Accessible Binary Interaction Techniques in Panoramic Virtual Reality Applications for Users with Motor Impairments

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Abstract:

The paper presents two binary interaction techniques for panoramic virtual reality applications, based on scanning methods common for 2D user interfaces: Automatic Item Scanning (AIS) and Continuous Cartesian Scanning (CCS). These allow users with motor impairments to interact with only one degree of freedom. Following a pre-study, both techniques were refined and evaluated in a user study. The study assessed interaction performance, usability, user experience, and motion sickness. The results showed no statistically significant differences across most metrics, except for interaction time, where AIS was significantly faster. Both techniques displayed particular limitations. CCS exhibited errors when switching between the two interaction modes for selection and navigation. AIS was mostly affected by timing errors and a rigid scan sequence. The comparison with the pre-study highlights the importance of perceived control, self-efficacy, and customizable interaction parameters. Despite these limitations, both approaches demonstrate potential for the development of accessible panoramic VR interaction techniques.

Keywords: Virtual Reality, Human-Computer Interaction, Accessibility

1 Introduction

Motor impairments refer to the loss or limitation of the ability to control muscles or movements. Causes vary and include conditions such as arthritis, paralysis, cerebral palsy, or repetitive strain injuries [YFH11]. These impairments not only affect physical mobility but can also limit access to digital technologies, which is particularly relevant with respect to the aging society. The design of accessible systems therefore aims to create products and applications that are usable by the broadest possible range of users with diverse requirements, abilities, and skills. This includes consideration of the context of use and the integration of assistive technologies [DINc]. Virtual Reality (VR) is an emerging technology with increasing relevance across a variety of domains, including education, healthcare, entertainment, and training. Due to the decreasing cost of hardware, VR is no longer a niche technology but is gaining popularity in the consumer market [Mo20]. This broader

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adoption also opens new possibilities for people with disabilities. For people with motor impairments in particular, VR has the potential to provide a platform that allows new forms of interaction and participation [Mo20]. However, VR currently lags behind other technologies in terms of accessibility. While common operating systems for smartphones and computers provide extensive accessibility tools (e.g. [Ap25]), standardized guidelines and tools have yet to be established in VR [CBL23]. Recent initiatives have emphasized the importance of inclusive design practices in immersive environments, particularly for users with disabilities (see, e.g., [Br25]). The development of inclusive VR applications is motivated by four key considerations: (1) The ethical and moral obligation to ensure equal access to technological advancements, (2) VR has the potential to remove barriers in rehabilitation and assistive technology, thereby improving quality of life, (3) addressing a larger user group also brings commercial advantages, as it enables access to a broader market and greater sales opportunities, and finally, (4) accessible design often leads to improved usability for all users, especially in situations where physical capabilities are temporarily limited due to external factors [Wo11]. To enable people with motor impairments to engage with VR environments, binary interaction techniques are a promising approach. These techniques use basic, low-effort input methods that rely on a one-bit input, e.g. as can be realized by a button, making them accessible to users with limited motor function. Binary interaction techniques follow a bottom-up design approach that minimizes the physical and cognitive demands placed on users. The only prerequisite is the ability to perform a controlled action, regardless of which body part is used, without assuming the availability of specific modalities such as head movement, gaze control, or fine motor skills. This design approach aims to accommodate a broad and heterogeneous user base, including individuals with severe motor impairments. Furthermore, these interaction techniques can enhance the usability of VR applications in situations where physical movement is limited or impractical, such as in confined spaces or when experiencing situationally induced impairments [Wo11].

The aim of this work is to design and implement two binary interaction techniques that allow all necessary system interactions to be performed using binary input. These interactions include the selection of hotspots to trigger actions such as scene transitions, audio playback or displaying and dismissing informational overlays. In addition, the interaction design must support choosing between multiple interface elements presented simultaneously, such as in dialog-based branching or multi-option prompts. The scope of this work is explicitly limited to panoramic VR applications based on 360-degree content. This restriction is motivated by the fact that such applications inherently offer a simplified interaction paradigm in comparison to fully spatial VR environments, which demand complex and multidimensional interaction mechanisms. To ensure accessibility, a dedicated interface will be developed and the interaction processes will be systematically conceptualized. The implementation of the interaction techniques will be carried out within an educational tool designed for the provision and creation of 360-degree training applications. The implemented techniques will then be evaluated in terms of interaction performance, usability, user experience, and the occurrence of motion sickness symptoms.

2 Related Work

2.1 Accessibility in VR

Accessibility in VR is an emerging research area that has gained increasing attention in recent years. Most research focuses on specific types of impairment, such as visual, auditory, cognitive, or motor impairments, by identifying user challenges and exploring potential solutions (see e.g.[Zh19], [MKK20], [Ei18]).

