Beyond Diagnosis: Why and How Virtual Reality Should be Used in Research on Neurodevelopmental Conditions?

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Abstract

Over the past two decades, virtual reality (VR) has emerged as a technique for studying neurodevelopmental conditions (NDCs) such as attention deficit hyperactivity disorder, autism spectrum disorder, and developmental coordination disorder. Until now, the predominant focus of VR applications in this field has been on developing new assessment and diagnostic tools, aiming to identify NDC symptoms in engaging and ecologically valid digital environments. However, despite these advancements, VR has yet to outperform traditional diagnostic methods and remains underutilized as an assessment tool. This paper advocates for a shift in the use of VR, urging researchers to harness its potential in testing embodied cognitive mechanisms underlying NDCs. That is, leveraging VR's functionality to systematically manipulate sensory and social experiences in real-world simulations and test participants in active, whole-body, daily tasks. This article asks why and how VR should be used in NDC research and points to its unique strengths compared to conventional methodologies.

Introduction

Neurodevelopmental conditions (NDCs), such as attention-deficit hyperactivity disorder (ADHD), autism spectrum disorder (ASD), and developmental coordination disorder (DCD), are increasingly being understood not as mere deviations from typical development but as part of the broader spectrum of neurodiversity. The concept of neurodiversity shifts the focus from defining rigid categories of 'normal' and 'abnormal' development to understanding the complex, dynamic interplay of cognitive, sensory, and motor processes that contribute to diverse developmental pathways (Baum et al., 2015; Bremner et al., 2012). This perspective recognizes that there are many ways for individuals to experience the world and that these differences should be valued as part of the richness of human variation (Dövencioğlu et al., 2013; Li & Shigemasu, 2021).

Traditional research methodologies, such as behavioral rating scales, neuropsychological tests (e.g., continuous performance tests; CPTs), and observational assessments, have been instrumental in identifying NDCs (Albrecht et al., 2015; Barkley, 2005; Unterrainer et al., 2020). However, these methods often fall short of characterizing the full complexity of neurodiverse experiences, particularly when it comes to understanding the interactions between cognitive, sensory, and motor systems in real time and in daily contexts. The limitations of these methods have led researchers to seek more ecologically valid tools for studying NDCs. That is, tools that can simulate real-world environments while still allowing for precise control over experimental manipulations (Aase & Sagvolden, 2005; Bioulac et al., 2014; Mangalmurti et al., 2020).

The advent of immersive technologies presents an exciting opportunity to address these limitations. Among these technologies, virtual reality (VR) has drawn particular attention (Alatalo et al., 2008; Bohil et al., 2011; D'Amelio et al., 2023) because it offers a complete sensory immersion, enabling researchers to manipulate environments, tasks, and sensory inputs in ways that are not feasible in traditional settings. VR researchers' capacity to create controlled yet naturalistic simulations opens new avenues for exploring mechanisms underlying NDCs (Jaiswal et al., 2023; Tarr & Warren, 2002; Wilson & Soranzo, 2015).

Thus far, most studies have attempted to leverage VR's immersive capabilities to create more engaging and ecologically valid assessments, often with the goal of improving accuracy of NDC diagnostic (Alcañiz Raya et al., 2020; De Leon-Martinez et al., 2022; Goharinejad et al., 2022; Satu et al., 2023; Seesjärvi et al., 2023). However, despite these advancements, VR has not yet been proven to be significantly superior to established diagnostic techniques. This raises the question: Is the true potential of VR being fully realized in NDC research? Perhaps the use of VR is limited by focusing too narrowly on applied research (Frolli et al., 2021; Jylkkä et al., 2023; Mesa-Gresa et al., 2018), whereas VR should be used as a technique for basic science in child neurodevelopment.

In this article, we begin by reviewing the traditional use of virtual reality in research of NDC and continue with the strength of VR and how it can be used in NDC research. We conclude by pointing to future directions for VR-based research of neurodiversity.

