A methodological framework and software tools for accessible by design extended reality environments

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Thesis submitted in partial fulfillment of the requirements for the

Masters' of Science degree in Computer Science and Engineering

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Abstract

The recent abundance of Extended Reality (XR) technologies has transformed the way we perceive and interact with digital information. XR spans along the reality-virtuality continuum permeating diverse sectors, from entertainment and gaming to education, healthcare, and industry. As XR continues to gain widespread acceptance, it has become increasingly clear that this innovative paradigm holds the potential not only to redefine our digital experiences but also to impact the way we engage with technology itself. However, amidst the excitement and promise of XR, digital accessibility is a crucial issue that demands our prompt attention. More specifically, in the current rapidly evolving technological landscape, it is essential to prioritize accessibility as a fundamental aspect of XR development. This necessitates a shift in current practices toward a proactive commitment to incorporating accessibility features from the outset of XR projects, which is a concept referred to as "Accessibility by Design" within the XR landscape. In this respect, XR becomes not only transformative, but also equitable and inclusive, ensuring that every individual, regardless of their abilities, can harness its full potential.

The concept of Accessibility by Design is stemming from the Universal Access and Design for All principles, advocating the importance of catering for the needs of all individuals, including persons with disabilities, at design time, avoiding a posteriori adaptation to products or services to make them accessible. In the context of XR, this approach takes on particular significance, especially considering that despite the fact that XR is still an emerging field, the discussion on accessibility has already yielded guidelines that should be adhered to for the development of accessible user experience. Furthermore, as a result of these efforts, XR technologies have shown great promise in developing tools to assist users with visual impairments. These tools focus on assisting users with visual impairments in interacting with the XR environment through basic assistive functionalities, such as zoom-in, text enlargement, as well as the provision of alternative input and output modalities. Nevertheless, despite considerable progress, most of these initiatives remain proprietary software solutions, often limited to the research prototype phase. The seamless integration of these solutions into mainstream XR applications or platforms remains an open challenge, mainly due to the lack of generic and cohesive approaches promoting accessibility across platforms in a consistent manner.

This thesis introduces a methodological accessibility framework and pertinent software tools for the development of inclusive Extended Reality (XR) applications, following the 'Accessible by Design' approach. The framework, built upon XR accessibility guidelines, best practices, and cutting-edge techniques, addresses the needs of individuals with disabilities, with a primary focus on blind and partially sighted users. Key features include customizable text settings, alternative text on visual elements, multiple user interaction controls, edge enhancement for visual elements, audio description of the visual elements, hierarchical navigation, foreground positioning of active objects, and adaptable scene configurations. Furthermore, it allows the enhancement of XR elements with haptics, providing force and temperature feedback, aiming to augment users' perception with additional information, allowing for example developers to realistically represent virtual elements by imparting information about their physical characteristics in the real world. The proposed framework was built following a human-

centered design approach, with the active involvement of individuals with vision impairments and pertinent stakeholders in the requirements specification phase, as well as in its evaluation. The proposed framework has been implemented as an assets package made on the Unity Game Engine, available to be installed in XR applications.

To facilitate testing and evaluation, a Unity 3D sample scene was developed, using the accessibility features of the framework. This scene presents a Virtual Reality (VR) museum, showcasing different virtual rooms exhibiting 3D cultural heritage (CH) artefacts. In order to assess the proposed framework, a user-based evaluation of the use-case VR museum was carried out, involving 20 participants with vision impairments who assessed the system's effectiveness, usability, mental workload, VR-induced sickness symptoms, and haptic experience. The evaluation results demonstrate that the framework enhances the exploration of VR environments, permitting users with vision impairments to efficiently navigate in the environment and effectively perceive the museum exhibits, providing at the same time a positive user experience without imposing undue cognitive load.

Μεθοδολογικό πλαίσιο και εργαλεία λογισμικού για τη δημιουργία, εκ σχεδιασμού, προσβάσιμων περιβαλλόντων εκτεταμένης πραγματικότητας

Περίληψη

Προσφάτως, η διαθεσιμότητα πληθώρας τεχνολογιών Εκτεταμένης Πραγματικότητας (XR, εφεξής ΕΠ) έχει αλλάξει τον τρόπο που αντιλαμβανόμαστε και αλληλεπιδρούμε με την ψηφιακή πληροφορία. Η ΕΠ εκτείνεται σε όλο το φάσμα μεταξύ πραγματικών και εικονικών περιβαλλόντων και επεκτείνεται σε διάφορους τομείς, από την ψυχαγωγία και τα παιχνίδια μέχρι την εκπαίδευση, την υγεία και τη βιομηχανία. Καθώς η ΕΠ γίνεται προοδευτικά ευρύτερα αποδεκτή, καθίσταται όλο και πιο σαφές ότι αυτή η καινοτομία έχει τη δυνατότητα όχι μόνο να επαναπροσδιορίσει τις ψηφιακές μας εμπειρίες, αλλά και να επηρεάσει τον τρόπο με τον οποίο χρησιμοποιούμε την ίδια την τεχνολογία. Ωστόσο, παρά τον ενθουσιασμό και τις προσδοκίες από την πολλά υποσχόμενη ΕΠ, η ψηφιακή προσβασιμότητα είναι ένα κρίσιμο ζήτημα που απαιτεί την άμεση προσοχή μας. Ειδικότερα, στο σύγχρονο και ταχέως εξελισσόμενο τεχνολογικό τοπίο, είναι σημαντικό να δοθεί προτεραιότητα στην προσβασιμότητα ως μια θεμελιώδη πτυχή της ανάπτυξης της ΕΠ. Αυτό καθιστά αναγκαία την αλλαγή των σημερινών πρακτικών προς μια εκ των προτέρων ενσωμάτωση χαρακτηριστικών προσβασιμότητας, με συνεπή τρόπο από την έναρξη του κύκλου ανάπτυξης εφαρμογών ΕΠ, μια έννοια που αναφέρεται ως "Προσβασιμότητα εκ σχεδιασμού". Από αυτήν την άποψη, η ΕΠ δεν θα αποτελεί απλώς μια σημαντική τεχνολογία ψηφιακής μετάβασης, αλλά καθίσταται επίσης «δίκαιη» και «συμπεριληπτική», διασφαλίζοντας ότι κάθε άτομο, ανεξάρτητα από τις δεξιότητές του, μπορεί να αξιοποιήσει πλήρως τις δυνατότητες που προσφέρει.

Η έννοια της "Προσβασιμότητας εκ Σχεδιασμού" εναρμονίζεται με τις αρχές της Σχεδίασης για Όλους και της Καθολικής Πρόσβασης, υποστηρίζοντας τη σημασία της μέριμνας για τις ανάγκες όλων των ατόμων, συμπεριλαμβανομένων των ατόμων με αναπηρία, από τη φάση της σχεδίασης, αποφεύγοντας έτσι εκ των υστέρων προσαρμογές σε προϊόντα και υπηρεσίες ώστε αυτά να γίνουν προσβάσιμα. Στο πλαίσιο της ΕΠ, η προσέγγιση αυτή αποκτά ιδιαίτερη σημασία, ιδίως αν ληφθεί υπόψη ότι πρόκειται για ένα αναδυόμενο τομέα για τον οποίο η έρευνα στον τομέα της προσβασιμότητας έχει ήδη παράξει κατευθυντήριες γραμμές που πρέπει να τηρούνται για την ανάπτυξη προσβάσιμης εμπειρίας χρήστη. Επιπλέον, ως αποτέλεσμα αυτών των προσπαθειών, οι τεχνολογίες ΕΠ έχουν δείξει αξιόλογη πρόοδο στην ανάπτυξη εργαλείων για την υποστήριξη χρηστών με προβλήματα όρασης. Τα εργαλεία αυτά επικεντρώνονται στην υποβοήθηση των χρηστών με προβλήματα όρασης στην αλληλεπίδραση με το περιβάλλον ΕΠ μέσω βασικών υποστηρικτικών λειτουργιών, όπως η δυνατότητα εστίασης (zoom-in), η μεγέθυνση γραμματοσειράς, καθώς και η παροχή εναλλακτικών τρόπων εισόδου και εξόδου. Ωστόσο, παρά τη σημαντική πρόοδο, οι περισσότερες από αυτές τις προσπάθειες παραμένουν "ιδιόκτητες" λύσεις λογισμικού, οι οποίες συχνά περιορίζονται σε ερευνητικά αποτελέσματα ή πρωτότυπα συστήματα. Η ομαλή ενσωμάτωση αυτών των λύσεων στις συνήθεις εφαρμογές ή πλατφόρμες ΕΠ παραμένει μια ανοιχτή πρόκληση, κυρίως λόγω της έλλειψης γενικών και συνεκτικών προσεγγίσεων που προωθούν την προσβασιμότητα σε όλες τις πλατφόρμες με συνεπή τρόπο.

Η παρούσα εργασία παρουσιάζει ένα μεθοδολογικό πλαίσιο προσβασιμότητας και τα συνοδευτικά εργαλεία λογισμικού για την ανάπτυξη συμπεριληπτικών εφαρμογών εκτεταμένης πραγματικότητας, σύμφωνα με την προσέγγιση της "Προσβασιμότητας εκ

σχεδιασμού". Το εν λόγω πλαίσιο, βασίζεται σε κατευθυντήριες γραμμές προσβασιμότητας ΕΠ, βέλτιστες πρακτικές και τεχνικές αιχμής, καλύπτοντας τις ανάγκες των ατόμων με αναπηρία, επικεντρώνοντας στους τυφλούς και μερικώς βλέποντες χρήστες. Οι βασικές λειτουργείες περιλαμβάνουν προσαρμόσιμες ρυθμίσεις κειμένου, εναλλακτικό κείμενο για οπτικά στοιχεία, πολλαπλά μέσα αλληλεπίδρασης, οπτική ενίσχυση του περιγράμματος οπτικών στοιχείων, ηχητική περιγραφή των οπτικών στοιχείων, ιεραρχική πλοήγηση, τοποθέτηση ενεργών αντικειμένων στο προσκήνιο και προσαρμόσιμη διαμόρφωση σκηνής. Επιπλέον, επιτρέπει την ενίσχυση των στοιχείων ΕΠ με απτική πληροφορία και διάδραση, παρέχοντας στους χρήστες ανατροφοδότηση ρεαλιστικών απτικών χαρακτηριστικών, όπως η αίσθηση της δύναμης και της θερμοκρασίας, με στόχο την ενίσχυση της αντίληψής τους σχετικά με τα εικονικά περιβάλλοντα με τα οποία αλληλεπιδρούν. Με τον τρόπο αυτό, το πλαίσιο επιτρέπει, για παράδειγμα, στους προγραμματιστές να αναπαριστούν εικονικά στοιχεία με ρεαλιστικό τρόπο ως προς τα φυσικά χαρακτηριστικά αντίστοιχων πραγματικών στοιχείων. Το προτεινόμενο πλαίσιο κατασκευάστηκε ακολουθώντας μια ανθρωποκεντρική προσέγγιση σχεδιασμού, με την ενεργό συμμετοχή ατόμων με προβλήματα όρασης και σχετικών φορέων στη φάση προδιαγραφής των απαιτήσεων, καθώς και στην αξιολόγησή του. Υλοποιήθηκε ως πακέτο προγραμματιστικών στοιχείων της μηχανής παιχνιδιών Unity 3D, ώστε να είναι εφικτή η ενσωμάτωσή του σε εφαρμογές ΕΠ.

Για τη διευκόλυνση των δοκιμών και της αξιολόγησης, αναπτύχθηκε μια δειγματική σκηνή στην Unity 3D, χρησιμοποιώντας τις λειτουργίες προσβασιμότητας που παρέχει το πλαίσιο. Η σκηνή αυτή απεικονίζει ένα μουσείο Εικονικής Πραγματικότητας (VR), παρουσιάζοντας διαφορετικά εικονικά δωμάτια που εκθέτουν τρισδιάστατα αντικείμενα πολιτιστικής κληρονομιάς. Προκειμένου να αξιολογηθεί το προτεινόμενο πλαίσιο και τα παρεχόμενα εργαλεία, διενεργήθηκε μια αξιολόγηση του μουσείου VR με χρήστες, στην οποία συμμετείχαν 20 συμμετέχοντες με προβλήματα όρασης (τυφλοί και μερικώς βλέποντες), οι οποίοι αξιολόγησαν την αποτελεσματικότητα του συστήματος, τη χρηστικότητα, τον φόρτο εργασίας, τα συμπτώματα ναυτίας που προκαλούνται από την VR και την απτική εμπειρία. Τα αποτελέσματα της αξιολόγησης δείχνουν ότι το πλαίσιο ενισχύει την εξερεύνηση των περιβαλλόντων εικονικής πραγματικότητας, επιτρέποντας στους χρήστες με προβλήματα όρασης να πλοηγηθούν αποτελεσματικά στο περιβάλλον και να αντιληφθούν με αποτελεσματικό τρόπο τα εκθέματα του μουσείου, παρέχοντας ταυτόχρονα μια θετική εμπειρία χρήστη, χωρίς ιδιαίτερη επιβάρυνση του νοητικού φορτίο.

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List of Abbreviations

Abbreviation	Definition
Alt Text	Alternative Text
AR	Augmented Reality
CH	Cultural Heritage
DBSV	Deutscher Blinden- und Sehbehindertenverband
HCI	Human-Computer Interaction
HMD	Head-Mounted Display
HXI	Haptic eXperience Index
MR	Mixed Reality
NASA TLX	NASA Task Load Index
SSQ	Simulator Sickness Questionnaire
TS	Total Simulator Sickness
UAP	Unity Accessibility Plugin
UEQ	User Experience Questionnaire
UI(s)	User Interface(s)
UX	User Experience
VE	Virtual Environment
VR	Virtual Reality
XR	Extended Reality

Chapter 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], [2]. XR technologies hold a transformative potential to revolutionize the way we interact with technology and extend across various sectors [3], such as education [4], healthcare [5], entertainment [6], industrial training [7], tourism [8], and cultural heritage (CH) preservation [2], [9]. XR technologies have achieved widespread adoption, becoming available to everyone, primarily due to remarkable advancements in hardware development, as well as by offering captivating and immersive experiences [10]. 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 [11] 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 [12]. This concept acknowledges the natural diversity in human abilities and strives to eliminate any barriers that might hinder people with disabilities from fully participating in various aspects of life [13], [14]. It transcends mere regulatory compliance, emphasizing the proactive consideration of accessibility right from the initial stages of developing applications.

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 [15]–[17], offering multimodal and alternative ways for input and output [18], [19], amplifying environmental awareness [20]–[22], and facilitating sensory substitution [23]. Novel user interaction techniques have also emerged, combining concepts such as object localization and spatial audio [24], [25]. It's worth noting that haptic interactions have been ingeniously incorporated into the immersive technology landscape [26]–[29]. Albeit these early endeavors, the hurdles in engaging with digital content within the context of XR notably persist. Persons with visual impairments grapple with barriers in perceiving visual information within XR environments, including text, images, videos, and 3D objects [25], [30].

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. One particular user category that is profoundly challenged in accessing XR technologies is persons with visual impairments, considering that XR experiences are mostly visual. Motivated by this, the focus of this thesis is on individuals with visual impairments. Aiming to shed light on the field of XR accessibility for users with visual impairments, this thesis delves into exploring the accessibility challenges and identifying solutions, that adapt to best practices and guidelines. It is noteworthy that although there are several research efforts providing methods and tools for enhancing accessibility for persons with visual impairments in XR, there is still a gap in solutions that offer a cohesive integration of accessibility guidelines alongside tangible application development tools of specific accessibility features [11], [31] to developers.

This thesis introduces a framework designed to provide developers with a cohesive approach for incorporating diverse accessibility features into their XR applications. 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, 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 recolouring tools to cater to specific visual needs.

Moreover, the framework features the automated tailoring of accessibility properties according to the specific functional limitations of the target end users. Developers can select the end-user accessibility profiles that their XR application will employ, from the following categories: individuals who are blind; partially sighted and low vision persons; or people with other visual disabilities. Based on this selection, the framework automatically integrates pre-configured accessibility options into the application. For instance, if the developer develops an application for blind users, the screen reader functionality is automatically incorporated, enhancing the accessibility for this specific user group. Similarly, by choosing low-vision as a designated target user group, the framework prompts the integration of multiple pertinent filters, such as applying high-contrast backgrounds to text components, optimizing the experience for individuals with low vision. The employment of multiple different user accessibility profiles is also supported.

Furthermore, the framework allows the enhancement of XR elements with haptic interaction, through haptic gloves, to provide force and temperature feedback, aiming to augment users' perception with cutaneous and kinesthetic properties of virtual objects, conveying this way information to the users about real-world physical attributes. In addition, the combination of haptics with the audio description of the visual elements and the 3D sound enhances the localization of the artefacts and the general user experience, providing a multi-sensory experience. The proposed framework has been implemented as an assets package made on the Unity Game Engine, available to be installed in XR applications.

A sample Unity 3D scene was developed, in order to support the process of testing and evaluation. This scene utilised the accessibility features of the framework, showcasing a VR museum exhibiting a variety of 3D heritage objects. To explore the effectiveness of the accessibility features of the framework, and identify any limitations, a user-based evaluation has been conducted[1]. 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 sickness symptoms were measured, in order to ensure that the system provides a comfortable and enjoyable experience. Given the framework's integration of haptic feedback, the participants' haptic experiences were measured, exploring how this additional sensory dimension contributed to their engagement.

The results of the evaluation indicated that the integration of the framework into a VR application significantly enhanced the exploration of the VR environment for users with vision impairments. Participants were able to navigate the museum efficiently and effectively perceive and engage with the CH exhibits. Most importantly, the evaluation showed that the framework not only met accessibility requirements but also delivered a positive user experience without imposing cognitive workload (the workload was 50% lower than that typically experienced in computer activities). The results yielded a remarkable overall task completion score (M:0.97, SD: 0.12) and a very good ease of completion (M:5.19, SD:1.91), validating its effectiveness in making XR content more inclusive and enjoyable for all users. Finally, the use of haptics as accessibility tool, received a positive overall impression.

The structure of this thesis is as follows: Chapter 2 presents foundational insights in fields pertinent to our approach, reviewing existing literature; in chapter 3, we analyze the followed methodology; in chapter 4, we propose a taxonomy for the classification of accessibility solutions for XR environments, providing a roadmap for future research endeavors; in chapters 5 and 6 we explain in depth the accessibility features of the framework and the implementation of it; in chapter 7 we outline the steps taken and the outcomes obtained in evaluating the effectiveness of the accessibility features, through a user-based evaluation; lastly in chapter 8, we summarize the findings of our research and outline potential future avenues for exploration.

[1] The user based evaluation was organized by the German Federation of the Blind and Partially Sighted (DBSV), in the context of the research project SHIFT, funded by the European Union (Horizon Europe research and innovation programme, G.A. 101060660)

Chapter 2

Related work

Numerous studies have proposed various XR-based systems and tools that can support accessibility, such as VR environments that provide immersive experiences for people with visual impairments or haptic feedback technologies that allow individuals with visual disabilities to interact with digital content. Such approaches demonstrate the potential of XR technologies to offer new opportunities for inclusion and participation for people with disabilities. However, there remain several challenges that need to be addressed, such as ensuring the usability of XR interfaces for diverse user groups and the availability of suitable hardware and software solutions that can support the integration of XR-based systems into existing infrastructures. There is a growing recognition that different categories of disabilities require different approaches to address their specific accessibility issues. The focus of this thesis is on individuals with visual impairments; therefore, the following desk review focuses on the accessibility of XR environments by users with visual impairments, identifying three main user categories, namely blind users, users with low vision, or persons with visual impairments in general.

The following section delves into a comprehensive exploration of digital accessibility barriers imposed by XR technologies, whereas technological solutions to address these problems are discussed and organized into three main categories, namely solutions for users who are blind, individuals with low vision, and persons with vision impairments in general (e.g., color blindness, macular degeneration, cataract, etc.). It also provides an overview of development tools for enhancing accessibility in XR. Finally, considering that the use-case of the proposed framework focused on enhancing accessibility in museums, a short review of accessible solutions followed by museums is presented.

2.1 Review Methodology

This literature review and meta-analysis adhered to the guidelines set forth by PRISMA methodology and guidelines [32], also applying the snowballing technique [33] to the selected set of papers for review. Overall, the methodology encompassed five distinct phases: identification, screening, eligibility assessment, snowballing, and inclusion. In the identification phase, the following keywords were searched: VR, Virtual Reality, AR, Augmented Reality, blind, visual impairments, digital accessibility. The search to identify relevant studies, systems, and reports was conducted across scientific databases, namely Science Direct, Scopus, ACM Digital Library, and IEEE Explore. The search was restricted in terms of time period to exclude works earlier than 2016. After removing the duplicates, the results were screened by evaluating abstracts against predefined inclusion criteria: the paper's language should be English, it should discuss accessibility issues or technologies developed for users with vision problems, it should pertain to Augmented, Virtual or Mixed Reality environments, and it should be a peer-reviewed manuscript. Papers meeting these criteria were then subjected to eligibility assessment, involving a thorough evaluation of the complete paper. Additionally, forward and backward snowballing techniques were employed by examining both the reference and citation lists of these papers to identify any additional pertinent literature. Analysis of the results also led to the development of a taxonomy of technologies for accessibility in XR environments, in the interest of visually representing the outcomes of this literature review and facilitating readers' comprehension (see Chapter 3).