Guidelines and Standards

While accessibility guidelines exist for many digital products, such as websites, mobile apps, and games, most of these guidelines are not suited to the demands of immersive VR environments. As Heilemann et al. [HZM21] point out, these guidelines often rely on conventional interaction methods and target particular devices, limiting their applicability in VR. The XR Association addressed this issue in its 2020 report [XR20], offering recommendations for designing accessible VR and AR applications. XR Access [XRAC22], a collaborative initiative involving universities and industry, advocates making inclusive design and accessibility a fundamental part of XR development. In a comprehensive review, Heilemann et al. [HZM21] synthesized existing guidelines on VR game accessibility, recommending control remapping and minimizing the need for gestures such as pinching or twisting. They also recommended ensuring compatibility with assistive technologies such as switches and multiple input devices.

Barriers for Users with Motor Impairments

Researchers have identified several barriers that users with motor impairments face when using VR systems, which can be categorized into three main areas.

1. *Setup and Use of VR Hardware:* The initial setup of VR devices often requires precise motor control and physical effort, creating a significant access barrier [GS21]. Tasks such as inserting batteries into controllers, connecting cables, or configuring play boundaries can already present challenges [Mo20]. Users in wheelchairs may experience further difficulties with tethered headsets, such as cables becoming tangled in the wheels or restricting movement [Mo20; WGP17].
2. *Assumptions about the Body:* The extensive physical involvement required by VR technology can create barriers for people whose bodies interact with the system differently [GS21]. The required body movements are often based on the abilities of people without disabilities. These include standing and using gestures and both hands to interact with virtual objects [Do19; WGP17]. Additionally, internal application requirements for energy and stamina are similarly based on the capabilities of people without disabilities [WGP17]. This can lead to physical, mental, and temporal fatigue for people with physical limitations. As a result, pain may occur or existing physical

symptoms may worsen [Cr24a]. Furthermore, many applications fail to integrate assistive devices or support alternative input methods, which can reduce users' confidence and sense of agency [Cr24a].

3. *Interaction with VR Controllers:* Using VR controllers requires users to have one or both hands available, along with full mobility of the fingers, wrists, and arms [Mo19]. Consequently, many users with motor impairments struggle to reach, press, and hold the buttons on the controllers, particularly when several buttons must be pressed simultaneously [Mo20]. Furthermore, many interactions rely on precise selections and controller visibility within the HMD's tracking field. Users with unintentional body or eye movements may face additional challenges, particularly in applications that require constant and deliberate gaze input [Cr24a]. For people with little to no mobility in their arms or hands, VR controllers are completely inaccessible [Mo20].

Approaches to Overcoming Barriers

Various strategies have been proposed to address these barriers. With regard to the headset setup, Mott et al. [Mo20] suggest relocating adjustment dials to more accessible positions and implementing automatic fitting mechanisms. Wireless HMDs may improve usability by eliminating the risk of entanglement. To broaden interaction capabilities, alternative input methods such as voice control or eye tracking have been explored [Mo20]. Reconfigurable control schemes and the ability to use multiple input devices simultaneously are also regarded as essential accessibility features [HZM21]. Research into alternative input systems has yielded promising prototypes. For instance, Minakata et al. [Mi19] compared the cognitive and physical demands of head-, gaze-, and foot-based input methods. Wang et al. [Wa18] developed a facial expression and eye movement-based interaction system for VR. Franz et al. [LJM21] introduced Nearmi, a system that aims to reduce upper body movement and simplify interaction with points of interest. However, it still relies on VR controllers. Valakou et al. [Va24] presented an XR Accessibility Framework offering a sequential scanning interaction method to support users who struggle with point-and-select tasks.

Despite these promising approaches, the majority of existing work still focuses on identifying barriers rather than providing practical solutions. Creed et al. [Cr24b] have proposed a research agenda to advance inclusive VR and AR systems. Key areas for future research include developing alternative input techniques (e.g. gaze and speech), filtering out unintended movement artifacts (e.g. tremors and falls), creating adaptive interfaces and headsets, and integrating common assistive devices into VR hardware ecosystems.

2.2 Binary Interactions

Binary interaction interfaces offer a basic method of controlling a system through basic inputs, typically distinguishing between two states, such as 'on' and 'off', or 'pressed' and 'not pressed'. These interfaces often rely on switches, assistive devices developed for people with motor impairments as an alternative to conventional input methods like mice, keyboards, or controllers. Switches can be activated using any body part capable of consistent voluntary movement and can be adapted to suit the user's physical abilities. Depending on the activation method, switches can be categorized as press-, pull-, pinch-, or breath-based devices [WD96; YFH11]. A common input method using switches is scanning. Selection options are presented sequentially and users activate a switch to select their desired item when it is highlighted. Scanning enables interactive control with minimal motor demands [CP15]. The most common types are Item Scanning (subdivided into automatic, step and inverse item scanning) and Continuous Cartesian Scanning. In Item Scanning, individual items are successively highlighted and users confirm their selection with a switch input when the target item is active [SC03]. In *Automatic Item Scanning*, the system cycles automatically through items, pausing for a fixed amount of time on each one. Selection is made if the switch is activated by the user during this interval. Although this reduces the number of required actions, this method can be slow and cognitively demanding [CP15]. In *Step Item Scanning*, the user manually advances the highlight by repeatedly pressing a switch. Selection can be made either via a secondary switch or by dwell time. This method offers control over scanning speed, but repeated activations may lead to fatigue [CP15]. *Inverse Item Scanning* automatically highlights items as long as the switch is held down. Releasing the switch when the target item is highlighted confirms the selection. While it minimizes the number of activations, it demands sustained attention [CP15]. *Continuous Cartesian Scanning* involves a two-dimensional search process along orthogonal axes. First, a horizontal scan line moves from top to bottom across the display. The user activates a switch when the line intersects the row containing the desired target, which locks the horizontal position. Then, a vertical scan line moves from left to right along the selected row. Again, the user activates the switch when the line passes over the desired item, completing the selection [Bl04].

