Asleep at the Virtual Wheel: The Increasing Inaccessibility of Virtual Reality Applications

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Abstract

Prior research has highlighted numerous accessibility barriers within virtual reality software, with guidelines emerging to address the requirements of diverse audiences. However, an empirical understanding of industry practitioner implementation of accessible guidelines within mainstream commercial applications is currently lacking. This review addresses this gap by categorising all accessibility features presented at a software-level in 330 of the most used virtual reality applications released between 2016 to 2023 on the Steam, Meta, Oculus, Viveport, and SideQuest platforms. Results suggest a growing lack of interaction customisation, with the number of applications allowing for alternative inputs and physical posture flexibility decreasing. Meanwhile, display output settings, such as text font resizing and colourblind alterations, are almost completely absent. Our findings highlight the evolution in the implementation of accessible features in virtual reality software, contributing to a representative overview of practitioner decisions, and acting as a catalyst towards the establishment of industry-wide guidelines.

CCS Concepts

• **Human-centered computing** → **Virtual reality**; • **General and reference** → **Surveys and overviews**.

Keywords

VR, Accessibility, Software review, Input, Output, Locomotion

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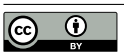

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1 Introduction

The technological advances in modern sensor-based consumer-level virtual reality (VR) head mounted display (HMD) hardware have led to an increase in development of VR software within fields such as healthcare, education, and entertainment [27], with novel experiences made possible by the technology offering potential benefits for people with disabilities [71, 148, 196]. The three-dimensional interfacing afforded by the 6 degrees of freedom (6DoF) tracking sensors in VR devices has however resulted in the emergence of VR-specific accessibility barriers beyond those present with two-dimensional displays. For instance, interaction barriers have emerged due to the required precision needed for gestural inputs [17], compounded by the inherent stereoscopic visual display deficiencies [13] and incompatibility of existing assistive technology (AT) devices such as screen readers [101]. Furthermore, the lack of standardisation practices and established VR accessibility guidelines has resulted in a fragmented landscape lacking clear conclusions on best practices [73, 205], leading to users with disabilities currently feeling excluded from the technology [69].

The emerging near-maturity of VR technologies presents an opportunity to integrate accessible design principles at a fundamental level [39, 140]. The benefits of designing with and for the more than one billion people worldwide who have some form of disability [147] universally extends to all users experiencing temporary or situational disabilities [140], such as the challenging listening conditions potentially present in social VR applications where audio access to verbal communication channels may be reduced [100]. An important facet in creating accessible experiences is in providing agency over input and output [124], allowing users to tailor experiences to their own, potentially dynamic, individual needs. The frequency in the co-occurrence of disabilities [179] further reinforces this need for customisation, with static designs for standard disabled experiences rarely reflective of actual needs [74].

As seen with the failure of VR consumer-level hardware in the 1990s due partially to the first-order barrier [71] negative simulator sickness impact [200], creating accessible experiences is vital for mainstreaming VR technologies. The transfer of academic VR sickness mitigation knowledge to industry design decisions [6] has

proven historically significant in the consumer acceptance of modern sensor-based HMD hardware, underscoring the importance of continued academic engagement with the emerging VR industry to further propagate novel accessibility insights.

Consumer-level HMD operating systems, although often based upon Android source code [174], lack a number of built-in accessibility features commonly found in desktop and mobile devices, resulting in a greater emphasis being placed on industry practitioners in the implementation of software-level accessible design choices [26, 202]. However, interviews suggest that VR practitioners appear largely unaware of best practices for accessible designs due to a lack of guideline knowledge [205]. Furthermore, it remains unclear as to how widely implemented accessibility features are in the most used VR applications, therefore making it difficult to empirically assess the accessibility of the mainstream VR experiences most commonly encountered by users [49]. Understanding current industry design decisions is crucial to enhance the practical relevance of future academic accessibility research, in particular in the underexplored area of general VR accessibility [63], with the representative overview of VR design decisions from this review providing researchers with a stronger understanding of real-world VR accessibility implementation.

This paper presents a review of the accessibility features presented at a software-level in 330 of the most used VR applications released between 2016 to 2023 on the Steam, Meta, Oculus, Viveport, and SideQuest platforms, for the first time empirically categorising how industry practitioners have implemented accessibility focused considerations in the titles users are commonly exposed to in modern consumer-level HMDs [49]. In particular, this data collection and subsequent systematic software review aims to explore the following two research questions (RQs) to provide a clearer state-of-the-art and historical understanding of how accessibility-related features are implemented within commercial VR applications:

- **RQ1**: Which accessibility features are available to tailor required interactions, physical positioning, locomotion, user interface (UI) elements, outputs, and social and communication considerations to individual needs?
- **RQ2**: How has the accessibility of mainstream VR applications evolved since the launch of the first wave of sensor-based consumer-level HMDs in 2016?

This software review provides a vital source of continued academic engagement, with the software implementation results both building an understanding of broader industry design decisions and acting as a reinforcement of the call to action in the development of inclusive VR software [148]. Our findings for RQ1 highlight a number of areas where practitioners have not widely implemented options to allow for alterations at a software-level, including little support for alternative adaptable hardware or low-friction input, minimal depth-fixed UI size adjustment, and an almost complete lack of control over HMD output settings. Additionally, RQ2 temporal trends unexpectedly highlight how a number of essential accessibility features for users with physical, visual, auditory, and cognitive impairments are becoming less prominently supported at a software-level, with these trends suggesting that further establishment of best practice guidelines and more stringent enforcement of platform-specific accessibility recommendations are urgently required to reverse the general growing inaccessibility trend within mainstream VR software.

2 Related Work

The following discussion of relevant related work will begin with an examination of emerging VR guidelines and recent academic accessibility research findings, before addressing the importance of legal adherence for industry practitioners to information and communications technologies accessibility regulatory requirements.

2.1 Accessibility Guidelines

Due in part to the novelty of sensor-based consumer-level HMD hardware, VR guidelines are still actively emerging, with practitioners largely unaware of accessibility-specific best practices [101, 205]. Examples of these emerging guidelines include the extended reality (XR) Accessibility User Requirements [68] published by the Accessible Platform Architectures Working Group from the World Wide Web Consortium (W3C), which reinforces the importance of flexibility, including the requirement that users should not have to be in a particular physical position to perform an action. Alternative guidelines have also emerged from the headset manufacturer-supported XR Association (XRA), with their Developer Guide [11] presenting best practice suggestions for users with sight, auditory, speech, mobility, and cognitive disabilities. The Meta Quest Virtual Reality Check (VRC) Guidelines [133] meanwhile provide a platform-specific checklist of nine accessibility recommendations for publishing on the Meta Quest Store, including the ability to use the application with a single hand. This review calls attention to the large number of titles available on the associated platform that do not adhere to the recommendations.

Along with the need for guidance, more work must be done both to establish and distribute practitioner tools to assist with accessibility-feature implementation [101], for example the Unity toolkit for low vision access [205]. Practitioners must also be encouraged to directly involve users with disabilities in all stages of research and product development [35, 39] in order to understand the emotional complexities virtual tasks may evoke for users with lived experiences of disability [175]. This inclusive ability-based design approach to development [141], along with the establishment of widely-distributed guidelines and tools, may prove vital in the effort to reverse the perception of VR as an ableist technology that fails to accommodate the needs of users with disabilities [64].

2.2 Accessibility Research

This section discusses prior accessibility research addressing the key components in the creation of accessible VR experiences, divided in to locomotion, input, and output categories, in line with Oculus [124], Meta [133], and W3C [68] accessibility guidelines.

2.2.1 Locomotion Accessibility. The ability to travel to spatially distant locations, commonly referred to as locomotion in the VR field [17], is an essential navigation task in the theoretically arbitrarily large [198] three-dimensional virtual environments (VEs) rendered in VR. Challenges around the usage of locomotion techniques designed for VR are however a significant barrier of use for people with disabilities [35], in particular due to the existence of spatialised points of interests [48] that may require accessible scene-viewing

techniques beyond head tracking [49]. The arm movement and gestural locomotion techniques afforded by consumer-level HMD tracking capabilities, such as virtual climbing, can additionally be particularly challenging for a range of diverse audiences, for example people using wheelchairs unable to perform the required gestures due to the physical constraints imposed by their mobility aid [63], as well as users with visual impairments who feel unsafe physically moving whilst wearing the HMD [107] or are unable to effectively aim visual-only travel targeting reticles [28]. Feedback has suggested that the addition of accessible audio or haptic cues, a key resource for supporting the spatial performance of people who are blind [2], may prove beneficial during low-light [138] and non-visual VR locomotion [28], whilst landmark and grid-based low-friction speech-controlled locomotion results from Hombeck et al. [75] demonstrates how locomotion is achievable in VR without hardware input or body tracking requirements.

Due primarily to being a first-order barrier of entry, locomotion techniques to mitigate simulator sickness have to date received the largest amount of accessibility research focus [71]. Locomotion sickness mitigation techniques include fixed interval snap rotation [159] and reducing the field of view (FoV) during continuous travel with visual vignetting, also known as tunneling [178], with results showing a widespread transfer of this academic sickness mitigation knowledge to mainstream VR locomotion implementation choices [6]. The potential interplay between various disabilities and VR sickness however is not well studied [10, 16, 65, 110]. Beyond visual sickness mitigation, prior research with users with physical [50, 121, 149], cognitive [3], and visual [28, 154] impairments has highlighted the importance of providing alternative and adaptable locomotion techniques to allow users to tailor locomotion demands to their own unique needs. Technique comparison results from Ribeiro et al. [154] showing no statistically significant differences between techniques with users who are blind further highlights the importance of allowing for individual customisation, with interactions, strategies, and preferences all highly user rather than disability-dependent.

2.2.2 Input Accessibility. The majority of modern consumer-level HMDs are equipped with 6DoF tracking sensors, allowing for highly accurate body and hand tracked interactions. Additionally, most consumer-level HMDs released since 2016 support spatially tracked wrist-based standardised bimanual handheld controller input [109], with physical buttons and precise finger positioning inputs provided via capacitive touch sensors [108], and tactile haptic responses provided in the form of vibrotactile feedback. Eye and facial tracking sensors meanwhile are often included in higher-end HMDs such as the Apple Vision Pro and Meta Quest Pro mixed reality headsets, which in combination can be used to create non-controller interactions [139], enabling hands-free spatial interfacing for users with motor impairments [192].

