Design Principles for Participatory XR Design with Autistic Users

Examples from the Virtuoso Project

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Autism
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Co-Design
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Extended Reality
Learning Experience Design
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This longitudinal study describes the iterative development of inclusive, participatory, and co-design principles for extended reality (XR) learning interventions tailored to autistic users. Drawing upon multiple cycles of design-based research (DBR) performed on an XR project entitled Virtuoso, the resultant design principles emphasize active involvement of stakeholders in the co-creation of XR experiences, including customization, accessibility, and adaptive scaffolding. This longitudinal research highlights *practical implications and challenges of designing XR interventions with and for autistic learners. Using a blend of theory and practice, this research provides guidance for instructional designers, educators, and researchers seeking to design, implement, and evaluate XR interventions with and for autistic users in an inclusive and ethical manner. All research studies published related to Virtuoso are summarized and synthesized, detailed design principles are provided, and a corresponding design conjecture is proposed.*

Introduction

This article synthesizes findings from two cycles of design-based research (DBR) focused on a virtual reality (VR) initiative named the Virtuoso project. We aim to offer insights and practical guidance for designers and educators striving to leverage extended reality (XR) technologies to support educational and training programs tailored for autistic individuals. The Virtuoso project, a pioneering venture in the use of VR for autism, serves as a case study for understanding the potential and challenges of integrating XR technologies in specialized educational settings. Through an analysis of the Virtuoso project's outcomes, we aim to bridge the gap between innovative technology use and the specific learning needs of autistic learners, thereby enabling designers to create more effective and inclusive XR-based learning environments for this learner population.

Integrating XR into educational contexts has ushered in a new era of immersive learning experiences. XR technology holds immense potential for creating authentic and engaging learning environments, particularly for individuals with diverse learning needs. The current article acknowledges the unique challenges and opportunities XR presents for autistic individuals and contributes to the field of learning design and technology (LDT) by providing a set of design principles for the effective and ethical design of XR for autistic users. These design principles, derived from the Virtuoso project’s three-year longitudinal DBR initiative, provide a foundational framework for designing XR interventions which cater to the specific needs, preferences, values, and requirements of autistic learners.

Description of the Virtuoso Project

The Virtuoso project, conducted from 2016 to 2019, was a DBR initiative deploying multimodal XR technologies to offer vocational training for autistic adults. These individuals were participants in the Impact Innovation adult day program at a large Midwestern university, a unique program designed to support adults with significant communication and behavioral challenges associated with autism. The program provides a comprehensive daily schedule, including vocational internships across various domains, health and lifestyle activities, and adaptive skills training—from basic hygiene to complex social interactions. Aimed at promoting employment exploration and a high quality of life, Impact Innovation emphasizes lifelong learning and practical skills essential for navigating daily and professional environments. Within this context, Virtuoso served as an immersive learning tool focusing on essential life skills, such as using public transportation, thereby enhancing participants' autonomy and ability to engage in the community.

Various challenges, including difficulties in social communication and repetitive behaviors characterize autism. One significant hurdle faced by autistic adults is the acquisition of essential life skills, such as using public transportation, which is often a prerequisite for gainful employment and community engagement. XR is an umbrella term encompassing VR, augmented reality (AR), and mixed reality (MR) technologies, all designed to provide users with technology-mediated immersive and interactive experiences that combine aspects of the physical and digital world. Virtuoso was conceived as an innovative response to the challenge of equipping autistic participants with the skills necessary to navigate public transportation effectively. The project adopted a design-based research methodological approach (Barab & Squire, 2004) because of (1) the paucity of established precedent and design principles in the area of XR for autism (discussed in depth in Glaser & Schmidt, 2021; Schmidt et al., 2023a) and (2) the remarkable and well-established complexity of designing for this neurodiverse population (discussed in depth in Parsons, 2016; Schmidt & Glaser, 2021a).

Virtuoso training was structured around teaching autistic participants how to utilize the university shuttle system, a vital aspect of their vocational training. The shuttle provided gratis access to various routes within the campus and the surrounding community. The shuttle system also utilized a mobile phone-based tracking app, making planning and monitoring rides possible. The training was characterized by three salient features: (1) an instructional scaffolding system, (2) a highly proceduralized set of instructions for catching the shuttle, and (3) a four-stage system of technology supports. First, the design of instruction involved a carefully articulated scaffolding system characterized by a gradual transition from a higher level of support to a lower level of support. Second, the training utilized a four-step procedure, derived from procedural task analysis (Jonassen et al., 1994), for catching the shuttle in which participants (1) checked the shuttle schedule, (2) viewed their route to the shuttle on a map, (3) walked to the shuttle stop, and (4) boarded the shuttle (Schmidt et al., 2023a). Third, a four-stage system of technology supports (Figure 1) was used to introduce the skill, model the skill, allow for rehearsal in the XR space, and practice the skill in the real world (Schmidt & Glaser, 2021a).

Figure 1

The four-stage system of technology supports used in Virtuoso

Stage 1: Comic Strip Style Social Narrative on a Phone/Tablet

Regarding the four-stage system of technology supports, training commenced with participants being introduced to the activities and technological tools via an iPad-based presentation. This utilized a social narrative format, an evidence-based practice ensuring the information is understandable and relatable to the participants (Hale & Schmidt, 2018). This initial stage prepared participants for the subsequent virtual and real-world experiences.

