibility Framework into Unity projects involves importing the provided package, adding the "Accessibility Framework Manager" prefab to the scene, and indicating interactive elements with the "InteractiveElement.cs" script and descriptive components with the "widget.cs" script. Through the intuitive "AccessibilityManager," developers can enable specific accessibility features catering to different disability categories, ensuring that their XR applications deliver a fully inclusive and accessible experience to all users.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

8. User-Based Evaluation

A user-focused evaluation was conducted aimed at testing the effectiveness of the accessibility features embedded in the first version of the framework. The primary goal was to assess how well these features enhance the VR experience, particularly for individuals who are blind or have low vision. The evaluation was conducted with 20 participants, all of whom had visual impairments. To perform the evaluation, a VR demo scenario was developed using the accessibility framework. This scenario simulated a virtual museum with multiple rooms and 3D objects that users could interact with. During the evaluation, participants wore the haptic glove and the VR headset, which allowed them to navigate and interact with the virtual museum. They were given various tasks to complete, and after each task, they were asked to rate how easy or difficult the scenario was. In addition to these task-specific ratings, questionnaires were used to gather more detailed insights into their overall experience. The main aspects explored in the context of this evaluation were:

Effectiveness of Accessibility Features: If the accessibility features in the framework genuinely helped users with visual impairments to understand and interact with the VE.

Mental Workload: How mentally demanding the VR system was for participants.

Overall UX: Assessment of the participants' overall experience with the VR system.

Considering the above goals, relevant hypotheses were formulated and explored with appropriate instruments. Furthermore, data on any symptoms related to discomfort during VR use were also gathered, to explore the safety and comfort of participants when using the developed system. Furthermore, participants were asked to provide their feedback on the haptic interactions that the system provides (D3.3). By addressing these research questions and analyzing the feedback from our participants, we aimed to contribute valuable insights to the field of accessible VR technology.

8.1 Hypotheses

In this section, the hypotheses that underpin the evaluation of the accessibility features in the VR system, are presented. These hypotheses aim to assess the impact of these features on users' perception, engagement, and overall experience within the VE that was developed with the framework. Each hypothesis addresses the effectiveness of the system and its accessibility provisions.

H1. The accessibility features provided by the framework enhance the users' ability to perceive and engage with the VE effectively.
H2. The system does not impose mental workload on the users.
H3. The overall experience of the participants when using the VR system is positive.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

8.2 Procedure

This first user-based study was conducted in the premises of the German Federation of the Blind and Partially Sighted (DBSV - Deutscher Blinden- und Sehbehindertenverband), who organized the evaluation. DBSV undertook participants' recruitment and handling of all personal data. Issues pertaining to data privacy and ethics were addressed by ERC ETICAS Research and Consulting SL. The study was technically supported by the FORTH team. The results of the study were anonymized, discarding any identifiable personal information, and then securely stored in the project repository as per the pertinent procedures specified within the project. SIMAVI provided access to this anonymized dataset for further analysis.

Each participant was allocated a one-hour time slot for the evaluation process, which consisted of four phases: Introduction to the study, system evaluation, questionnaire completion, and debriefing. The set up for the evaluation was a laptop, the Meta Quest 2 and controllers[5], as well as the Weart TouchDIVER[6] as the haptic device.

In the introductory phase, participants were welcomed to the study and provided with information about the study's aims and objectives, as well as an explanation of the system's features. Following this, participants were informed of their rights and explained that they retained the right to revoke their participation and consent at any time without facing any negative consequences. Then, they signed a printed informed consent form.

To familiarize themselves with the equipment and the system, participants had the opportunity to explore it before wearing it. During this phase, the various components of the equipment were explained to the participants. Participants were also given guidance on handling the headset's controller. Finally, they were asked to put on the equipment and make any necessary adjustments for comfort.

The main phase of the study involved scenario-based usage of the system along five tasks that were read to participants, one-by-one. Upon finishing each task, participants communicated their completion to the facilitator and proceeded to rate the difficulty of the task. While simultaneously observing the entire process via the laptop's display, the facilitator also made handwritten notes of user comments, interaction with the system, errors and assistance required, as well as task success. This process continued for all five scenarios. Following the completion of these scenarios, participants were requested to fill out questionnaires related to the system, which were made accessible through

[5] https://www.meta.com/quest/products/quest-2/
[6] https://weart.it/haptic-vr-products/touchdiver/

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

the EU Survey[7] platform. EUSurvey is an online survey platform, used for the creation and publishing of globally accessible forms, developed and maintained by DG DIGIT, the Directorate-General for Informatics of the European Commission. To facilitate this, participants were provided with a laptop equipped with an embedded screen reader and low-vision software to enable them to complete the questionnaires effectively.

Finally, participants were debriefed and thanked for their invaluable contribution to the aims and objectives of the study.

8.3 Methodology

In the preliminary stages of the evaluation process, participants completed a questionnaire providing background information. This included details about their age, gender, vision status, experience with assistive technologies, and prior exposure to VR. A use case scenario was meticulously devised to engage participants in the evaluation process, offering them an opportunity to interact with the VE and assess the comprehensiveness of the information provided by the system, as well as the overall UX and mental workload imposed. Five scenarios were created, each representing a facet of how users engage with the system and grasp the VE. To capture valuable insights into participants' thought processes the think-aloud protocol was followed throughout their testing sessions. In this regard, participants were asked to vocalize their line of thinking while interacting with the system. This facilitated the real-time collection of participant thoughts and opinions during task execution. In addition to the think-aloud approach, quantitative measures were employed to assess task performance. For each task, the completion success rate was recorded by the facilitator, thus exploring the effectiveness of each participant in task fulfillment. The rating scale employed was as follows:

Success: Signifying that the user completed the task without encountering any obstacles or challenges.

Partial Success: Denoting that the user faced difficulties, made efforts to surmount them, or accomplished the task with minor errors.

Failure: Indicating that the user was unable to complete the task and eventually relinquished their attempts.

Following the completion of each task, participants were asked to rate the complexity of the task on a scale ranging from 1 (very difficult) to 7 (very easy) [26]. Upon concluding the experiment, participants were tasked with filling out standardized questionnaires to provide comprehensive assessments: (1) NASA-TLX (NASA Task Load Index) [27] was utilized for workload measurement, capturing the cognitive demands imposed by the system in the given context. (2) UEQ (User Experience Questionnaire) [28]

[7] https://ec.europa.eu/isa2/solutions/eusurvey_en/

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

was employed to gauge the general UX, encompassing various facets of usability and satisfaction. (3) SSQ (Simulator Sickness Questionnaire) [29] was administered to assess symptoms of sickness induced by the VR experience. Furthermore, a debriefing interview was conducted, giving participants the opportunity to articulate their feedback about the system. This qualitative feedback encompassed aspects they found favorable, areas of discontent, and overall impressions.

Museum Case Study

For the purpose of testing and evaluation, we developed a Unity sample scene. This scene simulates a VR museum with two distinct rooms, namely the Egyptian room and the Ancient Greek room. Each room features a diverse collection of 3D CH artifacts, designed to offer accessible interaction for all users, including those with visual impairments. Initially, the scene starts with a menu displaying the museum and its available rooms, as shown in Figure 17. Once the user enters a room, they can view or hear the available artifacts within that room and select the one they wish to interact with, as shown in Figure 18. Subsequently, the user can engage with the chosen artifact and explore its various hotspots (Figure 19).

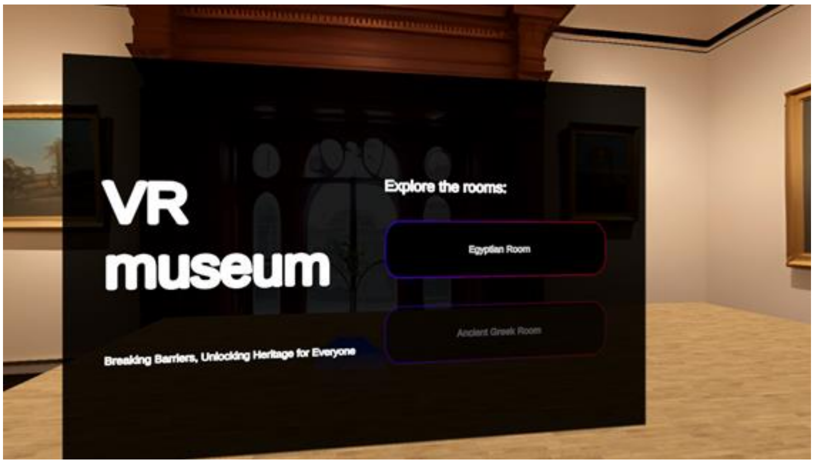

Figure 17: Initial scene menu

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Figure 18: Entering a room (left) and selecting an artefact (right)

Figure 19: Interaction with the hotspots of artifacts

8.4 Evaluation Scenarios

Participants were immersed in a simulated scenario wherein they assumed the role of guests visiting a physical museum employing a VR application to interact with virtual replicas of its exhibits. The scenarios were designed to engage participants in a range of tasks that would allow the assessment of all the system features, exploring their accessibility, comprehension of the virtual museum achieved, and the overall UX, including the effectiveness of the accessibility features integrated into the system. The scenarios were the following:

Scenario 1: You are a guest at a museum that lets you engage with virtual replicas of its exhibits. You put on the required equipment and begin using the museum's app. You are curious to explore the available rooms and see what they have to offer.
Task: Find out how many rooms are available to be explored.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Scenario 2: During your visit, you are particularly intrigued by the Egyptian exhibits. So, you choose to virtually explore the Egyptian room using this application.
Task: Determine how many artefacts are in this room.