2.2 Interaction Problems in XR 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 virtual environments. 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 [16], [34]. Furthermore, lighting effects in VR environments may cause difficulties, with some scenes being too dark or too bright, and others having effects that are overwhelming for users [16]. As the authors in [15] mentioned, the impact of visual impairments is more significant on the usage of VR due to the influence of the field of view, compared to visual acuity. This implies that certain VR features may be less effective for users with visual impairments, and adjustments to the content and user's environment may be necessary to improve accessibility.

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 [15]. Additional barriers that have been reported pertain to instructions and menus presented in small or difficult-to-read fonts, or inaccessible to screen readers [18]. 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 [34]. In addition, applications that use screen reader or magnification software, which is widely used by people with low vision, may cause loss of content [35]. Current approaches do not offer a natural way to request descriptions of virtual objects or control the flow of auditory information for these descriptions [36].

Furthermore, although some accessibility options may be provided, in general, users find it difficult to use menus in order to customize the vision settings on multiple applications in a unified way. Many systems lack an interaction concept to conveniently activate and control the vision aids provided [15], [37]. Additionally, there is limited flexibility in allowing users to configure and customize the features and functionalities they present [38].

Finally, 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 [35]. Some systems rely heavily on visual and auditory cues or facial expressions, as input methods, which can be difficult for blind people to perceive [24], [39]. 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 [18].

2.3 Accessible XR Solutions for the Blind

Analysis of the selected papers identified two key categories of solutions. The first pertains to users' interaction with the VR environment, whereas the second one refers to their navigation in it.

2.3.1 Interaction Modalities

One of the approaches discussed in the literature for enhancing user perception of the VR environment by blind users is haptic feedback. DualPanto [26], is a haptic device that allows users to track moving objects in virtual environments. The device has two handles - the "me" handle for the user's avatar and the "it" handle for the object being tracked. Participants during the evaluation of the system reported that the haptic feedback provided by the device was helpful in guiding their movements and keeping them oriented in the virtual environment. However, the study also identified several limitations of the device, including a limited range of motion, which made it difficult for participants to track objects that moved outside of their reach. The study found that for similar systems to work effectively, spatial content should be rendered with haptics, whereas non-spatial content should be rendered with audio. This approach was reinforced by user feedback and suggested guidelines for other games to render story and framing with audio, continuous spatial content with haptics, and spatial events using both modalities.

Recent research has also 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 virtual environments in a more natural and intuitive manner. Racing in the Dark [18] 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 Quest's[2] built-in haptic, tracking, auditory, and voice systems 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.

2.3.2 Navigation in VR

Haptic interaction has been explored as a promising approach for navigation in VR for individuals who are blind, but is also applicable to users who are visually impaired. This approach leverages haptic feedback, which provides tactile information, to enable users to perceive the virtual environment's layout and obstacles. Wang et al. [17] developed a haptic-based interaction approach for obstacle detection in VR navigation. The system consisted of a wearable device, a camera, a haptic belt, and a braille display. The camera captured the user's surroundings, and the system processed the visual data to identify obstacles within a 1-meter range. The haptic belt vibrated to alert the user to the presence of an obstacle, and three motors provided indications for obstacles at varying positions. The system was evaluated with a group of individuals who were blind or visually impaired, and they successfully completed navigation tasks using the haptic interaction approach. However, they reported encountering difficulties in using the system and potential sensory overload, given that all output information was conveyed solely through haptic feedback. This suggests that there may be a learning curve associated with using haptic feedback for navigation, and that the system may need to be adjusted to accommodate individual user preferences and needs.

In addition, audio-based interaction has been proposed as an effective solution to provide navigation assistance to blind users in virtual environments. Soundspace VR is one such system

[2] https://www.oculus.com/quest/refurbished/

that utilizes binaural audio technology to create a 3D soundscape for the visually impaired to navigate in virtual environments [23]. Binaural audio technology is based on the concept of replicating the natural sound processing mechanism of the human ear. It creates a 3D soundscape by simulating the sounds that the user would hear in a real-world environment. The system creates a virtual auditory space by positioning sound sources at specific locations relative to the user's head and ears. Soundspace VR's audio cues allow visually impaired individuals to orient themselves and move towards a target without visual information. The system provides diverse types of sounds to represent different objects in the virtual environment. 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 virtual environment. A similar approach was VStroll, an audio-based virtual exploration tool that encourages walking among people with vision impairments by using spatial audio [40]. 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. In order 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.

In recent years, hybrid techniques have also been introduced to enhance blind user navigation in VR environments. A method that facilitates navigation in large virtual environments with intricate architecture involves a white cane controller. This device utilizes a three-axis brake mechanism that is lightweight to help convey the overall shape of virtual objects on a large scale. Surface textures are simulated using a voice coil actuator that is based on contact vibrations. Spatialized audio is determined based on the propagation of sound through the surrounding geometry, allowing the user to effectively orient themselves in the virtual environment [27]. Additionally, several methodologies have emphasized the investigation of unexplored environments through the utilization of VR technology. In [28], individuals engaged in the traversal of a Virtual Environment (VE) by means of a VR treadmill, headphones, glasses, and a controller that served as a white cane. A comparable technique was employed in [41], where participants navigated novel spaces through the provision of haptic and auditory feedback triggered by pointing or walking in the virtual environment. Subsequently, they constructed a cognitive map to facilitate navigation in physical space. 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 [25]. 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.

2.4 Accessible Solutions for Visual Display Settings in XR for Low Vision Users

In the XR field, visual display settings have been increasingly examined as a means to improve accessibility for individuals with low vision. The literature provides an abundance of applications, systems, and tools, which mainly use screen adaptations to improve accessibility for people with low vision. In several systems, these adjustments are made automatically and are predetermined, according to the needs of the users. For instance, CueSee, is an augmented reality application that runs on a Head-Mounted Display (HMD), providing support to visually-impaired individuals for product search tasks. The application automatically recognizes the product and uses visual cues to guide the user's attention towards the desired product. Specifically, the system offers five customizable visual cues, which include Guideline, Spotlight, Flash, Movement, and Sunrays, enabling users to choose a combination that best suits their visual condition. A study conducted with twelve low vision participants showed that these cues were highly effective in improving product search performance [39].

Figure 1: The Visual Cues in CueSee: a) the original picture of a target product on the shelf; b) the basic enhancement on the target with magnification and higher contrast, c) Guideline; d) Spotlight; e) Flash; f) Movement, the target rotates between -30 (f1) and 30 (f2) degrees; g) Sunrays; and h) a combination of Spotlight and Sunrays

Research has demonstrated that various visual display parameters, such as brightness, contrast, and magnification lenses, can be adjusted to cater to the unique requirements of individuals with low vision. These adjustments can improve their ability to perceive and interact with virtual environments. SeeingVR[3] is a Unity plugin designed to enhance visual display settings in VR applications, offering 14 distinct tools to optimize visual accessibility for individuals with low vision. These tools include magnification and bifocal lenses, brightness and contrast adjustment, edge enhancement, peripheral remapping, text augmentation and speech, depth measurement, highlighting of points of interest, guidelines, and recoloring. A study involving eleven participants with low vision demonstrated that the use of SeeingVR improved their ability to navigate menus, perform visual searches, and complete target shooting tasks in VR more efficiently compared to when the toolkit was not employed [16].

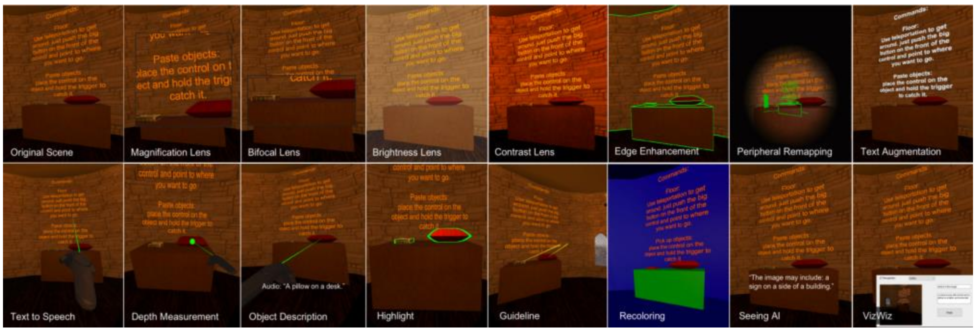

Figure 2: SeeingVR's 14 low vision tools.

A similar method proposed in [42] employs a varied set of display filters tailored to the user's field of view in conjunction with two distinct display modes, namely full *screen* and *window*. In *window mode*, the display filters are selectively applied to a small segment of the screen. The participants in the evaluation of the system achieved better outcomes when different combinations of these tools were applied.

Although there are systems available that assist individuals with low vision by adjusting display parameters, they often lack flexibility in terms of customization. In instances where customization options are provided, they are usually limited to a few features. For example,

[3] https://github.com/microsoft/SeeingVRtoolkit

Zhao et al. [39] observed that users of the CueSee system expressed an interest in personalizing the color used to highlight objects of interest. One such method, known as FlexiSee [38], utilizes a range of visual filters, including color correction, edge highlighting, and contrast adjustment, among others, which are made accessible through a web-based interface. The visual filters can be configured and customized by primary users of the eyewear device and complemented by the specialized intervention of a medical professional who has access to the primary user's field of mediated vision. The web-based interface is readily accessible from smartphones, tablets, smartwatches, and other devices with web browsers. Users can tune the level of contrast for a contrast-enhancing filter or the colors that are shifted by a color-changing or correction filter. FlexiSee provides configurable visual filters that allow users to create new functionality by combining multiple filters in a specific order. While this approach requires multiple devices that must be interconnected, it offers the ability to adapt the preselected user's settings from their personal devices.

Several approaches have also been proposed to facilitate the management of accessibility settings through visual menus. One such approach involves the placement of an accessibility menu on the HMD, which is always accessible to the user via a button located in the center-bottom section of the screen [34]. Nevertheless, this method poses a challenge for individuals with low vision, who may not be able to discern all parts of the display clearly, thereby compromising their ability to access the menu. An alternative approach involves the integration of two radial menus that are context-sensitive to enable convenient operation and customization of the aid [15]. Each radial menu features four buttons that either select a function or open a submenu. The round touchpad or joystick of the controllers is used to operate the radial menu, which is located above it. The functionalities are distributed between both hands, with the dominant hand controlling all settings and adjustments that directly impact the screen. Meanwhile, the non-dominant hand is responsible for controlling the aid and performing supporting actions, such as adapting the entire virtual environment to reduce brightness. Haptic feedback is triggered upon the selection of a menu option to enhance the user experience. To ensure legibility, the size of the radial menus can be scaled, and the foreground and background colors can be customized. Additionally, a text-to-speech feature is included for all controls. Attaching the menu to the controller provides the benefit of allowing users to move the menu closer to them with a basic hand gesture, thereby enhancing the ease of readability and interaction.

2.5 Enhancing Accessibility for Individuals with Visual Impairments in XR

2.5.1 Visual display configuration and customization

Individuals with visual impairments can benefit from various techniques and tools commonly used to assist individuals with low vision. These techniques include adjusting background and text colors, brightness, and magnification [35], [43], [44]. For instance, ChromaGlasses is a computational optical wearable device that employs an HMD to address color vision deficiency. In contrast to existing approaches relying on peripheral screen displays, ChromaGlasses employs a novel HMD design that enables users to observe their environment directly. The system leverages real-time analysis of the environment and makes pixel-level adjustments to modify the environment's appearance in a way that compensates for the user's visual impairment [45]. This approach enhances the user's ability to perceive color and provides a more natural viewing experience. On a similar note, many techniques were created in order to support people with colorblindness, overlaying the real world [46], [47]. A different approach involves controlling the brightness of a VR environment, enabling or disabling lights from different sources, or using a pocket torch to shine light in specific directions, facilitating better visibility of all areas of the VE [43]. A different method, aimed to evolve the way the environment is presented to the user, suggests that the ability to anchor virtual content in 3D space in the physical world can support a more natural and flexible reading experience, especially for short texts [48]. However, given that frequent adjustments to display settings due to environmental factors can cause discomfort for users, employing systems that autonomously adapt visual display settings in response to user requirements can provide a viable solution. For instance, an AR application can assess the user's visual rating using the Snellen chart[4] and reconfigure the environment accordingly [20]. Alternatively, capturing the environment and overlaying it on the remaining field of view could cater to individuals with visual field defects [49]. The VRiAssist system uses eye-tracking to make dynamic adjustments, such as distortion correction, color/brightness enhancement, and magnification tools, on VR scenes to improve the user's visual system, rather than the entire eye [44]. In a different direction, a method aiming to recode difficult-to-perceive information into a visual format that is more accessible, used symbolic and alphanumeric information representations on AR HMD [50]. For instance, it employed icon representations, like a smiley face, to symbolize facial expressions of people in a conversation. Additionally, it used a symbolic representation of an enlarged clock icon to indicate the current time.

Techniques for controlling accessibility settings and display options have also been reported. ChromaGlasses prototype [45] allowed users to select a customized shift in the RGB color space to compensate for various types of color blindness. Many approaches use a set of voice commands for controlling the accessibility features. Simple voice commands are used for controlling features such as font size, lighting, background color [43], speech rate, and volume of the voice reader [36]. A set of guidelines on voice commands that could be used for controlling various assistive vision features has also been proposed in the literature [51]. On the other hand, there are approaches that combine voice commands with gestures or haptics, such as a customizable library environment for people with visual impairments that has a collection of books that users can access and read from a customizable floating panel display. The user can move books with virtual motion-controlled hands via Oculus controllers, but use voice commands to simplify control schemes when making changes to the environment or book [43]. A user study with eleven persons with visual impairments indicated that the most preferred method for controlling the VR environment was using the headset controllers, while other methods such as voice commands and hand/finger detection were also of interest to some participants [35].

2.5.2 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 user experience. AIMuseum, a Unity application that integrates technologies with local museums, artworks, and exhibitions, is an example of such an approach [52]. 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. Another example is VRBubble, an audio-based VR application that provides surrounding avatar information based on social distance. More

[4] https://en.wikipedia.org/wiki/Snellen_chart

specifically, it divides the social space into three Bubbles—Intimate, Conversation, and Social Bubble—generating spatial audio feedback to distinguish avatars in different bubbles and provide suitable avatar information. The sound representations vary based on user distance, including earcons[5] for distant users, verbal notifications, and realistic sound effects as background noise [24].

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 that of the point-and-select paradigm which proves to be not effective; instead, there is a need for acquiring 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 [53].

2.6 Accessible Navigation Strategies in XR for Individuals with Low Vision and General Vision Impairments

2.6.1 XR Solutions for Enhancing Navigation in Physical Environments

Navigation in XR poses intricate challenges, particularly when it involves traversing through complex natural environments. To address this issue for individuals with visual impairments, various systems have been devised, often employing screen overlays with color-coded highlights of the surroundings, haptic feedback, 3D sounds for localization. Although these solutions pertain to navigation assistance in the built environment, they are highly relevant to navigation in virtual environments simulating the real world, and as such they are included in the current analysis.

These innovative technologies combine computer vision, sensor data, and spatial mapping to create an immersive and inclusive navigation experience. By utilizing distinct colors and visual cues, these systems aim to enhance the perception and interpretation of the environment for individuals with visual impairments. For instance, researchers have developed AR applications that employ user profile-based representations to highlight steps [54], while others utilize depth sensors and spatial mapping to create color-coded surfaces on walls and floors. Another system projects virtual guide braille blocks to aid navigation and display warning braille blocks when obstacles impede movement [55]. Moreover, color-coded overlays have been implemented to indicate varying distances from the user, particularly useful in dark environments for identifying obstacles [21], [56].

[5] https://en.wikipedia.org/wiki/Earcon

MR applications have also emerged, combining computer vision and machine learning to recognize signs such as "EXIT" and provide guidance [57]. Another approach focused on an MR headset with depth sensors and a haptic vest equipped with vibration points [22]. Depending on the distance, height, and angle of the obstacle, the system informed the user through variations on the haptic vest, diversified in frequency and intensity, tailored to the obstacle's position and proximity. Furthermore, a distinct system has harnessed 3D audio for enhanced localization [58]. This system introduces a virtual cognitive assistant positioned in front of the user, guiding them through the environment with step-by-step instructions and information about physical obstacles. Leveraging 3D audio descriptions, the user can accurately discern the direction to proceed, relying on cues from the virtual assistant's guidance. Another approach uses haptic and audio feedback to inform the user wearing the headset and provide information about the surroundings [59].

2.6.2 Navigating User Interfaces in XR applications

In the pursuit of achieving comprehensive scene comprehension within VR environments, numerous techniques have been developed to enhance the interpretability of elements present in the VR scenes. These techniques often involve the enhancement of visual elements with accompanying text descriptions announced by the screen reader, to glean contextual information about objects, scene structure, or interactive elements within the virtual space. However, to ensure that all users, including those with visual impairments, can access these textual descriptions, two distinct approaches have emerged.

The first approach permits users to individually point at and select objects within the virtual environment. For this purpose, a virtual laser is affixed to the VR controller, functioning as a pointing mechanism. When the user directs the laser towards an element, the screen reader is triggered to provide an automatic reading of the element's description [16], [60]. However, a notable limitation of this method is that users may need to physically move their hand, and consequently the controller, throughout the VE to access all elements. This requirement for manual navigation could present challenges for users who may face difficulties in fully exploring the scene or may not be able to discern all elements.

Instead, users with vision impairments require a method that allows them to sequentially access the interactive elements of the VR scene and the UIs, providing a structured and organized interaction process. A prevalent technique employed in addressing this challenge is scanning, which systematically highlights and brings focus to each interactive element present within the UI [53]. 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.

2.7 Development Tools

Realizing the pressing need for creating accessible XR environments, and adopting a 'by design' approach, several tools have been proposed in the literature to aid the development of XR experiences, focusing on streamlining and automating common functionalities. An illustrative example is the XR Interaction Toolkit [61], 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 framework offering developers some tools to create inclusive XR environments. Among its functionalities are adaptations like zoom, inverted colors, auto-reading (screen reader), and caption features, all tailored for VR settings [6]. 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 [60]. SeeingVR is a similar approach for Unity 3D, which can be used as a plugin by developers, towards enhancing the visual display settings of VR applications and offering 14 distinct tools to optimize visual accessibility for individuals with low vision [16]. 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 particular accessibility features [31].

2.8 Accessible museum exhibitions

Museums encounter notable accessibility obstacles when catering to individuals with visual impairments, predominantly revolving around the accessibility of their exhibits and issues related to mobility. The inaccessibility of museum exhibits significantly diminishes the overall experience for individuals with visual impairments, stemming from factors such as fragility, uniqueness, or spatial constraints that restrict physical interaction with the objects [62], [63]. In rare cases only are visitors permitted to touch the exhibits. While several museums have introduced tactile reproductions or replicas of their exhibits, the quality of such reproductions must not be disregarded [63]–[66]. Additionally, the provision of meaningful audio descriptions for exhibits is highly valued by all museum visitors, yet the availability and accessibility of audio guides and their accompanying descriptions cannot be consistently ensured [63], [66], [67].

Accessible museum exhibitions have seen significant advancements through innovative approaches and technologies. In [68] the concept of proxemic audio interfaces is introduced, allowing individuals with visual impairments to engage with 2D artworks through interactive sonic experiences. When user is moving closer or further away from the artwork they can access background music, unique sonifications, sound effects, and detailed verbal descriptions, enhancing their understanding and appreciation of the art. Another work focused on tactile exploration combined with audio descriptions [69]. Through a touchscreen-based mobile application, users can independently explore 2D paintings by touching different areas, triggering object-level verbal descriptions. This empowers individuals with visual impairments to comprehensively understand the artwork's details. Furthermore, a gesture-controlled interactive audio guide, is introduced in [70], that operates on tactile reliefs of 2.5D artwork surfaces. By utilizing gestures and location-dependent verbal descriptions, this system provides rapid tactile accessibility to spatial information, making art more accessible in various settings.

Furthermore, challenges in mobility and navigation hinder independent movement within museums, thereby deterring frequent visits [63], [71]. These challenges encompass inadequate signage, limited pathways, and the absence of universal design principles in museum layouts. The lack of alternative formats, such as braille or tactile maps, presents further hurdles for visually impaired visitors [72]. Moreover, the intricate nature of museum layouts and the lack of real-time guidance systems contribute to disorientation among individuals with impairments [72].