Stage 2: 360-Degree Videos Modeling Shuttle Training Skills

Following the iPad presentation, participants were shown a series of 360-degree videos in spherical video-based virtual reality (SVVR) format. These 360-degree videos provide learners with an immersive experience that allows them to look around in every direction as if they are physically in the video's environment. Learners could tilt and rotate their viewing device (or use a mouse on a computer) to explore the scene in all directions while the video plays. SVVR refers to the format of the 360-degree videos used in the training. "Spherical" describes how the video encompasses a full 360-degree view horizontally and vertically, creating a complete spherical panorama around the viewer. This format is a type of VR because it immerses the learner in the virtual environment. However, it is primarily visual and may not include interactive elements found in more complex, fully immersive VR systems. In the training context, these 360-degree SVVR videos were used to break down the complex task of using the university shuttle into four distinct segments. Each segment corresponded to a step in the training process, providing a clear observation platform for the skills needed to seek out, track, and board a university shuttle bus. The flexibility of the SVVR system, compatible with both VR headsets and smartphones, was intended to ensure accessibility for all participants.

Stage 3: VR Environment to Enact Shuttle Training Skills

Following engagement with SVVR videos, participants progressed to the first of two fully immersive VR scenarios delivered through high-end head-mounted displays, such as the Oculus Rift and HTC Vive (Schmidt et al., 2019a; Glaser & Schmidt, 2022). These scenarios, designed for virtual public transportation training, offered an engaging, safe, and controllable environment that could be repeated precisely (Parsons et al., 2004; Strickland, 1996, 1997). The first scenario provided extensive guidance, including marked paths and signage, to help manage potential sensory overstimulation. The subsequent scenario reduced these aids and introduced more complex tasks and higher graphical fidelity, encouraging participants to apply their skills (Figure 2) independently. This scaffolded progression allowed for repeated practice with increasing challenge.

Stage 4: Real-world Performance of Shuttle Training Skills

After engaging with the technology-supported aspects of the training, participants practiced the steps they had learned in the real world. Transitioning from virtual to real environments allowed participants to apply their newly acquired transportation skills in practical settings. The systematic approach, from scaffolded learning in virtual scenarios to real-world application, ensured efficient skill acquisition and provided a safe space to learn and practice before facing real-world challenges. The systematic scaffolding approach used in Virtuoso was implemented with a high degree of implementation fidelity, which facilitated the acquisition of transportation skills in an efficient and tailored manner while providing the ability to safely learn and practice associated skills in an XR modality before practicing these skills in the real world.

Figure 2

Fading scaffolding and supports in Virtuoso's interactive XR space

Confronting Known Challenges in the Design of XR for Autistic Users

The design and development of Virtuoso presented us with a myriad of challenges, perhaps the most notable of which was the lack of design precedent for developing realistic 3D models and interventions specifically tailored for autistic adults, which we discuss in Schmidt and Glaser (2021). Seeking to address this challenge, we endeavored to use the best available evidence from the field (Parsons, 2016), highlighting the importance of evidence-based practices in educational interventions for autistic individuals. Despite these resources, the complexity of designing a brief yet highly authentic and realistic learning scenario—lasting approximately 15 minutes—demanded an extraordinary level of detail and fidelity to adhere to the identified design principles. This scenario needed to be engaging, relatable, and beneficial for the target audience, incorporating their unique learning needs while providing an immersive experience. In our previous work (Schmidt & Glaser, 2021a), we delve into the intricacies of this process, the solutions we implemented, and the principles that guided our design choices. Another set of challenges was related to the rapid advancement of technologies, especially in terms of (1) the nascent state of VR development tools, (2) the advent of commercially available VR headsets, and (3) the relative lack of research concerning their potential adverse effects with autistic users (Glaser et al., 2022a; Schmidt et al., 2021c). Although researchers have created a range of VR interventions for autistic users (Bozgeyikli et al., 2018; Schmidt et al., 2023a; Newbutt, 2023; Parsons, 2016), the technologies used in these systems were quite dated in comparison to what we were developing.

Further, research articles sometimes overstated the impact of systems and learning outcomes on the target populations, and many research results tended to be overgeneralized and tremendously biased (Glaser & Schmidt, 2021; Karami et al., 2021). The unfortunate result was that the team could not rely on existing frameworks, necessitating a fresh design and functionality approach. Another significant hurdle was our desire to use Open-Source technologies, which, while advantageous in some respects, tended to lack comprehensive documentation, support, and guidance. The absence of established design models for creating realistic 3D environments tailored to autistic adults required our team to develop innovative solutions and employ a creative approach to problem-solving. This task was particularly challenging for our small team of three developers. In our design context within a college of education, where it is common for research and development projects to be undertaken by small design teams (Glaser et al., 2021), we encountered significant challenges in terms of resources, expertise, and the scope of what was technologically feasible to develop.