Scenario 3: You know that Nefertiti was an ancient queen of Egypt and had a lot of interesting jewelry. Specifically, you are interested in the necklace that she used to wear.

Task: Learn more details about it and the materials that it was made of.

Scenario 4: As you are exploring the Egyptian room you find an artefact about an Egyptian male. Explore the artefact.
Task: Is this artefact from the same material as Nefertiti?

Scenario 5: You are exploring the Egyptian room when you find a painting. Explore the painting.
Task: Describe the painting.

8.5 Participants

A total of 20 participants participated in the study, all of whom had visual impairments. The participants, aged between 18 and "75 or older", included 8 females and 12 males. Vision status within the cohort is equally distributed with 10 participants categorized as partially sighted and 10 as blind. Some participants had specific vision conditions, such as tunnel vision[8] and macular degeneration[9]. A significant proportion, 90%, reported daily use of screen readers and assistive technologies, while 5% used them several times a week. Only one participant mentioned that they do not have any experience with assistive technologies. In the participant group, digital content access methods varied, with the majority of participants utilizing screen readers (14 participants), followed by visual access with assistive technologies (11 participants), braille displays (10 participants), voice commands (7 participants), and magnification software (6 participants) as their preferred means of accessing digital content. A range of methods for interacting with digital content was reported, including the use of keyboards, mice, voice commands, and touch-based interaction. Some participants indicated that they use multiple interaction methods simultaneously, such as keyboard and mouse or keyboard and voice commands, while others primarily rely on a single interaction method, such as a keyboard or touch-based interaction. Finally, 35% of participants have previous experience with VR applications, using standard VR controllers, gamepads, and gesture-based interaction. Figures Figure 20 and Figure 21 show the distribution of participants' age, the age of the vision impairment onset, and ways of accessing digital content respectively.

[8] https://en.wikipedia.org/wiki/Tunnel_vision
[9] https://en.wikipedia.org/wiki/Macular_degeneration

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

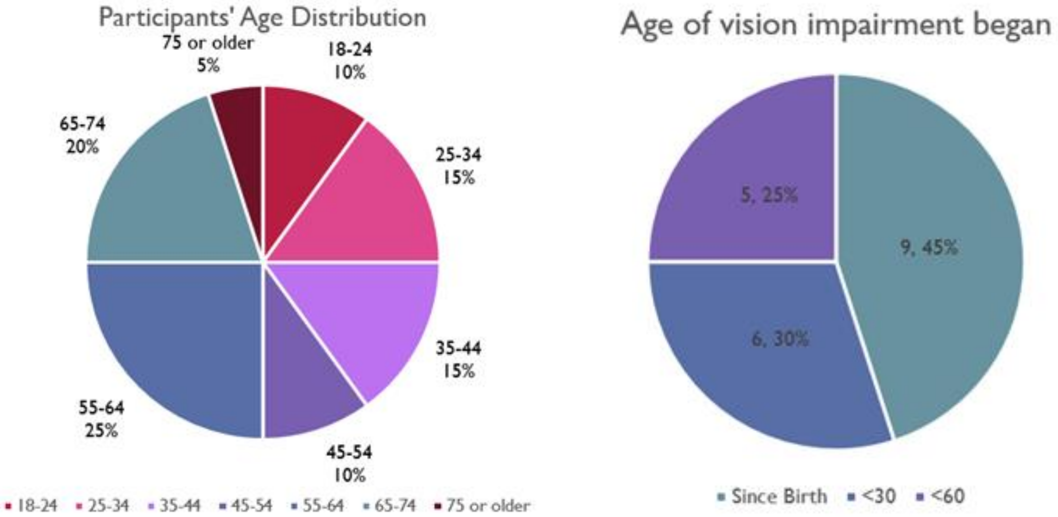

Figure 20: Participants' age distribution chart (left) and Participants' age when the vision impairment began (right)

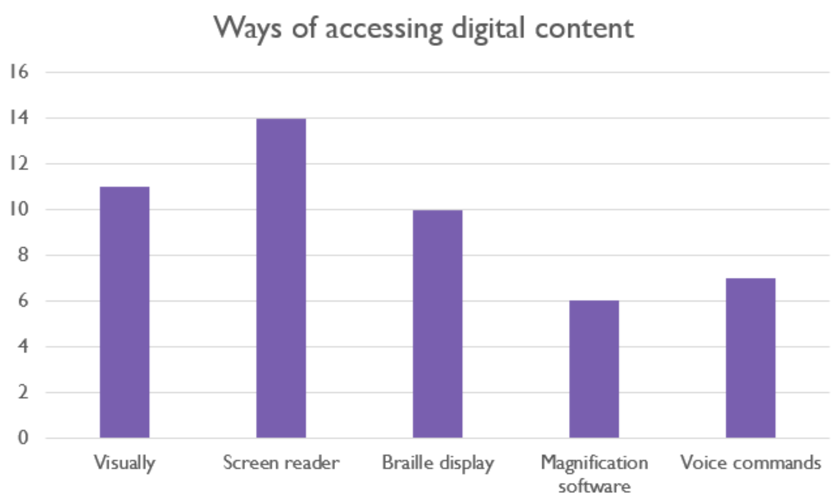

Figure 21: Methods of accessing digital content

Funded by the European Union
This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

8.6 Results

8.6.1 Effectiveness of the System

To evaluate the effectiveness of the system's accessibility features in assisting individuals with visual impairments, in alignment with our hypothesis H1, we examined scenarios' ease of completion (Figure 22) and success rates (Figure 23) for each scenario. In addition, we analyzed the outcomes of the debriefing session, as well as the observers' notes.

Notably, scenarios 1 and 2, which were perceived as quite easy by participants with average ratings of 6.05 and 6.15 out of 7, respectively, yielded a 100% success rate. However, it is important to note that to complete these scenarios successfully, participants had to comprehend the concept of hierarchical reading to navigate within the VE. They also relied on accessibility features such as text enlargement or magnified lenses. The fact that these scenarios achieved a 100% success rate suggests that the accessibility tools used were effective in facilitating navigation and interaction within the VE.

Task 3 was considered moderately easy at 4.2 on average out of 7, but still achieved a success rate of 90%. All of the participants were able to locate the requested museum exhibit (i.e. the Nefertiti statue) very easily, whether using the hierarchical audio description and the headset controller or relying on their vision enhanced with visual filters by the system. For blind users, the task's difficulty primarily stemmed from locating the necklace on the artifact and receiving additional information about it through auditory means. Partially sighted users encountered challenges related to reading the supplementary information on the artefact. Using the combination of the screen reader and the haptics, 90% of the blind participants effectively detected the necklace and learned more details about it. There was one blind participant who partially completed the scenario. The participant managed to locate the Nefertiti statue in the VE, find the necklace, and access additional information about it. However, they were unable to hear all the details due to the requirement of keeping their hand still. This is one limitation of the system that was identified and it is addressed in the second version of the SHIFT XR Accessibility Framework (Section 9). Similarly, to blind users, most partially sighted participants were able to complete the scenario. However, a participant with low vision couldn't read the necklace details because the text was located on the right side of the screen, which fell outside their field of view.

Proceeding to scenario 4, it was rated as moderately easy with an average score of 4.55 out of 7, and it boasted a 95% success rate. The successful completion of this scenario hinged upon the ability to discern variances in material between two artifacts. Participants could achieve this discrimination either through reliance on haptic feedback or by visual discrimination. A significant number of participants were successful in this task, whether through haptic cues or visual differentiation. The challenge in this scenario lay in the fact that there were relatively few hotspots available to guide participants. This limited number of hotspots was a deliberate choice made to test their importance in

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

achieving an effective interaction and emphasize their importance to developers. It is worth noting that a singular participant was unable to accomplish the task. This individual was blind and possessed an impairment impacting the tactile sensation on the fingertips. This limitation in the sense of touch was the primary reason for their inability to complete the task.

