

Effect of Immersive Virtual Reality-Based Dual-Task Training on Cognitive Function and Functional Mobility in Ambulatory Children with Pediatric Neurological Disorders

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DOI: <https://doi.org/10.51584/IJRIAS.2026.11080141>

Received: 04 September 2026; Accepted: 09 September 2026; Published: 18 September 2026

ABSTRACT

Immersive virtual reality (IVR) is increasingly being explored in pediatric neurorehabilitation because it provides an interactive and controllable environment in which motor and cognitive demands can be manipulated simultaneously. Children with pediatric neurological disorders may experience limitations in executive functions, attention, visuospatial processing, postural control, gait and functional mobility. Conventional rehabilitation often trains these domains separately, whereas everyday activities require children to walk, balance, navigate obstacles and make decisions while attending to competing cognitive demands. Dual-task training (DTT) therefore offers a clinically relevant approach to reducing cognitive-motor interference. This literature review examines the rationale for combining IVR with DTT in ambulatory children with pediatric neurological disorders, with particular emphasis on cerebral palsy. A structured narrative search of PubMed/MEDLINE, Scopus, Web of Science, PEDro and Google Scholar was considered for peer-reviewed literature addressing pediatric neurological rehabilitation, virtual reality, immersive virtual reality, dual-task performance, executive function, gait, balance and functional mobility. Current evidence indicates that VR can improve balance, gross motor function and gait-related outcomes in children with cerebral palsy, while dual-task studies demonstrate that concurrent cognitive demands can reduce gait and postural performance. Recent evidence also suggests that DTT may improve balance, gross motor function and functional mobility. However, direct evidence specifically evaluating IVR-based DTT on both cognitive function and functional mobility remains limited. Future adequately powered trials should use standardized cognitive and mobility outcomes, individualized task progression and longer follow-up.

Keywords: Immersive virtual reality; Dual-task training; Cognitive function; Functional mobility; Pediatric neurological disorders; Cerebral palsy

INTRODUCTION & LITERATURE REVIEW

Pediatric neurological disorders encompass a heterogeneous group of conditions that affect movement, posture, coordination, sensation, cognition and participation. Cerebral palsy (CP), acquired brain injury, developmental neurological disorders, spina bifida and other neurodevelopmental conditions can produce persistent limitations in mobility and participation. Cerebral palsy is particularly relevant to pediatric physiotherapy because the disorder affects movement and posture and is frequently accompanied by disturbances in sensation, perception, cognition, communication and behavior. Although the underlying neurological lesion is non-progressive, functional consequences change with development, task demands and environmental requirements. Consequently, rehabilitation should address not only isolated body-structure impairments but also the child's ability to perform meaningful activities under real-world conditions.

Functional mobility is a major determinant of independence and participation in children with neurological disorders. Walking, turning, transferring, negotiating obstacles, maintaining balance and changing direction require integration of anticipatory postural control, selective motor control, sensory information and attention. Standardized measures such as the Gross Motor Function Measure (GMFM), Pediatric Balance Scale, Timed Up and Go (TUG), 10-Meter Walk Test and functional gait measures are commonly used to quantify mobility-related performance. Importantly, performance during a simple walking test does not necessarily represent

performance during school, community or play activities, where children must simultaneously process information, communicate, remember instructions or respond to unexpected environmental events.

The concept of dual-tasking is therefore important in pediatric neurorehabilitation. A dual task requires the simultaneous performance of a primary motor task and a secondary cognitive or motor task. Examples include walking while counting, walking while responding to questions, maintaining balance while remembering objects, or navigating a virtual environment while making rapid decisions. The reduction in motor or cognitive performance produced by adding a concurrent task is commonly described as dual-task cost and provides an indication of cognitive-motor interference. In children with CP, observational evidence indicates that dual-task conditions can reduce walking speed and alter gait performance. A systematic review and meta-analysis of observational studies found that walking speed was significantly slower during dual-task conditions than single-task conditions in children with CP, supporting the clinical importance of cognitive demands during mobility.