A key component in the creation of an overall accessible user experience in VR, particularly for users with unintentional hand movement such as tremor [15], is found in the design of UI interactions. The additional spatial component of interactive VR UI elements [124], including interactions designed solely for standing users [62], adds complexity to VR interfaces beyond the interactions available for desktop or mobile interfaces [140]. Accessibility research has emphasised the importance of input customisation to allow VR software control to be tailored to match individual needs [39, 48], for example to allow for unimanual input access for people with full use of a single arm [50, 202], for user-defined gestures customised to the needs of users with motor impairments [182], or to accommodate the number of functions users with cognitive impairments [70] and neurodevelopmental disorders [12] are comfortable controlling. Additionally, the widespread requirement of utilising wrist-based standardised bimanual handheld hardware [109], such as the Meta Quest Touch and Valve Index controllers [8], emphasises the importance of remappable keys for actions that may require difficult to reach simultaneous button presses [141], whilst the spatial precision required for the gestural inputs afforded by consumer-level HMD 6DoF tracking capabilities [17] highlights the importance of providing control over the required gesture speeds and directions to match user capabilities [63].

W3C XR Accessibility User Requirements state that users should not have to maintain a specific physical position to perform any input action [68], with research suggesting that posture flexibility is vital in the creation of accessible experiences due to individual personal and situation-specific needs [206]. For example, due to the limited access to leisure activities, young people with muscular dystrophy list gaming as their most regular pastime [184], which along with highlighting the need for posture flexibility, including support for lying down postures [185], emphasises the importance of allowing for physically accessible game controller switch-based input devices such as the Xbox Adaptive Controller [68, 135]. The importance of providing multi-modal input support [36, 68, 197] for alternative accessible gaming-compatible input devices is further underscored by the prominent gaming focused marketing position of consumer-level HMDs [131], whilst multi-modality is becoming increasingly supported in non-VR computing control [197].

2.2.3 Output Accessibility. The primary reliance on the combination of HMD visual and sound output could make VR software inaccessible for users with cognitive impairments who experience sensory [20] and information overload [36]. Additionally, the large dependence on stereoscopic visual feedback to convey information about the VE may potentially make VR software inaccessible to users who are blind or visually impaired (BVI), whilst the binaural sound design may create inaccessible experiences for users with auditory impairments, such as users who are d/Deaf [71]. Along with increasing access to people who are BVI [205], the ability to tailor visual display characteristics in consumer-level HMDs [152] is particularly vital to users who may be more susceptible to vergence-accommodation conflict issues [14], users with photosensitive epilepsy [67, 166], and users with stereoblindness [71], whilst sound adjustments are potentially additionally important to users who experience listener fatigue [36].

The lack of standardisation for defining how to implement non-visual feedback for users with sensory impairments has resulted in both the creation of oversimplified specialised immersive experiences [69], as well as the feeling of exclusion from mainstream applications [7]. Non-visual sensory augmentation or substitution with haptic feedback may prove vital in addressing this concern [163, 195, 204], with vibrotactile cues demonstrating promising

guidance results in VR for d/Deaf [137] and BVI users [194], including successfully conveying spatial information in VR [106], mapping sounds [99], and assisting with locomotion [46, 105], such as with a physical white cane [103, 163, 204].

2.3 Legal Requirements

Although VR-specific accessible legal requirements are not yet in place, broader regulations as defined by the United Nations Convention on the Rights of Persons with Disabilities (UNCRPD) [143] indirectly apply to all VR content, obliging practitioners to adhere to international legal frameworks for disability compliance [145, 146]. The settlement agreement binding the provision of text captioning on the Viveport Infinity service [41], with updated developer guidelines requiring captioning in all future VR software releases on the platform [45], further underpins the importance of adherence to both emerging platform-specific requirements, as well as broader international regulations. The European Accessibility Act (EAA) [44], derived from the UNCRPD, addresses divergent accessibility requirements in different European Union (EU) member states, with worldwide practitioners offering digital software products and services within the EU following the 2025 compliance deadline required to ensure software adheres to EAA access requirements for persons with disabilities.

2.4 Key Research Gaps

Due to the emphasis placed on industry practitioners in the implementation of accessible VR features [26, 202], this software review analyses practitioner design decisions to determine the extent to which emerging guidelines [11, 38, 39, 68, 73, 124, 133] are implemented at a software-level. Additionally, the propagation of academic recommendations on best practice design, such as customisation control over input [50, 202] and output choices [39, 48], are empirically assessed, providing a representative overview in order to enhance the practical relevance of research in the academically underexplored general VR accessibility field [63].

3 Review Method

A systematic software review [104] was conducted to assess the accessibility of commercial VR applications, with inclusion criteria based upon application download metrics collected in August 2023 to provide a representative overview of mainstream VR accessibility design decisions in the titles users are commonly exposed to [49] in modern sensor-based consumer-level HMDs [29].

3.1 Application Inclusion Criteria

To allow for temporal trend analysis to answer RQ2, applications were selected from each year since the release of the first wave of sensor-based consumer-level HMDs in 2016 [29]. Download metrics were selected to ensure the most used VR applications were analysed from each year until 2023 (Table 1), providing a representative overview of mainstream VR applications by examining the titles most commonly used by VR consumers [49]. Due to the download inclusion criteria the number of titles analysed for each year are not identical, with recent applications potentially underrepresented due to having less time to satisfy inclusion metrics.

Table 1: Number of analysed applications by release year.

Year	Number
2016	29
2017	39
2018	35
2019	50
2020	54
2021	50
2022	51
2023	22

To ensure an understanding was reached of real-world accessibility implementation in mainstream consumer-level VR applications, all major PC VR and standalone VR software platforms were selected for inclusion. This includes the two market leading VR platforms, with 100 applications from the largest PC VR platform Steam [34] and 100 applications from the largest standalone VR platform Meta Quest Store [130]. For Steam, selections were made amongst the 'VR only' global top sellers list [34] and most owned 'VR only' tagged titles as categorised by the Steamspy database [51], with a total of 30 free and 70 one-time fee paid titles from Steam analysed. Meanwhile, the 50 'most popular' free experiences across all categories on the Meta Quest Store [130] were selected provided they were not originally included in the Steam selection, whilst the combined 50 top selling paid experiences across all categories which were unique from the Steam selections were anaylsed.

The remaining three platforms include fewer applications as they represent smaller entities in the mainstream VR market. Firstly, due to the historical significance of the Oculus tethered PC VR devices prior to the shift from Oculus/Meta to standalone HMDs in 2019, 50 unique titles from the Oculus Store [130] were included, with 25 of the 'most popular' free and 25 of the top selling PC VR experiences [130] selected. Sideloading is possible with the majority of consumer-level HMDs, with recent Google Ventures investment [162] showcasing wider industry interest in the practice, therefore warranting the inclusion of a further 50 novel titles from the largest independent sideloading and early access VR application platform SideQuest [161]. All 50 sideloaded titles were free, with a mixture of sideloaded and Meta App Lab early access applications chosen to ensure both sideloading methods were anaylsed. Finally, although representing only a small portion of the global VR software market, and therefore with only 30 titles included, the largest VR application subscription service Viveport Infinity [31] was included to ensure complete coverage of all the ways PC VR and standalone VR software can be accessed. All 30 applications selected from Viveport Infinity had an equivalent one-time fee paid version available on Steam. In total, 175 applications require a one-time purchase fee, with the remaining 155 available to download for free. Table 2 displays the number of non-repeated applications selected along with the total number of analysed titles available on each platform, with results showing widespread cross-listing of titles.

Table 2: Number of non-repeated applications selected and total number of available analysed titles on each platform.

Platform	Selected	Total (n=330)
Steam	100	240
Meta Quest Store	100	219
Oculus Store	50	175
SideQuest	50	191
Viveport Infinity	30	119

3.2 Analysis

Data were extracted manually, with attributes assigned for each application based primarily upon first author testing. Subsequent web searches allowed for full categorisation of features not available during first-hand testing, such as locomotion techniques presented in games only after extended progression. Applications were initially launched with bimanual handheld controllers, with alternative Xbox gamepad, computer keyboard, speech, head, eye, and freehand [168] tracked inputs tested in all titles. Primary features, such as the input(s) available upon first-time application usage, were recorded for each application, with all software-level alterations noted, for example alternative input modalities configurable within non-diegetic options menus. The online database was updated within the predefined categories covering a full range of accessibility considerations based largely upon the Oculus Developer accessibility categorisation scheme [124], XR Accessibility User Requirements [68], XRA Developer Guide [11], accessibility guidelines for VR games [73], and Meta Quest VRC [133]. Additional notes were recorded for unique accessibility features presented in titles that are not covered in the existing guidelines, such as the privacy bubble to remove hands of close avatars in 'Raw Data' [173].

The Locomotion Vault taxonomy [37] was chosen for the categorisation of locomotion techniques, due to the multifaceted unifying scheme categorising attributes from existing taxonomies, the inclusion of a large number of timely techniques, and the assignment of an accessibility attribute for each technique [37]. Earlier established locomotion taxonomies are often situated at a higher level of abstraction [153], potentially obscuring key differences between techniques that may be an important accessibility consideration, for instance the different arm movement directions required for spatial climbing and swimming gestures.

3.3 Accessibility Features

This section introduces how individual software-level accessibility features, highlighted in bold text, were extracted for each of the 330 applications. Features were derived from the analysis of emerging VR-specific guidelines [11, 38, 39, 68, 73, 124, 133, 151], with each broadly placed within interaction, physical positioning, locomotion, UI, output modalities, and social and communication categories. As this review analyses VR accessibility features at an individual software-level, platform, OS, and utility software functionalities, such as the SteamVR 'Controller Bindings', the recently released 'Use apps while lying down' experimental feature for Meta Quest [132], or the 'WalkinVR' locomotion driver software [190], were not factored in to the analysis. Whilst OS-level settings can allow for alteration of a selection of the accessibility features analysed in this review, for example mono audio balance control [123], OS-level, platform-specific, and utility software functionalities may not be available to all users accessing the same application on an alternative HMD device, OS, or software platform. Table 3 provides an overview of the accessibility features reviewed across all categories, whilst Fig. 1 highlights a selection of key accessibility features in the 'Arizona Sunshine' [61] game.