Scenario 5, received an average rating of 5 out of 7, culminating in a 100% success rate. The challenge in this scenario revolved around the exploration of the painting and its associated hotspots. Unlike previous artefacts, this particular painting adopted a 2D format and possessed relatively substantial dimensions, closely emulating the size of a real painting. The hotspots were strategically distributed across the expanse of the painting's surface. Notably, all participants ultimately succeeded in locating these hotspots and actively engaging with the painting. Their success was attributed to a combination of haptic feedback, three-dimensional sound cues, and comprehensive audio descriptions.

Table 1 presents the results along with statistical information. Overall effectiveness cores were outstandingly good in terms of task completion rate (*M*: 0.97, *SD*: 0.12) and very good in terms of perceived ease of completion (*M*: 5.19, *SD*: 1.91).

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

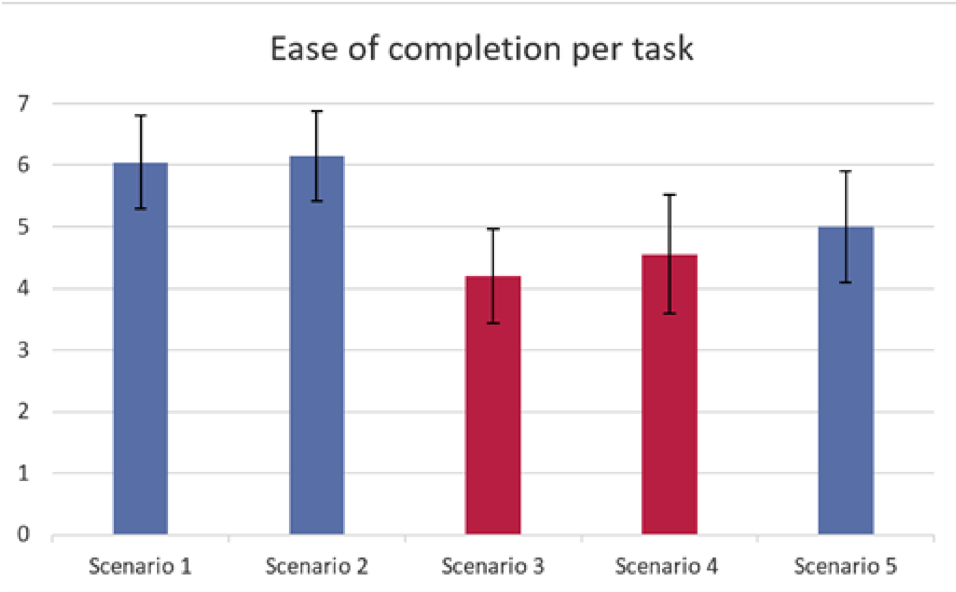

Figure 22: Scenarios Difficulty (very difficult 1, very easy 7). Error bars represent 95% CI

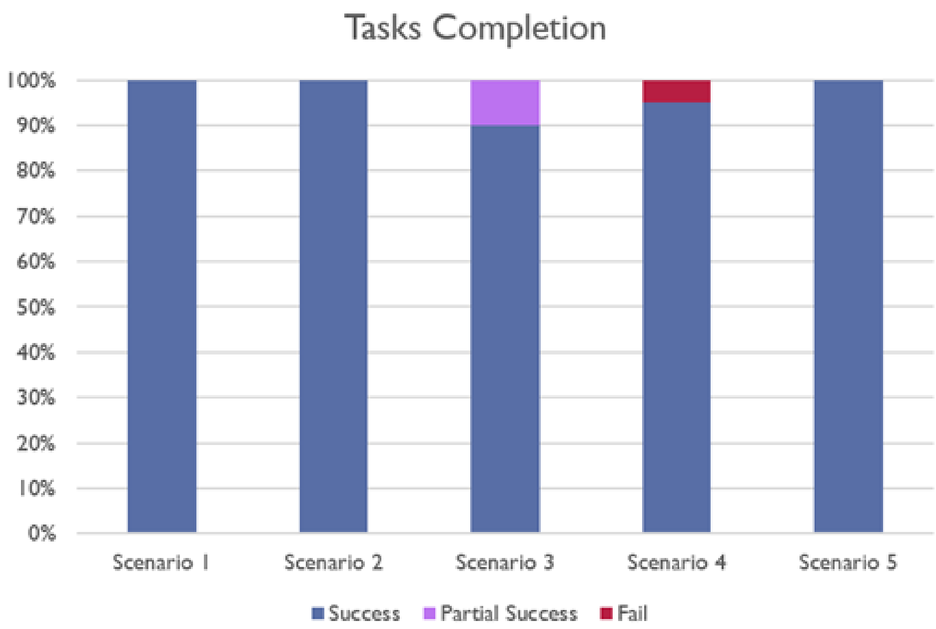

Figure 23: Tasks Completion results

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

	Task 1	Task 2	Task 3	Task 4	Task 5
Mean	6.05	6.15	4.20	4.55	5.00
Min	1.00	1.00	2.00	1.00	1.00
Max	7.00	7.00	7.00	7.00	7.00
Range	6	6	5	6	6
SD	1.60	1.57	1.64	2.06	1.95
95% CI [LL]	5.30	5.42	3.43	3.58	4.09
95% CI [RL]	6.80	6.88	4.97	5.52	5.91

Table 1: Ease of completion per task

An analysis of success rates per task is presented in Table 2, highlighting that the overall success rate for the entire system was 98%, a remarkably high rate, considering that the benchmark for this metric, i.e. the average task completion rate, is 78% [30]. Furthermore, it is observed that the lowest task success rate would be achieved by the general target population which remains a remarkable score. All in all, it is evident that despite any difficulties perceived participants were exceptionally successful in accomplishing the given tasks.

	Task 1	Task 2	Task 3	Task 4	Task 5	Overall
Mean	100%	100%	95%	95%	100%	98%
SD	0	0	0.15	0.22	0	0.12
95% CI [LL]	100%	100%	88%	85%	100%	96%
95% CI [RL]	100%	100%	100%	100%	100%	100%

Table 2: Task success rate

From the above, it is evident that even for the most difficult tasks, we can be quite certain that the wide population of target users, beyond the studied user sample, would not find any task as difficult, considering that the lowest end of all ratings corresponds to a medium task difficulty. While these findings are promising and suggest that the accessibility features effectively supported users in overcoming the perceived challenges, emphasizing their adaptability and utility in assisting users with moderately complex tasks, it is essential to complement them with qualitative feedback results from participants to gain a deeper understanding of their experiences and to identify any specific areas for improvement.

During the debriefing interviews, participants shared their experiences with the system's accessibility features for exploring VR museums. The majority of participants, accounting for 80% of the respondents, expressed a strong belief in the feasibility of the system for museum visits. They highlighted the system's ability to grant them independence during museum exploration, freeing them from the need for assistance. The interviews further uncovered participants' appreciation for the system's ability to bring artifacts closer to them. Nearly 93% of the participants mentioned this as a

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

notable positive aspect of the system, emphasizing the effectiveness of the active element forwarding and the magnification lens in providing them with an immersive and up-close interaction with museum exhibits.

In addition to these positive aspects, a remarkable 82% of participants found the combination of screen reader, 3D sound and haptic feedback to be highly beneficial. They highlighted that this combination provided them with a more comprehensive and engaging exploration experience, appealing to multiple senses. Notably, 98% of the participants found the screen reader functionality really useful and mentioned that it helped them understand the VE they were in. They found that the hierarchical reading was meaningful and provided useful information. Some participants commented that the interaction with the controller, as described in Section 6, was easy to learn and remember. Furthermore, 55% of them referred to the hotspots as really useful because they helped them understand the artifacts and aided in navigation. However, it is important to note that while participants generally appreciated haptic feedback, it was mentioned by some that its precision could be improved. This aspect reflects a potential area for system enhancement. Furthermore, 76% of the participants specifically expressed their satisfaction with the painting's thermal haptic feedback, underscoring its significant positive impact on their experiences. The thermal feedback not only provided a novel sensory experience but also added depth and realism to their interaction with artworks.

However, it is crucial to acknowledge some of the negative aspects voiced by participants. These included challenges related to text and hotspot interaction, where 28% of the participants found it difficult to locate and interact with hotspots effectively. Upon reviewing observers' notes, it became evident that the majority of users would prefer an alternative method for interacting with the hotspot. Presently, users are required to keep their hand steady while interacting with the hotspot to listen to or read the text, and many found this approach challenging. They expressed a preference for a system where they could press a button to keep the hotspot active. In addition, 30% of the partially sighted participants mentioned that they would like to be able to move the text of the hotspot to the position that they feel comfortable with in order to read it clearly. Some participants also mentioned issues with equipment weight, particularly regarding the headset and gloves. They desired lighter equipment for more comfortable and prolonged use. Additionally, blind participants made suggestions for providing a way in order to easily find the artefact in the space. All participants expressed a desire for more information and descriptions of everything in the scene, and 15% of them added that they would like to have the option of different levels of detail in the descriptions.

