Towards Personalized Navigation in XR: Design Recommendations to Accommodate Individual Differences

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ABSTRACT

Navigation interfaces in Extended Reality (XR) have traditionally targeted universal solutions that perform well for all users. However, research has shown that users exhibit distinct preferences and performance patterns when using different navigation techniques. This position paper argues for the necessity of and strategies for designing personalized navigation interfaces that accommodate individual differences in spatial abilities, navigation strategies, and individual needs. Drawing from empirical findings from previous work investigating locomotion and wayfinding techniques and research in spatial cognition and navigation, we demonstrate how different user groups respond uniquely to navigation interface components. Based on these insights, we propose design recommendations for developing adaptive navigation interfaces that cater to individual user characteristics while maintaining usability. Furthermore, we discuss opportunities for standardization in user assessment, interface adaptation, and inclusive design. This approach could lead to more inclusive and effective navigation solutions for XR environments.

Index Terms: Locomotion, Wayfinding, Extended Reality, Virtual Reality, Augmented Reality

1 INTRODUCTION

Navigation is a fundamental requirement for interaction in most Extended Reality (XR) applications, encompassing both locomotion - the motor component of moving between locations - and wayfinding - the cognitive process of determining and following a path to a destination. Over the past decades, researchers have developed numerous locomotion and wayfinding techniques [16, 6]. Each new technique typically aims to be superior to existing ones across standard metrics like task completion time, accuracy, and user comfort. However, this pursuit of universally optimal solutions overlooks a critical aspect of human spatial cognition - individual differences. Research in spatial cognition has established that people vary significantly in their spatial abilities, strategies, and preferences. For instance, some users naturally prefer and perform better with holistic mental rotation strategies, while others rely more on analytical, step-by-step approaches [3, 12]. These individual differences extend beyond basic spatial abilities to include variations in working memory capacity, navigation strategy preferences, and responses to different types of visual feedback [13, 10]. Multiple studies investigating navigation techniques in virtual environments have consistently revealed distinct user groups that respond differently to the same navigation interfaces. When Lee et al. [18] studied automatic parameter control for target-based locomotion where most users preferred flying with automatic speed control due to its continuous visual feedback, a subset of users still performed better with automatic distance-controlled teleportation, particularly in dense environments. In their other work on viewpoint transitions between remote locations [20], some users strongly preferred and performed better with techniques that separated rotation and translation components. In contrast, others were more successful with simultaneous movement approaches. Similarly, when evaluating scaling techniques for multiscale navigation [21], some users favored precise control through scrolling while others preferred more direct bimanual manipulation. These findings suggest that, instead of seeking a single optimal navigation solution, researchers should focus on developing frameworks that can accommodate and adapt to individual differences. This approach aligns with the broader goals of improving the inclusiveness of XR applications, as it explicitly recognizes and supports diverse user needs and capabilities [24]. Furthermore, developing standardized methods for assessing user characteristics and implementing adaptive interfaces could help establish more systematic approaches to navigation interface design [22, 26]. This position paper presents design recommendations for personalizing navigation interfaces in XR. We first discuss evidence for individual differences in navigation performance and preferences, then propose methods for user assessment and interface adaptation. Finally, we examine opportunities for standardization within this approach and discuss implications for future XR navigation research and development.

2 EVIDENCE FOR THE EXISTENCE OF INDIVIDUAL DIFFERENCES IN XR NAVIGATION

Numerous studies across spatial cognition, Virtual Reality (VR), and Augmented Reality (AR) have consistently demonstrated that individuals exhibit significant variations in their navigation abilities, strategies, and preferences. This section highlights the need for incorporating individual differences in XR navigation based on empirical findings from the authors' research on locomotion and wayfinding Techniques as well as supporting evidence from the literature on spatial cognition and navigation.

2.1 Locomotion and Wayfinding Techniques in VR and AR

In a series of user studies investigating different aspects and design components of locomotion and wayfinding interfaces in virtual environments, distinct patterns of individual differences in user performance and preferences were observed.

When comparing different techniques for viewpoint transitions between locations in a virtual environment [20, 19], users naturally divided themselves into two distinct preference groups. One group strongly favored and demonstrated higher navigation performance with techniques that separated the rotation and translation components of the transition. The other group preferred and showed higher performance with techniques that combined rotation and translation into a single, simultaneous motion. These differences were consistent across different user scenarios. Similar divergent preferences were observed for scaling techniques, where some users prioritized precise control, while others favored more

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direct and immersive techniques [1].