Beyond these challenges of technology development was the issue of addressing the high variability in the needs of autistic individuals (Chawner & Owen, 2022). Our goal was to create an intervention which was not only effective but also highly usable, accessible, and feasible for the wide range of cognitive and physical disabilities and comorbidities associated with autism (Schmidt & Glaser, 2021a). Such a goal requires a profoundly deep understanding of user needs and a highly flexible design approach to accommodate the diversity of an autistic user base. Lastly, and perhaps most daunting, was designing an intervention intentionally provisioned to promote the generalization of skills learned in the virtual environment to the real world (Schmidt et al., 2023a). Generalization is cited as perhaps the most challenging problem in all of autism research (Berggren et al., 2018; Church et al., 2015). The absence of compelling research or design precedent in this area made it challenging to create an intervention which could be effectively incorporated and executed.
Further, the absence of a standardized procedure for assessing the generalization of skills in XR (Khowaja et al. in 2020) necessitated we devise novel methods for evaluating generalization in Virtuoso (Schmidt et al., 2023a). Although our approach was fraught with unprecedented challenges in terms of design, technology, and user diversity, our results were predominantly positive, ultimately representing a pioneering step in XR applications for autistic individuals and thereby laying a fresh foundation for future innovations in this research area. In part, such positive outcomes were made possible due to our adoption of a DBR methodological approach, which we describe in the following section.

Methodology

The methodological framework for this project employed a DBR approach, an iterative process of designing, implementing, analyzing, and refining educational interventions within real-world settings. This approach, which unfolded over three years of research and development (Barab & Squire, 2004; Reeves & McKenney, 2015), is particularly valued for its emphasis on collaboration between researchers and practitioners to address complex educational problems and to create innovations that are grounded in practicality. Given the breadth of this longitudinal research, delving into the intricate details of the DBR process exceeds the boundaries of the current article. However, the details are elaborated on in Table 1 below. DBR was selected as the methodological approach for this project due to the unique challenges inherent in developing XR applications for autistic users. DBR, which integrates empirical educational research with the theory-driven design of learning environments, proved well suited for a project as innovative and uncharted as Virtuoso. Central to this was the iterative nature of DBR, which involves a continuous cycle of design, implementation, analysis, and redesign. Adopting an iterative approach was crucial given the absence of design precedent in creating realistic environments tailored for autistic adults, allowing for ongoing refinements towards effective and user-friendly outcomes. Moreover, DBR’s grounding in addressing real-world problems aligned well with the project's aim to tackle the practical challenge of creating XR-based shuttle training for autistic learners.

DBR’s focus on practical solutions helps ensure the research remains committed to producing tangible and usable outcomes. Furthermore, integrating enhanced theoretical understanding and a constantly improving intervention is another hallmark of DBR's benefit to our project. Faced with the challenge of integrating advanced technology with the specific needs of autistic users, the fusion of research and design in DBR meant technology development and impact assessment could occur concurrently. DBR also encourages collaboration with stakeholders, a feature particularly relevant given the high variability in the needs of autistic individuals. Involving educators, therapists, and autistic users in the design process allowed for more relevant alignment with our participants' actual needs and preferences. Finally, Virtuoso’s need to rapidly devise novel methods for evaluation in XR, particularly for generalization of skills, was a significant challenge DBR was well-equipped to address. Ultimately, adopting DBR as the methodological approach for Virtuoso was appropriate and instrumental in addressing the project's multifaceted challenges.

Multi-phase Cycles of Virtuoso Design-based Research

The Virtuoso project unfolded over two meso-cycles of DBR (Figure 3), taking three years to execute. The research and development work associated with the Virtuoso project has been documented in 13 publications, including refereed journal articles, book chapters, and conference proceedings (Table 1). The project commenced with one DBR micro-cycle, focusing on analysis and exploration through a literature review and product review to identify research gaps and align with the needs of autistic individuals, which formed the basis for our initial design principles. Meso-cycle 1 then progressed to the design and construction of a VR intervention and its evaluation by experts and autistic participants, aiming to refine the VR system based on user feedback and resulting in a refined set of design principles. Building upon these insights, Meso-cycle 2 further developed the intervention, incorporating input from both autistic and neurotypical participants, with a focus on educational scaffolding and environment fidelity and a significant emphasis on skill generalization. The comprehensive evaluation phase of Meso-cycle 2 led to a final set of design principles. These phases are described in the following sections.

Figure 3

Virtuoso Cycles of DBR, with Larger Loops Indicating More Substantial Effort

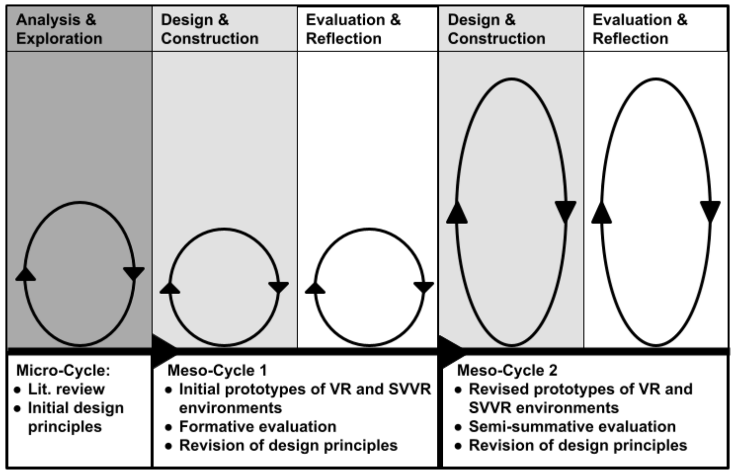


Table 1

Overview of Virtuoso Publications for Meso-cycles 1 and 2

Meso-cycle 1

Paper Name & Citation	**DBR Phase**	**Synopsis**
A prototype immersive, multi-user 3D virtual learning environment for individuals with autism to learn social and life skills: A Virtuoso DBR update (Schmidt et al., 2017)	Analysis & Exploration	Case study articulating evaluation methodology for prototype VR intervention
Promoting acquisition and generalization of skills for individuals severely impacted by autism using immersive technologies (Schmidt et al., 2020)	Design & Construction	Design paper explicating heuristics to use VR technologies to promote generalization for autistic learners