The positive feedback regarding feasibility, the ability to bring artifacts closer, and the effectiveness of multimodal feedback underscores the value of these features. Nevertheless, the feedback also highlights the importance of addressing challenges related to text and hotspot interaction, equipment

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

weight, and haptic feedback precision as the system evolves to further enhance the UX for individuals with visual impairments.
Lessons learned in this regard from the analysis pertain both to the framework and to how content should be designed.

Framework Insights
#1 - Do not impose unnecessary strain on the users: Once the screen reader for an element has been activated, there should not be a requirement for the user to continuously hold their hand over the artefact of interest to hear the entirety of its description.
#2 - Support personalization for artefact widgets: All widgets (e.g. text) should support user adjustment in terms of their position in the user's field of view to better fit their needs
#3 – Bring the currently active XR element to the foreground: This is especially helpful for partially sighted individuals.
#4 – The hierarchical reading of the XR scene is helpful, allowing users to better perceive the structure of the interactive elements in an environment and navigate all the contained interactive elements.
#5 – The magnification lens is useful for partially sighted users.
#6 – Enhance artefact findability: The framework should guide the users toward locating the artifact in the virtual space and exploring it through touch, by incorporating turn-by-turn audio guidance and audio feedback.

Accessible XR experiences findings
#1 – Multimodal output ensures effectiveness: Haptic feedback in combination with audio descriptions is an effective means of interaction in XR for blind and partially sighted persons.
#2 – Do not spare the hotspots: Enrich artefacts with an adequate number of hotspots to convey all the information that is important. Well-balance and disperse the hotspots on the artefact's surface to improve the UX.
#3 – Lightweight equipment: It is important for user acceptance to achieve hardware equipment that is comfortable to wear for prolonged use, considering weight among other factors.
#4 – Design the haptic feedback carefully: Use the haptic feedback in interactions that make sense in a realistic way.
#5 – Design artefact hotspots to be findable: Hotspots may be hard to locate for blind individuals. Consider enhancing it with additional feedback, such as haptics.

8.6.2 User Experience

In line with hypothesis H3, we assessed the UX of participants while they engaged with the system by analyzing their responses to the standardized UEQ and the SSQ questionnaires, as well as their responses in the debriefing discussion.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

UEQ Results

This questionnaire gauges various dimensions of the UX, including:

- Attractiveness: Reflects users' overall impressions of the product, indicating whether they have a favorable or unfavorable opinion.
- Perspicuity: Assesses the ease with which users become acquainted with the product and learn how to use it effectively.
- Efficiency: Measures users' ability to accomplish tasks without unnecessary effort or complications.
- Dependability: Gauges the extent to which users feel in control during their interactions with the system.
- Stimulation: Evaluates whether users find the product engaging, exciting, and motivating to use.
- Novelty: Considers the product's degree of innovation and creativity and whether it piques users' interest.

The scale used for these assessments' ranges from -3 (indicating an extremely negative experience) to +3 (indicating an exceptionally positive experience). Table 3 presents the results across all scales, which are also illustrated in Figure 24 (left). Figure 24 (right) provides the results across three coarser categories, namely attractiveness, pragmatic quality, which refers to task-related quality aspects, and hedonic quality. It is important to note that the results indicate positive scores for all categories thus contributing to the conclusion that the overall UX of the VR system was positive.

	Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation	Novelty
Mean	1.64	1.250	1.12	1.07	1.87	1.57
Variance	1.10	1.02	0.79	0.61	0.71	0.85
SD	1.05	1.01	0.89	0.78	0.84	0.92
95% CI [LL]	1.18	0.81	0.74	0.73	1.51	1.17
95% CI [RL]	2.10	1.69	1.51	1.42	2.24	1.98

Table 3: UEQ Results

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

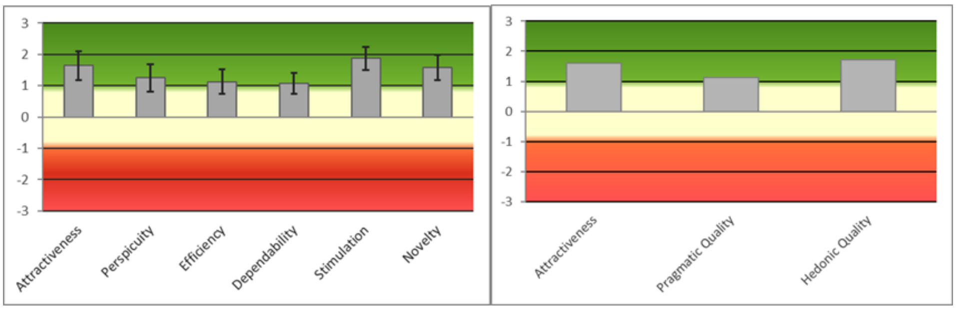

Figure 24: User Experience Scores per construct (left) and per pragmatic quality (right)

Further analysis of the responses, looking into the distributions of answers to each item, highlighted the system characteristics that raised heightened concerns among users. In particular, the item which was least favorably rated refers to the predictability of the system, showing that 45% of participants felt that the system's behavior was not easy to predict. This can be attributed to the fact that this was the first encounter of the users with such a system, making it difficult for them to feel familiar and predict how the system works. Some participants also provided explanations themselves, indicating that they did not consider it a problem and that in such a novel environment they would not know what to expect next, but this did not actually bother them. The next point of concern was the practicality of the solution, with 35% of the responses being closer to the lower end of the scale and denoting that the system was impractical. Notably, most of the UX aspects received very positive scores. The system was found to be: Very interesting, according to 95% of participants; exciting, organized, and innovative according to 90% of participants; understandable, creative, supportive, and leading edge according to 85% of participants; easy to learn, inventive, good, pleasing, motivating, friendly, and in accordance with expectations for 80% of participants; enjoyable, valuable, secure, and attractive for 75% of participants; and pleasant for 70% of the participants. Aiming to further elaborate on H3, the overall UX assessment was compared against benchmarks, consistently surpassing average benchmarks (Figure 25), thus confirming so far the hypothesis that the system ensures a positive UX.

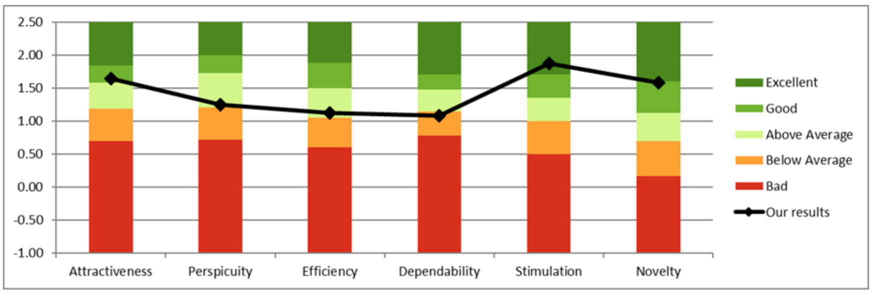

Figure 25: User Experience Benchmark Results

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

SSQ Results

In order to assess the sickness that the VR headset might cause to the participants during the study, we analyzed the results from the SSQ questionnaire. This questionnaire is standardized and focuses on symptoms like nausea, oculomotor disturbance, and disorientation. It is important to note that, in recognition of diverse user profiles, we included a "Not Applicable" option in the questionnaire for participants who may not have encountered certain symptoms due to specific conditions. For instance, symptoms like "Eye strain" or "Blurred vision" might not be applicable to blind users. Table 4 presents the results of the SSQ questionnaire, organized into three main categories as discussed above, including one additional score for the overall simulator sickness. Figure 26 presents the results in terms of their importance, classified into four categories, namely negligible, minimal, significant, and concerning.

