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REVIEW PAPER

# Applications of Motor Learning Strategies in Children With Neurodevelopmental Disorders: A Scoping Review

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## Abstract

Synthesized knowledge of motor learning strategies could be used to facilitate the motor development of children with neurodevelopmental disorders (NDDs). To map the current research, we followed the established framework and protocol for scoping reviews. Among the 25 papers, the most studied strategies include dual-task and observational learning. The studies predominantly involved children with cerebral palsy, but research is growing among children with intellectual disability, autism and developmental coordination disorder. Most of the studies integrated motor learning strategies in researcher-led interventions that are delivered over several weeks in school, home, or clinic settings. Further research using robust study designs and those that facilitate the use of motor learning strategies by practitioners who provide support for children with NDDs are needed.

**Keywords** Motor learning · Dual-task · Observational · Children · Neurodevelopmental disorder

Motor skills include a wide range of abilities, from simple movements like reaching or grasping toys to complex tasks such as playing a musical instrument or performing sports-related movements like dodging (Matheis & Estabillo, 2018). The acquisition of these motor skills plays a crucial role in child development, as these abilities are not only important for accomplishing activities of daily living but also influence other aspects of development, such as cognitive, social, and emotional growth (Leonard & Hill, 2014; Veldman et al., 2019). However, acquisition of motor skills often presents unique challenges for children with neurodevelopmental disorders (NDDs), including attention deficit-hyperactivity disorder (ADHD), autism spectrum disorder (ASD), cerebral palsy (CP), developmental coordination disorder (DCD), dyslexia, and intellectual disability (ID) (American Psychiatric Association, 2022).

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While each NDD is unique in its clinical presentation, they share a common thread of impairments in movement control, coordination, or cognition, which could affect both gross and fine motor skills. For instance, children with ASD have been shown to exhibit difficulties in motor coordination and imitation, which can impact social interaction and play (Zampella et al., 2021). Children with DCD, on the other hand, struggle with fundamental motor tasks such as handwriting or catching a ball, particularly in activities that require motor planning or sequencing of movements (Biotteau et al., 2016). Understanding how to effectively facilitate motor skill acquisition in children with NDDs is important, as it holds the potential to enhance their overall quality of life by contributing positively to their overall physical competence and independence (Cameron et al., 2016; Eguia et al., 2023).

Motor skill acquisition in children with NDDs is facilitated through motor learning strategies in the early years of their lives. Although there is a large body of research on motor learning strategies, their application in pediatric populations, particularly among those with NDDs, remains underexplored (Eguia et al., 2023). This knowledge gap is partly due to a lack of motor learning research on younger individuals, as most studies on motor learning involve older individuals in laboratory settings (Kleynen et al., 2015). Researchers argue that exploring the controlled application

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of motor learning strategies in pediatric settings could be challenging due to the necessity of adapting strategies according to individual child characteristics and reactive factors during intervention (Ryan et al., 2020). This need for adaptation is particularly heightened among children with NDDs. Furthermore, the inconsistent use of motor learning terminologies among practitioners and researchers adds complexity to the literature search (Zwicker & Harris, 2009), hindering the interpretation of study results (Ryan et al., 2020). Consequently, translating evidence-based strategies into practice for children with NDDs continues to be a challenge (Levac et al., 2009).

Motor learning strategies include analogy learning, dual-task learning, discovery learning, errorless learning, mental practice, observational learning, and trial and error (Kleynen et al., 2020). Analogy learning strategies deliver instructions by using a biomechanical metaphor, effectively concealing the complex rules for performing a movement task (Masters, 2000). An example of analogy learning instruction would be *"Shoot the ball as if you are trying to put cookies into a cookie jar on a high shelf"* to teach learners to shoot the ball into the basketball hoop (Tse & Masters, 2019). Dual-task learning involves the simultaneous performance of a motor or cognitive secondary task that requires attention, whereas discovery learning is described as one where skills are practiced without guidance or feedback from any information source (Kleynen et al., 2020). Errorless learning consists of constraining the environment to minimize practice errors, which is believed to limit the involvement of working memory during motor performance (Maxwell et al., 2001). One way to apply errorless learning when teaching movement tasks is by setting up the environment to minimize errors. For example, in a dart-throwing exercise for someone with sensorimotor issues, a larger dartboard and brightly colored bullseye could reduce the chance of missed throws. Mental practice or movement imagery involves a learner imagining oneself performing a movement task without actual actions (Kleynen et al., 2020). Observational learning has been described as one where a learner determines the spatial and temporal features of movement tasks through observation, whereas trial and error involves repeated attempts by the learner to perform a movement task while errors are detected and corrected (Kleynen et al., 2014).