Although scanning methods enable control with very limited motor input, they require good visual tracking and focused attention. They are also relatively slow compared to other input techniques [CP15]. Optimizing the scan rate remains a major challenge in the implementation of scanning. If the rate is too fast, users may miss selections; if it is too slow, interactions become tedious [Bl04; SKL07].

3 Design Process of Binary Interaction Interfaces

A structured design process was adopted, based on the principles of Zwicky's [Zw67] morphological analysis, and adapted to the requirements of developing binary interaction interfaces for immersive 360° video-based training. The process consisted of four key stages: (1) definition of the design space, (2) identification of potential design variants, (3) classification of options using evaluation parameters, and (4) derivation of two final interface concepts for implementation in the prototype.

3.1 Design Space

The design space is divided into three levels:

- **Interaction Tasks**, including *Selection* of interactive elements within the scene and *Navigation* of the user's viewpoint within the 360° panorama. This is essential for users with limited head mobility as it provides an alternative to physical gaze-based interaction.
- **Interaction Components**, including *Transition*, which defines how the virtual camera rotates, and *Initialization*, which specifies whether the interaction method is always active or requires manual activation.
- **Evaluation Parameters**, used to systematically assess and compare interaction variants. The selected parameters were based on established usability standards [DINa; DINb] and prior research in assistive technology. They include efficiency, effectiveness, learnability, and robustness, as well as interaction time [CP15] and comfort [Je15].

3.2 Interaction Design Variants

Selection: Binary input prohibits direct selection [CP15], so only common scanning methods were considered, including Automatic Item Scanning, Step Item Scanning with dwell-time activation, Inverse Item Scanning and Continuous Cartesian Scanning. These techniques are well-established within the field of assistive technologies and are frequently integrated into both smartphone and computer operating systems. Consequently, users with prior experience in switch-based interactions are likely to recognize these approaches, which facilitates transfer of skills and reduces the required learning effort.

Navigation: Due to the lack of literature on VR-specific binary navigation methods, interaction techniques were adapted from those used in mobile accessibility systems. One commonly used mobile method involves a scanning cursor that moves across the screen, allowing users to select a target by activating a switch [We23]. This principle can be adapted for use in VR through Cartesian Scanning, whereby the intersection of two scan lines defines a target point within the user's field of view. Once a target has been selected, the virtual camera rotates to center it.

Based on this concept, two variants could be derived. Integrated Selection and Navigation, whereby the system checks whether the selected point corresponds to an interactive element. If so, the element is selected. Otherwise, the viewpoint is adjusted towards the target point. A second variant is Mode Separation, where users switch between navigation mode (rotation only) and selection mode (selection only). This prevents accidental overlap between interaction types and ensures greater control.

Building on the principles of item scanning, an additional concept was inspired by the virtual button interfaces used in games and assistive tools [FLE11; Tr09], whereby UI buttons for

Tab. 1: Comparative Evaluation of Interaction Variants Based on Evaluation Parameters (IS = Item Scanning, CCS = Continuous Cartesian Scanning)

Design Variant	Efficiency	Effectiveness	Learnability	Robustness	Interaction Time	Comfort	**Score**
Automatic IS	5	4	4	4	3.5	3	**23.5**
Step IS (Dwell)	1.5	4.5	4.5	4.5	4	2	**21**
Inverse IS	1.5	4	4	4	3.5	2	**19**
CCS	4.5	4	3	3.5	3	3	**21**
Discrete Rotation (IS)	3	3	5	4.5	2	4	**21.5**
Continuous Rotation (IS)	4	5	4	3.5	3	1.5	**21**
Direct Navigation (CCS)	4.5	4	4	2	5	3	**22.5**
Interaction Mode (CCS)	4	5	3.5	4	4	4	**24.5**
Instant Rotation	-	-	5	-	5	4.5	**14.5**
Continuous Rotation	-	-	5	-	3	1.5	**9.5**
Automatic Initialization	5	-	5	3	5	3	**21**
Manual Initialization	4	-	4.5	5	4.5	5	**23**

’rotate left’ and ’rotate right’ are scanned and selected using a switch. Based on this concept, two more variants could be derived. Discrete rotation, whereby selecting a button triggers a fixed-angle turn requiring repeated selections for larger rotations, and continuous rotation, whereby selecting a button starts a continuous rotation in the chosen direction remaining active until the corresponding button is selected again to stop it.