Dual-task performance is closely related to executive functioning. Executive functions include working memory, inhibitory control, cognitive flexibility, planning, monitoring and goal-directed behavior. These functions allow a child to select relevant information, suppress competing responses and adapt movement to changing task requirements. Children with neurological disorders may have difficulties in one or more of these domains even when they are independently ambulatory. A rehabilitation program that deliberately combines cognitive and motor challenges may therefore provide opportunities for task-specific practice of both domains. However, cognitive loading must be graded carefully because excessive task difficulty may compromise safety, reduce movement quality and produce frustration.

Virtual reality (VR) provides an additional opportunity to deliver dual-task practice. VR systems can create simulated environments in which the child interacts with visual, auditory and sometimes haptic information. Non-immersive systems typically display the virtual environment on a monitor, whereas immersive VR uses a head-mounted display or comparable technology to provide a greater sense of presence. Immersion may increase ecological validity by allowing children to experience simulated walking paths, obstacles, targets, games and decision-making situations while receiving immediate feedback. The ability to control task complexity, speed, number of stimuli and cognitive demands makes VR potentially suitable for individualized rehabilitation.

Several mechanisms may explain the therapeutic potential of VR. Repeated practice in an engaging environment may increase motivation and adherence, while immediate visual or auditory feedback may support error detection and motor learning. VR also permits manipulation of environmental constraints without requiring the physical resources of a conventional therapy space. In pediatric rehabilitation, play-like tasks can transform repetitive exercises into goal-directed activities. These characteristics are particularly relevant when cognitive and motor tasks need to be combined because the therapist can introduce a cognitive rule, target selection task, memory requirement or response-inhibition challenge while maintaining a controlled motor environment.

Evidence for VR in children with CP has expanded considerably. An updated evidence-based systematic review reported moderate evidence for improvements in balance and overall motor development with VR-based rehabilitation. Subsequent systematic reviews and meta-analyses have generally supported beneficial effects on balance and gross motor function. For example, a meta-analysis of 16 randomized controlled trials involving 513 children found significant improvements in balance and gross motor function following VR training, although effects on activities of daily living were less consistent. Another systematic review reported positive effects of VR therapy on balance and walking. More recent reviews including larger numbers of randomized trials continue to report improvements in gait, balance, gross motor function and activities of daily living, although heterogeneity in VR platforms, treatment dosage and outcome measures remains a concern.

Importantly, most of this literature involves non-immersive or semi-immersive systems rather than fully immersive interventions. Therefore, findings from conventional VR should not automatically be generalized to IVR. A recent systematic review specifically examining immersive VR in pediatric CP identified 15 studies and concluded that IVR was generally non-inferior to conventional rehabilitation, with preliminary additional benefits in some domains. The review also emphasized substantial heterogeneity across interventions and outcomes. A pilot study using immersive VR to improve walking abilities in children with bilateral CP

demonstrated the feasibility of an immersive approach and highlighted the potential of ecological, interactive environments for gait training.