The centrality of interdisciplinarity for overcoming design and development constraints of a multi-user virtual reality intervention for adults with autism: A design case (Glaser et al., 2021)	Design & Construction	Case study providing insights into how a small interdisciplinary team (n = 3) was able to design highly realistic assets without existing design precedent. This paper provides rich design details to solve practical problems in a complex instructional design project.
Formative design and evaluation of an immersive learning intervention for adults with autism: Design and research implications (Schmidt et al., 2019b)	Evaluation & Reflection	Work-in-progress evaluation report with n=6 autistic participants. Data sources included screen, webcam, audio recordings, and field notes. Analysis comprised deductive qualitative analysis looking at usability and system errors and inductive qualitative analysis looking at user experience. Results suggested participants found Virtuoso-VR and Virtuoso-SVVR to be easy to use; Participants reported a very positive user experience; Virtuoso-SVVR was found to be easier to use and more relevant
Evaluation of spherical video-based virtual reality intervention designed to teach adaptive skills for adults with autism: A preliminary report (Schmidt et al., 2019b)	Evaluation & Reflection	A preliminary analysis focusing on the Virtuoso-SVVR application. Participants included expert evaluators (N = 4) and autistic participants (N = 6). Data sources comprised the System Usability Scale, the Adjectival Ease of Use Scale, structured expert interviews, screen, webcam, audio recordings, and semi-structured expert interviews. Analysis comprised quantitative descriptives, and inductive & deductive qualitative coding to examine the feasibility and user experience of Virtuoso SVVR. Results from this evaluation indicate autistic participants found the SVVR app to be easy to use and provide a positive user experience. Expert evaluators found Virtuoso-SVVR to be feasible, relevant, and easy to use.
Piloting an adaptive skills virtual reality intervention for adults with autism: findings from user-centered formative design and	Evaluation & Reflection	This study used a user-centered approach to assess the Virtuoso intervention. Participants comprised expert evaluators (n = 4) and autistic participants (n = 6). The study employed a mix of subjective and objective measures. The System Usability Scale and the Adjectival Ease

evaluation (Schmidt & Glaser, 2021b)		of Use Scale were used to gather quantitative data on the usability of the Virtuoso system. Additionally, structured and semi-structured expert interviews provided qualitative insights. Using screen, webcam, and audio recordings enriched the data, allowing for a more in-depth analysis of user interactions with the VR intervention. Autistic participants reported a largely positive user experience and found the system highly usable. However, the study also uncovered some challenges, such as evidence of cybersickness among some users. Despite this, preliminary evidence of skills transfer suggests the intervention could effectively teach adaptive skills to adults with autism. The expert evaluators found the intervention relevant and feasible, noting its above-average usability.
Investigating the usability and learner experience of a virtual reality adaptive skills intervention for adults with autism spectrum disorder (Schmidt et al., 2021a)	Evaluation & Reflection	In this study, a user-centered approach was adopted. The research included a group of expert evaluators (n = 4) and autistic participants (n = 6). The evaluation utilized both subjective and objective measures. Quantitative data on usability was gathered through the System Usability Scale and the Adjectival Ease of Use Scale. Additionally, a combination of structured expert interviews, screen, webcam, and audio recordings, unstructured post-usage testing interviews, and field notes provided rich qualitative insights. The analysis, encompassing quantitative descriptives and inductive & deductive qualitative coding, revealed a largely positive user experience and high usability of the Virtuoso system. This was particularly significant considering the specific needs of autistic adults. The study's findings were discussed in the context of Rogers' diffusion model, offering valuable directions for the ongoing development and refinement of the Virtuoso intervention.
Meso-cycle 2		
A process model for minimizing adverse effects when using head-mounted	Analysis & Exploration	This conceptual model proposes strategies to reduce adverse symptoms associated with using head-mounted displays in virtual reality systems for autistic learners. The research

display-based virtual reality for individuals with autism (Schmidt et al., 2021c)		adopted a structured approach, utilizing within- and across-case analyses of two independent studies. This analysis was instrumental in developing a stage-wise approach for implementing VR systems specifically tailored for autistic learners. The emphasis was on minimizing the adverse symptoms often experienced with HMDs, which can be a significant barrier to the effective use of VR in educational and therapeutic settings for individuals with autism. The process model developed through this study provides practical guidelines and strategies. These guidelines are intended to address the unique sensory sensitivities and needs of autistic individuals, ensuring a more comfortable and beneficial VR experience.
Learner experience and evidence of cybersickness: Design tensions in a virtual reality public transportation intervention for autistic adults (Glaser et al., 2022a)	Evaluation & Reflection	This multi-method study sought to evaluate and reflect the use of virtual reality headsets in Virtuoso. This study included neurotypical participants (n = 6) and autistic participants (n = 6). The data sources were comprehensive and tailored to capture the nuances of the user experience. These included the Motion Sickness Assessment Questionnaire, usage test recordings, field notes, and semi-structured interviews. This combination of tools was crucial in providing both quantitative and qualitative insights into the user experience. The analysis involved descriptives and deductive and inductive qualitative coding, specifically examining cybersickness and the overall experience with head-mounted displays. Findings indicate that the VR headsets deployed as part of Virtuoso were generally comfortable and provided a good user experience for autistic users. However, the study also identified evidence of cybersickness across sessions. Despite this, the level of discomfort was not severe enough to cause any user to discontinue participation.
Not perfect but good enough: a primer for creating spherical video-based virtual reality for autistic	Design & Construction	This case study focused on the design and construction of spherical video-based virtual reality for autistic users. The case study presented a primer for creating SVVR content, aiming to provide practical guidance and