Transition: There are mainly two ways to implement camera transitions between view directions (see, e.g., [FT20; LJM21; OK19]). Either a discrete (instant) rotation, where the viewpoint jumps directly to the target direction, or a smooth (continuous) rotation, which creates a gradual transition simulating natural head movement.

Initialization: Two variants were considered in regard to the initialization. Automatic initialization, where scanning is active throughout the experience, and manual initialization, where scanning must be triggered by the user at the start of an interaction.

3.3 Classification of design variants based on evaluation parameters

To determine the most suitable interaction variants, the identified design options were assessed based on the identified evaluation parameters. A comparative analysis was conducted to evaluate how well each variant addressed these criteria. Ratings were assigned on a scale from 1 (criterion not fulfilled) to 5 (criterion fully fulfilled). While a detailed discussion of the results exceeds the scope of this paper, they are summarized in Tab. 1.

Based on the classification results, two final interaction techniques were derived. These were selected with the objective of achieving a balanced trade-off between the considered parameters. Where no advantages were evident, user comfort was prioritized over other parameters in order to mitigate the risk of motion sickness.

4 Prototypically Implemented Interaction Techniques

Following the evaluation of potential design variants, two promising interaction techniques were conceptualized and prototypically implemented. In the following, the two interaction techniques will be presented. They are differentiated and referred to by the scanning method they are based on.

4.1 Item Scanning

The first interaction technique is based on Automatic Item Scanning. Each time a scene is loaded, the system automatically identifies all interactive elements that inherit from the *Interactable* class and incorporates them into the selection set. In addition, interface components such as the main and navigation menus are included by default, as they constitute persistent elements of the interaction environment, even though they are not explicitly defined as Interactable objects. The user can initiate scanning by pressing the switch, prompting the system to highlight each element sequentially with an orange outline (see Fig. 1). Pressing the switch again selects the highlighted item, providing immediate visual and auditory confirmation before executing the corresponding action, e.g. transitioning to another scene or opening the main menu. To navigate, the user opens the navigation menu (see Fig. 2), which restricts the selection set to the menu buttons. Pressing a rotation button instantly rotates the viewpoint by 40° in the chosen direction. Once the desired orientation is reached, the user closes the menu by selecting the menu button again. Both the scan rate and the next element in the sequence are visualized using a basic animation. A dashed line is progressively drawn from the current highlight to the subsequent element. Once the line is complete, the next element is highlighted and ready for selection.

4.2 Cartesian Scanning

The second interaction technique is based on Continuous Cartesian Scanning. A press of the switch starts the first scan line and pressing again stops it at the desired position. The second scan line then moves along the orthogonal axis and pressing the switch again sets the final intersection point. This point is then used to check for an underlying interactive element. If one is found, it is selected (see Fig. 3). If not, an auditory signal is played and the scan lines are cleared. To switch to navigation mode, the user holds the switch down for 1.5

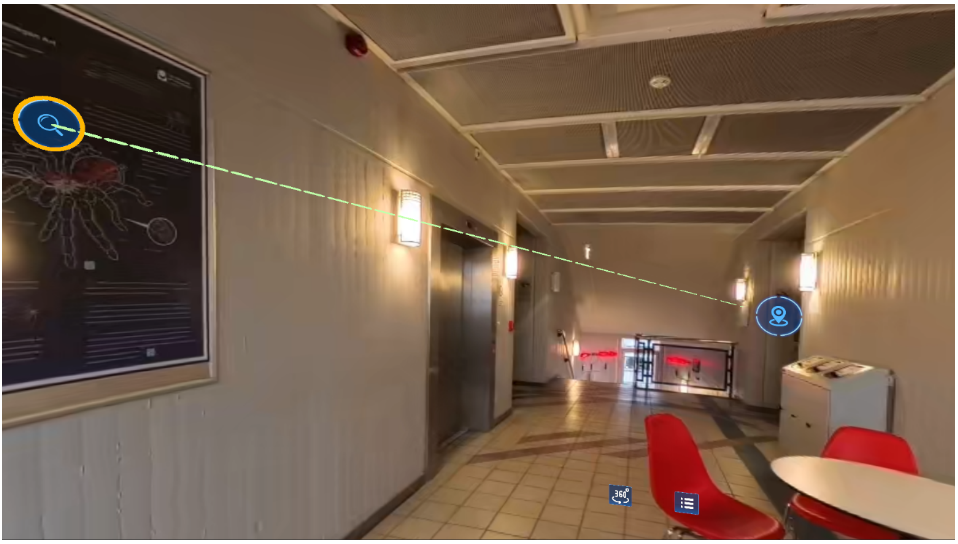


Fig. 1: Selection with Item Scanning: Interactive elements are sequentially highlighted. The highlighted element can be selected by pressing the switch

seconds. In this mode, the intersection point becomes the new center of the viewpoint and the camera instantly rotates to this position (see Fig. 4). Holding the switch again returns to selection mode. The modes are visually differentiated. Pink scan lines indicate selection mode and blue lines indicate navigation mode. The system prioritizes elements that are spatially closer to the user, e.g., UI elements are selected before background objects. If a scan line reaches the edge of the field of view without any input from the user, it restarts automatically. After three full cycles without further interaction, the scanning process ends. This also enables the user to cancel a misplaced first selection by allowing it to time out.