Table 3: Analysed accessibility features across all categories.

Category	Feature
Interaction	Input(s)
	Input customisation
	Input sensitivity
	Hold button requirements
	Handedness
	One-handed
Physical Positioning	Posture
	Seated accessible
	Head height
	Crouch control
	Front-facing
	Physical/space considerations
Locomotion	Motor effort
	Visual sickness mitigation
User Interface	Resizing the UI
	Text size
	UI customisation
	Assists
Output Modality	Visual focus indicators
	Colour and luminance
	Additional visual features
	Mono sound
	Volume and sound controls
	Haptics
Social and Communication	Subtitles and/or closed captions
	Speech speed
	Voice alteration
	Sign language
	Personal space

3.3.1 Interaction Features. The primary and optional supported **input(s)** [11, 38, 39, 68, 73] for each application consisted of hardware such as bimanual handheld controllers, gamepad controllers, and keyboards, along with non-hardware head-based, freehand, and speech-based input [168]. Primary inputs were noted where the application could be controlled via the input without software-level selection, that is the available inputs on first-time use. Optional inputs meanwhile were noted where explicit selection or configuration options were included within the application. The degree of software-level **input customisation** [11, 38, 39, 68, 73, 124] was additionally recorded for each of these input devices, from full remapping of all inputs, to partial remapping of specific buttons, for instance trigger and grip swapping. **Input sensitivity**

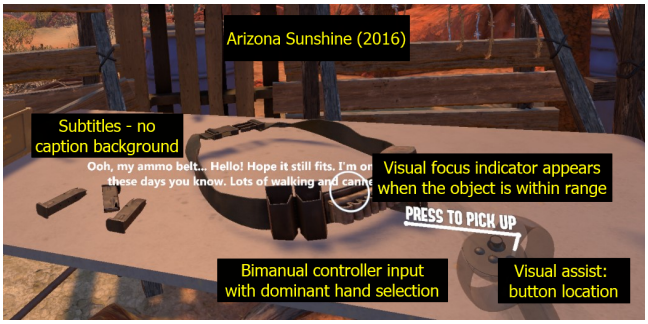

Figure 1: A selection of annotated key accessibility features found in 'Arizona Sunshine' [61].

[38, 68, 73] adjustments were recorded where the application allowed for software-level sensitivity-based input alterations, for example adjusting the joystick sensitivity, with input offset adjustments also noted, such as hand angle modification. The final consideration for hardware-specific input was the option to alter **hold button requirements** [73, 124] for sustained interactions.

Beyond hardware specifics, **handedness** [73, 124] choices were also recorded, with software which allows for both full and partial dominant hand selections labelled. Finally, **one-handed** [38, 133] accessible applications were marked either where options were presented which allowed for full or partial one-handed input selection.

3.3.2 Physical Positioning Features. The primary **posture** [11, 39, 133] of an application relates to the expected or supported stance upon first-time usage, with optional postures consisting of supported alternatives. Standing, seated, and lying down postures were recorded where titles explicitly supported the posture or automatically adapted the FoV and all required interactions for the posture. **Seated accessible** [11, 39, 124] applications meanwhile were recorded either where the FoV adapts to a seated posture, or where successful interactions do not require completion of standing-only actions. Methods presented in applications to initiate the alteration of **head height** [11, 39, 73] were also recorded.

Further physical positioning considerations include the available **crouch control** [11, 73] options, with crouch customisation, such as physical crouch offsets, also noted for each application. Due to the spatialised 360-degree VEs, combined with the limited horizontal FoV of HMD displays, applications may require some form of turning. Titles which require physical body, neck, or head rotations in either horizontal direction, beyond what can be achieved with artificial turning techniques, were deemed as not fulfilling the recommended **front-facing** [38, 39, 73] Meta Quest VRC guideline [133]. Finally, all other **additional physical or space considerations** were recorded, such as hand movement scaling [43].

3.3.3 Locomotion Features. During the creation of the Locomotion Vault, techniques were placed at one of three accessibility levels by Di Luca et al. [37], based solely on the extent of **motor effort** required to use the technique. Additionally, the number of techniques designed for **visual sickness mitigation** [151], that is snap rotation [159] and tunneling [178], were also noted.

3.3.4 User Interface Features. Options to **resize the UI** [11, 73, 133] were separated in to either full UI size alteration or resizing of individual UI elements. Due to the potential spatial component of VR UIs, size control was further separated in to either size-only adjustments with a fixed depth, or size adjustment via depth control [124]. Similarly, **text size** [11, 38, 39, 73, 124] adjustments were separated in to either full or individual element text size controls, with the depth-based feature again noted [124]. Beyond size, **UI customisation** [73] recorded where all or specific UI elements could be visually altered, such as turning off the appearance of the heads-up display (HUD). Finally, **assists** [11, 39, 73] include difficulty control, such as individual elements or global challenge adjustments, input action assists such as aiming assistance, as well as options to perform actions with button input rather than gestures.

3.3.5 Output Modality Features. **Visual focus indicators** [73] consist of interactable object and locomotion cues, such as teleportation aiming reticle colour feedback to convey the travel validity of the destination. **Colour and luminance** [11, 39, 68, 73, 124, 133] options meanwhile consist of global and individual element adjustments, including display luminance adjustment, most often labeled brightness [11, 124, 133], and alterations to the colour of elements within the VE. Finally, all other **additional visual accessibility features** presented in applications were noted, including disabling flickering or flashing lights [68, 73, 124].

For the sound modality, the **mono sound** [11, 68, 73] feature recorded where either full audio or specific audio elements were adjustable to appear through a single ear, whilst the **volume and sound controls** [73, 124] feature recorded all binaural music, effects, and other sound adjustments.

The final output modality, haptic feedback, was divided in to **interaction haptics** and **locomotion haptics**, split across hand-based controller and body-based hardware devices. All options to enable, disable, or adjust haptics were also recorded [39, 73, 124].

3.3.6 Social and Communication Features. The **subtitles and/or closed captions** [11, 38, 39, 68, 73, 133] feature recorded the type and customisation options available, such as text size, location, and caption background colour [11, 124]. The **speech speed** feature meanwhile recorded where either verbal or written speech speed playback was controllable, whilst **voice alteration** control options were recorded for either the user voice or the voices of others present in the VE [73]. The degree to which **sign language** [5, 11, 39, 68, 73] was available in each application was also noted, including both sign language input and output support. Finally, the **personal space** feature recorded the methods available to control how other users appear when in close physical range, a potential tool for combating shared VE harassment [120].

4 Results

In this section, results are presented for each accessibility feature across all categories. Fig. 2 shows the distribution of the key analysed accessibility features across all 330 applications. A number of features, such as mono sound, speech speed, and sign language, are not included in Fig. 2 as they are only partially supported in a small number of the analysed applications.

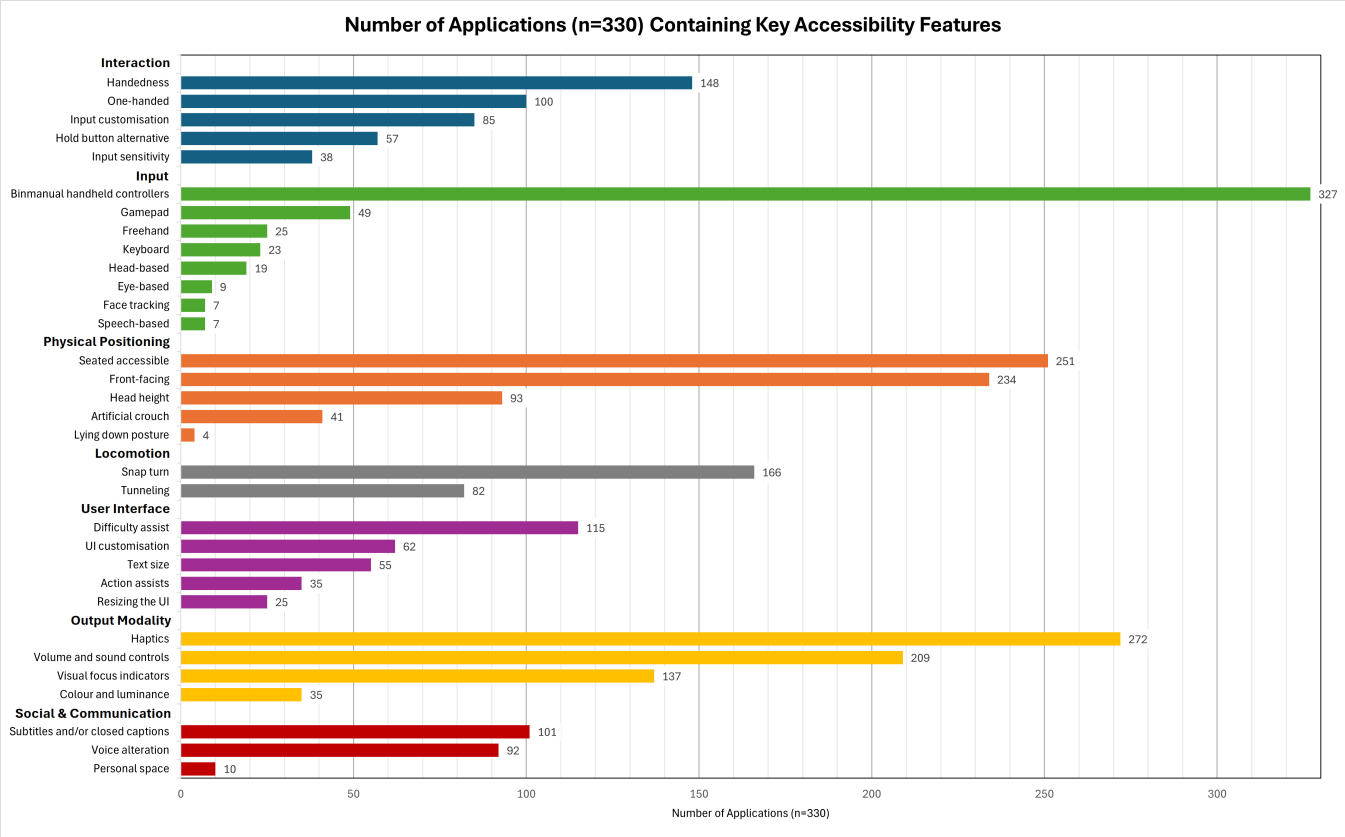

Figure 2: Distribution of accessibility features across all applications.