[6] https://github.com/gearvrf/GearVRf-Demos

ORASIS [67] is a prototype system aimed at enhancing the accessibility of museum exhibits specifically for individuals with visual impairments. The system utilizes touch-sensitive audio descriptions and touch gestures on a mobile device, allowing users to navigate exhibition halls and tactilely explore exhibit replicas. The mobile application serves as an informational tool, providing audio cues regarding the museum room, thematic areas, and exhibits. Notably, the mobile device screen serves a dual purpose, functioning as a multi-touch pad for seamless interaction through a set of simple gestures. This design consideration ensures discreet utilization of the technology in potentially crowded and noisy environments. Upon selecting a thematic area and exhibit, the system leverages preinstalled sensors within the room to provide relative navigation instructions based on the user's position. Subsequently, as the user approaches the chosen exhibit, they are able to tactilely explore its physical form. This is facilitated through capacitive sensors embedded in predefined segments of the exhibit, which trigger the automatic playback of audio descriptions presenting intricate details regarding the form, material composition, and culturally significant information.

In [71], the paper introduces a system that utilizes continuous tracking of user location and orientation to facilitate a seamless interplay between navigation and art appreciation in physical museums. By harnessing accurate localization and context-awareness capabilities, the system delivers turn-by-turn guidance in the ‘Navigation Mode’ and triggers the ‘Art Appreciation Mode’ when the user nears artworks, offering tailored audio content. Additionally, another approach [25] involves the use of audio cues at the location of historical figures to capture attention, coupled with controller vibrations when the player gazes towards a virtual object, subsequently activating the corresponding audio description. Many approaches have researched the construction of mental maps prior to the visit to the museum for the visually impaired. In [72] a three-dimensional museum map is presented with touchpoints for audio-tactile interactions. It helps users understand the museum's structure, exhibits, and navigation, leading to the development of a mental map and enhancing orientation and confidence during exploration.

2.8.1 Natural Interaction Techniques in Digital Museum Exhibitions

Natural interaction, in the context of human-computer interaction (HCI), refers to the design and implementation of interfaces that facilitate communication between humans and technological systems in a manner that closely resembles everyday human-human interactions. It seeks to reduce the cognitive load and barriers inherent in traditional interaction paradigms, enabling users to interact with technology using familiar and intuitive modalities such as speech, gestures, touch, and facial expressions [73]. The interaction interface is designed to be unobtrusive, or to seamlessly fade into the background through intuitive interaction methods that require minimal learning, responding to user input in a human-like manner [74]. By emulating the fluidity and adaptability of human conversation, natural interaction aims to enhance user engagement, improve user experience, and foster more efficient and effective interactions with technology. The goal is to bridge the gap between users and machines, making technology more accessible, inclusive, and user-friendly.

Natural interaction plays a significant role in the preservation and exploration of cultural heritage. By leveraging intuitive and familiar modes of interaction, such as touch, gestures, and voice commands, natural interaction interfaces enable users to engage with CH artifacts, sites, and virtual reconstructions in a more immersive and accessible manner [75]. These interfaces facilitate intuitive navigation, interactive storytelling, and dynamic exploration, enhancing the overall user experience. Natural interaction also allows for a more inclusive approach, breaking down barriers of language, age, and physical abilities, enabling a wider audience to interact with and appreciate cultural heritage.

The authors in [76] explore the integration of seamless AR experiences within interactive museum narratives. The research focuses on the design and implementation of AR activities that offer users four distinct ways to engage with the exhibits. These include virtual reconstructions of the original aspects, placing the exhibits in their original locations, visual highlighting of intriguing details and annotations, and recreating mythological appearances. To enhance personalization, the AR experiences are tailored to individual users by dynamically injecting different versions of AR activities into the narrative. This personalization is based on initial user profiling as well as real-time inputs received during the museum visit. The primary objective of this approach is to enrich the visitor experience by seamlessly integrating AR technology within the context of the museum narrative. However, it is noteworthy that users were constrained in their ability to engage in direct interaction with the presented virtual objects.

In [75] through the incorporation of off-the-shelf digital components, the authors propose an innovative approach to facilitate interaction with 3D replicas of museum objects. By creating a virtual environment that closely emulates physical surroundings, users can seamlessly engage with digital content. The system utilizes palm and finger tracking to accurately capture rotation, position, pinch and grab strength, hand movement, and pose. Despite providing a more intuitive and natural interaction approach for users to engage with virtual objects, the proposed system has inherent limitations. The absence of force feedback restricts the ability to perceive objects physically, diminishing the naturalness of the interaction. Furthermore, the reliance on gesture-based input may pose challenges for users with physical disabilities, limiting accessibility. Additionally, visually impaired users are unable to utilize the system effectively due to the lack of alternative output modalities such as audio or haptic feedback.

The authors of [10] present a critical examination of the foundational technological components necessary to realize the vision of achieving natural interaction with virtual statues, effectively bringing physical statues to life and enabling engaging dialogues with visitors, using XR technologies, introducing a conceptual architecture and a compelling use case example to demonstrate their effective orchestration. Moreover, the paper identifies open research issues, laying the groundwork for future explorations and advancements in natural interaction within the CH domain.

2.9 Summary of findings

The literature review provided a comprehensive analysis of various techniques and approaches aimed at making XR applications more accessible for individuals with visual impairments. The discussed techniques can be classified into several categories, each contributing to enhancing interaction, navigation, customization of visual displays, and overall accessibility for individuals with visual impairments.

Analysis of the results yielded several conclusions. An important finding is that no AR or MR systems were found specifically designed for blind individuals. This seems a reasonable outcome, since such systems depend heavily on users' spatial awareness as digital content is superimposed on the physical environment. This remains an open challenge and a complex problem to solve effectively. Nevertheless, with the use of computer vision and artificial intelligence technologies [19], [56] user awareness of the physical environment can be enhanced and combined with digital accessibility solutions, pursuing the development of by-design accessible AR and MR solutions.

Throughout the reported literature, an interaction modality often used to complement the user's sensory perception of the environment is haptics. In this regard, innovative haptic approaches have been proposed for handling avatars [26], for obstacle identification in VR environments [17], for navigating in the VR environment [27], to indicate the presence of a virtual object [25], or distance from it, even for feedback when driving a car in a virtual environment [18]. Another approach for complementing sensory perception often reported in the literature pertains to audio-based interaction. Audio feedback is one of the most common approaches adopted to provide access to computer applications for blind persons, and as such it constitutes a familiar output modality. In the reported literature audio has been employed as 3D sound for spatial navigation [23], spatialized audio for enhancing user awareness of their surroundings [27], for indicating collisions with virtual objects [28] differentiating the sound according to the object type [41], to indicate the presence of points of interest [25], or adding screen reader functionality [52]. Researchers have often aimed at combining the benefits of various modalities, thus resulting in hybrid techniques employing haptics, audio, or gestures.

Screen reader functionality is reported to be triggered following a point-and-click approach, so as to enable persons with visual impairments to perceive pointed objects in the virtual environment. However, a major challenge for users with visual impairments in this interaction paradigm is that it proves to be not ineffective; instead, there is a need for acquiring sequential access to the interactive elements of a UI, providing a structured and organized way to perceive the environment. A prevalent technique that can be employed in addressing this challenge is scanning, which systematically highlights and brings focus to each interactive element present within the UI [53]. 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.

For users with low vision or general visual impairments, the most common approaches applied entail customizations of the visual outcome through appropriate screen filters or accessibility tools. The aim of these approaches is to alleviate the barriers faced by persons with visual impairments, for instance by correcting color contrast, enlarging text, providing magnifications, brightness adjustments, or edge enhancements.

From the above, it can be concluded that great advancements have been achieved in the field. Nevertheless, it is also notable that the variety of approaches followed do not exhibit consistency with each other. This lack of consistency for cross-platform accessibility has been identified by XR software engineers as one of the reasons for not creating accessible user experiences [31]. This highlights the need for more generic approaches addressing not end users, but software engineers who develop XR environments. It also highlights the need for further elaborating on existing guidelines for XR accessibility, developing a 'cookbook' with easy-to-understand instructions and code examples.

Chapter 3
Methodology

The accessibility framework presented in this thesis 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 players with various abilities and impairments.

The foundation of our accessibility framework lies in our commitment to the following design goals and principles:

- Inclusivity: Ensure that players 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 [77], aiming to thoroughly understand the context of use, acquire user requirements, design and develop prototypes, and evaluate them, in an iterative approach (Figure 3). 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 user experience 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 [78].

Figure 3: Human-Centered Design Activities

This section outlines the key endeavors for each of the Human-Centered Design phases pursued in the context of the proposed framework.

3.1 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 systematic literature review that was carried out.

The target users have been identified as persons with visual impairments, including persons who are blind, 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. Globally, at least 2.2 billion people have a near or distance vision impairment, with 39 million being blind and 246 million having low vision [79]. 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 [80]. 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. [81]

Low Vision: Low vision refers to individuals with significant visual impairment that cannot be fully corrected by conventional glasses, contact lenses, or medical treatments [7]. 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 [81].

General Vision Impairments: General vision impairments include that can be corrected with conventional glasses, like myopia[8], astigmatism[9] and hyperopia[10]. Colorblindness is also referred to this category based on the fact that affects the perception of color, but not necessarily visual acuity [82]. 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[11]. In these individuals, specific cone cells responsible for detecting certain colors do not function correctly [82].

Based on the systematic literature review, the key interaction problems faced by persons with visual impairments when interacting with XR environments are summarized in Table 1.

Paper	User Category	Identified Interaction Problems
[16]	Low Vision, Persons with	• Small font sizes, low-contrast color schemes, and legibility issues.

[7] https://en.wikipedia.org/wiki/Visual_impairment
[8] https://www.mayoclinic.org/diseases-conditions/nearsightedness/symptoms-causes/syc-20375556
[9] https://www.mayoclinic.org/diseases-conditions/astigmatism/symptoms-causes/syc-20353835
[10] https://www.mayoclinic.org/diseases-conditions/farsightedness/symptoms-causes/syc-20372495
[11] https://www.colourblindawareness.org/colour-blindness/

	visual impairments	• Lighting effects causing darkness/brightness issues. • Challenges with judging distance and contrast while interacting with virtual elements.
[34]	Low Vision	• Low contrast backgrounds on text elements. • Limited accessibility settings • Limited alternative inputs (e.g. voice commands)
[15]	Low Vision	• Limited visual field of view. • Need for adjustments in the position of the VE and the content. • Menu item selection with a laser pointer.
[18]	Blind	• Inaccessible instructions and menus due to small fonts. • Lack of screen reader support. •Insufficiency of current haptic feedback technology in VR applications.
[36]	Persons with visual impairments	•Lack of natural ways to request object descriptions. • Absence of controlling auditory information.
[54]	Low Vision	•Difficulty in customizing display settings.
[38]	Low Vision	•Limited flexibility in configuring and customizing features and functionalities.
[35]	Persons with visual impairments	• Screen readers and magnification software may cause the loss of content. • Difficulty in navigating complex menus.
[24]	Blind	• Reliance on visual and auditory cues or facial expressions as input methods.

Table 1: Identified interaction problems in XR environments per user category per paper

Furthermore, analysis of the literature yielded a classification of solutions pursued in the XR field in the context of digital accessibility. These solutions are summarised in Table 2. Furthermore, a taxonomy of technologies for accessibility in XR environments has been developed (see Section 4), in the interest of visually representing the outcomes of this literature review and creating a blueprint that would guide the framework development.

Paper	User Category	XR domain	Supported functionality	Accessibility feature
[18], [26]	Blind	VR	Interaction	Haptics
[17]	Blind	VR	Navigation	Haptics
[23], [40], [83]	Blind	VR	Navigation	Audio
[25], [27], [28], [41]	Blind	VR	Navigation	Haptics and Audio
[16]	Low Vision	AR	Visual Display Configuration	Screen Overlay Filters
[16]	Low Vision	AR	Visual Display Configuration	Screen Overlay, Magnification and Bifocal Lenses, Brightness and Contrast adjustment, Edge Enhancement, Peripheral Remapping, Recoloring
[42]	Low Vision	VR	Visual Display Configuration	Screen Overlay
[38]	Low Vision	AR	Control Display Settings	Web Based Interface
[34]	Low Vision	VR	Control Display Settings	Visual Menus on Screen
[15]	Low Vision	VR	Control Display Settings	Visual Menus on the Controller, Haptic Feedback
[35]	Persons with visual impairments	VR	Visual Display Configuration	Screen Overlay, Text Adjustments, Brightness
[43]	Persons with visual impairments	VR	Visual Display Configuration	Screen Overlay, Brightness
[44]	Persons with visual impairments	VR	Visual Display Configuration	Screen Overlay, Bifocal Lenses, Magnification, Brightness

[45]–[47]	Persons with visual impairments	AR	Visual Display Configuration	Screen Filters, Recoloring
[48]	Persons with visual impairments	AR	Visual Display Configuration	Screen Overlay, Magnification
[20], [50]	Persons with visual impairments	AR	Visual Display Configuration	Screen Overlay
[49]	Persons with visual impairments	MR	Visual Display Configuration	Screen Overlay, Bifocal Lenses
[45]	Persons with visual impairments	AR	Visual Display Configuration	Web Based Interface
[35], [36], [43]	Persons with visual impairments	VR	Visual Display Configuration	Voice Commands
[52]	Persons with visual impairments	AR	Interaction	Screen Reader, QR Code, Screen Overlay
[84]	Persons with visual impairments	AR	Interaction	Screen Reader
[24]	Persons with visual impairments	VR	Interaction	3D audio
[36]	Blind and Persons with visual impairments	VR	Interaction	Haptics, Audio, Mid-Air Gestures
[54]	Low Vision	AR	Navigation in Physical Environments	Screen Overlay
[55]	Persons with visual impairments	AR, MR	Navigation in Physical Environments	Screen Overlay
[57]	Persons with visual impairments	AR	Navigation in Physical Environments	Screen Overlay
[22]	Persons with visual impairments	MR	Navigation in Physical Environments	Screen Overlay
[58]	Persons with visual impairments	AR	Navigation in Physical Environments	Screen Overlay, Step by step guidance, 3D audio
[85], [86]	Persons with visual impairments	AR	Navigation in Physical Environments	Step by step guidance, Audio

[87]	Persons with visual impairments	AR	Navigation in Physical Environments	Haptics, Audio
[59]	Persons with visual impairments	MR	Navigation in Physical Environments	3D audio, Haptics
[16], [60]	Low Vision, Persons with visual impairments	VR	Navigation User Interfaces	Pointer attached to controller

Table 2: Accessibility solutions in XR environments per paper

3.2 User Requirements Specification

The next phase of our methodology involves soliciting and meticulously analyzing the user requirements specific to our target application domain. This was pursued through user interviews, aiming to gather valuable insights and preferences directly from blind and low vision users, in order to understand their specific needs, challenges, and preferences related to the XR Accessibility Framework. The interviews focused on eliciting participants' requirements and expectations, in the context of virtual museums and particularly in terms of presenting paintings, museum artifacts, and other XR content in an accessible and inclusive manner. By engaging with vision impaired participants, the interviews sought to inform the design and implementation of the framework, ensuring that it caters to the diverse abilities and disabilities of its target users.

3.2.1 User interviews procedure

The user interviews were conducted in the context of the European project SHIFT, at the premises of The Homeland Museum of Knjaževac[12], Serbia. The user requirements gathering process involved conducting semi-structured interviews [88] with two blind participants, one male and one female, who have been blind from birth, as well as with one male low vision individual. The initial phase commenced with an introduction to the objectives and aims of the SHIFT project, setting the context for the participants. A presentation followed, elucidating the project's concept and potential use cases to familiarize them with the XR system's purpose. Subsequently, the participants were invited to share their insights and preferences regarding the presentation of paintings and museum artifacts within the XR environment. Following that, the interview was initiated, affording the blind participants the opportunity to articulate their thoughts and insights. Participants were welcomed in a cordial atmosphere, encouraging them to provide their unique perspectives in response to the prepared set of inquiries.

3.2.2 Participant Insights on XR Content Presentation and Multimodal Feedback

In this section, we delve into the valuable insights shared by the participants regarding XR content presentation and the integration of multimodal feedback. The participants emphasized the significance of conveying the emotional essence of paintings through alternative means, avoiding the imposition of specific emotions upon users. Highlighting key features of the

[12] https://muzejknjazevac.org.rs/en/

artwork and utilizing haptic feedback to provide tactile sensations emerged as an appealing approach to enable users to interpret the paintings in their unique way.

The participants also discussed their perception of color. Blind participants expressed that color descriptions were not essential for them due to their lifelong visual impairment. Instead, they stressed the importance of relying on other sensory inputs, such as haptics and auditory cues, to comprehend and engage with the XR environment fully. For persons with visual impairments, it was emphasized that considering the wide range of potential functional limitations, several assistive tools should be embedded in the XR environment, thus allowing users to adapt the experience to address in the best possible way their needs. Such tools could include a zoom-in facility, as well as color contrast enhancement, or the possibility to enlarge fonts.

In terms of information accessibility, the participants preferred initial abstract descriptions of artifacts, with the option to access more detailed information at their discretion. This desire for control over information intake was identified as essential to ensure a tailored and user-centric XR experience. Moreover, the prospect of experiencing haptic feedback through the use of haptic gloves excited the participants, despite the recognition that haptics might not precisely replicate the actual size and material of the 3D artefacts. They found the provision of size and material information through haptics to be valuable, underscoring the significance of multimodal feedback for comprehensive perception. Furthermore, the participants emphasized the value of combining various sensory inputs, such as haptics and background sounds, to create a more immersive and engaging XR experience. This integrated approach provided users with a holistic understanding of the XR environment.

In conclusion, the procedure of semi-structured conversations with visual impaired participants elicited valuable insights into their preferences and needs regarding the XR Accessibility Framework. Findings from this discussion are aligned with the results of the literature review that was conducted. In addition, concrete proposals were posited regarding user engagement with XR content in virtual museums. Overall, participants' feedback informed the design and implementation of the framework, ensuring inclusivity, customization, and an enriched XR experience for users with diverse abilities and disabilities.

3.3 Design and Development

The design and development process of the framework was informed by XR accessibility guidelines reported in the literature, The XR Association[13] 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 [89]. Meta has also published their own accessibility design documentation [90]. 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 summarised in Table 3 that follows.

Category	**Guidelines**
General	• Support undo and redo functions.

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

- Allow users to reduce the speed of the app or to increase the time required for making decisions or completing challenges.
- Support bypass functions (or a no-fail mode) to permit users to skip challenging or timed experiences while still allowing them to progress in the app.
- Allow users to save their progress at any time.
- Try making your goals attainable through multiple methods and support modular goals, segmenting the actions needed to be executed by the user to progress in the experience into various parts, leaving some as optional.
- Deliver your narrative through multiple methods including spoken dialogue or narration, text, in-application events, etc.
- Ensure that all areas of the user interface 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.
- Provide clear audio landmarks.
- Controller-based locomotion is imperative to providing a comfortable user experience 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.
- Allow users to change the speed they can travel or perform interactions, in an immersive environment.
- 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.
- Add ray casts to simplify navigation and selection.
- Navigation mechanisms must be intuitive with robust affordances. Navigation, location and object descriptions must be accurate and identified in a way that is understood by assistive technology.
- Objects that are important within any given context of time and place can be identified in a suitable modality. Allow the user to filter or sort objects and content. Allow the user to query objects and content for more details.

	• Avoid interactions that trigger epilepsy or motion sickness and provide alternatives. • Allow the user to set a 'safe place' - quick key, shortcut or macro. • Provide a platform integration with tools that support digital wellbeing
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 colour to differentiate between user options and communicate important information. Allow users to recolour the interface and objects, provide shapes or symbols alongside meaningful colours, or provide textures on objects or elements to help distinguish colour-based information. • Provide customised high contrast skins for the environment to suit luminosity and colour contrast requirements. • Allow users to add contrasts or edge enhancements to highlight objects and text. • Allowing users to change the foreground or background colours of text. • Allowing users to change the brightness levels in the app. • Allowing users to employ peripheral maps to show objects outside of the field of vision. • 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.

	• Ensure flickering images are at a minimum, will not trigger seizures (more than 3 times a second), or can be turned off or reduced. • Allow the screen magnification user to check the context of their view and track/reset focus as needed. Where it makes sense (such as in menus) interface elements can be enlarged and the menu reflowed to enhance the usability of the interface up to a certain magnification requirement.
Interaction Accessibility	• Allow users to automate some actions to reduce the number of physical actions they must make within an app. • 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. • Support 'Sticky Keys' requirements such as serialization for various inputs when the user needs to press multiple buttons. • Allow remapping of controls onto alternate controllers, sensors, or keyboards. • Allow remapping of controls on the standard controller to ensure the user can reach the necessary controls. • Controls need to support rearranging of position, resizing and sensitivity adjustment. • Ensure hit targets are large enough with suitable spacing around them. • Ensure multiple actions or gestures are not required at the same time to perform any action. • Allow timings for interactions or critical inputs to be modified or extended. • Minimize the complexity of your controller scheme. • Minimize button press requirements. • Consider supporting hand tracking. • 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.

Table 3: Guidelines for designing in XR for people with visual impairments

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 user experience, keeping also in mind that additional modalities addressing alternative sensory channels would be integrated. Figure 4 below illustrates initial mockups of accessible XR solutions for color blind individuals, whereas Figure 5 illustrates a mockup for museum artefact with active point of interest, a solution for low vision individuals.