5 Evaluation

To evaluate the developed interaction techniques, a two-stage user study was conducted. An initial pre-study with 16 participants served to identify usability issues and gather early performance feedback. Based on the insights gained, targeted refinements were made to the interaction techniques.

Specifically, the scan rate for Cartesian Scanning was slightly increased, as several participants noted that the original speed felt unnecessarily slow. The required duration for holding the switch to trigger a mode change was reduced from 2 seconds to 1.5 seconds as well. This alteration was made in response to reports that the original delay was disrupting task flow. To reduce errors arising from switching modes, a dedicated UI element was introduced to clearly indicate the current interaction mode. Adjustments were also made to the animation

Fig. 2: Open Navigation Menu in Item Scanning

timing in Item Scanning, with the objective of ensuring that elements were highlighted more precisely in accordance with the scan rate. Furthermore, the visible range was slightly restricted to avoid selecting elements located too far at the edge of the field of view. Finally, the menu positions were adapted in both techniques. In Item Scanning, the navigation menu was previously positioned too high in the field of view, resulting in ergonomic discomfort. In Cartesian Scanning, selection errors frequently occurred due to overlapping menu elements.

An additional methodological change was introduced in the second study to increase experimental control. During the preliminary study, participants were observed utilizing targeted head movements to compensate for limitations in selection precision and time, particularly in Cartesian Scanning, where such movement enabled quick corrections or acceleration of the selection process. In order to ensure consistent test conditions and allow for a clearer comparison of interface performance, the final study introduced a verbally communicated restriction on head movement during all interactions.

The evaluation design remained otherwise identical in both iterations and consisted of two core components: a technical and a content-based evaluation. The objective was to evaluate the technical performance of the interaction techniques and examine how they interact with immersive content, using designed VR scenarios. The *technical evaluation* focused on verifying assumptions made during the design process regarding interaction time, efficiency, robustness, and learnability. Each interface was tested using a scenario designed to challenge its specific technical characteristics. For example, the Item Scanning scenario featured a large number of elements, non-obvious scanning order, and targets placed at the edge of the visual field. The Cartesian scanning scenario included both densely positioned elements and

Fig. 3: Selection with Cartesian Scanning: (1) first Scanning Line moves from top to bottom, (2) second Scanning Line moves from left to right, (3) intersection point is used for selection

Fig. 4: Navigation with Cartesian Scanning: (l) intersection point of the Scanning Lines determines the new center of the viewport, (r) new camera orientation after navigation

elements positioned at the top or far left of the visual field. Both scenarios were comparable in terms of the number and type of interactions required. The *content-based* evaluation examined the interplay between interaction modality and narrative immersion, focusing on comfort, efficiency, and user experience (UX). Participants engaged in more realistic VR scenarios inspired by escape room mechanics. The quantity and type of interactive elements were kept consistent across the scenarios to ensure comparability. To control for possible order or content biases, participants were divided into four groups, each starting with a different combination of interface and content scenario. This counterbalancing ensured an even distribution of conditions. Throughout the study, standardized questionnaires were used, including the System Usability Scale (SUS) [Br96], the User Experience Questionnaire (UEQ) [LHS08] and the Simulator Sickness Questionnaire (SSQ) [Ke93]. Interaction times

Tab. 2: Mean interaction times in seconds (M) and standard deviations (SD) for each interaction technique and scenario type.

Scenario Type	Item Scanning	Cartesian Scanning
Technical	4.18 (5.41)	5.61 (4.17)
Content-Based	2.63 (2.42)	3.70 (3.73)

Tab. 3: Mean total times needed to finish the scenarios in minutes (M) and standard deviations (SD) for each interaction technique and scenario type.

Scenario Type	Item Scanning	Cartesian Scanning
Technical	7.60 (1.58)	9.1 (1.79)
Content-Based	5.60 (1.43)	8.4 (2.55)

were automatically recorded via a logging system embedded in the application. The study was conducted at a stationary test setup. The participants sat at a desk equipped with a laptop running the Unity application. A Meta Quest 3 VR headset was connected via LinkCable. The study procedure followed a fixed structure: welcome and introduction, interaction technique 1 in technical scenario, questionnaire part 1, interaction technique 1 in content-based scenario, questionnaire part 2, then the same sequence for interaction technique 2. Finally, participants were invited to provide feedback, anonymously in the questionnaire or verbally to the evaluation instructor. Each session lasted approximately 45 to 60 minutes per participant. Both the pre-study and the main study were conducted with participants who did not have motor impairments. This decision was made to enable controlled comparisons between interaction techniques without the influence of heterogeneous physical abilities.

6 Results

The results presented in this section are derived from the second user study, which involved ten participants who did not have any motor impairments and who had no prior experience with binary scanning-based interaction techniques.