METHODOLOGY

This manuscript was developed as a structured narrative literature review to establish the scientific rationale for investigating immersive virtual reality-based dual-task training in ambulatory children with pediatric neurological disorders. Literature was identified from PubMed/MEDLINE, Scopus, Web of Science, PEDro and Google Scholar using combinations of the following concepts: “pediatric neurological disorders,” “cerebral palsy,” “children,” “virtual reality,” “immersive virtual reality,” “head-mounted display,” “dual-task,” “dual-task training,” “cognitive-motor,” “executive function,” “attention,” “balance,” “gait,” “walking,” “functional mobility,” and “rehabilitation.” Boolean operators AND and OR were used to combine population, intervention and outcome terms. Reference lists of relevant systematic reviews and key primary studies were also considered to identify additional literature. Priority was given to systematic reviews, meta-analyses, randomized controlled trials, controlled clinical studies and influential rehabilitation literature. Recent evidence available through 2026 was considered when directly relevant to the topic. Studies involving children and adolescents with neurological or neurodevelopmental disorders were prioritized; adult-only studies were used only when necessary to explain a theoretical construct or rehabilitation principle. Literature concerning VR without a pediatric neurological population was not used as direct evidence of pediatric effectiveness. Particular attention was paid to whether interventions were immersive, non-immersive or semi-immersive, whether a cognitive task was explicitly incorporated, and whether outcomes represented cognition, balance, gait, gross motor function or functional mobility. Because this article is a narrative literature review rather than a systematic review with a registered protocol, no pooled effect estimate was independently calculated and no new participant-level data were analyzed. The synthesis was organized around four domains: (1) cognitive and executive-function problems in pediatric neurological disorders; (2) effects of dual-tasking on pediatric gait and balance; (3) evidence for VR and immersive VR in pediatric rehabilitation; and (4) the emerging evidence for DTT and the rationale for combining DTT with IVR. The review also considered methodological limitations reported in the literature, including small sample sizes, heterogeneity of VR platforms, variable intervention dosage, inconsistent cognitive outcomes, limited follow-up and inadequate reporting of transfer to real-world function. The synthesis compared findings across these evidence streams rather than calculating a new pooled effect estimate. Particular attention was given to intervention characteristics, population, outcome measures, clinical relevance, and limitations. Studies were prioritized when they included children or adolescents with neurological or neurodevelopmental conditions and reported functional or cognitive outcomes relevant to mobility. Adult studies were not used as direct evidence of pediatric effectiveness. Because this manuscript is a narrative review, the synthesis is descriptive and no original participant-level analysis was performed.

Table 1. Conceptual framework for IVR-based dual-task training

Domain	Example IVR task	Target process	Possible outcome
Motor	Virtual walking, stepping, obstacle negotiation	Postural control and mobility	TUG, gait speed, GMFM, balance
Attention	Respond to visual/auditory targets while walking	Selective/sustained attention	Cognitive task accuracy
Working memory	Remember and reproduce target sequences	Working memory	Memory/executive-function score
Inhibition	Ignore distractors and respond only to relevant targets	Inhibitory control	Response accuracy/time
Cognitive flexibility	Switch rules or target categories during movement	Set shifting	Switching accuracy/cost

RESULTS AND DISCUSSION

The literature synthesis indicates three consistent findings relevant to the proposed intervention. First, VR-based rehabilitation can improve several motor outcomes in children with CP, particularly balance and gross motor function. Second, the addition of cognitive tasks to mobility creates measurable cognitive-motor interference, demonstrating that single-task walking does not capture all functional demands. Third, DTT is emerging as a potentially effective rehabilitation strategy, with recent randomized evidence indicating improvements in balance, gross motor function and functional mobility. In contrast, direct evidence for IVR-based DTT targeting both cognition and mobility remains insufficient, which represents the principal research gap.

Evidence for VR and motor function is relatively strong compared with evidence for cognition. Warnier and colleagues' systematic review found favorable effects of VR therapy on balance and walking in children with CP. Liu and colleagues subsequently reported, across 16 randomized controlled trials involving 513 children, significant improvements in Pediatric Balance Scale and Berg Balance Scale outcomes as well as gross motor function. Other meta-analyses have similarly identified benefits for balance, motor function and activities of daily living. These findings suggest that virtual environments can provide meaningful motor practice rather than simply entertainment. However, differences in technology, therapist supervision, treatment duration and control interventions limit direct comparison between studies.

The distinction between immersive and non-immersive VR is important. Non-immersive systems may offer useful visual feedback and game-based practice but do not necessarily create a strong sense of presence. IVR, particularly through head-mounted displays, can surround the child with a simulated environment and potentially increase attentional engagement. The systematic review by Pazzaglia and colleagues identified 15 studies of immersive VR in pediatric CP and reported promising but heterogeneous findings. The available evidence suggests that IVR can be integrated safely with conventional therapy and may improve motivation and functional capacity, but the evidence base remains too heterogeneous to establish a definitive superiority over other VR modalities.