4.1 Interaction Considerations

4.1.1 Inputs. For hardware-based inputs, bimanual handheld controllers are the most supported modality, with 326 applications supporting them as the primary input method, one providing optional support, and just three titles designed for freehand tracked only input, such as the 'XRWorkout' exergame [89], containing no bimanual controller support. Hand-based input is expected in all of the bimanual controller supported software, with alternative uses including one application that additionally allows for real-walking locomotion via tracking of the controllers attached to the feet [96], one allowing for configuration of a controller attached to a baseball bat [199], and two titles with configuration of controllers at the end of golf putter extensions [66, 136]. Console gamepad controllers, including for example the Xbox Wireless or Adaptive Controllers [135], meanwhile are supported in 49 applications, of which 19 include primary gamepad input support on initial load, whilst computer keyboard input is included in 23 titles, of which all but one are as an optional modality. Finally, other hardware-based input devices include two flight simulators with flight rudder pedal support [18, 58], one fitness exergame with smart bicycle locomotion-control integration [186], one education application with optional MIDI piano support [122], and one action game with optional software-level 3D Rudder hardware foot control configuration [87]. Fig. 3 contains a sample of the included hardware input devices and extensions supported by the analysed applications. Explicit support or software-level configuration of AT hardware devices such as screen readers were entirely unsupported.

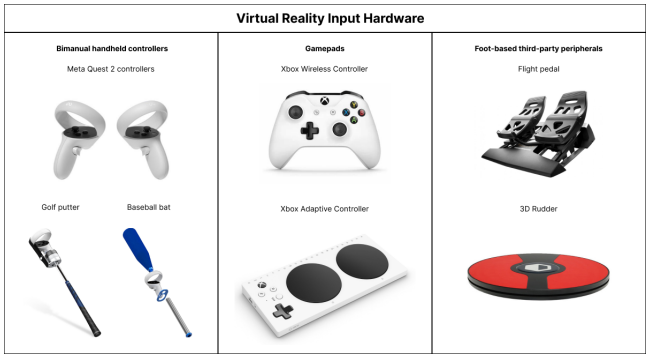

Figure 3: A selection of supported input hardware devices and extensions, from bimanual handheld controllers, switch-based gamepads, to foot-based third-party peripherals.

Although overall results suggest moderate support of hardware which can allow for accessible alternatives, most prominently with

the 49 gamepad-compatible applications which contain Xbox Adaptive Controller switch-based input support [68, 135], temporal results, as seen in Fig. 4, show a decline in support of these potentially accessible hardware devices, with the majority of titles increasingly supporting only bimanual tracked controller input.

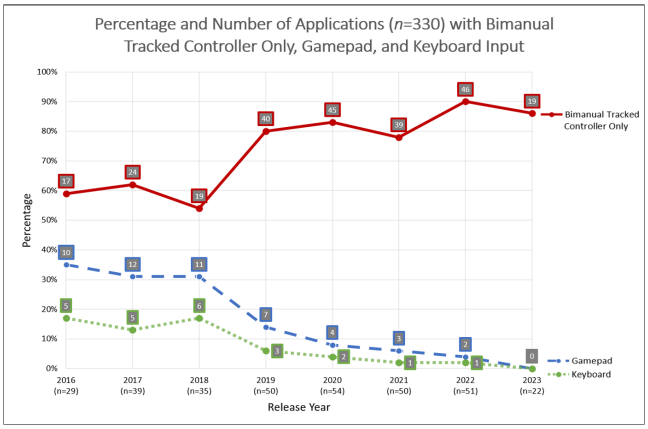

Figure 4: Percentage of applications released each year which contain bimanual controller only, gamepad, and keyboard input. Number of applications released each year highlighted with the data labels.

The sensors included with modern consumer-level HMDs allow for non-hardware input modalities, providing low-friction input without additional hardware requirements [124]. Support for input without a handheld external controller however is limited, with freehand gesture tracking in 25 applications as the most offered modality. Only three of these titles contain primary freehand tracking input however, whilst the remaining 22 include freehand tracking as an optional modality combined with primary hardware-based input. Head direction based input is included in 19 applications, with 15 including head directed input selection as a primary input method. These head directed inputs are commonly however solely for UI or menu selections, as seen for example in the 'L.A. Noire: The VR Case Files' adventure game [55], with additional hardware-based input required for all other input actions such as locomotion control. Eye tracking meanwhile is included in nine titles, although perhaps due to eye tracking sensors typically currently only being included in higher-end consumer-level HMDs, all eye-tracking use cases, for example in the multiplayer virtual poker 'Vegas Infinite' application [81], are optional. Similarly, facial tracking sensors, which may have the potential to assist with lip reading in shared online VEs, are typically only included in higher-priced HMDs, with just seven applications, including the collaborative spatial design applications 'Arkio' [40], 'Gravity Sketch' [164], and 'ShapesXR' [30], supporting this feature as an option. Finally, some form of speech-based voice command input [68] appears in seven titles, with one voice-based puzzle game requiring voice input to progress [54], three allowing for voice command input for specific actions [81, 86, 115], and a separate three containing an option for explicit voice controlled search [4, 47, 165]. No application contains speech-based locomotion control [75].

4.1.2 Input Customisation. Modification of one or more input is included in 85 total applications, although the majority (60) allow only for partial remapping, with swapping of trigger or joystick actions the most common options. Just 25 titles, such as the shooter 'Breachers' [23], support extensive or full remapping of inputs. Fig. 5 displays the number of applications per year which include extensive and partial remapping, with extensive remapping in particular showing no growth trends.

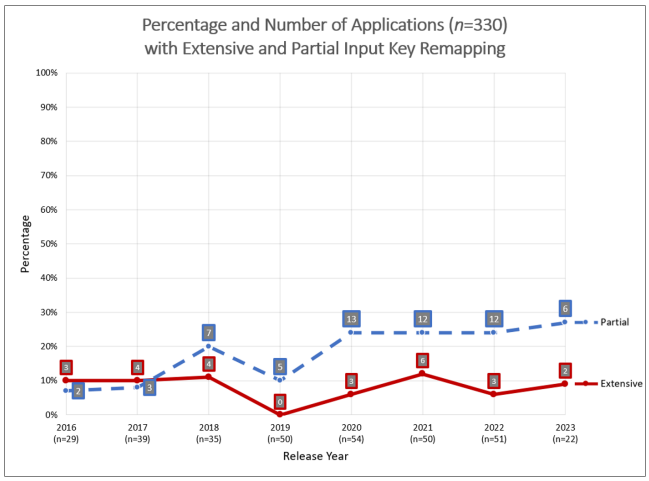

Figure 5: Percentage of applications released each year which contain extensive and partial key remapping. Number of applications highlighted with the data labels.

4.1.3 Input Sensitivity. Overall, 38 applications allow for sensitivity adjustments, with 15 titles providing joystick options such as the locomotion deadzone adjustment featured in 'Swordsman' [87], 19 containing aiming options as demonstrated by the smoothing of input aiming gesture sensitivity in 'SURV1V3' [25], and four containing sensitivity control over the required compression of analogue trigger buttons, as seen with the adjustment of trigger thresholds in the rhythm shooter 'AUDICA' [72]. Meanwhile, 37 total titles provide hand, controller, or weapon offset control, namely spatial position or angle adjustments, as seen for example with the vertical and horizontal weapon offset sliders in 'Hyper Dash' [22].

4.1.4 Hold Button Requirements. A total of 57 applications allow for control over whether the user is required to hold a button over time to perform an action, or the same sustained action can be performed with a toggle input.

4.1.5 Handedness. Dominant hand selection is the most commonly included interaction accessibility feature, with a total of 148 applications including options to either manually select the dominant hand through the menu, mirror hand inputs, or due to supporting input solely from either hand.

4.1.6 One-handed. Of the one-handed supported applications, 97 were deemed fully one-handed accessible, with a further three titles partially one-handed accessible on specifically labeled one-handed levels [52, 116, 189]. Fig. 6 displays the number of applications per year which allow for handedness selection and one-handed inputs.

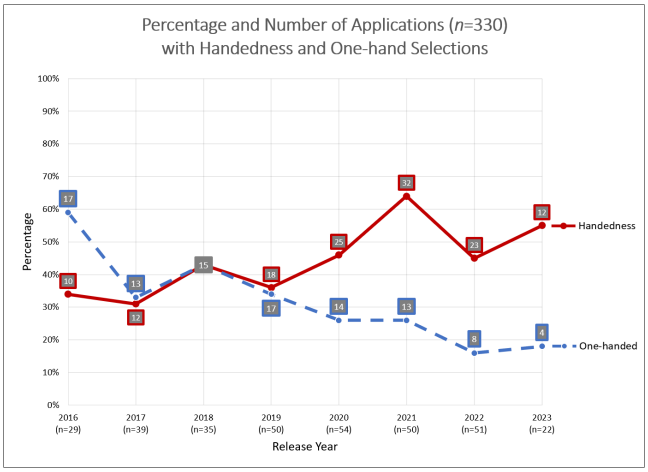

Figure 6: Percentage of applications released each year which contain dominant hand and one-handed selection. Number of applications highlighted with the data labels.

4.2 Physical Positioning Support

4.2.1 Posture. The number of applications which offer standing as the primary posture outnumbers those that provide primary seated access. In total, 268 titles provide primary standing posture support, whilst primary seated posture is included in 149 titles, with 87 of these primary seated applications additionally providing primary standing access, either through posture configuration during initial setup or menu selection, or by dynamically adapting to all actions regardless of posture. Although 149 total applications provide primary seated support, temporal trends, as seen in Fig. 7, suggest that primary seated posture support may be decreasing.