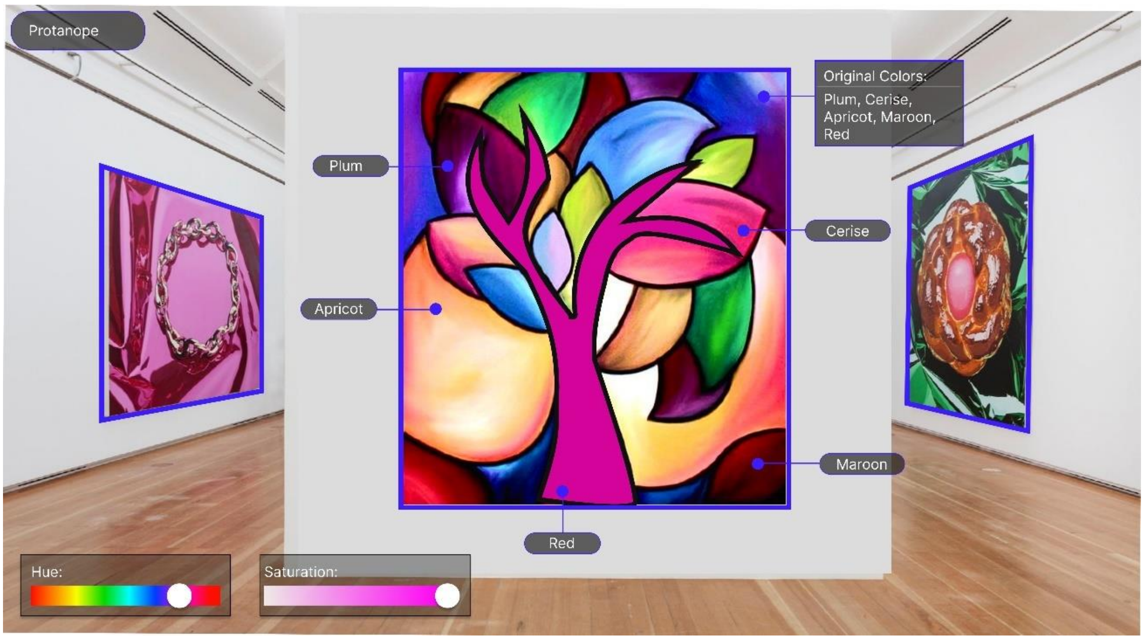

Figure 4: Mock-up for color blind users, with protanope. A colored overlay is placed over the red colors that the user can not distiquish. Points of interest are highlighted and there is a description of the original colors.

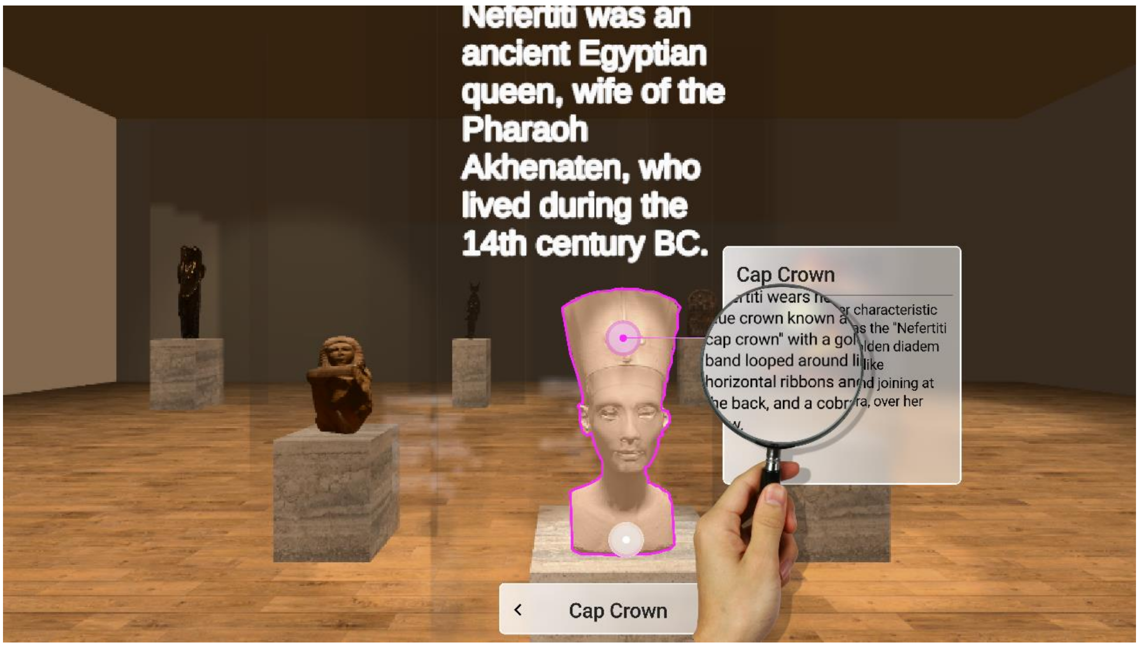

Figure 5: Mock-up for museum artefact with active hotspot.

3.4 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 current thesis, two evaluation methods were employed, namely expert-based reviews and user-based assessment.

In general, expert-based evaluation is a method where experts assess a design based on known or standard cognitive principles or empirical results. This type of evaluation is also referred to as expert analysis techniques, including heuristic evaluation, cognitive walkthrough, and review-based evaluation [91]. 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 in user-friendly and inclusive results [92].

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 2.0 guidelines. Furthermore, accessibility audits involved manual checks and empathic modeling techniques [93], 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 user-based evaluation are described in detail in Section 7.

Chapter 4

Taxonomy

In this section, we present a comprehensive taxonomy derived from the analysis of relevant literature on accessibility in XR solutions, aiming to consolidate this analysis to an easy-to-understand classification (see Figure 6). 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, **i**nstead 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 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 user experiences. 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 virtual environment 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.

Besides its contribution to the current thesis, the taxonomy's value for future work extends beyond its role as a categorization tool. It is hoped that this work can serve as a guide, helping researchers, developers, and practitioners toward innovative pathways that optimize input and output modalities, foster sensory substitution, and promote meaningful labeling for the development of accessible XR experiences.

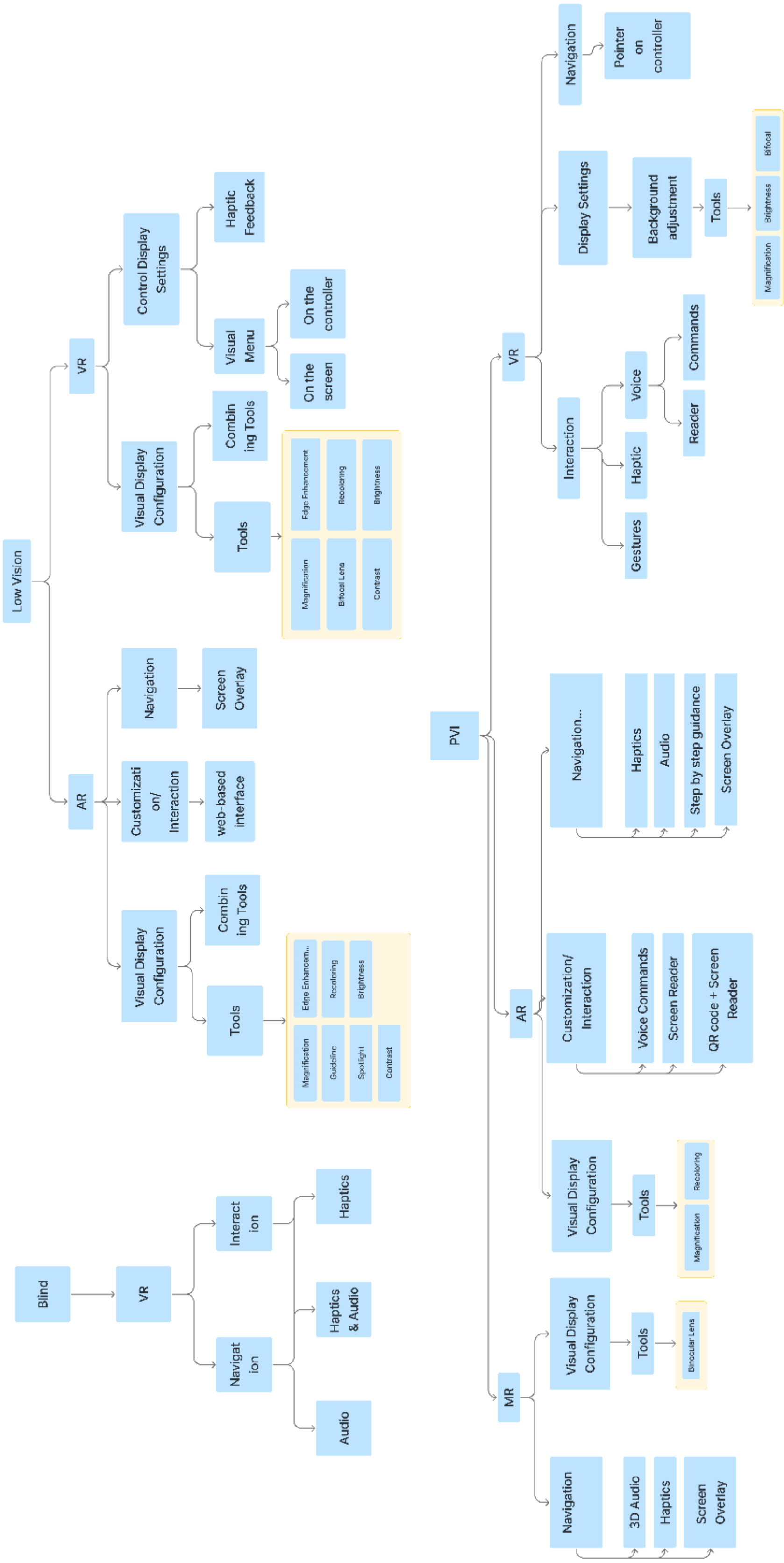

Figure 6: Taxonomy diagram

Chapter 5

The Accessibility XR Framework

The proposed Accessibility XR Framework is a comprehensive solution for XR application developers to seamlessly integrate accessibility features into AR or VR 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 Accessibility XR Framework aims to provide XR application developers with a user-friendly and adaptable approach to incorporating accessibility features in their software. The primary goal of this framework is to foster a cohesive and inclusive XR experience for users with varying abilities, empowering them to engage with XR content seamlessly. The development of this framework has been informed by a comprehensive review of relevant literature on accessibility needs and best practices.

Currently, the Accessibility XR Framework supports a range of content adaptations, focusing mainly on people with vision impairments, towards enhancing 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. Additionally, the framework extends accessibility features to video subtitles, allowing users to personalize font styles, sizes, and background colors, thereby optimizing the viewing experience for individuals with diverse accessibility needs. 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 user experience.

The Accessibility XR 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 utilizing haptic gloves to provide force and temperature feedback, aiming to augment users' perception with additional information. As a result, it allows developers to replicate virtual objects by conveying their real-world physical characteristics, but also to augment virtual objects with haptic feedback that is not achievable in the real world. Overall, the integration of haptics with audio descriptions and 3D sound elevates the user experience 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-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:

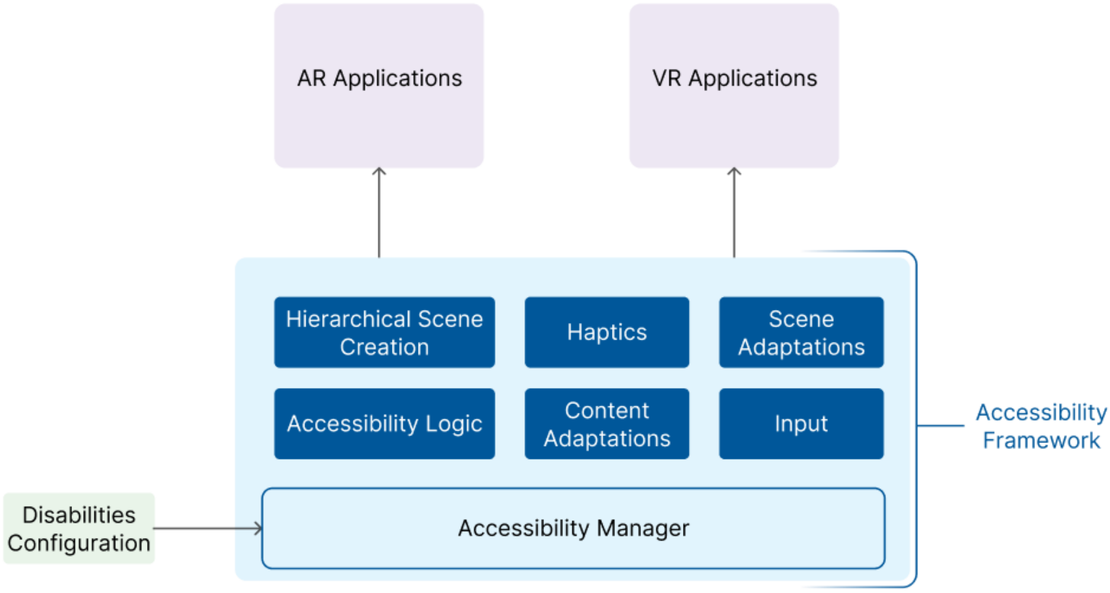

Figure 7: Core Components of the Accessibility Framework

- 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.

- 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 **Haptics Component** is responsible for augmenting user interactions and experiences within the virtual environment. By leveraging haptic gloves, developers can enhance 3D artifacts with tactile sensations, incorporating attributes like temperature, stiffness, and texture. As a result, users can explore the XR scene through touch, perceiving the size and physical attributes of objects. The seamless activation of hotspots on 3D artifacts further enriches the experience, allowing users to intuitively comprehend and engage with the virtual world.
- 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.

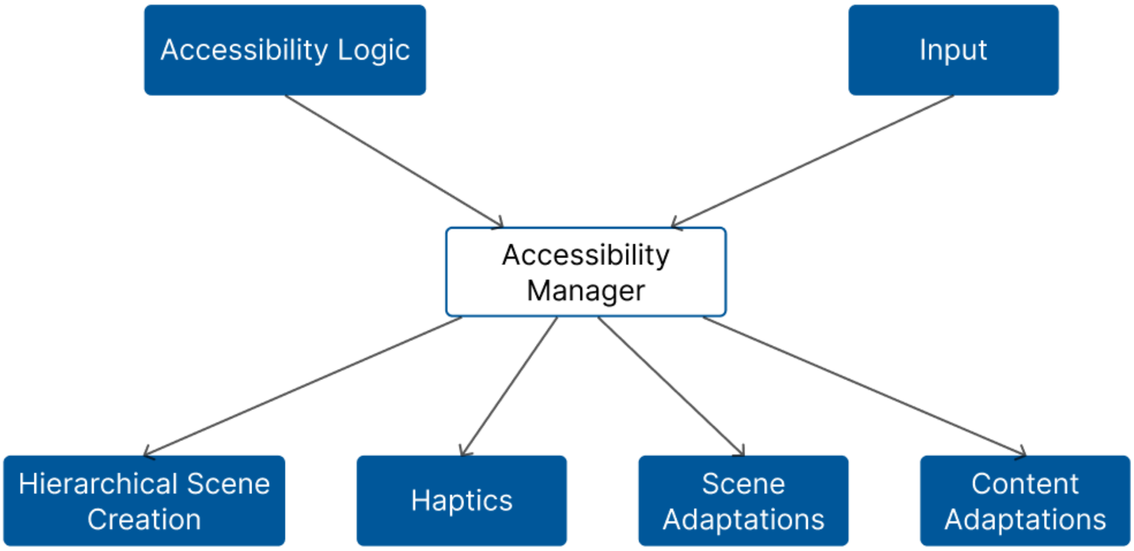

Figure 8: Information flow between the components

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. Figure 8 Illustrates this process. Further details of each component are discussed in the following sections 5.2.1-5.2.7 in the document.

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 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 of the users and applies the Accessibility Logic Section as described in Section 5.2.3 Accessibility Logic. 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 virtual environment. 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.

5.2.2.1 Interactive Element Definition

The process begins with developers indicating the interactive elements they wish to apply accessibility features to. 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. Meanwhile, users with hearing impairments may benefit from visual cues or sign language videos presented within the widget.

5.2.2.2 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 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 9). 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.

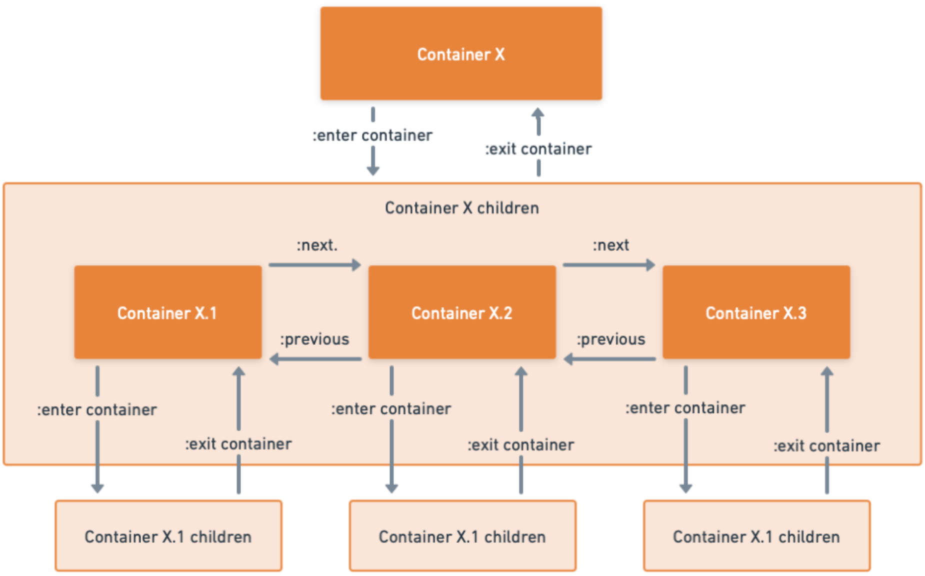

Figure 9: Screen reader commands flow

5.2.2.3 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.

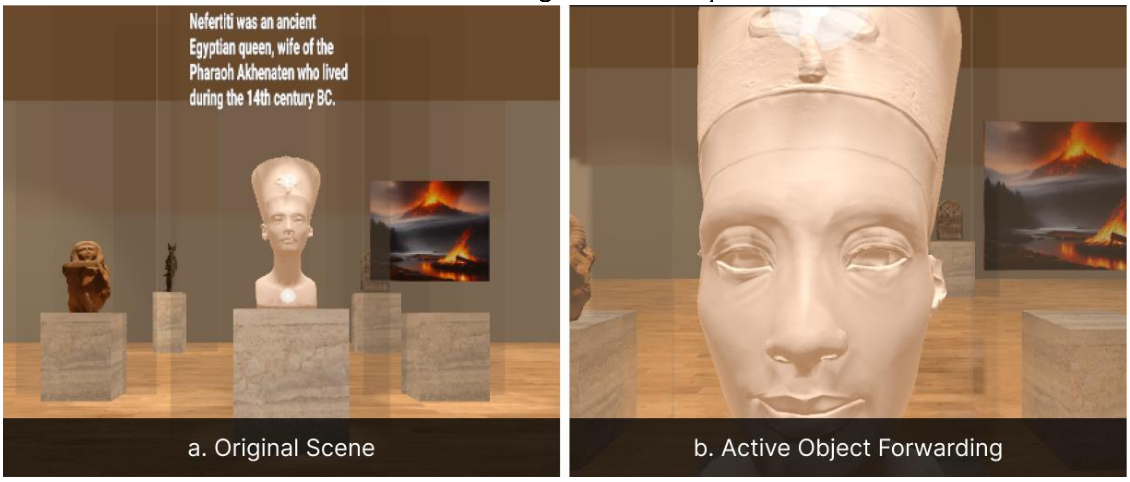

Figure 10: Active Object Forwarding feature

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 extend, our solution can be easily generalized to address the needs of persons with a diversity of disabilities.

5.2.3 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. Developerscan 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.

5.2.4 Haptics

The incorporation of haptics within the XR Accessibility Framework adds a layer of physical interaction and realism to 3D virtual artifacts, enhancing the overall XR experience for users, especially those with visual impairments. Haptics enable users to feel the virtual objects they are interacting with, providing them with vital sensory feedback and information that complements their exploration of the XR environment. Through the use of haptic gloves, developers can enrich the physical attributes of 3D artifacts by adding various haptic sensations, such as temperature, stiffness, and texture.

Figure 11: (Left) Temperature feedback in a sample scene. (Right) WeartDIVER haptic device.