	Nausea	Occ. Disturbance	Disorientation	Total Sickness
Mean	1.16	2.74	3.48	9.20
Variance	0.14	0.48	0.34	0.30
SD	0.38	0.69	0.59	0.55
95% CI [LL]	1.10	2.62	3.38	9.14
95% CI [RL]	1.23	2.85	3.57	9.26

Table 4: SSQ Results

Upon analyzing the results, it is evident that the overall simulator sickness levels, as indicated by the Total Simulator Sickness (TS) score, fall within the "Minimal" range, with a score of 9.20. This suggests that the simulated experience generally had a low impact on users' well-being. Specifically, the symptoms of Nausea, Oculomotor Disturbance, and Disorientation were reported with severity values of 1.16, 2.74, and 3.48, respectively, all falling within the "Negligible" category (scores below 5). Therefore, results from simulation sickness confirm findings on UX, since any inadvertent effects were negligible. The "Not Applicable" option was chosen by some participants for certain symptoms, such as “Blurred Vision”. Overall, the results indicate that the simulator experience has a generally low impact on users' health, with most symptoms falling into the "Negligible" category. However, the inclusion of the "Not Applicable" option serves as a

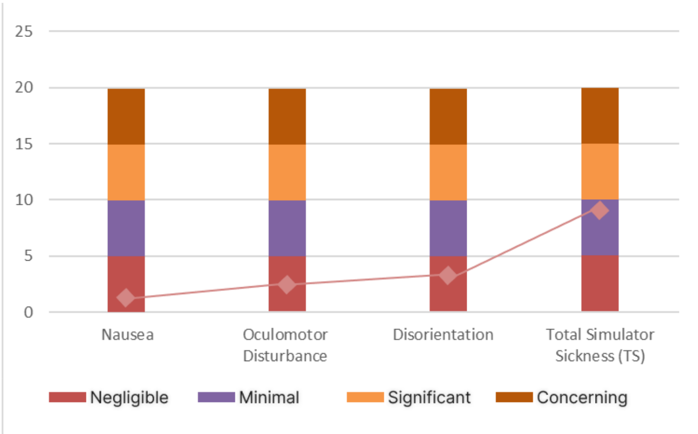

Figure 26: Simulator Discomfort Results against benchmarks

Funded by the European Union
This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement no 101060660.

reminder that UXs can vary significantly, and a personalized approach to addressing symptoms is essential to provide the best possible UX.

Participants' responses to the debriefing questions were further analyzed in terms of likes and dislikes, as well as suggestions for improvement. In particular, participants' likes were as follows:

- Haptic feedback in terms of temperature, which was explicitly mentioned by 40% of the participants
- The combination of different modalities, and in specific of sound and haptics, was appraised by 30% of the participants
- The artefacts which are brought close to the user, which was one of the most liked features for 20% of the participants
- The content descriptions (through hotspots) which were one of the most favorite items for 20% of the participants
- The magnifying lens and the haptic sensing of artefacts, for 15% of the participants
- The comfortable lighting, the adjustability offered, the navigation in the VE, the colors used, and the embedded screen reader, each pointed out by 5% of the participants

From the above, it can be inferred that innovative attributes, such as temperature sensing were well-received. Also, the combination of modalities, as well as specific features such as bringing items closer, enriching artefacts with hotspots, and offering tools such as magnifying lenses, and haptic feedback contributed positively to the overall UX.

On the other hand, participants' dislikes regarding their experience with the accessible VR museum were the following:

- 15% of the participants (30% of the blind participants) faced difficulties in locating the information accompanying an artefact upon selection. The issue arose because users had to keep their hand still to hear information. A potential solution is to let users choose what they want to hear by pressing a button and stop by deselecting the button.
- 25% of the participants (50% of the low vision participants) were not satisfied with the placement of the text next to the artefact. Their concerns stemmed from the fact that the text's location necessitated significant head movements, such as tilting the head upwards or to the right. This was particularly challenging because of the device's weight. Furthermore, in some instances, the text was positioned in a way that fell outside the participant's field of vision. Suggestions in this regard were to be able to move the placement of widgets or move oneself within the VE. This is an acknowledged limitation of the designed use case VR environment which was designed to act mostly as a demonstrator of the accessibility features.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

- 25% of the participants (50% of the blind participants) encountered challenges in locating the artefacts in the virtual space. In more detail, although they navigated effectively in the artefacts contained in the room, and the artefact was brought in front of them upon selection when they had to explore it with their hand to get additional information, they would not know exactly where in front of them the artefact was located. This made them feel uncertain.
- 20% of the participants were not satisfied with the weight of the haptic device, whereas 5% of the participants would like the haptic feedback to expand to all fingers (currently, the device provides haptic feedback equipment for the thumb and two fingers).
- 5% of the participants did not appraise interaction with the VR controller. It is notable though that another 5% of the participants classified interaction with the VR controller as one of their most liked system attributes. In this regard, future deployments should explore additional interaction devices to better address the needs of all potential users. The headset controller handles four specific commands, and some participants have suggested a triangular-shaped custom switch to perform these tasks, but this idea needs further assessment.

Additional features requested by users were the ability to move in the VE, but also have control over the position of the widgets. Considering that the latter may be unnecessary in VR environments supporting user navigation and movement, additional studies may be needed to further explore this. To address the issue with the findability of an artefact by blind individuals, additional navigation clues through 3D sounds and haptics should be added. Increased information and details were also requested by several participants, making clear the need for a focus on the content when designing VEs for blind persons. Additional information on the users' orientation when exploring an artefact (e.g. you are currently at the top left corner, middle of the artefact, etc.) was also highlighted as a useful feature. Finally, blind participants highlighted the need for adjustable speech rate, as customary in screen readers. Participants overall believed that such a system would assist them in exploring VR museums. In particular, 80% of the participants were very positive in this regard, appraising the combination of output modalities and the potential that such a system holds for a person with visual disabilities to explore a museum collection on their own without any assistance. The remaining 20% identified that they would like the system to be improved first, in accordance with their provided comments, before considering it as an alternative solution for museum exploration.

Framework Insights

#8 – Support customizable speech rate: To accommodate user preferences regarding the speed at which they wish to listen to audible information, the framework should support adjustable speech rate, to be initialized by the developers and modified by end users.

#9 – Incorporate orientation information within an artefact: To assist blind users in developing a mental map of the artefact provide position information when they explore the selected artefact through touch.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Accessible XR Experiences Findings
#10 – Avoid stationary experiences: Users appraise flexibility and freedom to explore VR environments by moving around
#11 – Support alternative interaction modalities besides the VR controller: Allow users to select their preferred input device, providing full support for alternative devices, such as the keyboard.

8.6.3 Mental Workload

In order to measure the mental workload of the participants while using the system (H2), the results of the NASA-TLX questionnaire were analyzed. The NASA-TLX is a widely used and standardized assessment tool originally developed by NASA in the 1980s to evaluate the perceived workload and task performance. The questionnaire comprises six key dimensions, each rated on a scale from 0 to 100, as follows:

- Mental demand: Assesses how much mental and perceptual activity is required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)
- Physical demand: Measures how much physical activity is required
- Temporal demand: Explores how much time pressure the user felt due to the rate or pace at which the tasks occurred
- Performance: Assesses how successful the participants think that they were in accomplishing the goals of the task set by the experimenter
- Effort: Explores how hard the user had to work to accomplish their level of performance
- Frustration: Measures how insecure, discouraged, irritated, stressed, and annoyed the user was as opposed to how secure, gratified, content, and relaxed they were.

Each of the dimensions is scored separately, whereas the overall NASA-TLX score indicates the overall workload of the user. It is noted that NASA-TLX foresees a weighting procedure according to which the importance of each workload dimension is determined for each individual participant. Studies in the literature report either the raw (unweighted) or raw scores [31], however, there is evidence that weighted scores should better be employed [32].

The results of the NASA-TLX questionnaire reveal valuable insights into the participants' perception of workload during the tasks (Figure 26). In more details, Table 5 presents the raw scores for each one of the dimensions, whereas Table 6 shows the weighted scores. The overall raw workload score was 24.70, whereas the overall weighted workload score was 25.97. Both workload scores are exceptionally good and rank our system in the first quartile (and more specifically in the top 10%) regarding the workload induced across various studies and in the second quartile regarding the workload induced by computer activities [106]. Unfortunately, there are no benchmark or summative studies on workload in VR environments, therefore it is not possible to draw any further conclusions.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Considering, however, that the overall workload induced is classified as substantially lower than 50% of the workload reported in computer activities, hypothesis H2 is (strongly) supported.