Studying techniques for automatic control of navigation parameters like velocity and distance [18] revealed similar patterns of individual differences. In general, users preferred and performed best with techniques that provided continuous visual feedback, such as automatic speed control for flying. However, a subset of users showed higher performance with discrete techniques like teleportation, particularly in cluttered environments. These differences suggest that the optimal navigation interface may depend on the interplay between individual characteristics and environmental constraints.

A study on AR navigation in endoscopic sinus surgery found that the performance of resident surgeons and senior physicians differed when using navigation systems with and without AR elements, indicating that individual factors like expertise can influence the effectiveness of different navigation approaches [22, 14].

A framework for classifying natural locomotion in VR identified variations in user preferences and performance across different combinations of task, technique, and modality. A study comparing gaze-directed and pointing-based motion control for navigation in VR found differences in user performance and preference [4].

Additionally, studies on user interface design for VR simulations have revealed that gender and individual differences in relevant spatial skills, such as object location memory, can affect the efficiency and emotional experience of users when using different interaction modes for navigation [2, 11].

In summary, the reviewed literature points to variations in how individuals navigate, including differences in abilities, strategies, and preferences across spatial cognition, VR, and AR domains. These individual differences should be carefully considered when designing effective navigation interfaces and techniques.

2.2 Human's Spatial Cognition and Navigation

The findings mentioned previously align with a substantial body of prior research establishing the existence and impact of individual differences in spatial cognition and navigation:

Spatial Ability Differences: Individuals vary significantly in their underlying spatial abilities, such as mental rotation, perspective-taking, and spatial visualization [3]. These abilities are strongly correlated with performance in spatial tasks like navigation, manipulation, and spatial inference [10]. Thus, designing navigation interfaces that can adapt to different levels of spatial ability could make them more broadly accessible.

Strategy Preferences: People also differ in their preferred strategies for spatial problem-solving. Some individuals rely more on holistic, global strategies like mental rotation, while others prefer analytical, step-by-step approaches [12]. In navigation tasks, strategic preferences can influence route choice, landmark usage, and the effectiveness of different visual and verbal guidance methods [5]. Consequently, supporting multiple navigation strategies within an adaptive framework could accommodate a wider range of users.

Working Memory Capacity: Variations in visuospatial working memory capacity have been shown to affect navigation performance and learning [13, 8]. Individuals with higher working memory capacity are often more efficient at maintaining spatial representations and integrating multiple viewpoints [7, 17]. Adapting the complexity and information density of navigation interfaces based on working memory assessments could thus provide a more calibrated experience.

Demographic Factors: Navigation performance and strategies can also vary based on demographic factors like gender [23, 13] and gaming experience [6]. Accounting for these factors in user modeling and adaptation could lead to more inclusive navigation interfaces.

These findings from prior research and the broader literature present a compelling case for the importance of individual differences in XR navigation. Failing to account for these differences can lead to suboptimal interfaces that are not equally accessible or effective for all users [24]. In the following section, we propose a framework for designing navigation techniques that can adapt to individual characteristics while maintaining core usability principles.

3 DESIGN RECOMMENDATIONS FOR USER-CENTERED NAVIGATION

Building upon the empirical evidence for individual differences in navigation behavior and performance, we propose a set of *design recommendations* for designing adaptive navigation interfaces that cater to diverse user characteristics and needs. These recommendations aim to provide building blocks for developing a comprehensive design framework in the future. Our recommendations consist of two main components: 1) assessment methods for capturing relevant user attributes and 2) adaptation mechanisms for tailoring the interface to the individual.

3.1 Assessment Components to Understand Individual Users

To effectively adapt navigation interfaces to individual users, we need holistic approaches to assess the key user characteristics that influence navigation behavior and performance. While previous work focused on fragmented aspects of the assessment components, our approach entails the following components to ensure that the users' needs and tendencies are assessed:

3.1.1 Standardized spatial ability measures

Established psychometric tests, such as the Mental Rotation Test [27], Perspective Taking Ability Test [10], and Spatial Orientation Test [9], can be administered to users to gauge their baseline spatial abilities. These measures provide a foundation for determining the appropriate level of navigation support and complexity.

3.1.2 Navigation strategy preference evaluation

Users can be surveyed or observed to identify their preferred navigation strategies, such as route-based vs. survey-based approaches [25], or egocentric vs. allocentric reference frames [15]. This information can guide the selection and presentation of navigation aids, such as maps, landmarks, or verbal instructions.

3.1.3 User experience level assessment

The user's prior experience with XR systems and 3D navigation interfaces should be assessed, as this can significantly influence their comfort level and proficiency with different interaction techniques. Novice users may benefit from more guided and constrained navigation methods, while experts may prefer greater control and flexibility.