The temperature feature allows the framework to represent objects with varying temperatures, creating a more immersive experience. For instance, a painting or artifact can be associated with fire, and users can feel the sensation of warmth or heat when touching the virtual flames. Stiffness refers to the force that the haptic glove applies to the user's finger when interacting with different materials. For instance, a rock material can feel more rigid and resistant to touch, while a fabric material may have a softer and more pliable haptic response. This customization allows developers to accurately simulate the tactile properties of various materials and objects within the XR scene, creating a more realistic and engaging interaction.

The texture feature allows the developer to choose from a list of textures that correspond to the material of the 3D artifact. When users touch the virtual object, they can feel the texture, providing a more detailed understanding of the material's surface characteristics. Additionally, the haptic feedback can convey the size of an artifact, giving users a sense of its dimensions and proportions. By feeling the size of an object, users can better understand its scale and spatial arrangement within the XR environment.

For blind users, haptics serves as a crucial tool for better understanding the virtual environment. By providing tangible feedback and physical sensations, haptics complements auditory cues, enriching the blind user's perception of the XR scene. The combination of haptics with auditory descriptions enables users to form a more comprehensive mental representation of the virtual world and its elements. Moreover, the activation of hotspots through touch allows blind users to explore specific points of interest or key elements within the 3D artifact. When a user touches a hotspot associated with a widget, the widget is activated, providing supplementary information. Additionally, if the developer has incorporated 3D sound into the hotspot, the user experiences an interactive auditory feedback. As the user's hand approaches the hotspot, the 3D sound becomes louder, and as the hand moves away, the sound gradually decreases. Each hotspot can be associated with unique haptic properties, further enhancing the understanding and differentiation of various features. This personalized haptic feedback facilitates a more meaningful and informative exploration, enabling users to engage with the XR environment more effectively.

5.2.5. Content Adaptation Components

5.2.5.1 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 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*> Game Objects 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 12c. 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.

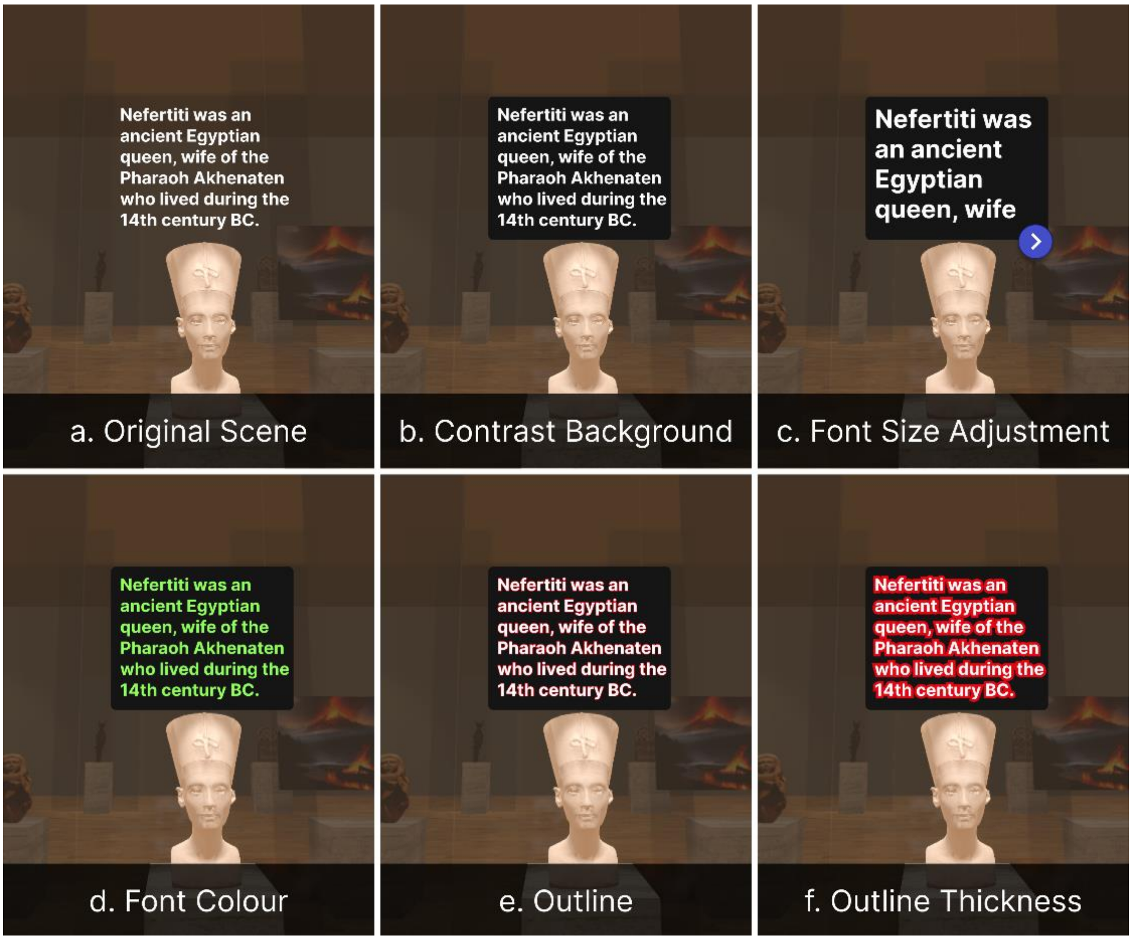

Figure 12: Accessibility Framework Text Adjustments

5.2.5.2 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, play, and pause, which facilitate a user-friendly and interactive experience.

5.2.5.3 Video Subtitles Customization

The Video Subtitles Customization component empowers users to personalize video subtitles according to their preferences. This feature offers a range of options, such as modifying font styles, background colors, and font sizes, allowing users with diverse accessibility needs to optimize the viewing experience and enhance their comprehension of video content.

5.2.5.4 3D Artefact Enhancement

The 3D Artefact Enhancement component is offering developers a way to enhance the visualization of 3D objects, thereby augmenting the overall user experience. By enabling the edge enhancement feature, developers can effectively improve the visibility of object edges, thereby facilitating better perception of the shapes and boundaries of 3D artefacts within the XR environment, as depicted in Figure 13. 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 the preferences and specific accessibility requirements of users. 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.

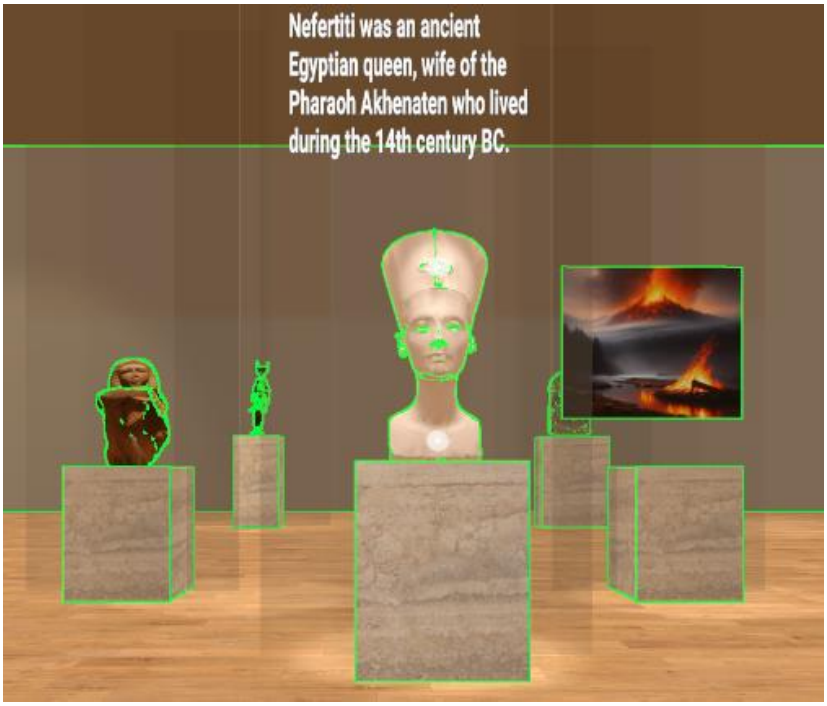

Figure 13: Edge Enhancement Tool

5.2.6 Scene Adaptations

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.

5.2.6.1 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 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 Accessibility XR Framework provides users with the ability to adjust the scene's brightness according to their unique visual preferences and needs as shown in Figure 14.

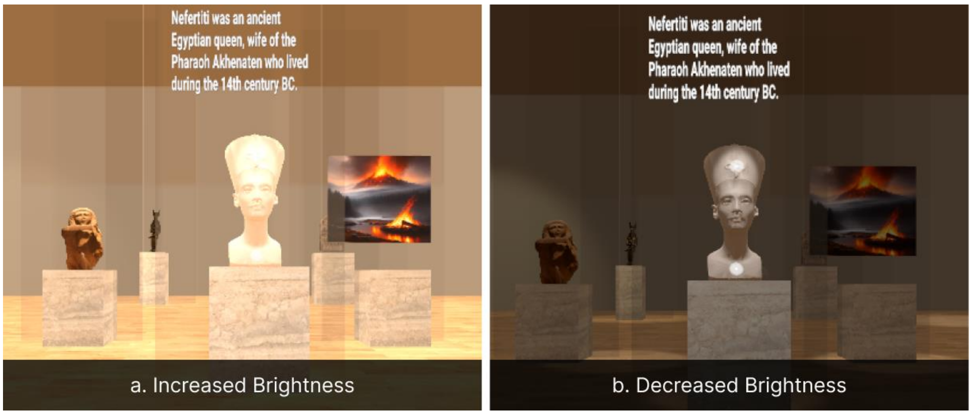

Figure 14: Brightness Adjustment

5.2.6.2 Magnified Lens

The most prevalent method for enhancing vision and enabling individuals with low vision to perceive details is through magnification [16]. 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. 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 15: Magnified Lens (2 times magnification level)

5.2.6.3 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 16b.

Figure 16: 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 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. 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.

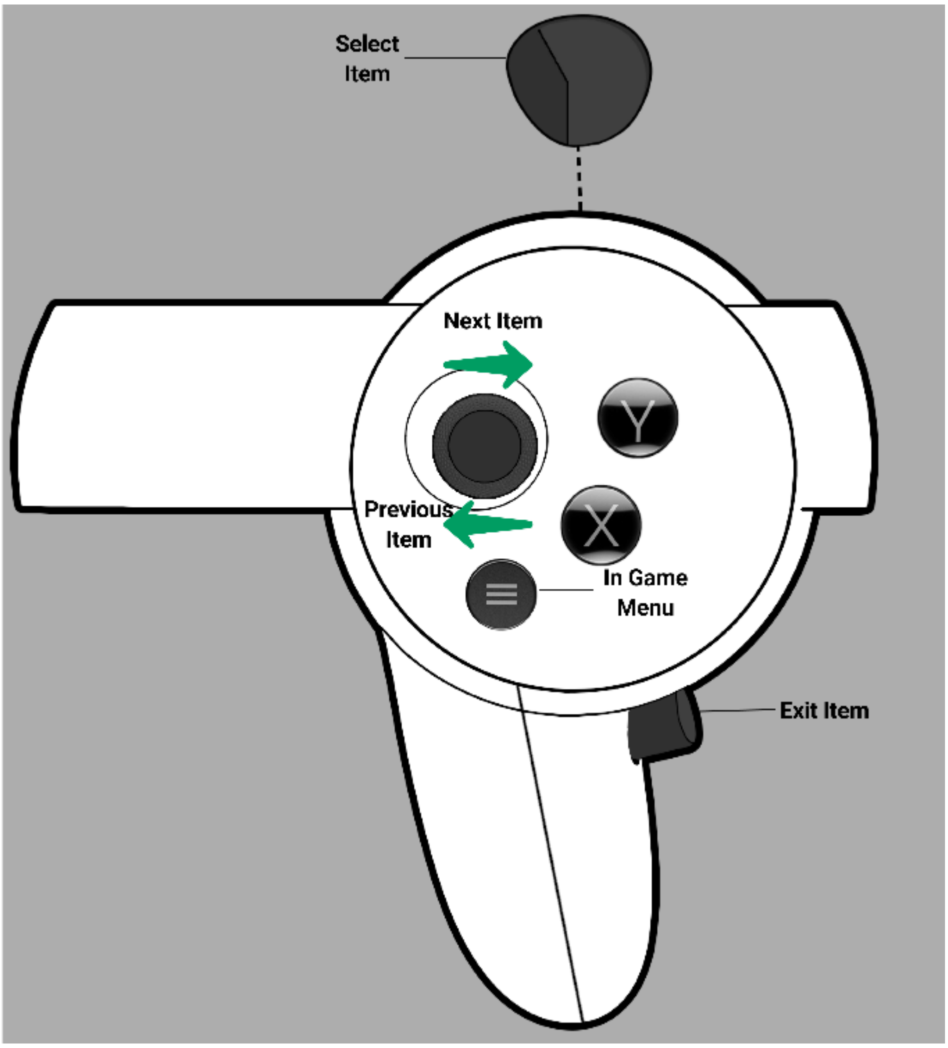

Figure 17: Left controller commands

Future plans for the Input Component encompass the integration of voice commands. Voice-based interactions present a natural and hands-free mode of engagement, particularly beneficial for users with mobility impairments and those who prefer voice-based interactions.

5.3 Summary of the proposed methodological approach

Summarizing the above, the methodological approach adopted by the framework entails accessibility adaptations at two levels, applying accessibility enhancement to individual XR components and to the entire scene.

The main components that are currently supported by the framework are text elements, images, videos, 3D objects and interactive elements (buttons, menus, 3D objects etc.). Following, we provide the proposed methods for making XR scenes accessible to people with visual impairments:

Text Elements:

- Customizable font size, color and outline.
- High-contrast background options.

Videos:

- Text transcript and alternative text.
- Captions with customization options.

Images and 3D Objects:

- "Hotspots" for better localization.
- Attached "Widgets" for alternative information pertaining to the image/3D object itself and/or the contained hotspots.

Interactive Elements:

- "Widgets" for alternative descriptions, including text, images, videos, 3D sound, and haptics.

Each interactive element will have an attached widget to alternatively describe it and may also have (e.g. if it is a 3D object) hotspots with attached widgets. This is an example of a short hierarchical structure. For all these main components it is essential to facilitate as many alternative ways of description for the “Widgets” as possible, but certainly all of them should have alternative text descriptions in order to be accessible from the screen readers.

With regard to accessibility support for the entire scene, the following components should be applied and be available to users to activate/deactivate as they prefer:

Scene Structure:

- Hierarchical order for accessibility by assistive technologies.
- Use of accessible switches like binary switches or keyboard for traversing the scene.

Screen Reader:

- Availability for users to activate as needed.

Visual Filters:

- Magnified lens.
- Edge enhancement.
- Brightness/contrast adjustments.
- Recolor options for colorblind users.

Alternative Navigation:

- Dynamic element positioning to bring active elements closer to the user if applicable.

Multimodal Feedback:

- Combine multiple outputs such as screen reader, 3D audio, and haptic feedback to provide a rich and immersive experience.

Multiple Hotspots:

- Offering multiple points of interest with attached widgets.

Meaningful Descriptions:

- Ensure that descriptions are clear and convey the relevant information accurately.

Multiple Input Methods:

- Provide users with various ways to interact with the XR environment to accommodate different preferences and abilities.

The accompanying figure (Figure 18) summarizes the proposed methods for enhancing XR accessibility.

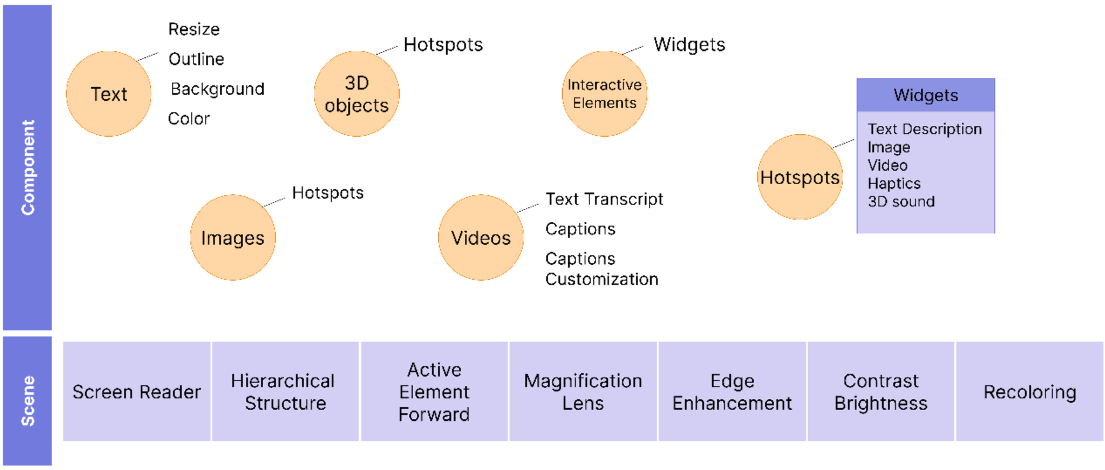

Figure 18: Our proposed methodological approach

Chapter 6

XR Accessibility Framework 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.

6.1 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 19. If desired, developers can add hotspots to the interactive elements for more precise interaction options.

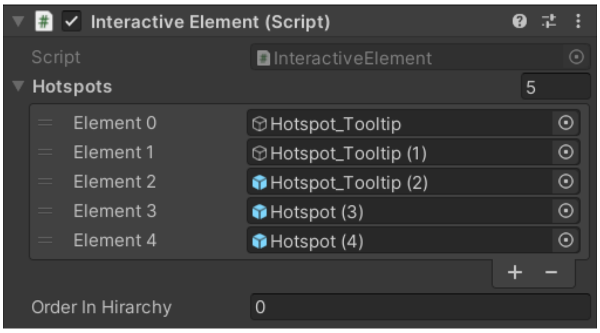

Figure 19: Interactive element script associated with a GameObject, with 5 hotspots GameObjects

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 20. 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 user experience within the XR environment.

[14] https://learn.unity.com/tutorial/prefabs-e#

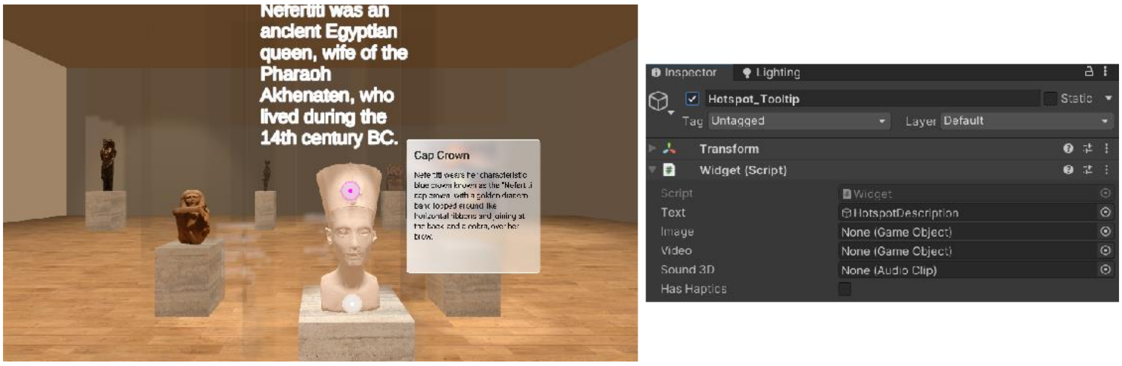

Figure 20: Hotspot with widget attached to it, supplementing information with text

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.

6.2 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)[15], 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 Game Objects 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 identifies the current interactive element and pass 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

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

framework utilizes this tree-based navigation to activate the corresponding container and present the relevant information to the screen reader.

6.3 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 virtual environment. 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 user experience, 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 21. 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 21: Next and previous element example

6.4 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 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 22.

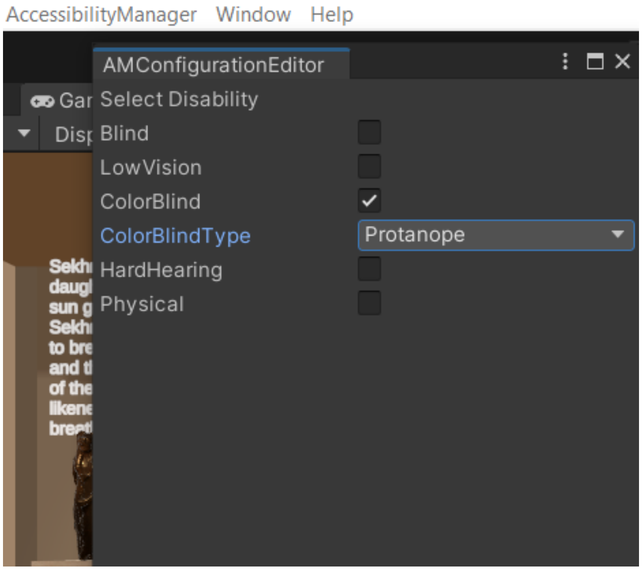

Figure 22: Accessibility Logic Configuration

As developers make their selections, a JSON-like element is generated that represents the game/application configuration, Figure 23. 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.

```json
{
    "blind": false,
    "lowvision": false,
    "colorblind": {
        "protanope": true,
        "deyteranope": false,
        "tritanope": false
    },
    "hardhearing": false,
    "physical": false
}
```

Figure 23: JSON object for configuration

6.5 Force and Temperature Feedback on 3D objects

To enhance 3D objects with force, texture, and temperature feedback, the XR Accessibility Framework seamlessly integrates with the Weart TouchDiver[16] haptic gloves and the corresponding Unity SDK[17]. Using the WeArtTouchableObject component provided by the SDK, developers can easily add haptic effects to specific 3D objects in the XR scene. To enable haptic feedback for a particular GameObject, the developer simply needs to attach the WeArtTouchableObject component to the desired 3D object. However, to ensure accurate

[16] https://weart.it/haptic-vr-products/touchdiver/
[17] https://www.weart.it/docs/sdkunity/

haptic feedback, the GameObject must also have a Rigidbody and a Collider component, as the haptic effects are applied upon collision with the user's hand.