Traditional Use of Virtual Reality in Neurodiversity: Same Old, Just Gamified

One of the key advantages of VR in NDC research is its ability to engage participants through gamification, enhancing motivation and data quality (Bioulac et al; 2014; Seesjärvi et al., 2023). Traditional cognitive tasks can be monotonous and disengaging, particularly for children with NDCs who often struggle with sustained attention. VR is useful in addressing this challenge because it provides children with interactive scenes. Merzon et al. (2022), for example, used VR to assess ADHD through eye-tracking in the EPELI task—VR environment simulating real-life scenarios, such as tidying up a room and following verbal instructions by an animated avatar. Findings showed that participant with ADHD can be identified from how they were fixated and their inefficiencies in information processing. The researchers conclude that eye movements recorded within a VR environment can serve as a good assessment tool. Nevertheless, important aspects regarding *how* participants with ADHD acted (e.g., real-time coordination between eye and body movements) and their cognitive performance were not explored (Merzon et al., 2022).

Other studies used VR to test attentional difficulties in more ecologically valid conditions compared to traditional inhibition and attention tests, such as Flanker or Stroop tasks on a computer screen which only requires interaction with a keyboard (Son et al., 2024) Fang et al. (2019) used an immersive version of the Stroop test, along with position tracking and object recognition tests to assess ADHD in school-aged children. Findings showed significant differences in correct responses and reaction times between children with ADHD and control groups. The measures in the VR task were also correlated with traditional CPTs.

Another advantage of VR systems as a tool for identifying NDCs is their combination with other technologies. As Merzon et al. showed, children with ADHD can be identified through their attentional distraction by combining VR and eye tracking. Stokes et al. (2022) also demonstrated this by creating an immersive VR classroom in which continuous eye movements were recorded while participants completed the Stroop task and the Continuous Performance Test (CPT). These tasks were performed in the presence of realistic school-based distractors. The study demonstrated that eye-tracking within an immersive VR setting could serve as a valuable attentional biomarker for ADHD, as it allows researchers to identify specific distractors that affect attention on the individual level (Stokes et al., 2022). These findings are aligned with prior work that tested the role of distractors in assessing ADHD using a paradigm known as ClinicaVR (Neguț et al., 2017). This neuropsychological test replicated the traditional CPT but was conducted in a fully immersive virtual classroom where auditory distractors, such as background noise, were introduced during the task. The study revealed that auditory distractors significantly impaired performance in children with ADHD when sustained attention was required. Because typically developing children were less susceptible to this interference, the researchers conclude that immersive environments capture how attentional deficits manifest in real-world contexts (Neguț et al., 2017).

In addition to assessment and diagnostics, VR has also been used for intervention. One notable domain is social cognition in individuals with ASD. For example, Didehbani et al. (2016) used a VR Social Cognition training (VR-SCT) program for children with high-functioning autism. The program recreated several social situations with virtual avatars of the participants and the clinician who conducted the sessions. The social interactions were dynamic, with immediate feedback on relevant true-to-life scenarios. Scenarios included a virtual classroom, restaurant and playground. Social attribution task was administered prior- and post-intervention. The 1-hour sessions were delivered twice a week (10 sessions overall) and involved three 10-minute scenarios-SCT. Those sessions resulted in higher analogical reasoning scores in social attribution tasks and affect recognition scores post-intervention. However, long-lasting effects were not tested, and the focus on traditional measurements neglected the examination of underlying cognitive mechanisms driving this change.

Beyond interventions in cognitive skills, the use of VR to facilitate motor skills of children with developmental coordination disorder (DCD) has garnered increasing interest in recent years. In one of these studies, children with DCD were tested in several tasks, including the Sword task, Hand Rotation task, and Pursuit Rotatory task—before and after an 8-week VR intervention (EbrahimiSani et al., 2020). The Sword task required children to plan and execute actions by picking up a sword and inserting it into a slot, focusing on achieving comfortable end postures. The Hand Rotation task measured mental imagery, asking children to identify the direction of a hand stimulus. The Pursuit Rotatory task assessed rapid online motor control as children tracked a moving target on a screen. Although the study reported improvements in task performance following VR training, the movement patterns themselves were not directly assessed during the intervention. Instead, the study focused on task reaction times and end-state effects, leaving uncertainty about the specific mechanisms contributing to these improvements. The intervention involved sports-based games (e.g., baseball, basketball, bowling, and football) and was based on Microsoft's Xbox Kinect system, which captures whole-body movements in three dimensions. The intervention was designed to enhance motor skills like throwing, striking, kicking, and catching. However, without a detailed analysis of the movement patterns within the VR environment, it remains unclear which aspects of the training led to the observed improvements.