users (Newbutt et al., 2022)		procedural steps for practitioners interested in developing their own SVVR systems. Central to this study were case studies of two SVVR projects, one of which was the Virtuoso project. These case studies were reported in detail to articulate the design procedures and steps involved in creating SVVR content. The primer provided by the study details the essential steps and considerations for designing SVVR content, including addressing specific needs such as sensory sensitivities, engagement factors, and user comfort.
Computer vision methods to examine neurodiverse gaze patterns in 360-video (Glaser et al., 2022b)	Evaluation & Reflection	Work-in-progress paper reporting how the research team intended to use artificial technology and pattern recognition analyses to examine learner engagement with Virtuoso-SVVR.
Programming for generalization: Confronting known challenges in the design of virtual reality interventions for autistic users (Schmidt et al., 2023a)	Evaluation & Reflection	In this study, autistic participants (n = 6) were involved in evaluating the effectiveness of the Virtuoso-VR intervention. The evaluation employed various data sources, including Virtuoso-VR usage videos, the Temple Presence Inventory, field notes, semi-structured interviews, and recordings of generalization sessions. The analysis, which encompassed behavioral coding, qualitative analyses, descriptives, and statistical tests, focused on examining the fidelity of tasks and the generalization of skills from virtual to real-world contexts. Key findings indicated a high fidelity of implementation from the real world to the virtual world, along with high sensations of telepresence experienced by the users. Notably, there was evidence of skills generalization to real-world scenarios, highlighting the potential effectiveness of VR interventions in practical applications for autistic users.
Through the lens of artificial intelligence: A novel study of spherical video-based virtual reality usage in autism and neurotypical	Evaluation & Reflection	This study focused on evaluating the usage of Virtuoso-SVVR among autistic (n = 6) and neurotypical participants (n = 6). The primary data source for this evaluation was SVVR usage videos. The analysis utilized artificial intelligence-supported data mining and pattern recognition techniques. These included Markov chains, sequential pattern mining, and entropy

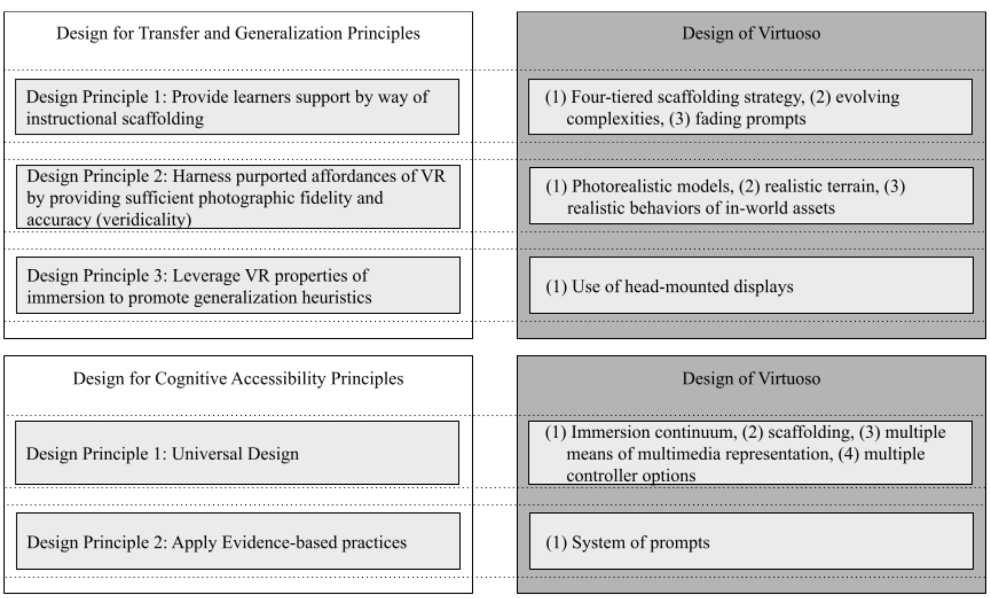
participants (Schmidt et al., 2023b)	analyses to provide a nuanced understanding of user engagement patterns. Findings indicated that the neurotypical group displayed greater homogeneity and predictability in their viewing patterns than the autistic participants. On the other hand, autistic users demonstrated a broader range of stimuli engagement, indicating varied and less predictable interaction patterns with the SVVR environment.