To enrich 3D objects with dynamic haptic feedback, the XR Accessibility Framework seamlessly integrates with the Weart TouchDiver haptic gloves and utilizes the corresponding Unity SDK. The WeArtTouchableObject component, provided by the SDK, serves as the key interface for applying haptic effects to specific 3D objects within the XR scene.

The WeArtTouchableObject component offers a range of haptic attributes that developers can customize for enhanced realism and user engagement. These attributes include:

- **Temperature:** The temperature value implemented on the target thimble or thimbles, ranging from 0.0 to 1.0. A value of 0.5 represents the environment temperature, while lower values indicate colder sensations and higher values convey hotter sensations.
- **Force:** The force value applied on the target thimble(s), ranging from 0 to 1. A value of 0.0 indicates no force, while a value of 1.0 represents maximum force.
- **Texture:** The type of texture rendered on the thimble or target thimbles, represented by an index ranging from 0 to N. The Weart SDK provides a selection of textures that can be applied to the haptic feedback, such as crushed rock, plastic and more, as shown in the Figure 24
- **Volume Texture:** This attribute allows developers to configure the intensity of the texture rendering, adjusting the strength of the tactile feedback provided by the texture.
- **Graspable:** Enabling this option grants users the ability to grasp the virtual object with virtual hands.

To simplify the integration process and reduce developer workload, the XR Accessibility Framework offers a convenient solution. Through the widget, the developer can easily designate which GameObjects require haptic feedback by selecting the "Has Haptics" option. If the GameObject lacks the necessary components (Material, Rigidbody, Collider and WeArtTouchableObject), the framework automatically adds them to ensure proper haptic functionality. Once the "Has Haptics" option is selected, the WeArtTouchableObject component appears in the Unity Inspector window, allowing the developer to customize and fine-tune the haptic effects for the specific 3D object, as depicted in Figure 24.

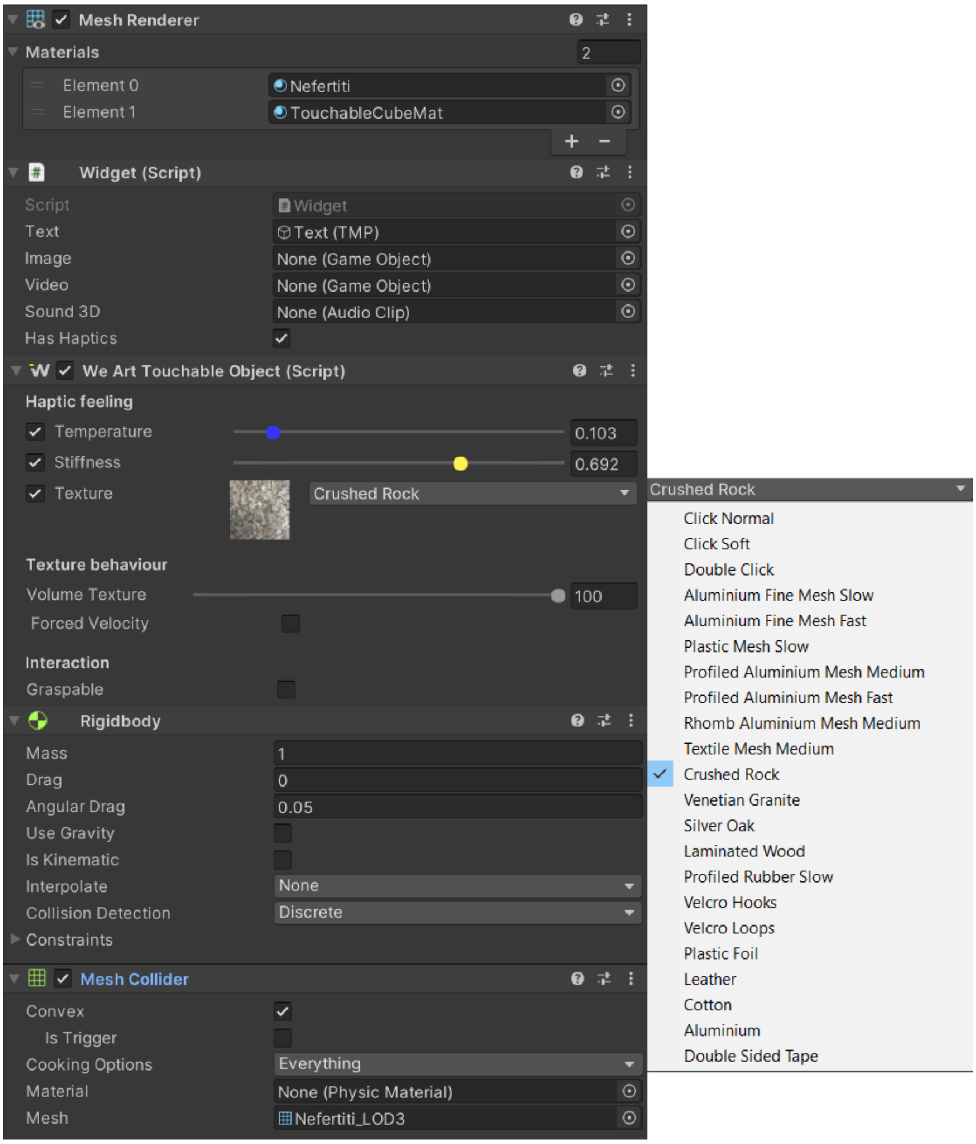

Figure 24: Haptic feedback configuration and list of available textures

6.6 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 developer prefers within the widget, 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.

6.7 Making the content components accessible

Text Adjustments: 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:

- 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.

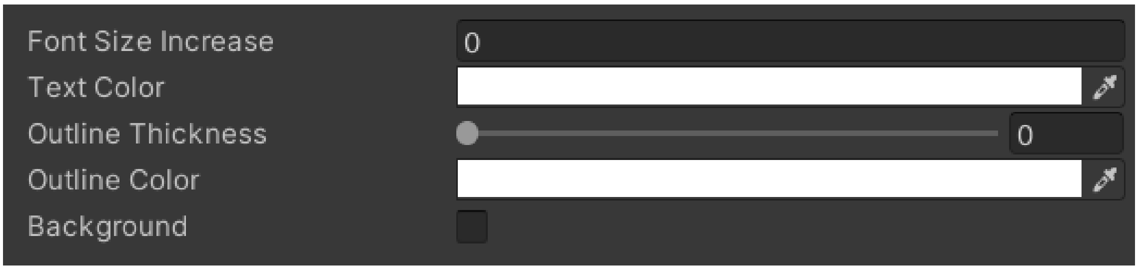

Figure 25: Text Adjustments Component

Subtitle Adjustments: Similarly, to the text adjustments, this implementation is driven by a scanning mechanism that identifies all subtitle elements *<Subtitle>* in the scene, ensuring that adjustments are applied accurately based on the developer options on Accessibility Manager script.

6.8 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) [94].

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.

6.9 Integrating the XR Accessibility Framework to 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," "colour 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.

Chapter 7

User Based Evaluation

A user-focused evaluation was conducted aimed at testing the effectiveness of the accessibility features embedded in the proposed 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 haptic gloves and Oculus 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.
Haptic Experience: If the incorporation of haptics as an accessibility tool enhanced the effectiveness of the system.
Mental Workload: How mentally demanding the VR system was for participants.
Overall User Experience (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. 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.

7.1 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 virtual environment that was developed with the proposed 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.
H4. The incorporation of haptic feedback as an accessibility tool enhances the overall user experience.

7.2 Procedure

The user-based study was conducted in the context of the SHIFT EU-funded project. The German Federation of the Blind and Partially Sighted (DBSV - Deutscher Blinden- und Sehbehindertenverband)[18], who is a SHIFT project partner, organized the evaluation in their premises, in Berlin. DBSV undertook participants' recruitment and handling of all personal data. Issues pertaining to data privacy and ethics were addressed by ERC ETICAS[19] Research and Consulting SL, who is the SHIFT project partner responsible for the societal, legal, ethical, and data protection issues. 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's repository as per the pertinent procedures specified within the project. The, the project coordinator 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 Oculus Quest 2 and controllers[20], as well as the Weart TouchDIVER[21] 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 retained the right to revoke their participation and consent at any time without facing any negative consequences. Then, they signed an informed consent form developed by the SHIFT project partners, which was made available online through the EUSurvey[22] 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.

[18] https://www.dbsv.org/
[19] https://www.eticasconsulting.com/
[20] https://www.meta.com/quest/products/quest-2/
[21] https://weart.it/haptic-vr-products/touchdiver/
[22] https://ec.europa.eu/isa2/solutions/eusurvey_en/

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 also made accessible through the EU Survey platform. Finally, participants were debriefed and thanked for their invaluable contribution to the aims and objectives of the study.

7.3 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 user experience 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-[95] 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) [96]. Upon concluding the experiment, participants were tasked with filling out standardized questionnaires to provide comprehensive assessments: (1) NASA-TLX [97] was utilized for workload measurement, capturing the cognitive demands imposed by the system in the given context. (2) UEQ (User Experience Questionnaire) [98] was employed to gauge the general user experience, encompassing various facets of usability and satisfaction. (3) SSQ (Simulator Sickness Questionnaire) [99] was administered to assess symptoms of discomfort or sickness induced by the VR experience. (4) A specific questionnaire was employed to gather feedback on the participants' haptic experience [100] within the VR environment. Furthermore, a debriefing interview was conducted, affording participants the opportunity to articulate their feedback about the system. This qualitative feedback encompassed aspects they found favorable, areas of discontent, and overall impressions.

7.4 Museum Case Study

For the purpose of testing and evaluation, we are developed a Unity sample scene. This scene simulates a Virtual Reality 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 26: Initial scene menuFigure 26). 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 27 and Figure 28). Subsequently, the user can engage with the chosen artifact and explore its various hotspots (Figure 29).

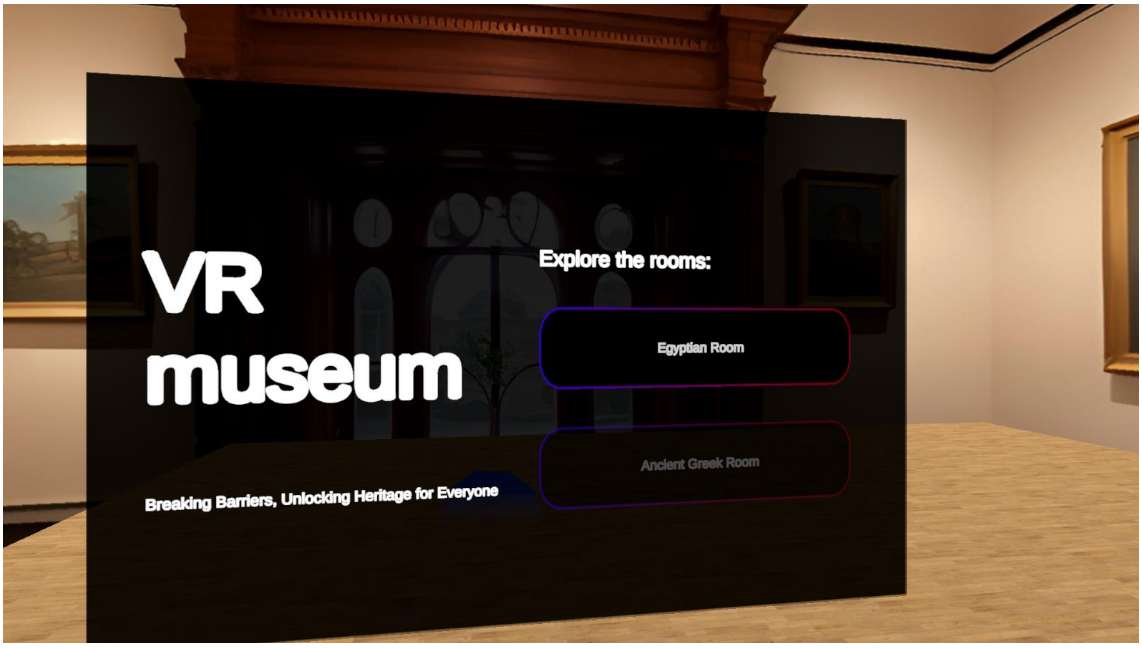

Figure 26: Initial scene menu

Figure 27: Entering a room

Figure 28: Selecting an artifact

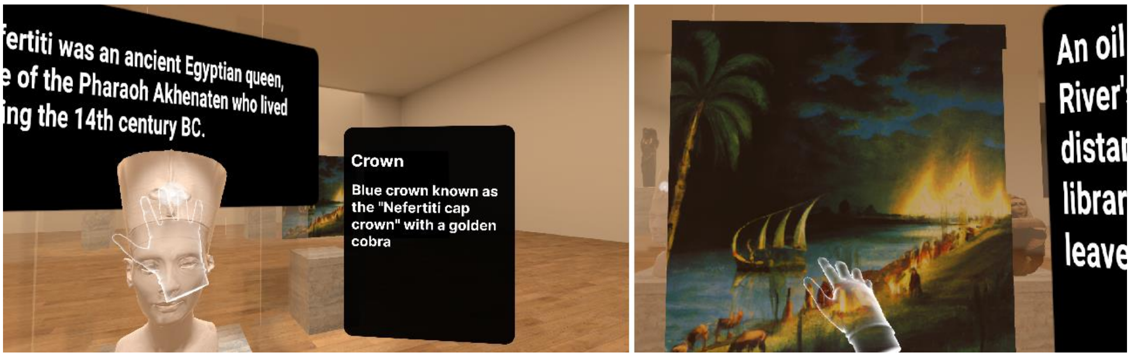

Figure 29: Interaction with the hotspots of artifacts

7.5 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 user experience, including the effectiveness of the accessibility features integrated into the system. The scenarios were the following:

Scenario 1: You are a guest to 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 how many rooms are available to be explored.

Scenario 2: During your visit, you're 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’re interested in the necklace that she used to wear. 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.

7.4 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[23] and macular degeneration[24]. 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, gamepad and gesture-based interaction. Figures Figure 30, Figure 31 and Figure 32 show the distribution of participants' age, age of the vision impairment onset, and ways of accessing digital content respectively.

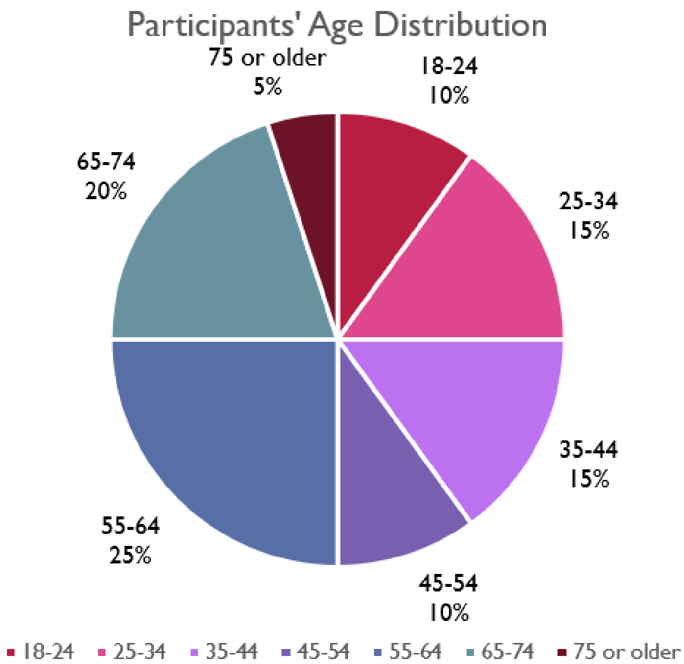

Figure 30: Participants' age distribution chart

[23] https://en.wikipedia.org/wiki/Tunnel_vision
[24] https://en.wikipedia.org/wiki/Macular_degeneration

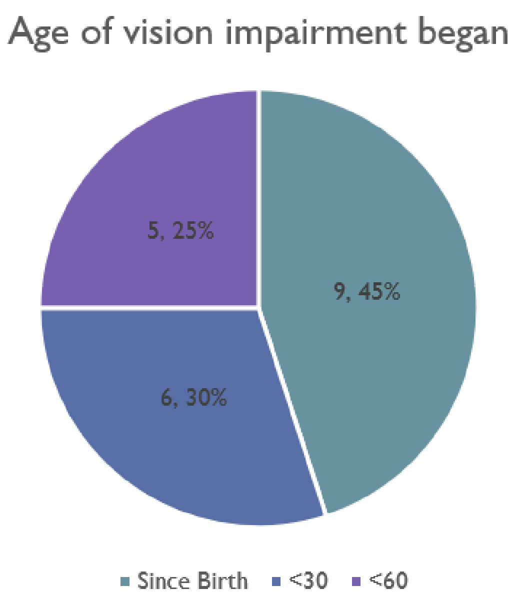

Figure 31: Participants' age when the vision impairment began

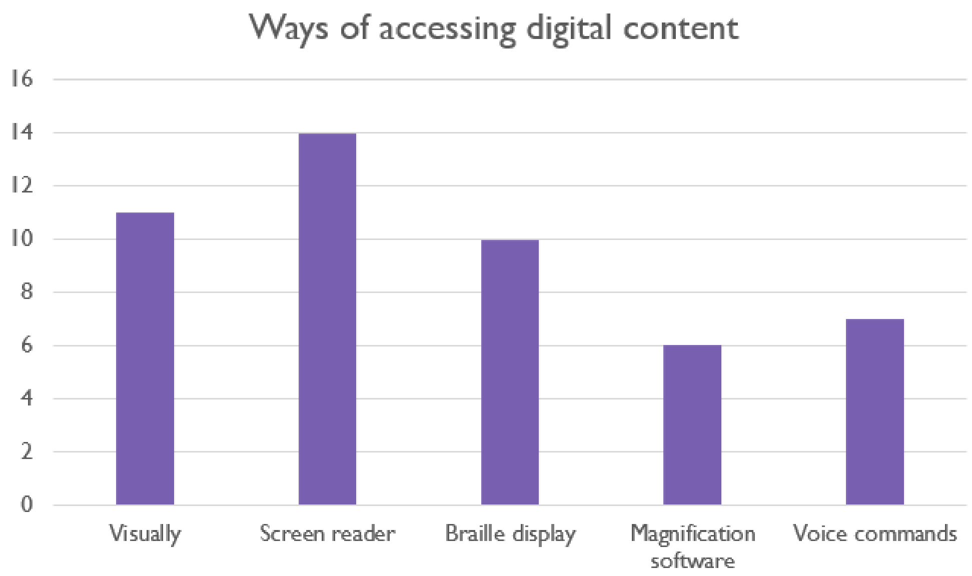

Figure 32: Methods of accessing digital content

7.5 Results

7.5.1 Effectiveness of the system

7.5.1.1 Quantitative metrics

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 33) and success rates (Figure 34) for each scenario. In addition, we analyzed the outcomes of the debriefing session, as well as observers' notes. Participants rated the scenarios on a scale from 1 (very difficult) to 7 (very easy). Success was measured on a scale of success, partial success, or fail, with partial success indicating that the user was in the correct direction but couldn't complete the task, or that they completed the task with errors.

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's important to note that to complete these scenarios successfully, participants had to comprehend the concept of hierarchical reading to navigate within the virtual environment. 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 virtual environment.

Task 3 was considered moderately easy at 4.2 in 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 easy, 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 virtual environment, 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 through the user-based assessment and is further discussed in Section 8 ‘Conclusions and Future work’. Similarly, to blind users, mostly all 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 laid 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 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.

An overview of the average scores on scenarios' ease of completion and task completion is provided in Figure 33 and Figure 34 respectively. Table 4 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).