6.1 Interaction Performance (Efficiency and Robustness)

Tab. 2 summarizes the mean interaction times (in seconds) per target for Item Scanning and Cartesian Scanning across technical and content-based scenarios. Overall, interaction times were significantly ($p = 0.000$) longer in technical scenarios than in content-based scenarios, regardless of the interaction technique. In both types of scenario, Item Scanning resulted in significantly shorter interaction times than Cartesian Scanning. This is also reflected in the

Tab. 4: Mean number of errors (M) and standard deviations (SD) per scenario.

Scenario Type	**Item Scanning**	**Cartesian Scanning**
Technical	3.9 (1.66)	3.1 (2.38)
Content-Based	2.10 (1.37)	2.0 (1.64)

Tab. 5: Observed error types with absolute frequency and affected participants (errors / affected participants).

Technique	**Error Reason**	**Frequency (n)**
Item Scanning	Timing	44 (10/10)
Item Scanning	Comprehension	16 (7/10)
Cartesian Scanning	Missed target	14 (10/10)
Cartesian Scanning	Mode not switched	35 (9/10)
Cartesian Scanning	Timing	2 (2/10)

Tab. 6: Mean scores (M) and standard deviations (SD) for System Usability Scale (SUS).

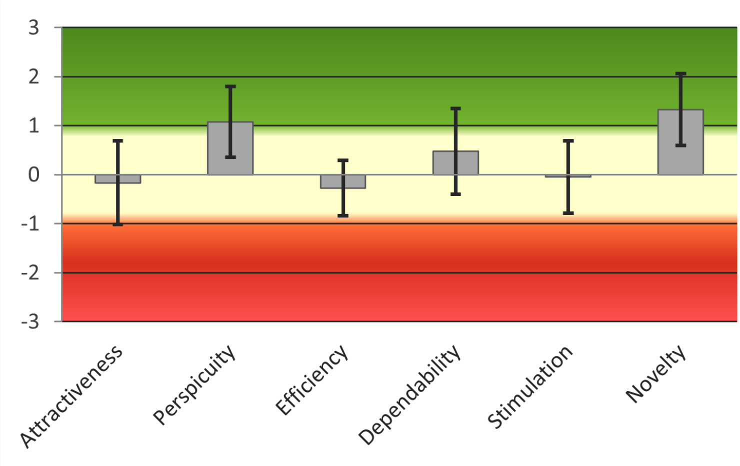
	Item Scanning	**Cartesian Scanning**
SUS Score (0–100)	61.0 (15.60)	72.50 (12.75)

total scenario completion times shown in Tab. 3, where Item Scanning resulted in shorter scenario durations than Cartesian Scanning.

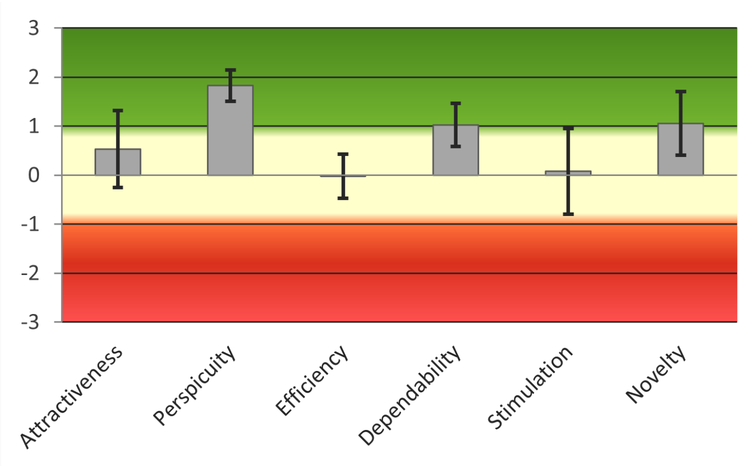
Tab. 4 presents the mean number of interaction errors per scenario. Error rates were slightly higher in technical scenarios than in content-based scenarios. In technical scenarios, Item Scanning led to a slightly higher mean error rate than Cartesian Scanning. However, in content-based scenarios, both techniques produced similar error rates. Statistical analysis confirmed that there were no significant differences in error rates between the interaction techniques in either scenario type. Tab. 5 provides a breakdown of the error types. For Item Scanning, timing errors (selecting either too early or too late) were the most common, affecting all participants, followed by comprehension errors due to a misinterpretation of the feedback or scan progress. For Cartesian Scanning, missed targets and forgotten mode switches were the most common types of error. Nine out of ten participants made mode-switching errors, which accounted for a large part of the total errors.

6.2 Usability and User Experience

The System Usability Scale (SUS) scores indicate acceptable usability for both interaction techniques (see Tab. 6. Cartesian Scanning scored slightly higher (M = 72.50, SD = 12.75) than Item Scanning (M = 61.00, SD = 15.60), although this difference was not statistically significant ($p = 0.0954$).