	Mental	Physical	Temporal	Performance*	Effort	Frustration
Mean	25.75	24.75	19.75	23.00	35.50	19.50
Min	0.00	0.00	0.00	0.00	0.00	0.00
Max	70.00	60.00	100.00	60.00	70.00	80.00
Range	70.00	60.00	100.00	60.00	70.00	80.00
SD	18.37	21.68	24.63	16.41	19.25	24.33
95% CI [LL]	17.15	14.61	8.22	15.32	26.49	8.11
95% CI [RL]	42.90	39.36	27.97	38.32	61.99	27.61

*Table 5: NASA-TLX raw scores per scale. * It is noted that performance is an inverted scale.*

	Mental	Physical	Temporal	Performance*	Effort	Frustration
Mean	46.00	54.50	53.75	90.75	93.50	50.25
Min	0.00	0.00	0.00	0.00	0.00	0.00
Max	210.00	200.00	400.00	240.00	210.00	400.00
Range	210.00	200.00	400.00	240.00	210.00	400.00
SD	54.25	61.26	92.26	70.15	63.60	98.49
95% CI[LL]	20.61	25.83	10.57	57.92	63.73	4.15
95% CI[RL]	71.39	83.17	96.93	123.58	123.27	96.35

*Table 6: NASA-TLX weighted scores per scale. * It is noted that performance is an inverted scale.*

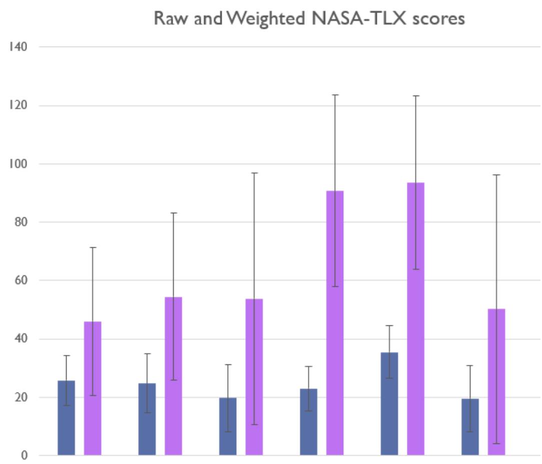

Figure 26: Raw and weighted NASA-TLX scores ion

Furthermore, the weights assigned to the various NASA-TLX dimensions by participants highlight the most important parameters of their interaction with the system. In particular, the average weights are ordered from the highest to the lowest values as follows: Performance (*M*: 4.43; *SD*: 0.73), Effort (*M*: 2.71; *SD*: 0.96), Temporal (*M*: 2.71; *SD*: 1.33), Physical (*M*: 1.93; *SD*: 1.49), Frustration (*M*: 1.64; *SD*: 2.00), and Mental (*M*: 1.57; *SD*: 1.40). Therefore, it is evident that performance was the workload attribute that was more important to participants, thus highlighting that what matters most is to be able to effectively achieve the tasks they were given. On the other hand, mental demands were the attribute with the lowest relative importance, signifying that participants would not mind investing some mental effort in order to achieve their performance. Further analysis of the results acquired in the weighted scores highlights

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

that the two most important points of workload pertain to effort and performance. This means that the main point of distress for participants would be the effort they had to invest in order to achieve their performance. This is an expected finding, considering that this was a novel environment for participants, the majority of whom had never used a VR system in the past, probably due to the lack of accessibility. It is notable that although the raw score for performance was very good (M: 23.00; SD: 16.41), performance emerged as the second most significant contributor to overall workload when considering the participant-assigned weights in the final weighted scores (M: 90.75; SD: 70.15). Furthermore, based on the other scores of the NASA-TLX scales, it can be inferred that participants did not feel that the mental and physical effort entailed was high, and neither were any temporal demands or frustration imposed by the use of the system.

Framework Insights

#1 –Do not impose unnecessary strain on the users: Once the screen reader for an element has been activated, there should not be a requirement for the user to continuously hold their hand over the artefact of interest to hear the entirety of its description.

#2 – Support personalization for artefact widgets: All widgets (e.g. text) should support user adjustment in terms of their position in the user's field of view to better fit their needs.

#3 – Bring the currently active XR element to the foreground: This is especially helpful for partially sighted individuals.

#4 – The hierarchical reading of the XR scene is meaningful, allowing users to better perceive the structure of the interactive elements in an environment and navigate all the contained interactive elements.

#5 – Magnification lens is useful for partially sighted users.

#6 – Enhance artefact findability: The framework should guide the users toward locating the artifact in the virtual space and exploring it through touch, by incorporating turn-by-turn audio guidance and audio feedback.

#7 – Haptic output is useful as a modality complementing other senses: Although the maturity and detail provided by current haptic devices are not sufficient to make haptics an independent output modality, its complementarity with other output modalities is highly appraised in promoting more holistic experiences.

#8 – Support customizable speech rate: To accommodate user preferences regarding the speed at which they wish to listen to audible information, the framework should support adjustable speech rate, to be initialized by the developers and modified by end users.

#9 – Incorporate orientation information within an artefact: To assist blind users in developing a mental map of the artefact provide position information when they explore the selected artefact through touch.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

Accessible XR Experiences Findings
#1 – Multimodal output ensures effectiveness: Haptic feedback in combination with audio descriptions is an effective means of interaction in XR for blind and partially sighted persons.
#2 – Do not spare the hotspots: Enrich artefacts with an adequate number of hotspots to convey all the information that is important. Well-balance and disperse the hotspots on the artefact's surface to improve the UX.
#3 – Lightweight equipment: It is of paramount importance for user acceptance to achieve hardware equipment that is comfortable to wear for prolonged use, considering weight among other factors.
#4 – Design the haptic feedback carefully: Use the haptic feedback in interactions that make sense in a realistic way.
#5 – Design artefact hotspots to be findable: Hotspots may be hard to locate for blind individuals. Consider enhancing it with additional feedback, such as haptics.
#6 – Strive for detailed haptic design to pursue well-perceived feedback: Besides conveying temperature and material, haptics could also convey distance from an artefact.
#7 – Include temperature feedback when possible and applicable: Temperature was a well-perceived haptic information offering additional insights to users regarding the attributes of an artefact they were exploring.
#8 – Consider employing alternative artefact positioning, disassociating it from real-world conventions: Haptic exploration may be facilitated by a horizontal placement of some artefacts such as paintings. Unlike physical museums where participants cannot alter the positioning of exhibits, in VEs users can be free to explore artefacts as they prefer.
#9 – Employ haptic feedback beyond real-world conventions: Although an item in the real world may not be explored via touch, this is a convention that should not be transferred to the VE.
#10 – Avoid stationary experiences: Users appraise flexibility and freedom to explore VR environments by moving around.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

9. Refinements and Final Version of the Extended Reality Accessibility Framework

Following the Human-Centered Design methodology, we refined the XR Accessibility Framework based on insights gained from the user-based evaluation. This evaluation highlighted both the strengths and areas for improvement, guiding our efforts toward enhancing the framework's effectiveness. The primary focus of the refinements was to improve the findability of artefacts within the VE and to provide better guidance for users as they navigate from one hotspot to another. A key aspect of these refinements was the integration of multimodal interaction strategies, ensuring that users with diverse accessibility needs could engage seamlessly with the VE. These enhancements were closely aligned with the developments in T3.4 *Haptic Techniques for 3D Digital Asset Perception*, as detailed in D3.7. While the haptics tool primarily focuses on leveraging haptic feedback to improve artefact discovery and user orientation, the XR Accessibility Framework extends these functionalities by incorporating additional layers of accessibility, such as adaptive visual cues, audio feedback, and customizable settings. Furthermore, the XR Accessibility Framework has integrated the rest of the tools developed in the context of WP3, namely contemporary asset description (T3.2) and text-to-speech tool (T3.3). To enhance accessibility, both textual and audio descriptions of artefacts are now dynamically adjusted based on the user profile, ensuring a more personalized and inclusive experience.

9.1 Findability of Artefacts within the Virtual Environment

In the initial version of the XR Accessibility Framework, artefact findability within the VE was facilitated by automatically bringing the artefact in front of the user, ensuring it was within their reach. While this approach allowed users to interact with objects more easily, it proved insufficient for blind users, who lacked spatial awareness of the artefact's exact position and orientation. Without clear guidance, users struggled to determine where to place their hands or how to begin exploring the object effectively.

To address this challenge, and in response to user feedback, we introduced a "starting point" prefab for all artefacts, as described in D3.7. This prefab acts as an initial contact point between the user's hand and the artefact, establishing a structured and predictable way to engage with objects in the VE. Instead of repositioning the artefact within reach, the framework dynamically adjusts its placement to ensure that the starting point aligns precisely with the user's hand location. This way, users always begin their exploration from a designated location. Beyond spatial positioning, the starting point prefab has been further enhanced with context-aware audio descriptions that provide directional guidance, that the developer can add. These descriptions are tailored to each artefact and adjust based on where the starting point is located. For instance, as illustrated in Figure 27 (right), if the starting point is positioned on the top right corner of a painting, the screen reader announces: "Top right corner of the painting, move your hand left." Alternatively, if the starting point is placed at the bottom of a

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

statue (Figure 27 left), the screen reader provides a different instruction: "Bottom of the artefact, move your hand up." This method ensures that users receive precise feedback on how to proceed with their exploration, reducing guesswork and enhancing engagement. Additionally, this structured approach enables a more consistent and repeatable way to interact with CH artefacts, which is particularly beneficial for users who rely on non-visual cues to navigate the VE.