Another example comes from the work of Gonsalves et al. (2015). They explored the use of sports-based active VR gaming in a comparative study of children with DCD and typically developing children. The children engaged in virtual table tennis were tested in two VR systems—the Xbox Kinect and Sony PlayStation 3 Move—which track wand movement via a single motion-sensing camera. Their motor performance was analyzed using the Movement Assessment Battery for Children (MABC-2) test. Findings showed that children with DCD exhibited a significantly slower hand path speed with greater wrist extension and elbow flexion than typically developing children. However, VR allows addressing many other questions related to motor learning as whether greater wrist extension and elbow flexion could have been a compromise due to slower hand path speed.

Similar examples can be found in ASD research. Minissi et al. (2023) tested motor abnormalities in children with ASD, showing significant differences in upper limb movements during a goal-directed task. They incorporated the CAVE system – a room without windows where the visual stimuli of the virtual world were projected at 100º and 55cm of distance from the participant's standing point with two lateral surfaces left black. Two groups performed 3 VR tasks: a ball-kicking task (requiring precise movements of lower limbs to kick the virtual ball), a flower-picking task (participants had to move flowers horizontally from a pick-up area to a designated leaving area) and a bubble-blowing task (participants had to explode falling bubbles by touching them). All the tasks required precise and goal-directed movements to complete them and showed differences across these tasks between individuals with ASD and their typically developing peers. Nevertheless, the use of VR in these studies focused on fine motor control, and the strength of using VR to measure whole-body movements was not harnessed.

Taken together, harnessing VR for NDC research had impressive success in classifying individuals as 'having' or 'not having' a specific condition, with an increasing focus on 'treating' these conditions within immersive environments. Yet, such an approach paradoxically undermines the essence of neurodiversity, which challenges the binary notion of pathology. Neurodiversity advocates for a broader understanding that embraces individual differences as part of the natural variation in human cognition and behavior. By focusing VR research primarily on classification and diagnosis, there is a missed opportunity to fully leverage the richness of immersive environments. This narrow focus risks reinforcing a reductive view that frames neurodiversity as a condition to be 'fixed' or 'corrected', rather than as an opportunity to explore and understand the neural and behavioral spectrum.

Why and How to Use Virtual Reality in Neurodiversity

What does VR have to offer? We believe that the greatest potential of VR in neurodiversity research lies in its functionality to *systematically* manipulate sensory and social experiences. Unlike conventional tools that often isolate individual cognitive functions or rely on static assessments, VR can simulate real-life scenarios to simultaneously evaluate the unfolding interaction between perceptual, motor, and cognitive processes. We review multidisciplinary studies highlighting the integration of various sensory modalities and how these can be implemented in research on NDCs.

Multisensory Integration. Children and adults affected by NDCs are known to have more variability in the processing and integration of sensory information compared to their neurotypical peers (Allen & Casey, 2017; Feldman et al., 2019; Marhenke et al., 2023). Those Differences are also linked to variations in cognitive function (Bohil et al., 2011). VR is a powerful scientific tool for manipulating multimodal sensory inputs in a systematic manner and therefore is beneficial to test multisensory integration. For example, Girondini et al. (2024) designed a task where participants completed size-discrimination tasks, followed by a VR game where invisible colliders were manipulated to provide haptic feedback. Smaller colliders influenced the perception of object size, and visual incongruence reduced adaptability during object interactions. Although this study involved only neurotypical individuals, it demonstrated how VR gives insights into variations in sensory processing that are limited through traditional methods.

Through VR, research can also tailor sensory experiences to isolate and test specific domains while still eliciting whole-body behaviors. For instance, Alatalo et al. (2008) constructed a novel three-dimensional graphics engine to measure body balance in VR environment and showed how body balance can be affected by virtual perturbations only. Similarly, Alcañiz et al. (2020) used movement measures to identify repetitive behaviors in children with ASD as fingers wriggling and hands flapping (Lewis and Kim, 2009).. Participants in that study were instructed to imitate the movements in a VR environment while provided with three different types of sensory information: visual, visual-auditory, and visual-auditory-olfactory. Researchers showed that children with ASD have more repetitive head and leg movement than typically developing children. Other results include more movement in some joints by typically developing children. The study concluded that the greater the sensory stimulation, the greater the repetitive movements that differ between typically developing and ASD children.