(a) Mean values and 95% confidence intervals for the six UEQ scales for Item Scanning



(b) Mean values and 95% confidence intervals for the six UEQ scales for Cartesian Scanning

Fig. 5: Results of the User Experience Questionnaire (UEQ)

Tab. 7: Mean scores (M) and standard deviations (SD) for the Simulator Sickness Questionnaire (SSQ) total and subscales by interaction technique.

SSQ Scale	Item Scanning	Cartesian Scanning
Total Score	16.46 (12.98)	13.09 (12.74)
Nausea	8.59 (13.07)	6.68 (11.94)
Oculomotor	17.43 (11.33)	13.64 (9.32)
Disorientation	16.70 (15.80)	13.92 (16.07)

The User Experience Questionnaire (UEQ) further differentiates perceptions across six scales: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation and Novelty. Fig. 5a and Fig. 5b show the mean values and 95% confidence intervals for these UX Scales. Item Scanning scored positively on Perspicuity and Novelty, more neutrally on Attractiveness and Stimulation, and slightly negatively on Efficiency. Cartesian Scanning showed a comparable trend, with positive scores on Novelty, Perspicuity, and Dependability, and moderate ratings on the remaining scales. Overall, neither technique received strongly negative ratings for any scale, and no significant differences were identified between the two techniques on any of the UX scales.

6.3 Motion Sickness

Simulator Sickness Questionnaire (SSQ) results indicate low to moderate symptom severity for both techniques, with comparable overall SSQ scores. As shown in Tab. 7, Item Scanning produced a slightly higher mean total SSQ score (M = 16.46, SD = 12.98) than Cartesian Scanning (M = 13.09, SD = 12.74). This pattern persisted across the nausea, oculomotor, and disorientation subscales, with Item Scanning consistently associated with slightly elevated symptom levels. However, none of these differences between the techniques reached statistical significance ($p = 0.566$).

6.4 Qualitative Feedback

Participants were asked to provide open-ended feedback regarding their experiences with both interaction techniques. A thematic analysis of the responses revealed several recurring topics, particularly regarding perceived usability, interaction time, and suggestions for improvement. The majority of participants expressed a general preference for Cartesian Scanning. They described it as more intuitive, efficient and allowing a greater sense of freedom and control. In contrast, Item Scanning was perceived as more restrictive and passive. A recurring theme in the feedback was the perception of slowness in both techniques. It was a common request among the participants that the scan rate should be adjustable in order to accelerate the interaction. Several participants noted limitations in the usability of the Item

Scanning, particularly with regard to the navigation. One frequently mentioned issue was the inability to quickly repeat selections of the same element, such as directional controls. Participants recommended implementing a short delay or reset period after activation to enable repeated inputs without prematurely advancing the scan cycle. Furthermore, the fixed scan order was considered inefficient. Users expressed a desire to customize or optimize the sequence to prioritize frequently used elements, such as the navigation menu, which sometimes required unnecessary intermediate steps to access.

Despite challenges in terms of usability, participants generally perceived the interaction concepts as innovative and promising, particularly from the perspective of users with motor impairments. Some commented that they could see themselves using it privately and praised the idea as "cool" and "useful". These comments suggest that, despite the need for refinement in the execution, there is an overall acceptance of the system's goals.

7 Discussion

The present study systematically compared two prototypical binary interaction techniques, which are based on Automatic Item Scanning and Continuous Cartesian Scanning. The evaluation included interaction performance, usability, user experience, and comfort. Building on a prior pre-study, the results both confirm earlier observations and reveal new insights into each approach's strengths and limitations, culminating in concrete recommendations for future design refinements. In the follow-up experiment, participants' head movements were deliberately constrained to prevent compensatory motions that could accelerate scanning or correct minor errors. Minor interface adjustments, informed by the pre-study outcomes, were also implemented.

Consistent with previous observations, Item Scanning yielded significantly faster interaction times than Cartesian Scanning across both technical and content-based scenarios. Moreover, both techniques demonstrated shorter total interaction times compared to the pre-study, despite participants' inability to employ compensatory head-movement strategies. This improvement underscores the sensitivity of performance to modest increases in scan rate. Despite these objective gains, users reported lower perceived efficiency for both techniques than in the pre-study. The restriction of head-movement freedom may have diminished participants' sense of self-efficacy and control, thereby negatively affecting their subjective efficiency ratings.

A principal frustration regarding efficiency also stemmed from the inability to rapidly re-trigger selections, particularly within the navigation menu in Item Scanning. Introducing a "cooldown" mechanism that resets after each selection could support faster input sequences and alleviate this concern. Similarly, standardizing scan rates across both techniques, while methodologically necessary, contributed to user dissatisfaction. Participants expressed a strong preference for configurable scan parameters that adapt to individual motor skills, cognitive pacing, and task complexity. Future designs should therefore offer adjustable scan speeds to enhance both perceived efficiency and overall user satisfaction.