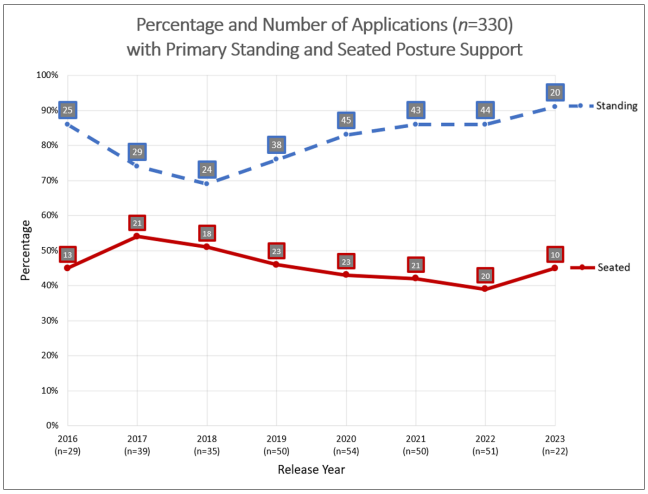

Figure 7: Percentage of applications released each year which contain primary seated and standing posture support. Number of applications highlighted with the data labels.

Support for lying down posture access at a software-level meanwhile is almost completely absent, with just four titles providing explicit lying down configuration. Of these, two are media players [4, 144] and one a desktop mirroring application [77], with lying down support consisting of options to move virtual two-dimensional panels to comfortable lying down view positions. The final title is primarily focused on providing minimally interactive meditation experiences [189], with no application that demands precise or complex inputs accessible whilst lying down.

4.2.2 Seated Accessible. Standing is universally supported, with all applications that are designed primarily for seated access also usable whilst standing. Not all software is seated accessible however, with a total of 251 applications either offering primary, optional, or adaptable seated access, whilst unadaptable FoV settings, out-of-reach objects, or required standing-only actions, as seen with the full body movements required in 'RUMBLE' [42], are examples of reasons why the remaining 79 titles are only usable whilst standing.

4.2.3 Head Height. Explicit options to alter eye level or head height, which can be of particular benefit to allow for seated access to standing-only applications [62], are available at a software-level in 93 titles. Automatic alteration of height following a button press is included in 29 of these 93 applications, of which 12, such as 'Gym Class VR' [80], require a sustained arm stretched T-pose from the user, whilst the remaining 64 provide fully manual calibration with height offset control.

4.2.4 Crouch Control. All but one application accurately reflects physical crouching in the VE, with 39 applications additionally containing an artificial crouch toggle button, whilst 12 contain a crouch hold button. Ten titles allow for choice between toggling and holding a button to crouch, with a total of 41 applications including at least one artificial crouch control method. Other crouch options include three titles with physical crouch offsets to adjust the required crouch depth [85, 102, 156], whilst the game 'Tea For God' [187] contains an option to turn off the need to physically crouch in order to progress.

4.2.5 Front-facing. Fixed position front-facing access appears generally well supported, with 234 applications accessible without physical rotation, one front-facing on select levels only [189], whilst the remaining 95 require horizontal physical body, neck, or head rotations. The most prominent method to maintain front-facing access is the provision of artificial turning methods, included in 198 applications, with the most common options including snap turning in 166 titles, of which 133 are the primary turning method, and continuous artificial turning in 135 titles, which is more likely to be offered as an optional turning method, with just 23 applications containing it as the primary technique. Fig. 8 shows the percentage and number of applications per year which include at least one artificial turning method. Of note is one front-facing inaccessible application, 'Gorilla Tag' [9], which whilst containing artificial rotation options, and therefore potentially front-facing accessible, at the time of data collection only allowed for selection of artificial rotation after tutorial tasks are completed which require physical rotations. This emphasises the importance of allowing users to tailor physical positioning demands prior to any required interaction inputs. Providing accessibility features only after extended progression, particularly when only accessible via diegetic menus in specific VE locations, can prevent users who require assistance from experiencing the

application. Additional options for maintaining front-facing access include five titles with a toggle between 360-degree or front-facing only access [97, 134, 170, 172, 177], one application which can pause gameplay and warn users to reorintate when not facing forward [57], and two titles [53, 112] containing the Snap N' Motion technique [37] where the user controlled viewpoint turns automatically to ensure the user faces a specific physical direction.

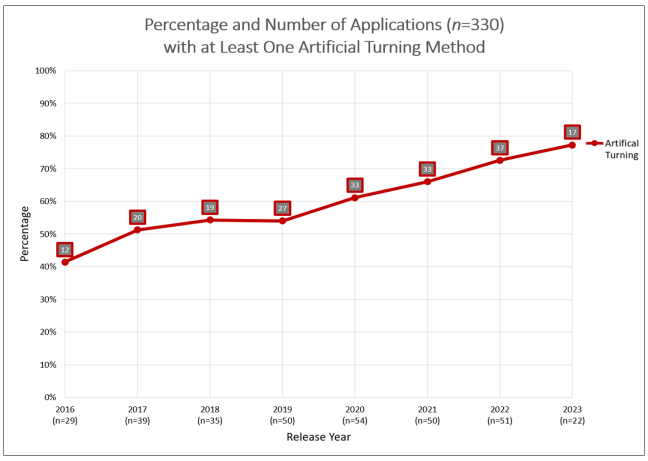

Figure 8: Percentage of applications released each year which contain at least one artificial turning method. Number of applications highlighted with the data labels.

4.2.6 Physical/Space Considerations. Additional physical or space considerations include target scaling within five titles and 180-degree quick turn buttons included in 13 applications, as seen in 'After the Fall' [60]. These are important options both for users with limited real-world space, as well as for users with varied body types who may be unable to comfortably move or rotate around larger distances [73]. Additional options for users in limited spaces include software-level visual grids [102], playspace centre markers [155], and safety alerts when approaching borders [116], collectively included in nine titles. Rearrangement of body inventory space via the adjustment of item positioning in peripersonal space meanwhile is included in 17 applications, including combat equipment body storage location selection in 'Aim XR' [201]. Finally, physical movement speed or gesture distance input adjustments, particularly important to allow for posture flexibility during locomotion [50, 124], are rarely included, with one title providing a slider to adjust the distance the arms must be extended to perform a gliding movement [78], two providing control over the required distances the arms must be moved to draw a bow [85, 160], with the 'Primal Hunt' game [85] additionally allowing for unequal arm length adjustment, and a single title, 'Hot Dogs, Horseshoes & Hand Grenades' [118], where the required arm speed for each arm can be manually adjusted for arm swinging locomotion.

4.3 Locomotion Techniques

4.3.1 Motor Effort. Each locomotion technique presented in all 330 applications, for a combined total of 1,365 techniques [6], was recorded according to the Locomotion Vault accessibility motor effort categorisation, from least to most motor accessible, levels one to three [37]. The average overall motor accessibility level for locomotion is 2.37, with primary techniques at 2.25 and optional techniques at 2.9. These results indicate that optional locomotion techniques are more motor accessible than the primary locomotion techniques, with optional techniques requiring less motor ability to successfully perform [37].

4.3.2 Visual Sickness Mitigation. Although optional locomotion techniques appear more motor accessible, further analysis suggests that these techniques largely consist of visual sickness mitigation tunneling and snap turning visual alterations rather than alternative locomotion travel control categories, suggesting that users are largely unable to select locomotion control techniques suitable for their own needs. These tunneling and snap turn visual sickness mitigation techniques appear overall amongst the most offered techniques across all titles [6], with snap turning provided in 166 applications and tunneling included in 82 titles. Results highlighting how practitioners are largely providing modifications to visual locomotion feedback rather than alternative viewpoint travel control suggest that accessibility guidelines recommending users should be given flexibility in tailoring locomotion to their own abilities [39, 50] are largely not being adhered to by industry practitioners.

4.4 User Interface Considerations

4.4.1 Resizing the UI. A total of 25 applications contain options for resizing the UI, with 11, such as 'Blade and Sorcery' [193], containing extensive resizing support, seven allowing for resizing of specific elements, as seen with the chatbox size percentage control in 'VRChat' [88], Fig. 9(a), and seven allowing for resizing in depth only, such as the option to spatially move the in-game map in 'Among Us VR' [113].

4.4.2 Text Size. In total 55 applications allow for text resizing, primarily in menus, with 51 of these however providing text resizing control in depth only, including for example the pause menu distance slider in 'Half-Life: Alyx' [33], Fig. 9(b), and the diegetic wrist-worn 'Pip-Boy' menu in 'Fallout 4 VR' [92], Fig. 9(c). The remaining four contain text size alteration in line with menu window scale resizing [79, 126, 127, 158]. Surprisingly, separate UI text adjustment control, beyond the caption text size alteration options included in five applications such as 'Hubris' [21], Fig. 9(d), are completely absent at a software-level, with selection of UI or menu font style, size, and magnification [11, 39, 68] all unsupported.

4.4.3 UI Customisation. Of the 62 titles which contain UI customisation options, 37 contain individual element control, such as turning on damage indicators in 'Vader Immortal: Episode I' [76], whilst 23 applications allow for full UI HUD appearance control. Adjustment of position is less common than toggling the visual appearance on or off, with three titles allowing for UI position control over individual elements [92, 171, 176] and two allowing for overall HUD position adjustment [155, 158]. Finally, UI opacity adjustment options are included in six applications, including 'SURV1V3' [25] and 'VRChat' [88].

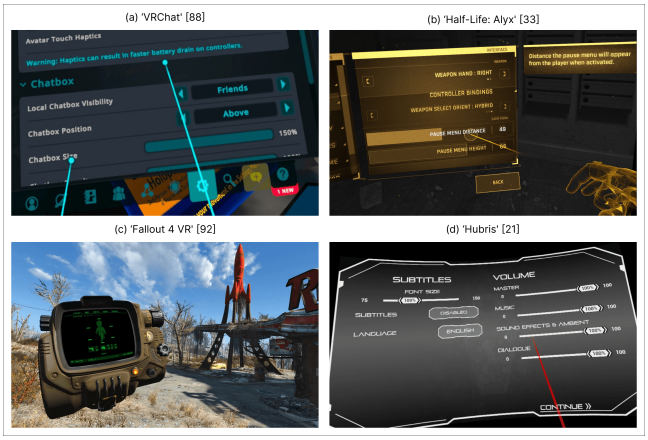

Figure 9: A selection of in-application screenshots showing highlighted UI modifications.