Micro-cycle

The initial phase of the Virtuoso project was characterized as an analysis and exploration micro-cycle. This phase consisted of conducting a comprehensive literature review and a detailed product review. The literature review served to gather and synthesize existing knowledge and research findings relevant to the use of VR for autistic individuals, helping the team to identify research gaps and better align our work with known needs of the target user group. Concomitantly, a product review was performed to examine extant VR technologies and educational interventions, assess the current state of VR applications, identify best practices, and understand the limitations and challenges of existing products. The initial micro-cycle of our DBR study laid the groundwork for the two subsequent meso-cycles. Insights gained from the literature and product reviews were formalized into an initial set of design principles (Figure 4), which were used to guide Meso-cycle 1.

Figure 4

Preliminary Design Principles Based on Analysis & Exploration Micro-Cycle



Meso-cycle 1

A multimodal approach was undertaken in Meso-cycle 1, comprising both the design and construction of the VR intervention and the evaluation and reflection of the resultant prototype VR environment. During the design and construction phase, the focus was on the initial development of the prototype Virtuoso intervention. The resultant prototype consisted of an Android SVVR app that allowed participants to experience 360-degree training videos and a fully immersive VR experience, delivered using an Open-Source software system called High Fidelity (now defunct) in which participants could practice catching the university shuttle. For the evaluation, four expert evaluators and six autistic participants participated in the system's participatory design and evaluation. The data sources for this phase included the System Usability Scale, the Adjectival Ease of Use Scale, structured and semi-structured expert interviews, and screen, webcam, and audio recordings. The data analysis in this phase was twofold. Firstly, quantitative descriptives were used, providing an overview of the ease of use of the Virtuoso system. Secondly, inductive and deductive qualitative coding methods were employed to analyze video-based data. This qualitative analysis provided insights into how experts and autistic users received the system and what improvements might be necessary.

The purpose of Meso-cycle 1 was not to establish the efficacy of the intervention on learning outcomes (i.e., “research to prove”) but instead to focus on the formative aspects of design and development, emphasizing the refinement of the virtual reality intervention based on user feedback and expert evaluation (i.e., “research to improve,”; see Honebein & Reigeluth, 2021). Our push towards a constantly improving intervention aimed to iteratively enhance the usability, accessibility, and overall experience of the Virtuoso system for autistic adults, ensuring the intervention was tailored effectively to meet their specific needs and preferences. The comprehensive effort of Meso-cycle 1 provided insights to refine our initial design principles, which were articulated using the design vocabulary proposed by Kali (2006). Kali’s framing relies on a hierarchy to describe design principles using three levels of generalization, (1) specific principles, (2) pragmatic principles, and (3) meta-principles. Specific design principles describe single features. Pragmatic principles connect multiple specific principles. Meta-principles “capture abstract ideas represented in a cluster of Pragmatic Principles” (p. 190). The design principles are provided in Table 2.

Table 2

Meta-, pragmatic, and specific design principles from Meso-cycle 1

Meta-principle 1: Provide embodiment in the learning process	
Examples of Pragmatic Principles	**Examples of Specific Principles**
• Provide photographically and behaviorally realistic representations of users and non-player characters • Provide highly realistic spaces • Provide a high level of task fidelity • Provide learning experiences which are avatar-mediated (require the user to act through the avatar)	• Avatars look like participants, the online guide, etc. • Avatars with realistic behaviors (e.g., walking, gesturing, etc.) • Realistic campus model, office setting, shuttle, etc. • Realistic physics (e.g., collision, gravity, water, etc.)

• Convey rules and constructs through experience, not simply words or models of what others can do	• Procedural task analysis • Exact task recreation • Support social interaction with social cues (gestures, proximity, facing the speaker, etc.) during the learning tasks • Modeling and practice of skills (curricular scaffolding model)
Meta-principle 2: Promote cognitive accessibility	
Examples of Pragmatic Principles	**Examples of Specific Principles**
• Incorporate principles of Universal Design for Learning • Concrete presentation and practice of skills	• Support for multiple display types (e.g., head-mounted, desktop, mobile) • Virtual and real-world based tasks
Meta-principle 3: Scaffold and facilitate target skills	
Examples of Pragmatic Principles	**Examples of Specific Principles**
• Provide environmental supports and cues • Provide coaching with consistent and predictable responses • Fade scaffolds over time	• Use of intuitive supports in the environment (highlighting, modeling etc.) • Making the space minimalistic and not including objects which might detract from social interaction or be distracting • System of prompts • Modeling of the skill • Four-tiered scaffolding system, fading from a high level of scaffolding to a low level of scaffolding

Meso-cycle 2

In Meso-cycle 2, the team built upon the foundational work from Meso-cycle 1, incorporating improvements and insights gained from the initial design and evaluation phase. Meso-cycle 2 was characterized by a more comprehensive design and construction phase, incorporating the perspectives of both autistic and neurotypical participants. While Meso-cycle 1 focused on the initial development and preliminary evaluation, Meso-cycle 2 focused on directly applying insights to enhance the intervention. For instance, the varied engagement patterns of autistic users identified in Meso-cycle 1 led to a more tailored approach in Meso-cycle 2, where the team incorporated more sophisticated educational scaffolding, higher fidelity virtual environments, and more realistic avatars and scenes. A more sophisticated approach was crucial in understanding how different user groups interacted with the system and making necessary adjustments to better cater to the diverse needs of autistic individuals. A key concern in Meso-cycle 2 was skill generalization, which was partly influenced by the initial observations of user interactions and learning outcomes in Meso-cycle 1. The team sought to ensure high fidelity of implementation from the virtual world to the real world and rigorously assess the extent to which skills learned in the virtual environment could be transferred to real-world contexts, a remarkably difficult and resource-intensive effort.