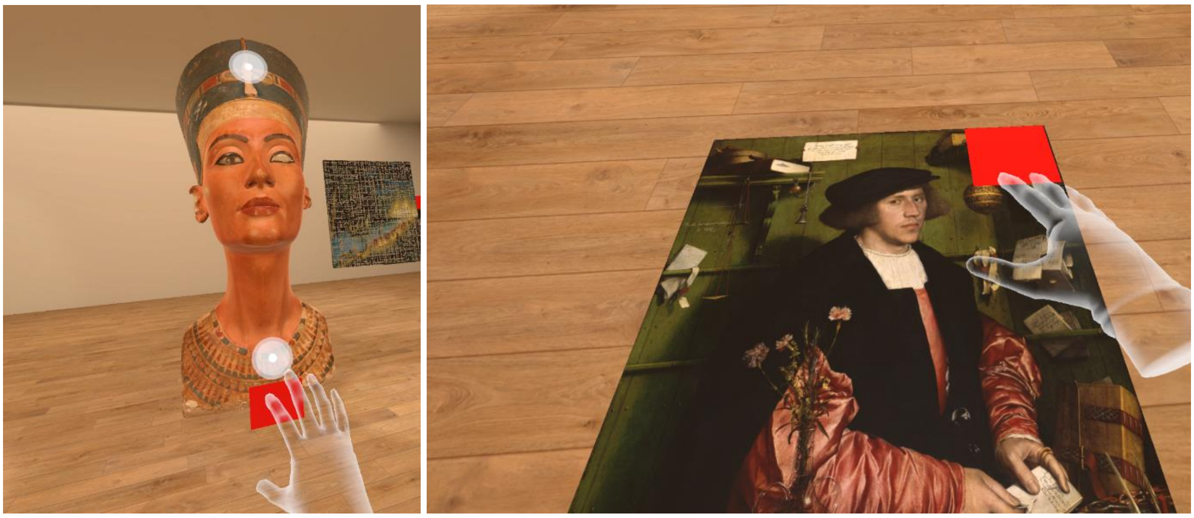

Figure 27: Starting points on a statue (left) and on a painting (right)

Furthermore, another challenge identified during user evaluations was that, as users explored artefacts, they often moved beyond the artefact's boundaries without realizing it. Relying solely on haptic feedback was not sufficient, as it took time for users to recognize that they were outside the artefact. To address this, the Accessibility Framework enhances the haptic bounds developed in D3.7 by integrating screen reader and audio feedback. When a user touches a haptic bound (an area outside the artefact), a distinct sound is triggered to provide an immediate auditory cue. Following this, the screen reader delivers a verbal instruction based on the specific bound that was touched. For example, if the user moves beyond the right boundary of an artefact, the screen reader announces: "You are outside of the artefact, move your hand left." To generate these instructions dynamically, the Accessibility Framework constructs the screen reader's response using a predefined directional dictionary: [{"up", "down"}, {"down", "up"}, {"left", "right"}, {"right", "left"}]. Each key in this dictionary corresponds to the tag of the haptic bound, while the associated value represents the direction in which the user should move. For instance, if the user touches the right bound (which has the tag "right"), the framework selects the left command, prompting the screen reader to announce: "You are outside of the artefact, move your hand left." This approach ensures that users receive both

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

immediate auditory feedback and clear directional guidance, improving spatial awareness and navigation within the VE.

9.2 Hotspot-to-Hotspot Guidance

Another key challenge identified during user evaluations was the findability of hotspots on an artefact. Users expressed the need for a structured way to be guided across an artefact, ensuring they could systematically explore all hotspots and points of interest. Without such guidance, users often had difficulty locating subsequent hotspots, resulting in a disjointed and less efficient exploration process.

To address this, the haptics tool introduces a guidance system that creates virtual haptic paths connecting the hotspots, allowing users to follow tactile feedback along a predefined route (D3.7). While this haptic feedback is effective, additional cues were necessary to enhance clarity and reinforce the user's spatial awareness. To this end, the XR Accessibility Framework extends this functionality by integrating 3D spatialized sound alongside haptic feedback. When the user's hand enters a guidance path, a beep sound is triggered, providing an immediate auditory cue that they are on the correct route. As long as the user's hand remains on the virtual path, the beep continues to play at a steady interval, reinforcing that they are following the correct trajectory. As the user moves closer to the next hotspot, the beep frequency increases, signaling proximity. For example, at the start of the path, the user hears "beep ---- beep --- beep", but as they approach the next hotspot, the frequency accelerates to "beep--beep--beep", creating a clear audio gradient. If the user's hand strays off the virtual path, the beep sound stops, signaling that they have deviated from the intended route. This combination of haptic and audio feedback creates a multimodal navigation system that allows users to intuitively follow the designated exploration path while receiving continuous spatial guidance. The dynamic nature of the beeping frequency reinforces a sense of direction and distance, helping users understand how close they are to the next hotspot.

9.3 Integration of WP3 Tools to Extended Reality Accessibility Framework

For the final version of the XR Accessibility Framework, all tools developed within WP3 have been fully integrated, ensuring a multimodal approach to accessibility. The contemporary asset description tool (T3.2) allows artefact descriptions to be dynamically adjusted based on the user's profile, ensuring that the information presented is relevant, accessible, and appropriately detailed for different audiences. The text-to-speech tool (T3.3) enables users to listen to artefact descriptions rendered in varied voices, with narration styles tailored to different user categories. Additionally, the haptics tool (T3.4) provides tactile exploration of CH assets, enhancing interaction, particularly for blind and visually impaired users. The XR Accessibility Framework supports a broad range of adaptations, accommodating user categories such as blind and visually impaired individuals, CH professionals, children, and the general

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

public. When a user selects a category, the system automatically adapts all content to align with their specific needs and preferences. For example, when the system is set to CH professionals, descriptions include more detailed historical, artistic, and technical insights, catering to experts who require in-depth information. Conversely, when set to children, the framework simplifies descriptions, ensuring they are engaging, easy to understand, and age-appropriate. Additionally, the text-to-speech system adjusts the narration style, using a more animated and expressive voice to capture children's attention and make the exploration process more immersive and enjoyable (D3.5, D3.6).

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

10. Conclusion

This deliverable presents the work that was carried out in T3.5 and its outcomes. The deliverable introduces the SHIFT XR Accessibility Framework, designed to address the need for enhanced accessibility in XR applications. A wide array of features is provided, ranging from customizable text settings to scene adaptations, alternative text for visual elements, hierarchical audio descriptions, hotspots, and versatile user interaction mechanisms.

To evaluate the first version of the framework, a user-based evaluation was conducted with 20 participants with visual impairments, aiming to assess the accessibility features regarding the effectiveness, the workload, and the overall UX. Regarding effectiveness, the evaluation results showed a high overall task completion score (*M*: 0.97, *SD*: 0.12) and excellent ease of completion (*M*: 5.19, *SD*: 1.91), testifying that users effectively interacted with the system and accessed virtual museum artefacts without significant hindrance. Furthermore, the results show that the system does not induce workload. The UX feedback was overwhelmingly positive, with participants expressing satisfaction in terms of system attractiveness, efficiency, and ease of use. However, practical concerns were raised, particularly by blind users who struggled with locating objects through touch. Suggestions included improving audible and haptic navigation instructions to aid blind users in effectively navigating the VR space.

Responding to valuable user feedback, multiple refinements were made. For the final version of the framework, artefact findability was improved through the introduction of a “starting point” prefab, ensuring a structured way for users to locate artefacts upon interaction. Additionally, the hotspot-to-hotspot guidance system was extended with 3D spatialized sound, complementing the haptic feedback and allowing users to follow structured virtual paths between key points of interest. To address the issue of users moving outside artefact boundaries, the framework now integrates audio cues and screen reader messages, informing users when they exit the artefact and guiding them back onto the interactive area. Finally, the final version of the framework harnesses the technologies developed in WP3, ensuring an adaptable experience for diverse user groups. The contemporary asset description tool (T3.2) allows for customized text descriptions, the text-to-speech tool (T3.3) provides personalized narration styles, and the haptics tool (T3.4) enables tactile exploration of digital artefacts. The system supports distinct adaptations for blind and visually impaired individuals, CH professionals, children, and the general public, dynamically adjusting content based on the selected user profile.

This deliverable marks the completion of Task 3.5 *Accessible framework of inclusive museum exhibits for 3D digital asset perception* and its outcomes will be evaluated during the SHIFT pilots (SMB-PK).

Funded by the European Union

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement no 101060660.