4.4.4 Assists. Difficulty modifications are the most offered assistance in VR, with 115 titles allowing for global and/or specific element challenge modification. Global or level difficulty selection is included in 101 of these applications, with modification of individual elements, such as in the creation of custom lobbies with cooldowns for specific actions in 'Among Us VR' [113], included in 47 applications. Assists for actions meanwhile include gesture toggle options within 35 titles, most often to allow for automatic sprinting or button input in the place of physical reloading actions, both of which are included in the action game 'Hubris' [21]. Additional assists for actions include aim or throw assists, for example when throwing a basketball [80], included in 13 applications. Visual assists include text hints within 18 titles and visual labels in 26 applications, for instance highlighting button positions on the virtual representations of the handheld controllers [124], as seen in Fig. 1. Finally, visual guidance for the wayfinding locomotion task [19], such as the guidance arrows seen in 'Kayak VR: Mirage' [111], are provided within 25 total applications.

4.5 Output Modality Considerations

4.5.1 Visual Focus Indicators. Menu highlighting, most commonly displayed with button colour alterations when hovering with raycast selection, is included in 137 applications. Meanwhile, virtual objects which are available to be interacted with or gripped are highlighted in 125 titles through object colour changes, shade alterations, or non-diegetic UI feedback, as illustrated with the white circle on the ammo belt in Fig. 1. Lesser explored visual indicators for interactions include eight titles with off-screen attack indicators, including with the option to toggle indicators on or off in 'After the Fall' [60], and six games, as seen in 'Primal Hunt' [85], with a toggle for an aiming laser sight across all weapons. Locomotion-based visual focus indicators are less supported than menu or object interaction indicators, with 46 applications including focus indicators for locomotion. These locomotion visual cues primarily consist of teleportation or dash-based aiming reticle feedback for reachable target locations, most commonly displayed with successful green and unsuccessful red reticles at the location the user is aiming at in the VE, seen for example in the teleportation-based 'Vacation Simulator' title [83] and the dash-based 'Hyper Dash' [22] game.

4.5.2 Colour and Luminance. Although 35 applications contain colour and luminance modification, just five, including 'Beat Saber' [52], contain extensive colour alteration. Partial colour choices with alteration of a limited selection of individual elements are more common, with 13 applications containing UI element colour change options, one of which locks this colour change selection behind a paywall [59], and six containing object colour selections only, such as the gun colour modification in 'AUDICA' [72]. Meanwhile, just three titles contain dedicated colourblind settings [25, 87, 90], with only one application, 'Synth Riders' [95], allowing for control of both colour and texture patterns to distinguish between objects [124]. These results are particularly surprising given that the sixth Meta Quest VRC accessibility guideline [133] recommends all Meta Quest practitioners provide colour blindness options, suggesting that practitioners are choosing not to follow these recommended steps. Finally, 12 applications contain luminance adjustment, whilst only one title contains contrast settings [158], again demonstrating that the fifth Meta Quest VRC accessibility guideline [133], which may be particularly beneficial for increasing the usability of consumer-level hardware for users with low-vision [152], is also largely ignored.

4.5.3 Additional Visual Accessibility Features. Other visual accessibility options include six applications which allow users to disable flickering or flashing lights [33, 52, 57, 95, 187, 191], an important safety feature for people with photosensitive epilepsy [68, 71, 73, 124]. Targeting considerations include toggable crosshairs, included in three titles [91, 111, 157], as well as dominant eye selection, contained in the 'Onward' tactile shooter game [94]. VE visual alterations include one application with a 2D toggle [155], five titles with passive movement toggles to remove moving backgrounds during non-user controlled locomotion, as seen in the running on rails [37] 'Synth Riders' music application [95], and 22 titles with screen shake or excessive movement options to reduce non-user controlled viewpoint motion, such as removing head bobbing in 'ChilloutVR' [93]. Dedicated safe harbour controls [68, 73] meanwhile are not present at a software-level in any application. Finally, a software-level augmented reality pass-through toggle, of particular importance for users who rely on visual feedback as their main means of interacting with their physical surroundings [36], is included in eight titles.

4.5.4 Mono Sound. Only one application contains partial mono sound control, with voice chat and enemy sounds balance adjustable per ear in 'Aim XR' [201], with no instances of full software-level mono sound support in any application.

4.5.5 Volume and Sound Controls. Binaural volume and sound controls are widely supported within 209 titles, of which 32 offer a global volume slider or toggle, whilst 177 provide individual volume and sound controls, with music, effects, and dialogue sliders, as seen in 'Hubris' [21] in Fig. 9(d), the most included controllable audio elements. No application contains audio descriptions or the ability to pause audio tracks [39].

Table 4: Number of applications with each form of hand and body interaction haptic feedback.

Interaction haptic	Hand number	Body number
Character interaction	20	6
Combat	142	79
Consumables	6	24
Diegetic sound	29	43
Object grasp	195	26
Menu/non-diegetic	98	16

Table 5: Number of applications with each form of hand and body locomotion haptic feedback, with locomotion techniques seen in [37].

Locomotion haptic	Hand number	Body number
Environment contact	39	30
Footsteps	6	6
Hand walking	10	1
Rotate or turning	8	0
Teleport/dash	27	12
Vehicle (user controlled)	19	14
Zipline and passive move	13	16

4.5.6 Haptics. A total of 272 applications contain at least one handheld controller interaction haptic cue, whilst body haptic feedback associated with interactions are included in 97 titles. Table 4 highlights the total number of applications that contain each type of interaction haptic cue. For locomotion haptic feedback, 107 applications contain at least one hand-based haptic cue, whilst 57 titles contain at least one body haptic cue, with Table 5 displaying the locomotion haptic feedback results.

Of the titles with any form of haptic feedback, 85 contain options to tailor cues, with binary global haptic feedback control the most often included alteration in 58 applications. A further seven titles provide alteration of individual elements, such as the separate weapon and UI haptic control contained in 'Swordsman' [87], an additional 19 contain feedback modification, often labelled strength [32] or intensity [21], and a single title, 'Ragnarock' [191], provides modular control over haptic frequency, amplitude, and duration.

4.6 Social and Communication Considerations

4.6.1 Subtitles and/or Closed Captions. Text captions are available in 101 applications, with 38 subtitles and 65 closed captioning options. Similar to UI colour customisation, one title locks captions behind an additional paywall [167]. Alterations to subtitles and/or closed captions, namely text size, location in the VE, or closed caption background colour, are available in 13 of these applications, with five titles [1, 21, 33, 56, 187] allowing for text size alteration, eight titles [24, 56, 82, 114, 117, 169, 180, 188] with location alteration options such as vertical offsetting, and caption colour choices in just two titles [128, 180]. Fig. 1 highlights one of the potential issues in providing fixed colour subtitles in VR applications where the user can control their FoV, with the overlap between the white visual focus indicator element and white subtitles negatively impacting reading comprehension. Fig. 10 shows how the overall number of applications with either subtitles or closed caption options has remained low throughout the data collection period.

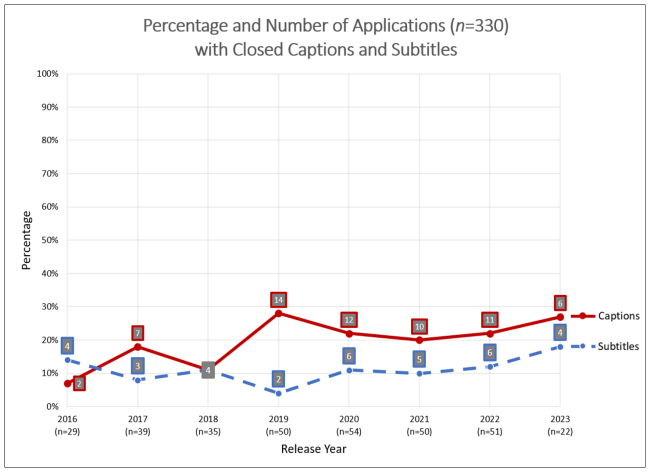

Figure 10: Percentage of applications released each year which contain closed captions and subtitles. Number of applications released each year highlighted with the data labels.

4.6.2 Speech Speed. Only two applications allow for speed playback adjustment, both of which are text-based narrative games [82, 183]. Alteration over audio speech playback beyond volume control is completely absent, including no software-level implementations of text-to-speech [11, 39, 68, 142].

4.6.3 Voice Alteration. For speech options, voice alteration is more widely supported than speech speed modification, with control over voice audio levels included in 92 applications. A total of 14 titles, such as the social VR applications 'VRChat' [88], 'Rec Room' [155], and 'ChilloutVR' [93], provide control over when the user's voice is heard in the shared online VE with open microphone or push to talk selection. Modification of the user voice beyond sound volume level with voice modulation however is less supported within two titles [125, 155], with just 'Meta Horizon Worlds' [129] additionally providing a distortion option for the voices of unfamiliar user controlled avatars.

4.6.4 Sign Language. Little support exists for users who communicate with sign languages, with one game providing a small number of American Sign Language instructions from the in-game avatar [150], and two social VR applications with precise finger tracking allowing for partial sign language support when communicating with other user-controlled avatars [88, 93]. No title however contains full dedicated signing interpretation, with no signing support for text, objects, or item descriptions [68] in any application.

4.6.5 Personal Space. Finally, privacy or personal space boundaries are provided in ten titles, such as the default invisible radius social bubble in 'Meta Horizon Worlds' [129] and the adjustable personal space bubble in 'Rec Room' [155].

5 Discussion

In this section, results are discussed in terms of accessibility features to explore RQ1, followed by analysis of historical trends covering RQ2. Individual key takeaways for both researchers and practitioners will then be listed, followed by key collaboration takeaways to bridge the academic and industry gap, before concluding with limitations and suggestions for future work.