The benefits of VR in studying multisensory integration was also shown at the neural level when the combination of VR with neural recording devices such as functional near-infrared spectroscopy (fNIRS) or electroencephalography (EEG) has proven effective (Seraglia et al., 2011). Putze et al. (2019) demonstrated that VR with fNIRS in a naturalistic n-back task is more reliable for decoding cognitive load than computerized lab experiments. In the classic n-back task, participants are shown a sequence of symbols or shapes and must respond whenever a symbol matches the one presented 'n' steps earlier in the sequence. This task is traditionally administered on a computer and requires participants to press a button to respond. Adapting this classic task to VR introduced an embodied element, allowing researchers to explore how spatial navigation, head movement, and even subtle body language interact with cognitive processing. Rather than isolating the task to a two-dimensional screen, VR expands the scope to incorporate the complexities of real-world sensory and motor interactions.

Motion and Biometric Measures. Objective physiological and behavioral measures, such as biometric and motion data, offer a critical advantage over subjective questionnaire reports or continuous task performance metrics in differentiating the unique characteristics of NDCs. Given the high heterogeneity of NDCs, incorporating physiological metrics beyond traditional cognitive and motor assessments is essential (Parsons, 2015). VR provides an environment for capturing these biometrics, circumventing the spatial interaction limitations inherent in conventional computerized tasks. By integrating VR systems with biometric devices, researchers can measure key physiological signals—such as heart rate variability, galvanic skin response (GSR), and pupil dilation—within immersive and dynamic contexts (Freeman et al., 2017; Rebenitsch & Owen, 2016). VR paradigm, in this case, provide a direct link between cognitive measures and underlying physiological states in whole-body tasks.

A compelling example of this integrated approach is provided by Marrucci et al. (2021), who combined VR with electroencephalography (EEG) and GSR in a driving simulation to investigate multisensory integration and cognitive load. Participants operated a steering wheel while immersed in a VR environment that delivered visual, auditory, and tactile feedback to simulate real-world driving conditions. By manipulating perceptual load at two levels—low and high—the study assessed driving performance alongside mental workload (via EEG) and physiological arousal (via GSR). This experimental design highlighted how incorporating physiological biometric measures in real-life simulated tasks can elucidate the links between cognitive and behavioral outcomes and their neurophysiological substrates.

Motion measures have also been extensively used in neurotypical populations and hold significant promise for NDC research. VR facilitates the investigation of motor planning through responses to cognitive tasks and allows for the capture of granular movement data, such as isolated joint motions (Levac et al., 2019). Movement trajectories, particularly reach-to-grasp motions, serve as critical markers in neurorehabilitation, and haptic-free VR paradigms provide effective methods for their measurement (Adamovich et al., 2009). The inherent flexibility of VR enables seamless incorporation of these movement measurements into experimental designs, enhancing the depth and quality of data collected.

In neurotypical populations, motion measures have also been validated as effective tools for individual differentiation. Pfeuffer et al. (2019) demonstrated that head motion measures yield the highest accuracy in distinguishing individuals across tasks involving grasping, walking, and throwing. Similarly, Liebers et al. (2024) found that dynamic movements like walking offer superior identifiability compared to static movements such as pointing. Importantly, static components remain valuable; the combination of low static and high dynamic components in study designs achieved a 90.91% accuracy rate in participant differentiation within VR environments. Despite these advances, movement patterns like walking have not been extensively studied in NDCs, with the notable exception of developmental coordination disorder (DCD; Wilson et al., 2017; Adams et al., 2017). This gap underscores the need for further research leveraging VR's capabilities to explore motion measures in NDC populations.