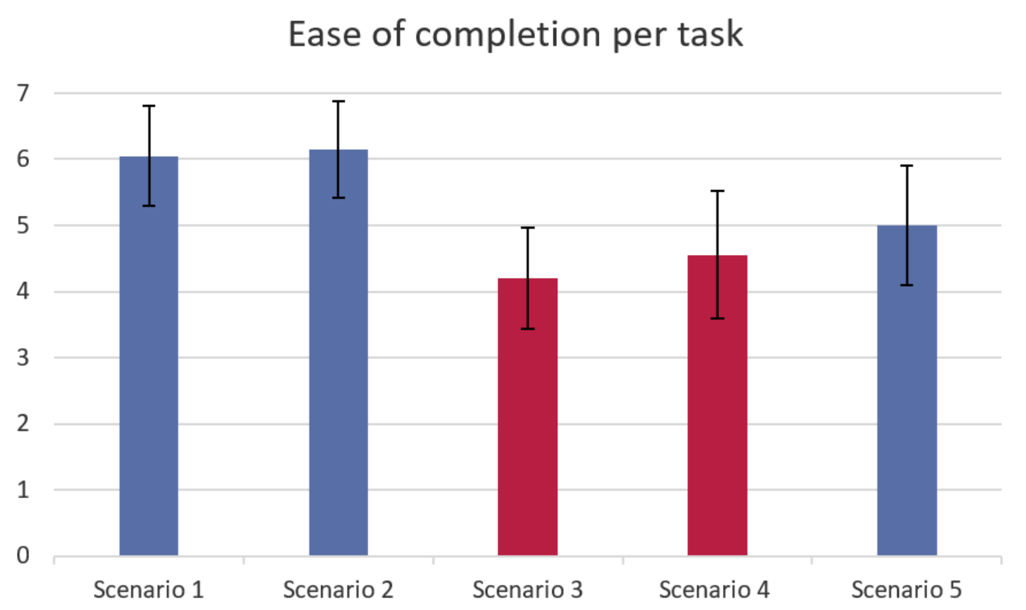

Figure 33: Scenarios Difficulty (very difficult 1, very easy 7). Error bars represent 95% CI

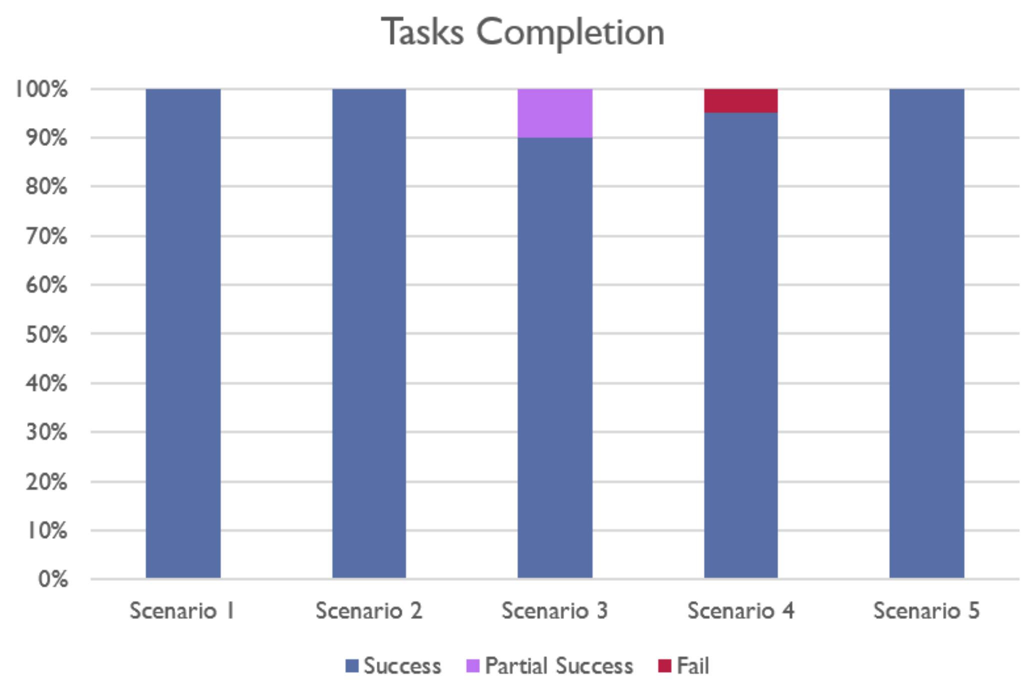

Figure 34: Tasks Completion results

	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 4: Ease of completion per Task

An analysis of success rates per task is presented in Table 5, 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% [101]. 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 5: Task Success rate per task

From the above, it is evident that even for the most difficult tasks we can be 95% 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.

7.5.1.2 Qualitative feedback

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 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 that it helped them understand the virtual environment 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 5.2.7 Input Component, 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's 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's 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 stationary. 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 a 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 weight, and haptic feedback precision as the system evolves to further enhance the user experience for individuals with visual impairments. Other improvements identified

7.5.1.3 Discussion

In summary, the effectiveness of the system can be discerned from a holistic analysis of the debriefing interviews and observer notes, coupled with the success rates and perceived task ease of completion. Considering the high success rate, the rather high perceived ease of the assigned tasks although it was participants’ first encounter with the system, as well as the positive comments provided for the system, collectively, these results substantiate the hypothesis that the system's accessibility features are indeed beneficial for individuals with visual impairments engaging in VR museum exploration. As a result, hypothesis H1 is confirmed.

To provide a more detailed overview, it is noteworthy that participants perceived scenarios 1 and 2 as highly manageable, with a remarkable success rate of 100%. This high success rate underscores the efficacy of the system's accessibility features in facilitating participants' navigation through the complexities of these scenarios. Scenario 3, while yielding a success rate of 90%, emerged as the most challenging according to participant feedback. However, the debriefing interviews revealed that the system played a pivotal role in aiding participants during this task. Notably, the abundance of hotspots with auditory feedback for the Nefertiti artifact facilitated the identification of the necklace. Furthermore, the haptic feedback proved invaluable in assisting participants in keeping their hands within the interactive area of the artifact. For blind users, the primary challenge centered on locating the necklace on the artifact and obtaining supplementary auditory information about it. Partially sighted users encountered difficulties in reading the additional information displayed on the artifact and expressed a desire for the ability to adjust the position of the text to a more comfortable location.

Moving on to scenarios 4 and 5, the overarching observation is that while haptic feedback enhances the user experience, developers should consider augmenting it with supplementary text and audio information. Moreover, the utilization of multiple hotspots can facilitate users' navigation within the artifact. Additionally, it is advisable for the framework to incorporate a means of assisting users in pinpointing the exact location of artifacts and their associated hotspots within the virtual environment.

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 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.

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 user experience

#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.

7.5.2 Haptic experience

7.5.2.1 Quantitative metrics

To assess the effectiveness of haptics in enhancing the user experience and facilitating a deeper understanding of the VE, aligning with hypothesis (H4), we utilized the Haptic eXperience Index (HXI) [100]. This index was derived from a 20-item questionnaire designed to evaluate the haptic experience in multi-sensory applications incorporating vibrotactile feedback. The analysis of the questionnaire results was conducted across the following dimensions provided by the questionnaire:

- **Realism:** This dimension aims to assess how closely the haptic feedback resembled real-world sensations, providing insights into the authenticity of the haptic experience.
- **Immersion:** Immersion measures the extent to which the haptic feedback contributed to users feeling fully engaged and absorbed in the virtual environment.
- **Expressivity:** Expressivity examines the haptic feedback's ability to convey a wide range of tactile sensations, offering users a rich and diverse haptic experience.
- **Autotelic:** Autotelic explores whether the haptic feedback inherently contributed to users' enjoyment and satisfaction, regardless of the specific task at hand.
- **Harmony:** Harmony considers how well the haptic feedback integrated with other sensory inputs, such as visual and auditory cues, to create a cohesive and unified user experience

Participants responses to the questionnaire ranged on a scale of -2 to 2. The results are detailed in Table 6 and illustrated in Figure 35. The overall score of the haptic experience amounts to 0.61. It is evident that all parameters achieved a positive score, thus highlighting an overall positive haptic experience. Nevertheless, realism received a neutral score (close to 0). It's important to recognize that this result aligns with our expectations, considering the inherent limitations of the haptic device used in the study. This is also aligned with findings from the literature, which underscores that affordable, less costly haptic devices cannot deliver a high level of realism [102]. Furthermore, it's worth noting that the ability to recognize various materials and textures is closely intertwined with visual information, and haptic feedback can serve to augment this sensory experience [102]. However, if visual information is unavailable, the potential for haptic feedback to be effective is significantly limited. These limitations may have contributed to a somewhat lower realism score.

	Realism	Immersion	Expressivity	Autotelic	Harmony
Mean	0,02	0,86	0,73	0,82	0,62
Variance	1,68	1,35	1,39	1,81	1,19
SD	1,30	1,16	1,18	1,34	1,09
95% CI[LL]	-0,31	0,63	0,47	0,56	0,41
95% CI[RL]	0,34	1,09	0,98	1,08	0,83

Table 6: Results of the haptic experience questionnaire

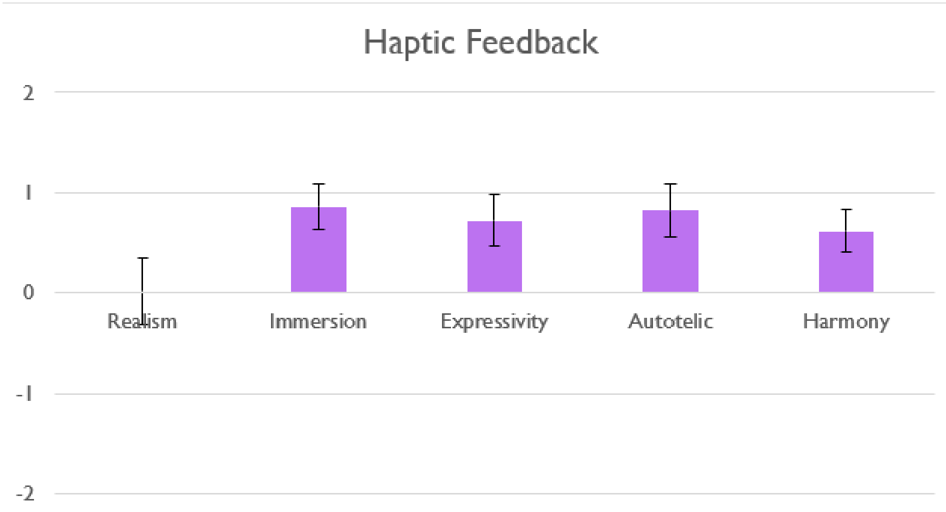

Figure 35: Haptic Experience Results. Standard Errors represent 95% CI.

Aiming to further explore participants' experience, an analysis of the distribution of responses per category was conducted, as shown in Figure 36.

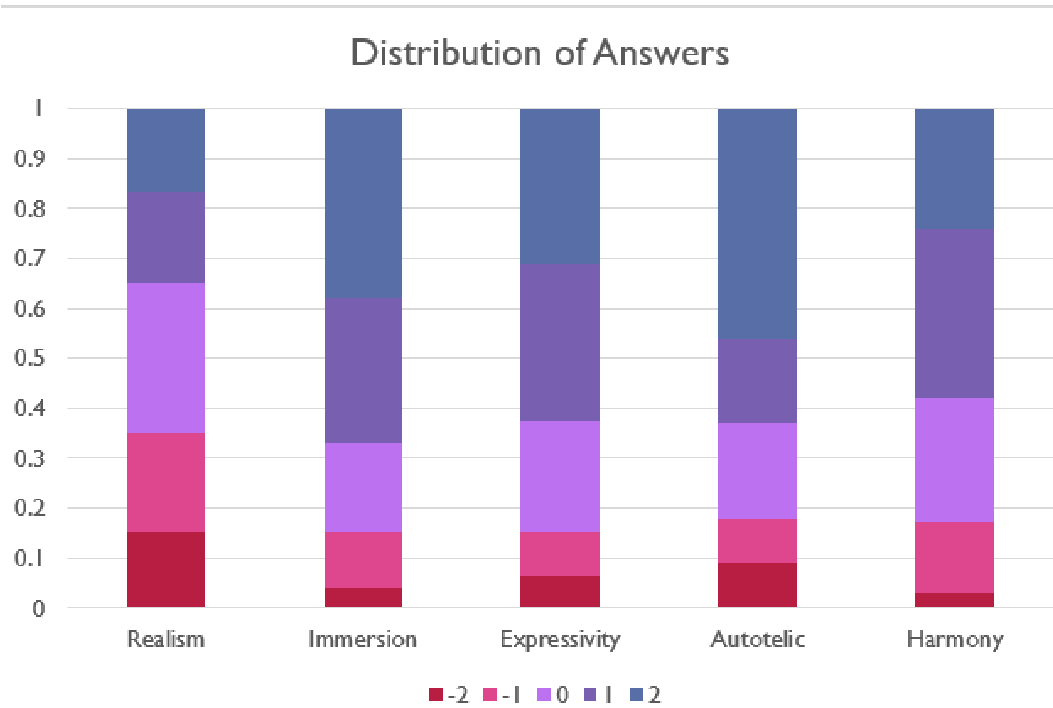

Figure 36: Distribution of responses to the haptic experience questionnaire

It is noteworthy, that all dimensions besides realism received mostly positive ratings. The dimension of Immersion received positive scores by 67% of participants. This underscores the significance of haptic feedback in enhancing the overall user experience. In terms of Expressivity, 62.5% of participants acknowledged experiencing diverse haptic sensations, indicating that the system effectively provided varying tactile feedback in response to different inputs and events. Notably, in the context of Autotelic, 63% of participants found the system intrinsically enjoyable and fulfilling, highlighting that haptic feedback played a role in enhancing the system's overall appeal. Regarding Harmony, 58% of participants felt that the haptic feedback harmonized well with other sensory inputs, such as sound and visuals. This synergy between haptic feedback and other sensory cues contributes to a more comprehensive and immersive user experience.

In summary, the results suggest that integrating haptic feedback into the system has a positive impact on immersion, expressivity, satisfaction, and enjoyment. This enhancement occurs while maintaining harmony with other sensory elements, supporting the hypothesis that haptic feedback contributes to a more engaging, informative, and enjoyable user experience in the virtual environment. These findings are further reinforced by the responses obtained during the debriefing interviews, where participants expressed their appreciation for the haptic feedback and its role in enhancing their overall interaction and satisfaction with the system.

7.5.2.2 Qualitative feedback

Qualitative feedback regarding haptics analyzed pertinent observers' notes and user comments during the debriefing session. Observer notes regarding the haptics employed highlighted that several users found the temperature feedback in the painting to be particularly immersive, with one user even remarking, "The water in the river feels cold, and it genuinely feels wet!" However, some participants were cautious about touching the area with fire, as they were unsure if it might cause a burning sensation. In terms of the interaction with the painting, one participant tried to explore it as if it were laid flat on the physical table and suggested that it might be more comfortable to have the paintings placed horizontally on a physical surface due to the weight of the haptic device. Most older participants commented on the weight of the device, indicating that it might need some improvements in this regard. An interesting observation was made when users experienced their first collision with virtual objects and felt force feedback on their fingertips. They expressed surprise at how the sensation felt, saying, "Oh, that's how it would feel." For blind participants, the haptic feedback proved beneficial in detecting the shape and dimensions of 3D artifacts and the painting, and they acknowledged the usefulness of this information. However, nearly all blind participants expressed a desire for more precise haptic feedback. One participant pointed out, "I can hear that Nefertiti has eyes, and my hand is touching them, but I can't feel the bumps of her eyes."

Participants' comments highlighted that haptics were appraised by participants as a modality, for its contributions toward a more holistic experience engaging all the senses. Other positive comments identified that it is a novel experience. Overall, haptic feedback – combined with other output methods – was identified as a positive highlight of the system by 50% of participants, explaining that their engagement with the system was attributed to the presence of haptic feedback and that it helped them maintain focus on their tasks. Participants also mentioned that "it could be an add-on for haptic experiences, as most physical artefacts in museums are not touchable". Only 5% of participants classified haptic feedback as one of their least like features, identifying that the system's haptic feedback interfered with their primary objectives. 20% of participants suggested that it should be further improved and provided specific suggestions such as to the need for providing a more detailed and refined experience (e.g., catering for changes in force feedback depending on the distance from an artefact), the need for increased precision, and the deficiencies in realism.

7.5.2.3 Discussion

Quantitative and qualitative results concur with the conclusion that haptic is a useful modality of interaction in XR environments, yet not as the primary source of information. Instead, haptics can constitute a modality complementary to other output methods, conveying additional details and enriching the overall user experience. In this regard, hypothesis H4 is supported, with findings revealing that haptic feedback enhanced immersion, expressivity, satisfaction, enjoyment, and harmony with other sensory elements.

In the context of experiencing CH, haptic is a useful modality, analogous to the haptic physical museum artefacts, which have started being included by contemporary inclusive museums addressing blind users [62], [64], [103], yet to a limited extent. At the same time, it should be noted that higher realism and precision are sought by end users to ensure that the haptic output is meaningful and useful. Useful findings from the conducted analysis are summarized below.

Framework Insights
#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 a self-standing output modality, its complementarity with other output modalities is highly appraised in promoting more holistic experiences.

Accessible XR experiences findings
#6 – Strive for detailed haptic design to pursue a 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 the 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 virtual environments 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 virtual environment.

7.5.3 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.

7.5.3.1 Quantitative metrics

7.5.3.1.1 UEQ Results

This questionnaire gauges various dimensions of the user experience, 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 7 presents the results across all scales, which are also illustrated in Figure 37 (left). Figure 37 (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 user experience 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 7: UEQ Results

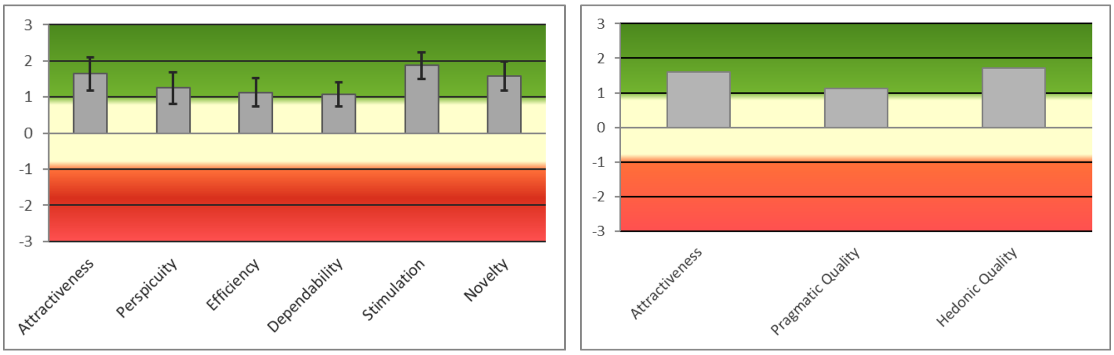

Figure 37: User Experience Scores (left) per construct (right) per pragmatic quality

Further analysis of the responses, looking into the distributions of answers to each item, highlighted the system characteristics that raised the heightened concerns to users. In particular, the item which was least favorably rated refers to the predictability of the system, highlighted that 45% 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 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. Further insights into this were acquired through the analysis of the qualitative results as described in section 7.5.1.2. 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.

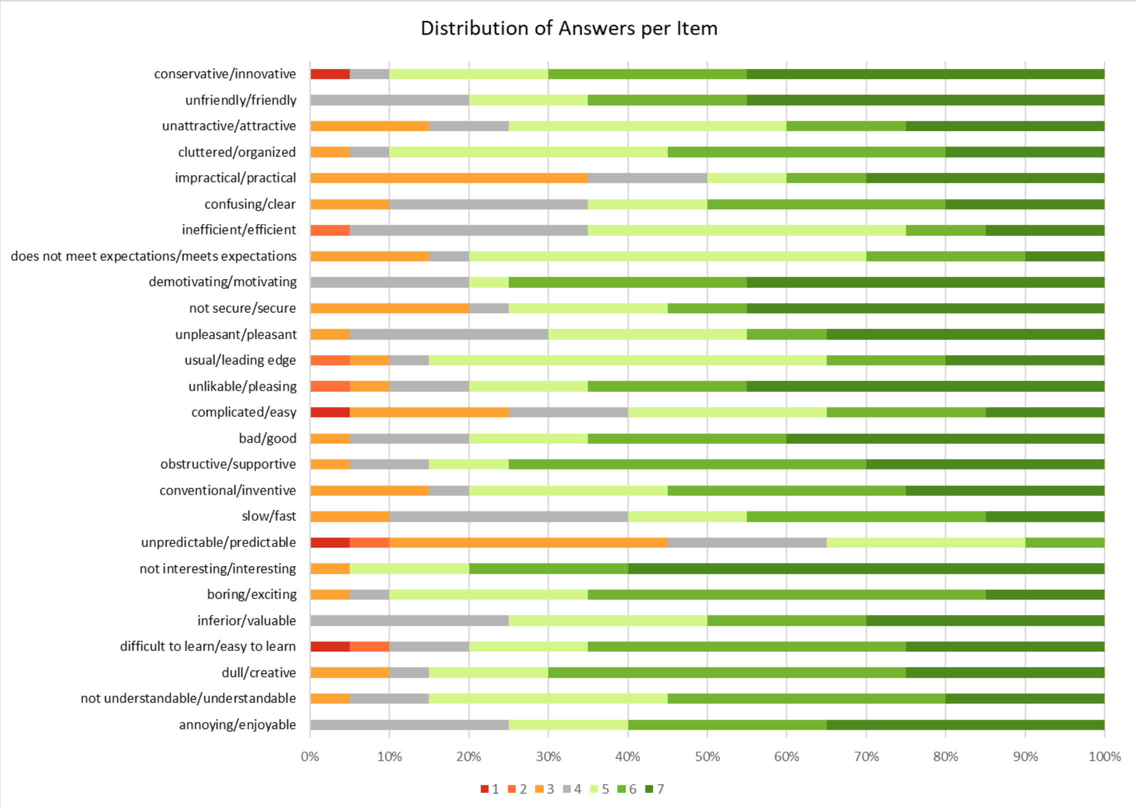

Figure 38: Answer distributions for UEQ

Aiming to further elaborate on H3, the overall UX assessment was compared against benchmarks, consistently surpassing average benchmarks (Figure 39), thus confirming so far the hypothesis that the system ensures a positive user experience.