Following design and construction, a comprehensive evaluation and reflection phase was performed. This phase sought to investigate the use of the Virtuoso intervention by both autistic (n=6) and neurotypical participants (n=6). It included diverse studies, each contributing to a deeper understanding of the intervention's impact and user experience. We closely examined SVVR usage patterns among the participants (Schmidt et al., 2023b). Our findings revealed neurotypical participants tended to display homogeneous and predictable viewing patterns, whereas autistic participants engaged with a wider variety of stimuli within the virtual environment. Another significant study (Schmidt et al., 2023a) assessed the generalization of skills from the virtual to the real world among autistic participants, revealing high fidelity of implementation and evidence of generalization.
Furthermore, the user experience, particularly concerning cybersickness with head-mounted displays, was evaluated, highlighting the design tensions in VR interventions for autistic adults. On the heels of these studies, a process model was developed to minimize adverse effects when using HMD-based VR specifically for individuals with autism. Following rigorous data analysis and reflection, the findings and insights from this phase led to a refined set of design principles, which reflected those developed following Meso-cycle 1 while expanding on them substantially. These design principles are presented and discussed in the Discussion section below.

Discussion

In this paper, we have synthesized the outcomes from two meso-cycles of DBR on the Virtuoso project, aimed at developing and refining a multimodal XR intervention for autistic adults. The project's journey, from the initial analysis and exploration of the micro-cycle through two successive meso-cycles, illustrates the iterative nature of DBR in addressing the unique challenges of designing XR for autistic users. Meso-cycle 1 focused on developing and evaluating a prototype VR intervention, leading to refined design principles. Building on these, Meso-cycle 2 expanded the design, incorporating feedback from both autistic and neurotypical participants and emphasizing skill generalization. This cycle's comprehensive evaluation phase further refined the design principles, considering diverse user experiences, including challenges like cybersickness with head-mounted displays. On this basis, we present the final set of design principles that we developed based on the outcomes of Meso-cycle 2. These principles encapsulate the refined insights and enhancements derived from extensive evaluations and feedback gathered across all phases of the Virtuoso project, mainly focusing on the unique needs and experiences of autistic and neurotypical participants.

Design principles for the use of XR with autistic users

This section presents the final set of three design principles developed following Meso-cycle 2. These include (1) embracing and accommodating individual variability, (2) facilitating the generalization of skills to real-world contexts, and (3) giving precedent to overall user experience.

The first principle, embracing and accommodating individual variability, underscores the importance of recognizing and valuing the diverse characteristics and needs of autistic users. It calls for creating systems, products, or environments that are not one-size-fits-all but are adaptable and flexible enough to cater to the broad variety of individual differences found on the autism spectrum. This includes for example, variations in abilities, learning preferences, and other personal attributes. The principle advocates for a user-centric approach in design, where individualized experiences and interactions are prioritized, ensuring each user can engage in a manner that is most effective and comfortable for them.

The second principle, facilitating the generalization of skills to real-world contexts, emphasizes the need to ensure skills learned in the virtual setting are transferable to everyday life situations. This principle involves designing learning experiences and interventions in a way that bridges the gap between the controlled, often simulated learning environment and the varied, unpredictable nature of natural settings. Using established generalization heuristics, designers should create opportunities within the learning process for autistic users to apply what they have learned, thereby bridging the gap between theoretical and practical application to one’s daily life.

The third and final design principle, giving precedent to overall user experience, places autistic users' holistic experience at the forefront of the design process. This principle prioritizes crafting an experience that is effective in promoting learning experiences and also enjoyable, intuitive, and accommodating to autistic users’ needs, preferences, and abilities. This includes minimizing risks for adverse effects, such as cybersickness (i.e., discomfort, disorientation), utilizing a broad spectrum of mixed-reality tools, from lower fidelity smartphone-based applications to higher-fidelity headset-based systems, to better cater to a wide range of preferences, abilities, and comfort levels. Ultimately, this principle emphasizes the importance of stakeholder involvement, ensuring the perspectives and insights of all parties, including end-users, clinicians, and providers, are considered.

These design principles represent the culmination of longitudinal DBR, offering a robust framework for future XR interventions tailored to autistic users. The discerning reader will note the principles from the initial micro-cycle of analysis and exploration and Meso-cycle 1 are subsumed within this set of design principles, although the language to describe the design principle has been revised and refined as we worked through multiple cycles of DBR. Following this, we present a conjecture map (Sandoval, 2004) which visually and conceptually illustrates the interconnections and rationale of our approach to XR design for autistic users, providing a clear and comprehensive guide for application in future XR design endeavors.

In Table 3 below, we present the principles that emerged from Meso-cycle 2, again using Kali's (2006) structured framework, categorizing them into three hierarchical levels: (1) specific principles detailing individual features, (2) pragmatic principles linking these features, and (3) meta-principles representing overarching themes.