Social Cognition and Emotional Responses. For some NDCs (e.g., ASD), social impairments form a significant part of the diagnostic assessment**.** This can be more effectively studied using VR than traditional research methods, which often simplify the stimuli to elicit specific responses, such as using pictures in emotional recognition tasks. Within NDC research, VR has primarily been used to deliver interventions targeting social impairments and assess their effectiveness (Dechsling et al., 2021; Soltiyeva et al., n.d.; Yuan & Ip, 2018). Nevertheless, VR technology with higher immersion levels has been demonstrated to be a useful tool in the investigation of social cognition, where higher levels are required to create an “illusion of being there” (Slater, 2018). The mechanism proposed for this is that higher immersion VR is capable of generating a believable sensory experience, which is detected by the perceptual system that momentarily overrides the cognitive system, and a physical reaction occurs (Slater, 2018). This quality is valuable for attaining ecologically valid data more feasibly unlike other stimuli.

A prominent example is proxemics—how people use space in interpersonal interactions, including the physical distance they maintain from others, and how this varies across cultures, social situations, and relationships. Proxemics is an important component of social interactions that is atypical in children and adults with NDCs (Candini et al, 2020, Brown and Forster, 2023, Farkas et al 2022, Asada et al, 2016). Bailenson et al (2003) showed how research on proxemics is enhanced in VR because immersive technology allows for detecting and recording of participants location and orientation continuously and objectively, when participants are free to move. In that study, participants kept the greatest physical distance from virtual female avatars and from avatars that maintained mutual gaze. This finding highlights the value of immersive VR in proxemics research, where the technology allows for systematic control and covert measurement of how participants behave in their physical environment in response to social stimuli. Thus, VR is beneficial in tracking location/orientation and interpersonal interactions. Specific to neurodivergent populations, Gessaroli et al. (2013) and Simoes et al. (2020) used immersive VR to examine interpersonal distance regulation in children with ASD, compared to a control group. They showed difficulties in interpersonal distance regulation among children with ASD. Both studies used a stop-distance paradigm, which consists of participants approaching experimenters until they reach a distance that makes them uncomfortable (Hecht et al, 2019). Such paradigm is limited outside the VR environment, because measuring the distances between participants and experimenters is challenging (Kroczek et al, 2020).

Another core building block of social interactions is empathy, which is often argued to be diminished in children with NDCs. This claim is largely grounded in the widely discussed Theory of Mind ToM deficit, highlighted by Baron-Cohen et al.'s (1985) influential work, which found that children with ASD frequently fail tasks where they need to impute beliefs to others to predict their behavior (Senju, 2013). These findings have faced criticism, both from the autistic community and from researchers in the field (Gernsbacher & Yergeau, 2019). In recent years, VR has been heralded as the "ultimate empathy machine" due to its effectiveness in perspective-taking tasks (Herrera et al., 2018, Sora-Domenjó, 2022). The scoping review by Trevena et al. (2024) analyzed 44 studies and had the same conclusion when—there is significant evidence of VR being an effective tool for delivering interventions aimed at increasing empathy. These studies primarily tested the effectiveness of VR as an intervention tool, but we argue that the simulated experience afforded by VR engages cognitive processes more deeply than merely imagining the stimuli.

Conclusions

This article assessed the potential of virtual reality as a research tool on neurodevelopmental conditions and whether the existing literature overlooks the potential of VR as a tool for basic science.

Research on neurodiversity is extensive. Continuous performance-based tests and gamified experimental designs that utilize varied measures like eye gaze, error rate or reaction times reveal that individuals with NDCs differ in these measures from control groups. However, most of these experiments do not take the aspect of embodied experience into account, measuring these outcomes either by observation, questionnaires or cognitive tasks that aim to measure one function in isolation.

These methods, while valuable in identifying NDCs or lack of, are limited in measuring embodied, real-time behavior. We reviewed the literature on immersive VR and found that its use is primarily for assessments of NDCs with a focus on identifying deficits. We suggest that VR should shift to basic science with focus on mechanisms underlying cognitive outcomes in neurodiverse populations. Now, VR capabilities are not fully harnessed, from fully embodied experiences to capturing moment-to-moment interactions.

With virtual reality being a fast-developing field, we hope that it will be more widely adopted in neurodevelopmental research for the purposes of basic science and not as a diagnostic tool. We believe that this should be done through multidisciplinary collaborations between developmental psychologists, neuroscientists, computer scientists, designers, and engineers.

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