5.1 RQ1: Accessibility Features

5.1.1 Interaction. Key interaction results indicate that alternative hardware-based inputs, particularly accessible gamepad controller (49) and keyboard (23) switch-based devices [68], are largely unsupported in mainstream VR software. In addition, key remapping (85) appears largely overlooked, with extensive or full customisation (25) in particular rarely included, suggesting that mapping potentially complex controls to macros for switch input, a potentially vital consideration for users with physical impairments [39, 68, 73] such as gamers with muscular dystrophy [184], is mostly unavailable in the titles most commonly encountered by users [49]. Moreover, the ability for users to interact with multiple input devices simultaneously, often an important consideration for users with disabilities [68, 73], is largely not supported, with no software-level AT support, such as screen readers [101], lightweight pens [109], or white canes [103, 204], particularly problematic for users with additional interaction requirements. Results showing a limited exploration of non-hardware low-friction input modalities, which may be beneficial to both users unable to use controllers [192] or who may have difficulty learning how to use the hardware [124], suggest that mainstream VR applications overwhelmingly do not provide diverse non-hardware input support [139]. The low freehand tracking (25) in particular is potentially vital in the results showing such limited sign language support [39, 124] across all applications.

Whilst alternative input modalities appear undersupported, perhaps due to the near ubiquity of primary bimanual tracked controller input support (326), bimanual controller hand input adjustments appear more widely available, with both dominant hand selection (148) and full one-handed input (97) more commonly configurable at a software-level than alternative input modalities. More work is needed however to allow users to modify bimanual controller input demands, including allowing for the configuration of joysticks for spatially tracked inputs for BVI users [107], physical one-handed modifications for expected bimanual actions for users with full use of a single arm [50, 202], and control over the number of functions presented to users with cognitive impairments [12, 70]. These accessible interaction modification best practice research suggestions are almost universally unavailable in mainstream experiences, where users are given few options to customise bimanual controller interaction demands.

5.1.2 Physical Positioning. In addition to the inflexibility of supported input modalities, alternative physical positioning posture support appears limited in mainstream VR software, with less than half of the applications containing primary seated support (149), and 79 titles only usable whilst standing. Additionally, the near-universal inability to configure lying down (4) access at a software-level supports the concern of users who are bed-bound that their access needs are not currently satisfied [185]. Expanding support for explicit manual head height adjustment (64) could help to address this posture inflexibility [11, 39, 73] without negatively impacting the performance of standing actions whilst seated [62]. An increase in artificial crouching (39) additionally could potentially be beneficial so that non-standing users do not have to perform challenging [39, 141] and confusing physical crouch motions [185]. Although manual head height adjustment and artificial crouching appear undersupported, a large number of applications support front-facing only access (234), which is also potentially vital for supporting these non-standing postures [38]. Further research is needed however to explore the potential interplay between disability and comprehension when utilising artificial turning to maintain this front-facing access [28], whilst the lack of support for alternative point of interest [48] and accessible scene-viewing techniques [49] beyond camera panning suggests that practitioners must include alternative options for physically viewing spatial VE elements.

Results highlight that software-level physical space alterations appear limited, with scaling (5) for example, which is undetectable in virtual hand movements up to 1.43 scale [43], rarely included. Expected physical gesture movement speed or distance adjustments (4) are also very limited, with only two titles allowing for control over expected movements of unequal limbs and no support for personalised gesture sets [182] reinforcing findings that practitioners do not account for the experiences of disabled bodies [64].

5.1.3 Locomotion. The number of applications providing tunneling (82) and snap turning (166) visual sickness mitigation techniques suggests a largely successful transfer of academic visual-based sickness mitigation best practice design guidelines [151], additionally suggesting that the large academic focus on locomotion techniques to mitigate simulator sickness [71] is shared by industry practitioners [6]. The lack of alternative viewpoint travel technique options however suggests that practitioners are largely not adhering to accessible travel recommendations [39, 50, 73], suggesting that users are rarely able to tailor locomotion control to their own abilities and mental model of walking formed by their lived experiences [175]. The user-dependent BVI results from Ribeiro et al. [154] further emphases this importance in providing personalised software-level customisation with the choice of multiple locomotion techniques rather than providing an inflexible static choice for a standard disabled experience. The lack of applications allowing for low-friction locomotion control, including no support for speech-based locomotion [75], additionally suggests that practitioners are largely not offering alternative locomotion control for users who are unable to use wrist-based standardised hardware [109].

The categorisation within existing academic taxonomies on the accessibility of locomotion techniques from general simulator sickness and motor ability levels [37] emphasises the importance of further research exploring locomotion from alternative disability perspectives, such as the underexplored potential interplay between sickness and stereoblindness [110], autism spectrum disorder [65], or multiple sclerosis [10]. These potential locomotion accessibility trade-offs for diverse audiences must be more fully explored, in turn allowing for more nuanced accessibility categorisation for a range of disabilities in future locomotion taxonomies.

5.1.4 User Interface. Potential vergence-accommodation conflict issues with depth-only adjustments [14] suggest that size adjustments at a fixed-depth may be important in VR, particularly for users with low vision [124] and unintentional hand movements [15]. Along with limited fixed-depth size adjustment results, such as no support for text font size control, customisation of the UI also appears limited, with adjustment of spatial positioning in particular rarely offered (5). Adjustable UI sizing settings are standard in two-dimensional PC applications [124], with these limited size and positioning results suggesting that VR software, in particular gaming applications [73], may be less accommodating to the existing visual sizing expectations of users.

5.1.5 Output Modality. Although visual focus indicators for menu selection (137) and object interaction (125) appear relatively well supported, both of which are particularly important to address the potential peripersonal space interaction issues caused by the vergence-accommodation conflict [13], other essential display visual modifications for low-vision support [39] appear under offered. The lack of full display colour (5), luminance (12), and contrast (1) control, along with no inclusions of low vision augmentation tools [196, 205], is concerning due to the close proximity and typically larger FoV coverage of VR displays in comparison to PC monitors, with just three applications containing dedicated colourblind settings [38, 124] particularly alarming. Results showing only one application containing partial mono sound control meanwhile is problematic given the spatialised binaural soundscape design typically found in VR [11, 68], which along with the lack of sensory substitution control such as haptic sound localisation [137], suggests that users across the spectrum of sensory impairments, including users with cognitive impairments who have sensory integration disorders [65], are largely not able to tailor mainstream VR titles to their sensory requirements.

Although it appears that the unique display characteristics of HMDs do not increase seizure risk in comparison to two-dimensional visual display feedback [67], the general lack of controls for disabling flickering or flashing lights [68, 73, 124], combined with results showing zero safe harbour control [68, 73] options, reinforces the perceived inaccessibility of the technology amongst users with photosensitive epilepsy [166]. These visual and audio output results strongly suggest that the needs of users with spatial orientation, cognitive, visual, and/or auditory impairments are not being adequately addressed by industry practitioners, with overall little support for sensory-inclusive techniques [20].

Finally for output modality considerations, tactile results highlight a widespread industry interest in handheld haptic feedback associated with interactions (272), vital from an accessibility perspective in order to provide additional interaction clarity [124], in particular for people who are blind [2]. There appears to be a gap in exploration of both hand (107) and body (57) locomotion related haptic feedback in comparison however, in particular for haptic cues associated with continuous locomotion such as footsteps (6), with results demonstrating how tactile feedback may be beneficial to spatial understanding [204] and orientation [46] in VR suggesting this form of redundant haptic feedback allowing users to leverage the output channel that matches their capabilities [39] may be under offered.

5.1.6 Social and Communication. The low level of closed caption and/or subtitle support, as seen in Fig. 10, zero implementations of text-to-speech [11, 39, 68, 142], and a severe lack of options for users who communicate with sign languages [39], suggest that users with additional communication requirements are largely unaccounted for in mainstream VR application design. Additionally, although social personal space boundaries (10) are more widely supported than speech adjustments, in particular in social VR applications such as 'VRChat' [88], the overall lack of control over communication in shared VE titles, such as voice modulation control only appearing in one game [125], suggests that more work must be conducted to combat shared VE harassment concerns [120], particularly for users who choose to disclose their disabilities via avatars [203] or who have neurodevelopmental disorders [36].

5.1.7 Summary. Overall, these results, which show numerous failures to accommodate the needs of users with disabilities across all categories, further reinforce the perception of VR as an ableist technology [64], with industry practitioners largely appearing to display little consideration for accessible design. The XR-specific specialised software solutions presented in academic research and guidelines including the XRA Developer Guide [11], such as undo and bypass sequence functions, in particular appear unavailable in mainstream titles, suggesting that practitioners may be largely unaware of the evolving best practice design options presented in academic literature and emerging guidelines.

5.2 RQ2: Historical Trends

Due to the limited inclusion of a number of accessibility features over the eight years covered in this analysis, particularly for UI customisation [73] and output modality alterations [11, 39, 68, 73, 124, 133], clear historical trends for many features do not exist. A selection of our key findings however highlights a number of worrying accessibility trends in mainstream VR software, particularly in terms of interaction and physical positioning flexibility. The most concerning negative temporal trend is found in the reduction of applications that allow for alternative hardware input support [11, 38, 39, 68, 73], as seen in Fig. 4. Gamepads, which can allow for adaptive controller switch-based input [68], were supported in over 30% of titles released each year between 2016 and 2018, with keyboards, which can allow for ergonomic one-handed keyboard-only input [68], supported in over 10% of applications in the same three years. In the three years between 2020 and 2023 however, both gamepad and keyboard support has reduced to below 10% of titles released each year, suggesting that accessible input options, such as mapping macros [68, 73], are becoming increasingly scarce. The number of applications which allow for any form of alternative or multi-modal [36, 68, 197] input, although becoming increasingly common as both a field of study and for commonplace computing control for users with disabilities [197], has similarly reduced over time, from 54-62% of titles between 2016 to 2018 supporting bimanual tracked controller input only, to over 78% of released applications each year since 2019 providing no alternative hardware input support beyond the standardised bimanual handheld hardware. This inflexibility of hardware-based input is compounded by the input key remapping results, as seen in Fig. 5, demonstrating no increase in the ability to extensively remap input

keys [11, 38, 39, 68, 73, 124], and Fig. 6, highlighting how users are increasingly unable to utilise a single handheld controller to engage with mainstream VR titles, with no application supporting customisable unimanual inputs for bimanual actions [50, 202]. Additionally, each low-friction non-hardware based input, including freehand tracking [168] which has the potential to be beneficial for users with motor impairments who are unable to interact with the hardware [192], users who have difficulty learning how to use the controllers [124], and users who communicate with sign languages [39, 124], has been supported in fewer than 14% of released applications each year. Taken together, these results emphasise how users are increasingly being required to use both handheld controllers for all interactions in VR, with options for alternative keybindings rare and potentially accessible alternative or multi-modal additional input options continuously being withdrawn.