Table 3

Meta-, pragmatic, and specific design principles from Meso-cycle 2

Meta-principle 1: Embrace and accommodate individual variability	
Examples of Pragmatic Principles	**Examples of Specific Principles**
• Incorporate multi-user affordances (when appropriate) • Implement adaptive scaffolding • Embrace and accommodate individual variability	• Facilitate interaction through human-controlled online guide • Provide multiple interaction modalities (i.e., controllers, headsets, virtual environments, etc.) • Customizable virtual environment • Fade scaffolds over time • Increase complexity and difficulty over time
Meta-principle 2: Facilitate the generalization of skills to real-world contexts	
Examples of Pragmatic Principles	**Examples of Specific Principles**
• Incorporate principles of Universal Design for Learning • Provide concrete presentation and practice of skills • Present exact replication of task structures across modalities (i.e., social narrative, video, immersive simulation, real-world)	• Present realistic 3D assets that mirror the real-world • Provide high fidelity of task representation within the virtual environment • Design identical task structures across all devices • Leverage a fully immersive virtual reality system to promote telepresence • Incorporate Stokes & Osnes'(2016) generalization heuristics • Illustrate abstract concepts using concrete representations
Meta-principle 3: Give precedent to the overall user experience	

Examples of Pragmatic Principles	Examples of Specific Principles
• Minimize risk of adverse effects • Leverage a spectrum of mixed-reality tools • Prioritize stakeholder involvement • Incorporate LXD methodologies	• Provide orientation training sessions with VR devices • Gradually acclimate participants to the immersive experience • Utilize lower-fidelity (i.e., smartphone-based) and higher-fidelity (i.e., headset-based) VR tools • Conduct multiple rounds of user testing, making refinements after each successive round • Formatively evaluate and refine the system over time • Identify and engage with all stakeholders, from end-users to clinicians to providers.

Towards a design conjecture on the use of extended reality with autistic users

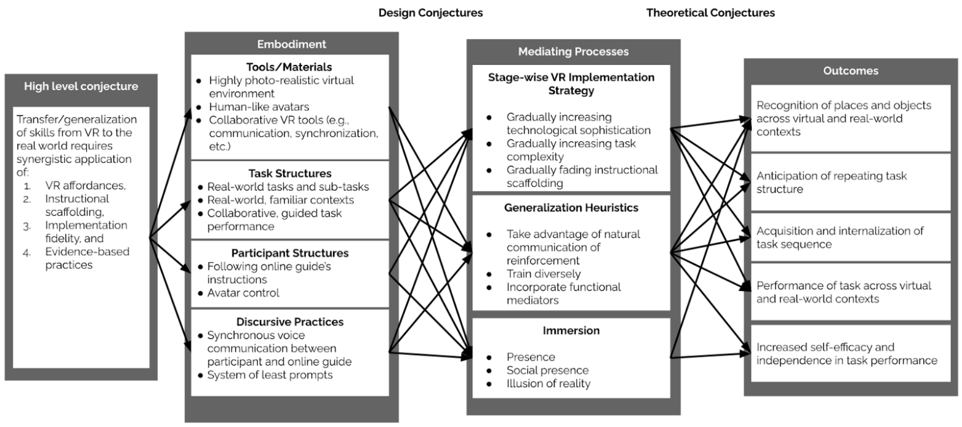
A second outcome of our longitudinal DBR effort is the conjecture map presented in Figure 5. According to Sandoval (2004), a conjecture map is a critical tool in DBR for articulating and organizing hypotheses underlying an educational design. It serves to clarify the intentions behind design choices by explicitly linking theoretical assumptions to specific design elements and anticipated outcomes. Ultimately, conjecture maps provide a visual and structured representation of how and why an intervention is expected to work. The conjecture map (Figure 5) we present here illustrates the core components of Virtuoso. The program's foundation lies in the high-level conjecture that VR's effectiveness is contingent upon the harmonious integration of affordances, structured instructional support, fidelity in simulation, and established pedagogical methods. The embodiment through tools and materials such as photo-realistic environments, lifelike avatars, and task structures mirroring real-life scenarios is instrumental for participants.

This is complemented by participant structures promoting active engagement and discursive practices encouraging communication between users and guides. The mediating processes advocate for a staged VR implementation strategy, emphasizing the gradual enhancement of VR complexity and a reduction in guidance, fostering independence. The program's anticipated outcomes include improved recognition of real-world objects and environments, anticipation of task structures, and mastery of task sequences, culminating in a heightened sense of self-efficacy and autonomy in the actual task execution. Taken together, the conjecture map presented in Figure 5 provides a holistic ecology for understanding the design, implementation, and expected outcomes of a VR learning environment, which incorporates the design principles discussed in the previous section.

Overall, the conjecture map provides a detailed and structured overview of how various elements of the VR learning environment are theorized to interact and contribute to effectively transferring skills from the virtual to the real world.

Figure 5

Conjecture map for promoting skills generalization and increased independence using VR with autistic users



Closing Remarks

This research study contributes to the evolving field of instructional design by providing a comprehensive exploration of effective and ethical XR design for autistic users. By delving into the critical components of the preliminary theory derived from the longitudinal Virtuoso research, we offer practical insights and evidence-based recommendations for designing XR interventions that cater to the unique needs of autistic learners. This DBR study's findings hold implications for educators, instructional designers, and researchers seeking to create authentic and inclusive learning experiences through immersive technologies which can generalize to real-world application contexts. However, we acknowledge the need for further research to validate and refine the design principles and conjectures. This could pave the way for more impactful and empowering XR interventions for autistic individuals, an endeavor we feel worthy of pursuit.

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