3.1.4 Inclusive design considerations

Users have diverse sensory, motor, and cognitive capabilities that influence their navigation preferences and needs. Users with limited sensory, motor, or cognitive capacities may have specific requirements for navigation interfaces. Consultation with experts in each related field and user testing with diverse populations will help to identify these needs and inform the design of inclusive navigation solutions.

3.2 Adaptation Mechanisms Towards Personalized Navigation Interface Design

Once the relevant user characteristics have been assessed, a navigation interface can be adapted to better suit the individual's needs and preferences. We propose the following adaptation mechanisms:

3.2.1 Parameter adjustment based on user profile

Navigation parameters, such as movement speed, acceleration, and control-display gain, can be automatically adjusted based on the user's spatial ability, experience level, and physical and cognitive capacities. For example, users with lower spatial ability may benefit from slower, more gradual movement to reduce disorientation, while expert users may prefer faster, more responsive control.

3.2.2 Alternative interface options

A navigation interface can offer multiple interaction techniques and customization options to accommodate different user preferences and strategies. For instance, users could choose between controller-based, gesture-based, or gaze-directed navigation methods, or between egocentric and exocentric viewpoints, depending on their comfort level and task requirements.

3.2.3 Hybrid techniques combining different methods

Adaptive navigation interfaces can dynamically blend different techniques to provide the benefits of each approach while mitigating their limitations. For example, a hybrid interface could combine the precision of teleportation for distant travel with the continuity of steering for local exploration, or the immersion of egocentric navigation with the overview of exocentric navigation.

3.2.4 Contextual support systems

Navigation aids and support features can be dynamically triggered or adapted based on the user's context and inferred needs. For instance, if the user appears lost or disoriented, the system could automatically display a map or reorient the view to a known landmark. If the user is approaching a complex or visually cluttered area, the system could highlight salient features or provide additional navigational guidance.

By combining these assessment and adaptation components, we envision navigation interfaces that can intelligently and seamlessly adapt to the diverse needs and preferences of individual users, ultimately improving the usability, inclusiveness, and effectiveness of XR navigation for all.

4 OPPORTUNITIES FOR STANDARDIZATION

The complexity of personalized navigation in XR demands a comprehensive approach to standardization that can simultaneously support individual adaptation and maintain a consistent user experience. This requires a multifaceted strategy addressing several critical domains within user interaction and system design.

The development of common metrics for user profiling represents a foundational challenge in creating personalized navigation interfaces. Current psychometric approaches are insufficient for capturing the nuanced spatial cognition required in XR environments. Researchers must move beyond traditional spatial ability tests to create more comprehensive assessment protocols that quickly capture the dynamic and interactive nature of spatial perception in virtual spaces. This involves developing multidimensional scoring mechanisms that integrate quantitative measurements of spatial reasoning with qualitative assessments of navigation strategy preferences and interaction proficiency.

Standardized assessment protocols emerge as a crucial infrastructure for meaningful personalization. The goal is to create a universal framework that enables reliable, comparable user assessments across different XR platforms and applications. Such protocols must be rigorous enough to provide meaningful insights while remaining adaptable to diverse technological ecosystems. This requires developing validated testing methodologies that efficiently capture user characteristics without introducing significant cognitive load or disrupting the user experience.

Further, interface adaptation guidelines represent another critical area of standardization. These guidelines must establish core principles that enable responsive design while maintaining fundamental usability standards. The challenge lies in creating a flexible framework that can map user characteristics to interface parameters without compromising the core navigation system functionality. This involves defining clear mechanisms for interface modification, establishing minimum requirements for customization, and developing strategies for graceful system adaptation.

Personalized navigation interfaces with inclusive design demand a nuanced approach to standardization. Beyond existing general design guidelines, XR navigation interfaces require a comprehensive taxonomy that captures the diverse needs of users with different cognitive, sensory, and motor capabilities. This goes beyond traditional usability design considerations, requiring a holistic approach that integrates adaptive support mechanisms directly into the core design of navigation interfaces.

Finally, data collection and privacy standards present a complex challenge at the intersection of personalization and user protection. The detailed profiling required for effective navigation adaptation must be balanced against stringent privacy protections. This necessitates developing sophisticated consent protocols, advanced anonymization techniques, and transparent data management practices specific to the unique challenges of XR interaction data.

5 BEST PRACTICE FOR IMPLEMENTING PERSONALIZED XR NAVIGATION INTERFACE

Translating these design recommendations into practical implementations requires careful consideration of technical and user experience challenges.

Successful implementation of such systems demands effective algorithms that can efficiently profile users and dynamically modify navigation interfaces. Developing real-time user profiling algorithms requires advanced computational approaches that rapidly assess and respond to user characteristics without introducing perceptible latency. This demands innovative computational models that can dynamically interpret user interaction data, making instantaneous decisions about interface modification while maintaining the immersive quality of the XR experience.