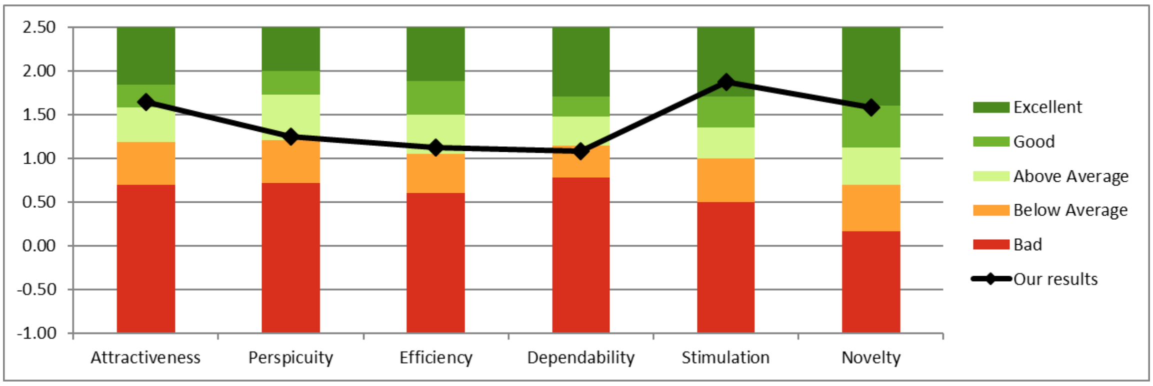

Figure 39: User Experience Benchmark Results

7.5.3.1.2 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 8: SSQ Results presents the results of the SSQ questionnaire, organized in three main categories as discussed above, including one additional score for the overall simulator sickness. Figure 40 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 8: 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 User Experience, 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 reminder that user experiences can vary significantly, and a personalized approach to addressing symptoms is essential to provide the best possible user experience.

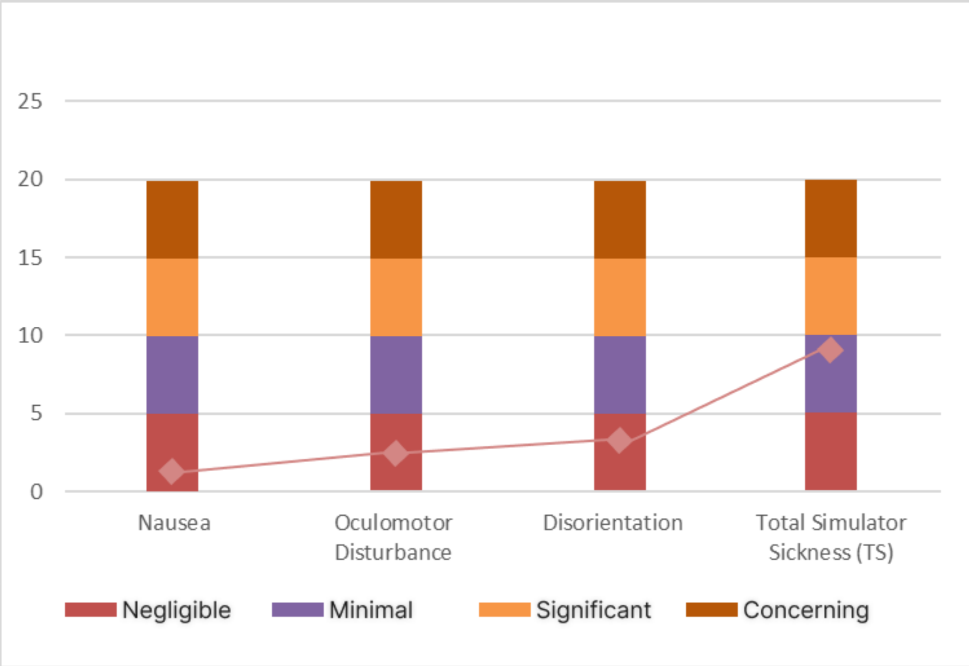

Figure 40: Simulator Sickness Results against benchmarks

7.5.3.2 Qualitative Results

This section analyzes participants' responses to the debriefing discussion 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, 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 was 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 lens, 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 virtual environment. 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.
- 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, which 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 three 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 to be able to move in the virtual environment, 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 virtual environments 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.

7.5.3.3 Discussion

Analysis of the user experience quantitative and qualitative feedback yielded useful findings and suggestions for improvement. First of all, it was clear that the user experience entailed was very positive and no sickness symptoms were caused. Participants were highly satisfied with the system's attractiveness, efficiency, novelty and stimulation, as well as how easy it was to learn it and be in control of the interaction.

Participants' concerns in terms of user experience revolved around practical issues. At the same time, suggestions were provided for improving the system, some of which pertain to the framework and some to the design of the VR environment. Blind participants were mostly annoyed by the difficulty to locate an artefact in order explore it through touch, highlighting the need for additional navigation instructions in this regard. Location and orientation instructions were also recommended as a means to assist blind users in creating a mental representation of the artefact. Furthermore, system adaptability in terms of customization of the speech rate was highlighted by participants as a shortcoming of the system which should be addressed, to accommodate to the best possible extent users' preferences.

Users with visual impairments expressed their desire for freely moving in the virtual environment and not be forced to a stationary exploration. Furthermore, they expressed their preference for being able to adapt the position of displayed widgets to better suit their needs.

All participants appraised the information provided through hotspots, and at the same time stressed the need for further enriched content describing the artefacts. The haptic feedback was highly appreciated, especially novel haptic attributes such as temperature sensation. The combination of haptics and 3D sound was also applauded. At the same time, concerns were raised regarding the hardware employed in terms of weight. Finally, interaction with the designated HMD device controllers was in one case deemed as uncomfortable.

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.

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.

7.5.4 Mental Workload

In order to measure the mental workload of the participants while using the system (hypothesis 2 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:** it assesses how much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)
- **Physical demand:** it measures how much physical activity as required
- **Temporal demand:** it explores how much time pressure the user felt due to the rate or pace at which the tasks occurred
- **Performance:** it assesses how successful the participants think that they were in accomplishing the goals of the task set by the experimenter
- **Effort:** it explores how hard the user had to work to accomplish their level of performance
- **Frustration:** it measures how insecure, discouraged, irritated, stressed and annoyed was the user as opposed to 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 [104], however there is evidence that weighted scores should better be employed [105].

The results of the NASA TLX questionnaire reveal valuable insights into the participants' perception of workload during the task. Table 9 presents the raw scores for each one of the dimensions, whereas Table 10 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 10%) regarding the workload induced across various studies and in the second quartile regarding the workload induced by computer activities [106]. Unfortunately, there is no benchmark or summative studies on workload in Virtual Reality environments, therefore it is not possible to draw any further conclusions. Considering, however, that the overall workload induced is classified as substantially lower than the 50% of workload reported in computer activities, hypothesis H2 is confirmed.

	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 9: 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 10: NASA-TLX Weighted scores per scale. It is noted that performance is an inverted scale.

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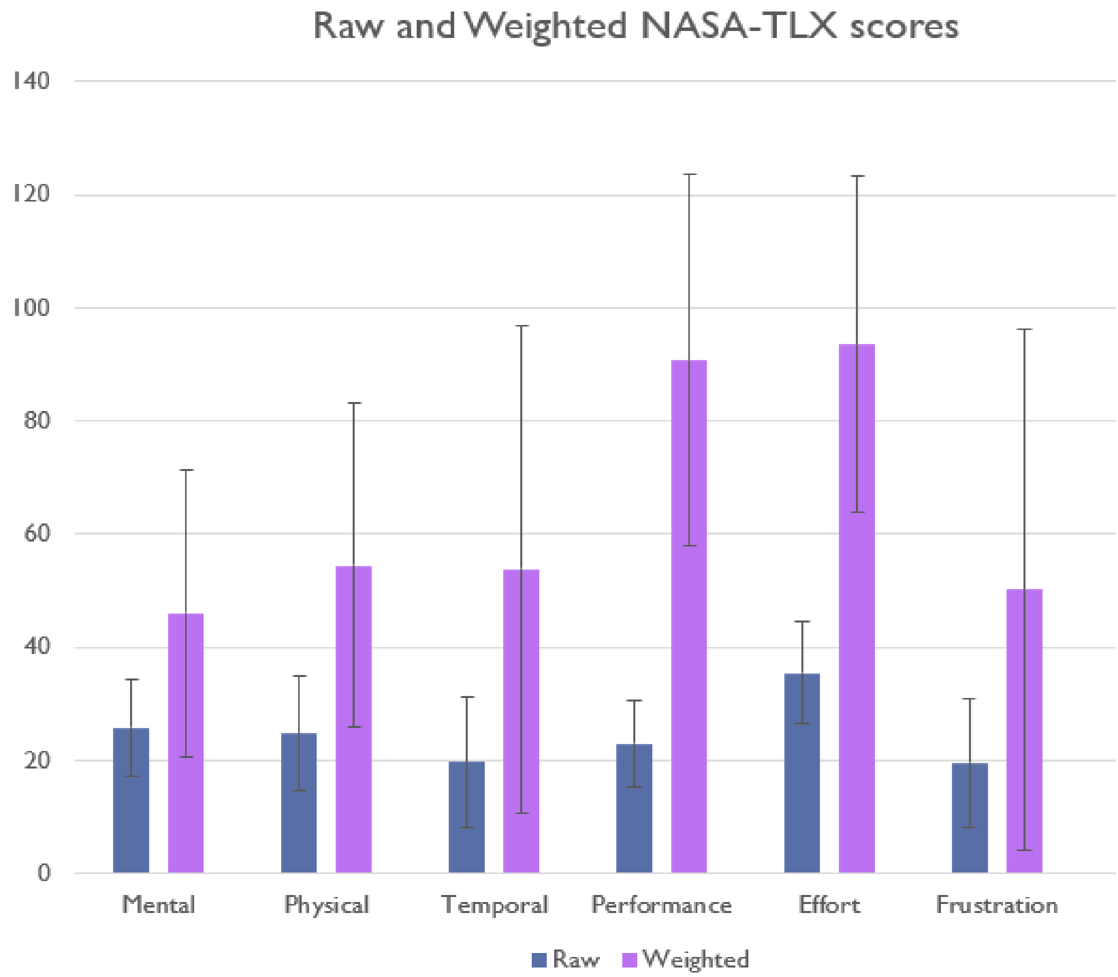

Figure 41: Raw and weighted NASA-TLX scores

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 highlight 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 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), however, considering the weights assigned by participants it became the second most important factor of workload 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, neither were any temporal demands or frustration imposed by the use of the system.

7.6 Discussion

The user-based evaluation of the framework aimed to assess the accessibility and user experience of a VR system that was developed with the proposed framework. In particular, the aims of the study were to assess the embedded accessibility features as a means to support users in perceiving and engaging with the VE effectively, without imposing mental workload on the users, ensuring at the same time a positive overall user experience. Furthermore, considering that haptics constitute a novel modality of the framework, its impact on the overall user experience was studied separately.

Regarding effectiveness, the results yielded a remarkable overall task completion score (M:0.97, SD: 0.12) and a very good ease of completion (M:5.19, SD:1.91) as perceived by the users. This signifies that although users encountered some difficulties in their interaction with the system, as revealed through observer notes and participant interviews, these did not interfere with their interaction, allowing them to effectively receive information and interact with the virtual museum artefacts.

In terms of workload, an excellent overall score was achieved for raw workload (24.70) and weighted workload results (25.97) classifying the workload induced by the system as substantially lower than 50% of workload reported for computer activities. Further insights into aspects of the system that may impose workload were drawn by analysis of weighted scores across each of the scales supported by NASA-TLX, highlighting that the required effort to achieve one's performance was participants' main point of distress.

Concerning the overall user experience, quantitative results highlighted that negligible nausea (M:1.16, SD:0.38), oculomotor disturbance (M:2.74, SD:0.69), and disorientation (M:3.48, SD: 0.59) were reported, and minimal overall simulator sickness (M:9.20, SD:0.55). Furthermore, positive scores were achieved for the system's attractiveness (M: 1.64, SD: 1.10), perspicuity (M: 1.25, SD: 1.02), efficiency (M:1.12, SD:0.79), dependability (M:1.07, SD:0.61), stimulation (M:1.87, SD:0.71), and novelty (M: 1.57, SD:0.85). As a result, it can be safely inferred that an overall positive user experience was provided by the system.

With regard to the haptic experience, positive scores were achieved for all dimensions, besides realism. More specifically realism received a neutral score (M:0.02, SD:1.30), whereas immersion (M:0.86, SD:1.16), expressivity (M:0.73, SD:1.18), autotelic (M:0.82, SD:1.34), and harmony (M:0.62, SD:1.09) received positive scores. The finding regarding realism was expected considering the limitations of the haptic device that was used in the study, a relatively simple device that a museum could afford.

Analysis of qualitative feedback yielded valuable insights both for the framework and the design of accessible XR experiences, which are summarized below.

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 a self-standing 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.

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 user experience
#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 a 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 the 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 virtual environments 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 virtual environment.
#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.

The limitations of the current study are twofold. First, the demo scene to be tested was developed by ourselves to act as a demonstrator of the accessibility features. One potential limitation regarding the proposed scene is the lack of complexity. The scene comprised of 3 elements and 2 rooms, whereas in a realistic virtual museum more artefacts would have been added. Furthermore, the experience designed was rather simplistic and stationary, with users of the VR museum exploring it from a fixed position. Nevertheless, it is noted that the current study was carried out as an initial exploration of the qualities of the proposed framework. Future studies will address this limitation by deploying the framework on highly complex XR scenes. Furthermore, the number of users was adequate to reach useful findings and identify areas of improvement for the proposed framework. Considering that each target user category involved 10 participants, the number of users could be identified as a limitation of the current work. Nevertheless, it is noted that trials with users with disabilities rarely achieve very large numbers of participants, mainly due to the increased complexity of the endeavour. Future work will address this limitation by including additional users to assess the refined version of the framework.

Chapter 8

Conclusions & Future Work

This thesis has introduced a methodological framework designed to address the need for enhanced accessibility in XR applications, with the aim of providing a cohesive approach for developers, supporting them to make XR applications accessible for people with visual impairments. The framework's comprehensive toolkit equips developers with features to seamlessly integrate diverse accessibility options into their XR applications, as it is implemented as an asset package. Rooted in the 'Accessible by Design' philosophy, the framework was developed following a Human-Centered Design approach, involving end users and encompassing extensive research on digital accessibility barriers imposed by XR technologies, existing technological solutions, and development tools. It harnesses all the proposed best practices and tools, gathered by the literature and the input of relevant stakeholders, empowering developers to prioritize accessibility without adding unnecessary complexity to the development process.

The framework provides ready-to-use accessible adaptations to the developers for specific user groups, such as those who are blind, have low vision, or other visual impairments. Developers can define their target audience, and the framework then automatically integrates pre-configured accessibility features into the XR application, simplifying the accessibility integration process. However, despite these automated adaptations, 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. It enhances XR elements with haptic feedback, specifically focusing on force and temperature, to enable developers to accurately represent virtual objects by conveying information about their real-world physical characteristics. In an effort to enhance sensory substitution and alternative localization methods, the framework also provides the capability to describe visual elements using a combination of audio descriptions, haptic feedback, and 3D sound.

Regarding the contributions of the thesis, firstly, this is, to the best of our knowledge, the first systematic review in the field of XR accessibility for individuals with vision impairments. This review not only establishes a foundational understanding of the current state of accessibility solutions but also presents an organized discussion categorizing these solutions according to user needs and XR domains, effectively serving as a valuable reference for both researchers and practitioners. Furthermore, the thesis introduces a novel taxonomy for classifying accessibility solutions within XR environments, thereby providing a roadmap for future research endeavors. Additionally, it offers practical guidance for the design and development of accessible XR applications for people with visual impairments and presents an innovative ready-to-use framework equipped with a range of accessibility features derived from literature and user requirements, that can be easily integrated into XR applications. The framework includes pre-configured profiles catering to specific user needs, such as blindness or color blindness. It is noted that although the framework focuses on users with visual impairments, it is readily extensible. In fact, several of the accessibility solutions included can be used to address accessibility needs of additional user categories, such as the incorporation of haptic feedback for persons with hearing impairments, or the sequential access of the elements of an XR scene for persons with motor impairments who can use scanning employing the functionality already developed. Moreover, the effectiveness of the framework's accessibility features is underscored by the positive feedback received from both expert-based and user-based evaluations. Lastly, the thesis contributes a systematic methodology for evaluating systems designed to enhance accessibility for individuals with visual impairments, enhancing the tools available for advancing XR accessibility in a meaningful way.

The framework was developed as part of the European project SHIFT, aiming to make cultural heritage artefacts accessible for all individuals, including those with disabilities. To evaluate the effectiveness of the accessibility features of the framework in the context of the project, a Unity sample scene was developed featuring a VR museum with artefacts to be explored. A user-based evaluation was conducted with a well-balanced sample of 20 participants with visual impairments, aiming to access our approach and its accessibility features regarding the effectiveness, the workload, the overall User Experience and the incorporation of haptic feedback as an accessibility tool. The evaluation aimed to explore four hypotheses regarding the effectiveness of the embedded accessibility features, the workload induced, the overall user experience, and the impact of haptic output.

Regarding the effectiveness of the accessibility features of the framework, 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 artifacts without significant hindrance. Furthermore, the results from NASA-TLX, both weighted and raw, indicate that the system does not induce workload, compared to workload induced by computer activities as reported in the literature. The user experience 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. Novel attributes proposed by the framework, such as hotspots in interactive elements and haptic feedback were appreciated by participants, though concerns about hardware weight and discomfort with HMD device controllers were raised. Participants had a positive overall impression of the haptic experience, valuing its contribution towards a holistic experience, commenting however on the lack of realism, an anticipated flaw due to the use of a budget-friendly haptic device suitable for a museum context.

Responding to valuable user feedback, future work will explore innovative methods for aiding users in locating artefacts within virtual environments. This could entail a combination of 3D sound cues emanating from artefacts and dynamic "turn-to-turn" directions based on the user's hand position. The aim is to provide users with a more intuitive and spatially aware experience, simplifying the process of discovering and interacting with virtual objects. The positive reception of haptic feedback highlights the potential for further exploration in this area. Future research will delve deeper into haptic design, focusing on enhancing the precision and variety of haptic sensations associated with different hotspots on artefacts. Acknowledging current limitations in haptic technology's ability to replicate real object dimensions, future work aims to optimize the haptic experience. This may include enhancing force feedback when users explore the volume of artefacts and providing supplementary sensory cues, such as sound or screen reader output.

To ensure a more comprehensive approach to accessibility, the framework will be extended to provide enhanced support for users with low vision. This encompasses the integration of features like binocular lens support. Furthermore, there is a need for users with visual impairments to customize the scene in a way they feel comfortable with. Empowering end users to tailor their XR experiences, future iterations of the framework will introduce user-customizable accessibility menus. These menus will enable users to personalize accessibility features based on their individual preferences and requirements. Drawing upon insights from existing literature, this user-centric approach aims to make customization options intuitive and effective in facilitating accessible interactions.

After testing the accessibility features of our framework with targeted users, our future work seeks to focus on a more comprehensive evaluation involving developers using the framework. This next phase will involve conducting interviews with developers specializing in XR applications, ensuring seamless alignment between the framework and their specific requirements and needs. After making the necessary adjustments to adapt the framework accordingly, following the Human-Centered approach, we intend to move to a user-based evaluation involving developers. This evaluation will delve into several aspects, such as the ease of integration in XR applications and games, the effectiveness of the introduction and use of accessibility features, and the extent to which these features satisfactorily meet the accessibility needs of developers. In view of delivering an easy-to-use tool by XR developers, the framework will be further extended with XR accessibility guidelines and examples illustrating how these can be adhered to with the use of the framework's accessibility features.

Owing to time constraints, statistical analysis of the results for comparisons between different user groups, namely blind and low-vision users, as well as young, middle-aged, and older adults, has not been conducted at this stage. Nevertheless, it remains a pivotal component of our future work, as its completion is anticipated to yield invaluable insights that will further enhance the comprehensiveness of our findings.

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