A key advantage of IVR is its ability to manipulate environmental complexity. A child can be asked to walk toward a virtual target, avoid obstacles, remember a sequence, select a correct object, respond to a changing rule or divide attention between two streams of information. These tasks approximate real-world mobility more closely than repetitive walking in an unobstructed corridor. In theory, such training may improve anticipatory control and the allocation of attention during movement. Nevertheless, the ecological validity of an intervention should be demonstrated through transfer outcomes rather than assumed from the appearance of the virtual environment.

Dual-task research provides strong justification for targeting cognitive-motor interference. The systematic review by Ghai and colleagues found that children with CP walk more slowly under dual-task conditions than under single-task conditions, with a pooled mean difference of approximately 0.29 m/s. Carcreff and colleagues also showed that dual tasks reduce gait performance in children with CP and that greater task complexity is associated with greater reductions. These findings indicate that the child's walking capacity may deteriorate when attention is divided. From a clinical perspective, this is relevant to school corridors, playgrounds, community environments and sports, where children rarely walk without simultaneously processing information.

The clinical relevance of dual-task cost extends beyond gait speed. During dual-task conditions, children may alter cadence, step length, variability, postural strategies and attentional allocation to maintain stability. A child may prioritize the motor task, resulting in poorer cognitive accuracy, or prioritize the cognitive task, increasing the risk of gait deterioration. Understanding this trade-off may help physiotherapists identify children who appear independent during simple mobility tests but experience difficulty in complex environments. Therefore, assessment should consider both motor performance and cognitive-motor interference.

The emerging intervention literature on DTT is encouraging. The 2026 systematic review and meta-analysis by Peng and Sun included 11 randomized controlled trials with 582 children with CP. Compared with conventional rehabilitation, DTT improved balance, GMFM dimensions D and E, and TUG performance. The magnitude of improvement varied by outcome and heterogeneity was substantial for some measures, leading the authors to

VR evidence provides a strong foundation for this approach. Systematic reviews and meta-analyses generally support improvements in balance and gross motor function following VR-based rehabilitation in children with CP. Immersive VR adds the potential advantages of presence, engaging multimodal feedback and controlled manipulation of environmental complexity. However, the current immersive evidence remains relatively small and heterogeneous, and there is insufficient evidence to conclude that immersion alone is superior to non-immersive VR or conventional therapy.

The dual-task literature provides the second component of the rationale. Observational studies consistently demonstrate that concurrent cognitive demands can reduce walking performance, while emerging intervention studies suggest that DTT can improve balance, gross motor function and functional mobility. Recent randomized evidence is encouraging, but differences in cognitive tasks, motor tasks, intervention dose and outcome measures limit direct comparison. Cognitive outcomes are also less consistently assessed than motor outcomes, leaving an important gap in the literature.

Combining IVR and DTT may allow therapists to provide graded, task-specific cognitive-motor practice. A program can progress from simple target identification during standing or stepping to walking, obstacle negotiation, direction changes and complex decision-making. Cognitive components can address attention, working memory, inhibition and cognitive flexibility, while mobility tasks can address balance, gait and functional transitions. Such progression should be individualized according to the child's developmental level and functional capacity and should incorporate principles of repetition, feedback, task specificity and progressive challenge.

Future research should use adequately powered controlled designs, clearly define participant characteristics, standardize the IVR platform and intervention dose, and report the cognitive and motor components in sufficient detail for replication. Both cognitive and mobility outcomes should be measured using validated tools, with dual-task cost included where possible. Safety, adherence, cybersickness, fatigue and adverse events should also be reported. Importantly, follow-up and real-world transfer outcomes are required to determine whether improvements achieved in the virtual environment generalize to everyday mobility.

In conclusion, IVR-based DTT is a scientifically plausible and clinically promising intervention, but its effectiveness on both cognitive function and functional mobility in ambulatory children with pediatric neurological disorders remains insufficiently established. The convergence of evidence from VR, immersive rehabilitation and dual-task training provides a clear rationale for a rigorous clinical trial. Such research may help move pediatric physiotherapy toward engaging, ecologically relevant interventions that prepare children to think, move and participate simultaneously in real-world environments.

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