Maintaining usability during personalization emerges as a paramount concern. The adaptive interface must walk a delicate line between customization and predictability. This requires establishing robust mechanisms that ensure core navigation functionality remains consistent while allowing for nuanced individual adaptations. Designers must develop sophisticated transition strategies that enable interface modifications without disorienting the user or compromising the fundamental navigation experience.

The balance between standardization and personalization represents a philosophical and practical challenge in interface design. Researchers must identify core navigation components that should remain consistent across different user profiles while creating modular design patterns that allow for meaningful customization. This involves developing flexible frameworks that can support both universal design principles and individual adaptation strategies.

One applicable strategy is to support multiple navigation methods simultaneously. Rather than relying only on a single optimal solution, systems can integrate the most effective navigation techniques from different classes. With this approach, users can then easily switch between methods either through an explicit mode switch or, for instance, by seamlessly transitioning from controller-based to gesture-based navigation Users with varying physical capabilities, spatial reasoning skills, or technological familiarity can then select the interaction method that best suits their *current* needs. The key is designing an instantaneous switching mechanism that maintains spatial context and prevents disorientation during such transitions.

Integration with existing XR systems demands a pragmatic approach to technological compatibility. Developing cross-platform adaptation frameworks requires creating middleware solutions that communicate effectively across diverse hardware and software ecosystems. This necessitates establishing robust communication protocols and ensuring backward compatibility with existing technological infrastructure.

5.1 Challenges and Limitations of Personalization

While personalization offers significant benefits for XR navigation, several important potential disadvantages and limitations must be considered, along with potential approaches to address them:

Technical Complexity and Performance The computational overhead of real-time user assessment and interface adaptation could impact system performance, particularly in resource-constrained mobile XR devices. To address this, developers could implement efficient profiling algorithms that leverage lightweight heuristics and cached user profiles. Computational costs can be reduced by conducting intensive assessments during initial setup and then only making incremental adjustments during runtime. Edge computing solutions could also offload complex calculations while maintaining responsive local adaptation.

Skill Development Concerns Excessive personalization might impede users' spatial skill development by constantly adapting to limitations rather than encouraging improvement. A balanced approach involves implementing progressive challenge systems that gradually adjust the difficulty as users improve, similar to how many games adjust the challenge a user faces over time. Interfaces could also incorporate optional "training modes" that deliberately present more challenging navigation scenarios while maintaining personalized fallback options. This allows users to push their boundaries while ensuring inclusiveness in interface design.

Multi-user Consistency In collaborative scenarios, wildly divergent navigation behaviors could lead to communication difficulties and reduced efficiency. Solutions include developing shared awareness mechanisms that visualize different users' navigation capabilities to team members, establishing common reference points regardless of individual navigation styles, and providing temporary alignment of navigation interfaces during critical collaborative tasks. Additionally, implementing "collaboration modes" that temporarily standardize navigation behavior during group activities while maintaining individual preferences during solo work could also help balance personalization with consistency.

Resource Allocation Another argument is that resources invested in personalization systems might be better spent developing more intuitive universal navigation methods. This concern is best addressed by designing modular frameworks where improvements to core navigation techniques directly enhance the foundation for personalized interfaces. By developing standardized adaptation layers that work with multiple navigation techniques, resources can be efficiently allocated to both improving basic methods and supporting personalization. This approach ensures that advances in either area benefit the overall system.

6 FUTURE DIRECTIONS

The outlined components facilitate actionable research that reduces the gap between the theory and practice of personalized XR navigation interfaces. A critical next step is developing and validating formal frameworks that implement the proposed design recommendations. Such frameworks will require rigorous empirical validation, clear specification of components and their relationships, and formal models of user assessment and adaptation processes.

The development of standardized assessment tools represents a critical research priority. Future research will focus on creating comprehensive testing methodologies that capture the complex and multidimensional nature of navigation in virtual environments. This involves exploring advanced algorithmic approaches that can provide more nuanced inferences of users' capabilities, moving beyond traditional psychometric assessments to develop intelligent user profiling systems.

The implementation of such systems for inclusive navigation interfaces demands a holistic approach. Researchers must develop flexible schemas that capture the user's diverse needs while providing sufficient granularity to support meaningful adaptation of interface design. This requires exploring dynamic, context-aware profile adjustment methods that can quickly respond to changing user capabilities and environmental contexts. Additionally, research should examine the cognitive and perceptual impacts of adaptive navigation interfaces to expand our understanding of their long-term effects. Longitudinal studies are needed to trace how personalized navigation interfaces influence spatial learning, cognitive load, and user performance over time.

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