11. References

[1] G. Margetis, K. Apostolakis, S. Ntoa, G. Papagiannakis, and C. Stephanidis, “X-Reality Museums: Unifying the Virtual and Real World Towards Realistic Virtual Museums,” *Appl. Sci.*, vol. 11, p. 338, Dec. 2020, doi: 10.3390/app11010338.

[2] D. Gavgiotaki, S. Ntoa, G. Margetis, K. Apostolakis, and C. Stephanidis, “Gesture-based Interaction for AR Systems: A Short Review,” Aug. 2023, pp. 284–292. doi: 10.1145/3594806.3594815.

[3] M. Antona and C. Stephanidis, Eds., *Universal Access in Human-Computer Interaction. Design Methods and User Experience: 15th International Conference, UAHCI 2021, Held as Part of the 23rd HCI International Conference, HCII 2021, Virtual Event, July 24–29, 2021, Proceedings, Part I*, vol. 12768. in Lecture Notes in Computer Science, vol. 12768. Cham: Springer International Publishing, 2021. doi: 10.1007/978-3-030-78092-0.

[4] A. H. Hoppe, J. K. Anken, T. Schwarz, R. Stiefelhagen, and F. van de Camp, “CLEVR: A Customizable Interactive Learning Environment for Users with Low Vision in Virtual Reality,” in *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility*, in ASSETS ’20. New York, NY, USA: Association for Computing Machinery, Oct. 2020, pp. 1–4. doi: 10.1145/3373625.3418009.

[5] Y. Zhao, E. Cutrell, C. Holz, M. R. Morris, E. Ofek, and A. D. Wilson, “SeeingVR: A Set of Tools to Make Virtual Reality More Accessible to People with Low Vision,” in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, in CHI ’19. New York, NY, USA: Association for Computing Machinery, May 2019, pp. 1–14. doi: 10.1145/3290605.3300341.

[6] H.-C. Wang, R. K. Katzschmann, S. Teng, B. Araki, L. Giarré, and D. Rus, “Enabling independent navigation for visually impaired people through a wearable vision-based feedback system,” in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, May 2017, pp. 6533–6540. doi: 10.1109/ICRA.2017.7989772.

[7] “Racing in the Dark: Exploring Accessible Virtual Reality by Developing a Racing Game for People who are Blind.” Accessed: Oct. 13, 2022. [Online]. Available: https://journals.sagepub.com/doi/epdf/10.1177/1071181321651224

[8] Z. Chi, Z. Niu, and T. Sawabe, “Enabling Augmented Reality Incorporate with Audio on Indoor Navigation for People with Low Vision,” in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, Mar. 2022, pp. 882–883. doi: 10.1109/VRW55335.2022.00292.

[9] T. F. Ji, B. Cochran, and Y. Zhao, “VRBubble: Enhancing Peripheral Awareness of Avatars for People with Visual Impairments in Social Virtual Reality,” in *Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility*, in ASSETS ’22. New York, NY, USA: Association for Computing Machinery, Oct. 2022, pp. 1–17. doi: 10.1145/3517428.3544821.

[10] H.-Y. Wu, A. Calabrèse, and P. Kornprobst, “Towards accessible news reading design in virtual reality for low vision,” *Multimed. Tools Appl.*, vol. 80, no. 18, pp. 27259–27278, Jul. 2021, doi: 10.1007/s11042-021-10899-9.

Funded by the European Union

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement no 101060660.

[11] K. Weir, F. Loizides, V. Nahar, A. Aggoun, and A. Pollard, "I see therefore i read: improving the reading capabilities of individuals with visual disabilities through immersive virtual reality," *Univers. Access Inf. Soc.*, Nov. 2021, doi: 10.1007/s10209-021-00854-8.

[12] A. F. Siu, M. Sinclair, R. Kovacs, E. Ofek, C. Holz, and E. Cutrell, "Virtual Reality Without Vision: A Haptic and Auditory White Cane to Navigate Complex Virtual Worlds," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, in CHI '20. New York, NY, USA: Association for Computing Machinery, Apr. 2020, pp. 1–13. doi: 10.1145/3313831.3376353.

[13] T. Zaal, A. A. Akdag Salah, and W. Hürst, "Toward inclusivity: Virtual reality museums for the visually impaired," in *2022 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, Dec. 2022, pp. 225–233. doi: 10.1109/AIVR56993.2022.00047.

[14] L. Fialho, J. Oliveira, A. Filipe, and F. Luz, "Soundspace VR: spatial navigation using sound in virtual reality," *Virtual Real.*, pp. 1–9, Nov. 2021, doi: 10.1007/s10055-021-00597-0.

[15] G. India, M. Jain, P. Karya, N. Diwakar, and M. Swaminathan, "VStroll: An Audio-based Virtual Exploration to Encourage Walking among People with Vision Impairments," Oct. 2021, pp. 1–13. doi: 10.1145/3441852.3471206.

[16] Y. Zhao, S. Szpiro, J. Knighten, and S. Azenkot, "CueSee: exploring visual cues for people with low vision to facilitate a visual search task," in *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, in UbiComp '16. New York, NY, USA: Association for Computing Machinery, Sep. 2016, pp. 73–84. doi: 10.1145/2971648.2971730.

[17] T. Langlotz, J. Sutton, S. Zollmann, Y. Itoh, and H. Regenbrecht, "ChromaGlasses: Computational Glasses for Compensating Colour Blindness," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, in CHI '18. New York, NY, USA: Association for Computing Machinery, Apr. 2018, pp. 1–12. doi: 10.1145/3173574.3173964.

[18] L. S. Guedes, L. A. Marques, and G. Vitório, "Enhancing Interaction and Accessibility in Museums and Exhibitions with Augmented Reality and Screen Readers," in *Computers Helping People with Special Needs*, K. Miesenberger, R. Manduchi, M. Covarrubias Rodriguez, and P. Peňáz, Eds., in Lecture Notes in Computer Science. Cham: Springer International Publishing, 2020, pp. 157–163. doi: 10.1007/978-3-030-58796-3_20.

[19] S. Ntoa, G. Margetis, M. Antona, and C. Stephanidis, "Scanning-Based Interaction Techniques for Motor Impaired Users," 2013, pp. 57–89. doi: 10.4018/978-1-4666-4438-0.ch003.

[20] "XR Interaction Toolkit | XR Interaction Toolkit | 2.3.2." Accessed: Aug. 26, 2023. [Online]. Available: https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@2.3/manual/index.html

[21] M. Teófilo, V. F. Lucena, J. Nascimento, T. Miyagawa, and F. Maciel, "Evaluating accessibility features designed for virtual reality context," in *2018 IEEE International Conference on Consumer Electronics (ICCE)*, Jan. 2018, pp. 1–6. doi: 10.1109/ICCE.2018.8326167.

[22] 14:00-17:00, "ISO 9241-210:2019," ISO. Accessed: Oct. 12, 2023. [Online]. Available: https://www.iso.org/standard/77520.html

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.

[23] "Vision impairment and blindness." Accessed: Oct. 12, 2023. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment

[24] B. Wong, "Points of view: Color blindness," *Nat. Methods*, vol. 8, p. 441, Jun. 2011, doi: 10.1038/nmeth.1618.

[25] M. Antona, S. Ntoa, I. Adami, and C. Stephanidis, "User Requirements Elicitation for Universal Access," in *The Universal Access Handbook*, 2009, pp. 15–1.

[26] J. Sauro and J. Dumas, "Comparison of three one-question, post-task usability questionnaires," presented at the Conference on Human Factors in Computing Systems - Proceedings, Apr. 2009, pp. 1599–1608. doi: 10.1145/1518701.1518946.

[27] S. G. Hart and L. E. Staveland, "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," in *Advances in Psychology*, vol. 52, P. A. Hancock and N. Meshkati, Eds., in Human Mental Workload, vol. 52. , North-Holland, 1988, pp. 139–183. doi: 10.1016/S0166-4115(08)62386-9.

[28] M. Schrepp, "User Experience Questionnaire Handbook," Sep. 2015. doi: 10.13140/RG.2.1.2815.0245.

[29] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness," *Int. J. Aviat. Psychol.*, vol. 3, no. 3, pp. 203–220, Jul. 1993, doi: 10.1207/s15327108ijap0303_3.

[30] J. S. PhD, "What Is A Good Task-Completion Rate? – MeasuringU." Accessed: Oct. 19, 2023. [Online]. Available: https://measuringu.com/task-completion/

[31] R. Grier, "How high is high? A metanalysis of NASA TLX global workload scores," presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Oct. 2015. doi: 10.1177/1541931215591373.

[32] K. Virtanen, H. Mansikka, H. Kontio, and D. Harris, "Weight watchers: NASA-TLX weights revisited," *Theor. Issues Ergon. Sci.*, vol. 23, Nov. 2021, doi: 10.1080/1463922X.2021.2000667.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060660.