Error rates for both scanning methods were significantly higher than in the pre-study. This increase may be attributed to the additional cognitive load imposed by suppressing instinctive head movements, which likely diverted attentional resources away from the core interaction tasks. Under these conditions, maintaining a constrained posture while engaging with the interface appears to have elevated the frequency of selection errors. Cartesian Scanning in particular revealed a persistent usability flaw: the mode switch between navigation and selection remained a significant error source. Although additional visual cues were added, all participants encountered mode-switching difficulties in the current study. This finding suggests that visual indicators alone are insufficient and that a more fundamental redesign of the interaction design or a reimagining of the navigation-selection paradigm may be required to eliminate these errors.

Measures of usability and user experience converged on a coherent pattern. System Usability Scale (SUS) scores indicate acceptable overall usability for both techniques. Cartesian Scanning scored slightly above the general usability average (M = 72.50), while Item Scanning scored below it (M = 61.00), though the difference was not statistically significant. Notably, Cartesian Scanning's SUS ratings declined significantly relative to the pre-study, again implicating that the loss of freedom of head movement and the inability to form individual strategies lead to reduced perceived control and acceptability. The User Experience Questionnaire (UEQ) deepened this insight. Both methods retained strengths in Novelty and Perspicuity, yet registered neutral to negative appraisals on Attractiveness, Stimulation, and especially Efficiency. These lower UEQ ratings mirrored the SUS downturn and were significantly reduced across most scales compared to the pre-study, with no meaningful differences between the two techniques. Together, these results imply that objective performance gains cannot compensate for users' diminished sense of agency and adaptability when interaction parameters are fixed.

Lastly, Simulator Sickness Questionnaire (SSQ) scores fell within the expected range for VR applications, with no significant differences between techniques or relative to the pre-study. Oculomotor and disorientation subscales registered the highest values, indicating visual and cognitive fatigue rather than severe vestibular discomfort. Excluding data from participants who reported pre-existing fatigue or discomfort yielded substantially lower SSQ averages, particularly for Cartesian Scanning (M = 8.01), suggesting that pre-session symptoms may have inflated initial scores. Accordingly, these findings warrant cautious interpretation.

Although targeted design adjustments improved certain issues, such as unintended menu selections in Cartesian Scanning and interaction times, they failed to enhance overall usability and UX. Participants ultimately perceived the systems as less attractive and efficient. These results imply that technical optimizations alone are insufficient when core interaction paradigms conflict with users' expectations of agency, adaptability, and control.

In summary, despite their respective limitations both Automatic Item Scanning and Continuous Cartesian Scanning delivered promising initial results. Objective measures revealed a clear advantage for Item Scanning in interaction time, yet all other key metrics (SUS, UEQ, SSQ) showed no statistically significant differences between the two methods. This convergence suggests that each technique constitutes a viable foundation for binary selection in VR, offering comparable usability and UX when head movements are constrained. Moving forward, integrating user-configurable pacing, enhancing mode-switch feedback, and exploring alternative navigation paradigms in Cartesian Scanning will be critical to unlocking their full potential and aligning interaction design more closely with users' needs for agency and adaptability.

8 Limitations

It is important to note that both studies exclusively involved participants with no motor impairments. For these individuals, the use of binary interaction techniques represented a considerable deviation from their habitual sensorimotor strategies, thereby introducing artificial constraints to them that likely contributed to the lower subjective ratings observed. Accustomed to faster and more efficient interaction modalities, participants were able to draw direct comparisons with conventional input methods, which likely fostered impatience and contributed to lower ratings of usability and user experience. Conversely, individuals with motor impairments may encounter these interaction techniques as providing novel pathways to access and autonomy, thereby fundamentally shifting their evaluative perspective. The findings of this study should thus not be generalized to users with motor impairments without additional empirical investigation involving the actual target population. The rationality of our approach is to iteratively improve interaction prototypes based on the feedback of people without impairments before starting larger tests with those with impairments, as this requires much more efforts on both sides and places too much strain on the participants' willingness to take part in further studies, when faced with early prototypes. Furthermore, the present studies did not investigate the tolerance of the binary interaction techniques, including how the system handles unintended activations, varying input intensities, or different durations of actuation. These factors are of particular relevance to people with motor impairments and may exert a significant influence on the effectiveness and potential success of the interaction techniques. Consequently, future research should address these aspects.

9 Conclusion

This paper outlines a methodical approach to developing binary interaction techniques for panoramic virtual reality applications. Two interaction techniques were designed and evaluated in terms of interaction performance, usability, user experience and comfort. The results revealed no statistically significant differences across most metrics, except for interaction time, where Item Scanning performed significantly faster. However, both techniques exhibited specific shortcomings. Cartesian Scanning was particularly sensitive to mode-switching errors, which persisted even after the introduction of additional visual cues. In contrast, Item Scanning suffered from timing errors and a rigid scan sequence, leading to user frustration. The differences between the pre-study, which allowed free head movement, and the main study, where head movement was restricted, highlight the importance of perceived control, self-efficacy, and customizable interaction parameters. In light of these findings, future designs should aim to incorporate greater flexibility and adaptability to mitigate the identified limitations. Despite these challenges, both approaches provide a promising basis for further development and exploration in the design of panoramic VR interaction techniques.

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