A slight but concerning trend appears to exist in the number of applications which have primary seated posture support [11, 39, 133], as seen in Fig. 7. Except for increases between the first and most recent two years, primary seated support has decreased yearly. Combined with the almost complete lack of support for lying down [185] access at a software-level (4), along with no visible trends in the increase of artificial crouching, with button hold and toggle options included in fewer than 20% of titles released each year, results reinforce the physical positioning issue addressed in the XR Accessibility User Requirements [68], with the supported flexibility of body positioning in mainstream titles continually decreasing. The increasing provision of head height adjustment control [11, 39, 73] is however a positive development, in particular as results from Ganapathi et al. [62] show how head height adjustment allows seated users to successfully perform standing-only actions.

The growing shift within the HMD hardware market towards HMDs with untethered connections and inside-out tracking sensors, away from earlier tethered HMDs with outside-in base station tracking [8], has perhaps surprisingly not resulted in a decrease in front-facing accessible [38, 39, 73, 133] applications, although results showing an increase in the number of titles which contain at least one artificial turning method [159], as seen in Fig. 8, indicate that users are increasingly required to utilise hardware-based artificial turning techniques to remain front-facing. Further work is required to understand the potential barriers presented by turning techniques for diverse audiences however, as seen with the reduced comprehension results from Collins et al. [28] when snap turning was presented to social VR users with visual impairments. This potential interplay between disability and artificial turning must be more fully explored across a wider range of disability perspectives.

5.3 Key Takeaways for Researchers

- **Explore Alternative Inputs:** Investigate how VR interactions can support a broader range of input devices, such as switch-based [39, 68, 73], unimanual [50, 202], and multimodal devices [36, 68, 197].
- **Investigate the Impact of Limited Output Customisation:** Research is needed to understand how HMD characteristics, such as the large display coverage and limited horizontal FoV, impacts spatial UI and output requirements, particularly for users with sensory impairments [7].
- **Assess Accessibility Trends:** Examine the reasons behind the overall lack of and declining support for features like customisable locomotion [39, 50, 73] and posture flexibility [206] in collaboration with industry practitioners [101, 205].
- **Focus on Locomotion From Diverse Perspectives:** Further studies are needed to understand potential trade-offs in locomotion techniques [10, 65, 110, 154], in turn allowing for more nuanced taxonomies and recommendations.
- **Evaluate the Role of Guidelines:** Assess the effectiveness of existing VR accessibility guidelines [11, 38, 39, 68, 73, 124, 133] and further establish new or refined recommendations.

5.4 Key Takeaways for Practitioners

- **Prioritise Inclusive Input Support:** Ensure that VR applications support a variety of input devices [36, 68, 197], allow for extensive remapping of controls [39, 48], and implement personalised gestures [63, 182].
- **Enhance Physical Positioning Flexibility:** Incorporate seated [11, 39, 124] and lying down [185] postures with head height [11, 39, 62, 73] and crouch control options [11, 73].
- **Provide UI and Output Customisation Options:** Implement text resizing [11, 38, 39, 73, 124], spatial UI customisation [11, 73, 133], and redundant outputs such as haptic feedback for locomotion [163, 195, 204].
- **Support Sensory and Communication Needs:** Include features like mono sound [11, 68, 73], closed captions [11, 38, 39, 68, 73, 133], and sign language support [11, 39, 68, 73].
- **Adhere to Accessibility Guidelines:** Follow established and evolving VR accessibility guidelines and practices, such as those from the XRA [11], W3C [68], and Meta VRC [133].

5.5 Key Collaboration Takeaways

- **Joint Research Projects:** To bridge the gap between academic research and industry practice, future projects should facilitate co-creation to translate academic findings into designs practitioners can readily adopt [35, 101].
- **Resource Sharing:** Open source toolkits and open access guidelines can allow for more efficient feature implementation [101, 205]. Researchers must distill concepts into practical tools and recommendations, whilst practitioners must provide feedback on accessibility feature integration.
- **Further Establish Workshops and Working Groups:** Foster a community-driven approach to accessibility that brings together researchers, practitioners, and users with disabilities at all stages of research and development [35, 39].
- **Promote Accessibility Education:** Collaborate across educational institutions and industry bodies to integrate accessibility teaching and training into curricula and professional development programs [35].

5.6 Limitations and Future Work

Although inclusion criteria were designed to include the most downloaded applications in order to analysis the VR titles most commonly encountered by users [49], the precise usage levels of each individual application in a given year is not a factor in this analysis, therefore making it difficult to accurately analyse the total number

of users potentially exposed to each application. Furthermore, separation by release year may not always accurately reflect application states at the time of release, with software updating available on all platforms potentially negatively impacting temporal analysis accuracy. A more in-depth analysis of application update releases may reveal the prevalence of post-launch accessibility specific updates, such as the 2023 vision accessibility update to the 2022 released 'Cosmonious High' adventure game [84]. This title, which has received strong post-launch accessibility support, was not included in the database as it did not fulfil the download inclusion criteria. Download metrics alone may have limited the diversity of the analysed applications, including potentially minimising the representation of applications specifically designed for or by people with disabilities. Moreover, as this review did not account for the potential differences between free and paid applications or the resources available to practitioners during development cycles, future reviews should determine whether economic factors have an influence on the implementation of accessibility features. Finally, due to the potential complexity of VR software, certain features may have been missed during data collection, such as locomotion techniques that first appear only in the later stages of lengthy games.

As this review is based upon identifying the prevalence of accessibility features presented at a software-level, with results building an understanding of practitioner decisions in the underexplored area of general VR accessibility [63], future accessibility audits are required to understand the effectiveness of individual implementations, whilst further accessibility analyses must be conducted with users to understand the perspectives of diverse audiences. This would allow for categorisation on the perceived accessibility of individual titles in terms of required or repetitive button inputs for example, along with allowing for the further formation of guidelines following ability-based design principles [141]. Engaging a wide range of users with disabilities in the evaluation process would provide more nuanced insights into the practical usability and impact of the included accessibility features, in turn ensuring that accessibility recommendations align with the actual needs and preferences of the intended users.

Additional categorisation features influenced by emerging VR guidelines may be beneficial to record in future analyses to further understand the state of accessibility in VR, with potential features including avatar self presentation options [119], how effectively visuals assist with balance [39], and body motion requirements [181]. Sound should also be further explored beyond the audio mixing customisation levels currently analysed, for example to categorise the types of UI, diegetic VE, or user action sounds [98], the presented frequencies and dynamic ranges [124], and the effectiveness of potential audio scaffolding techniques with users who are BVI [194]. Movement of UI and text elements such as captions in relation to the head should also be noted, for example to determine if UI or text elements are head-locked or locked in space, with the detail level of captioning descriptions also a potentially vital feature to investigate [36]. Finally, data for this analysis showed that 18 titles contained hints or tutorial toggles available through a button press, although further analysis of tutorials, such as whether an application contains access to the tutorial on demand beyond initial completion, or contains a separate training area to give users the space and time to become comfortable with the mechanics [124], is needed to further understand how difficulty is handled.

This review for the first time empirically categorises the degree to which software-level accessibility features are implemented in the most used consumer-level VR titles. Results showing a widespread lack of awareness of best practice accessible design choices reinforce previous findings from Zhao et al. [205] highlighting how practitioners are largely unaware of accessibility-specific designs, indicating that future research, tool creation, and sharing of design guidelines are urgently required in priority areas such as multimodal and customisable inputs, spatial interfacing, and alternative output modalities.

6 Conclusion

As the mainstreaming of VR continues it is vital to address the key accessibility considerations presented by the technology, potentially allowing for the integration of accessible design solutions at a fundamental level. Our analysis however indicates that the most used applications available on consumer-level HMD software platforms are in multiple areas becoming less accessible for diverse audiences, with trends since the release of the first-wave of sensor-based devices in 2016 indicating that mainstream VR software is increasingly interaction input and physical positioning inflexible. In addition, UI and output modality results indicate that users are largely unable to tailor the sensory experience to their own preferences or needs, with text size adjustment seldomly included beyond depth-based control, disabling of flickering or flashing visuals rarely possible, and dedicated colourblind alterations provided in just three titles. These results indicate a widespread lack of awareness by industry practitioners of best practice accessible design, suggesting that more work is urgently required to propagate industry-wide accessibility guidelines. A greater level of collaboration between industry practitioners and academic researchers is urgently needed, including joint research projects, the sharing of best practices, and the development of tools and resources to support the design and implementation of accessible VR applications. Stricter enforcement of platform-specific guidelines are also needed to ensure accessible designs are adhered to, with evidence suggesting that the current practice of presenting recommendations rather than enforcing compliance is ineffective.

The representative overview of industry practitioner design decisions presented in this review highlights the continuing, and often concerning, evolution of mainstream VR software-level accessibility. Results showing a decline in the offering of a number of accessible features emphasises the urgency needed in a renewed focus on addressing the accessibility of mainstream VR. This review indicates that the current lack of VR guidelines, standardisation practices, and developer tools [39, 73, 196, 205] has largely resulted in VR industry practitioners not widely implementing options to allow for alterations to match individual and situation-specific needs. We intend for this review to highlight the priority concerns that must be addressed in future research and application development, in turn acting as a catalyst towards the further establishment of industry-wide VR accessibility guidelines, and ultimately leading to the creation of inclusive VR experiences for all audiences.

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