Previous reviews have synthesized evidence of specific motor learning strategies but for typically developing children (e.g., implicit motor learning strategies, van Abswoude et al., 2021; focus of attention, van der Veer et al., 2022; motor imagery, Behrendt et al., 2021). While van Abswoude et al. (2021) assessed both typically developing children and those with developmental disabilities, they identified only seven studies with significant variability in methodological rigor. Similarly, van der Veer and colleagues (2022) found 13 studies of low methodological quality, with only six involving children with atypical development, and focused narrowly on implicit and explicit motor learning strategies. For children with NDDs, an earlier review of motor learning strategies in the context of physical therapy interventions suggested that the strategies need to be understood better to be integrated into interventions (Levac et al., 2009). More recently, motor learning elements and principles have been reviewed but limited to the diagnosis of CP (e.g., feedback provision, Schoenmaker et al., 2023; motor learning theories for upper limb function, Taghizadeh et al., 2022; virtual reality, Demers et al., 2021). A review that maps motor learning strategies specifically across a range of NDDs could facilitate knowledge translation and integration into the practice of occupational therapists, physiotherapists, and trainers. We therefore aim to identify the specific motor learning strategies that have been applied to specific NDD diagnoses and the reported outcomes. We seek to aid the translation of research to practice by consolidating and mapping the research that examined motor learning strategies in children with NDDs. Considering our research objective, a scoping review is deemed appropriate. Scoping reviews provide a comprehensive platform for exploring the breadth and diversity of available evidence (Tricco et al., 2018). Furthermore, they are well-suited for the systematic examination of research characteristics pertaining to a given topic, the identification of knowledge gaps, and the shaping of future research endeavors (Peters et al., 2021), and contribute to reducing research waste (Khalil et al., 2022).

## Methods

We registered this review on OSF Registries (https://doi.org/10.17605/OSF.IO/DSQYR). The procedures were guided by the framework for scoping reviews proposed by Arksey and O'Malley (Arksey & O'Malley, 2005) and the enhanced protocol endorsed by the Joanna Briggs Institute (JBI) (Peters et al., 2021). The first five steps of the framework consisted of (1) identifying the research question, (2) identifying relevant studies, (3) selecting studies, (4) charting the data, and (5) collating, summarizing, and reporting the results. We deemed the sixth step, which involved expert consultation, unnecessary for this review. Following the JBI protocol for scoping reviews, we did not conduct a critical appraisal to assess the risk of bias.

### Identifying the Research Question

Using the Population, Concept, and Context (PCC) format for scoping reviews (Kao et al., 2017), the following review question is posed: *What motor learning strategies (concept) have been examined among children with NDDs (population) as a means to acquire movement skills (context)?*

The specific objectives of this review are further defined below:

1. To identify the specific motor learning strategies that have been used in studies of children with NDDs.
2. To identify the specific diagnostic groups within NDDs for which motor learning strategies have been applied.
3. To map the research, including study designs and outcomes, to inform future research directions and practice recommendations.

### Identifying Relevant Studies

We located published studies that included quantitative, qualitative, and mixed-methods designs. We conducted the search in November 2023 and did not apply any restrictions for the date of paper publication. We updated the search in January 2024. We searched the following electronic databases: PubMed, Scopus, EBSCO, ProQuest, JSTOR, and Web of Science. We used the Boolean operators "AND", "OR", and "*" to conduct the search with multiple combinations of keywords. Based on the PCC elements outlined in the review question, we constructed the following search phrases: ("child*" OR "early child*" OR "young child*" OR "adolescen*" OR youth) AND (("motor" OR "movement") AND ("skill" OR "task" OR "development")) OR "skill acquisition" OR "locomotor" OR "manipulative" OR "stability") AND ("errorless learning" OR "analogy learning" OR "trial and error" OR "observational learning" OR "dual-task" OR "discovery learning" OR "mental practice" OR "movement imagery") AND ("neurodevelopmental disorder*" OR "cerebral palsy" OR "down syndrome" OR autism OR "developmental coordination disorder" OR dyspraxia OR ADHD OR "intellectual disability" OR "special education needs"). The search results were uploaded into Zotero 6.0.15 (Digital Scholar, VA, USA).

### Selecting Studies

The study selection process followed the Preferred Reporting of Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement (Page et al., 2021) and the PRISMA Extension for Scoping Reviews (PRISMA-ScR; Tricco et al., 2018), as shown in Fig. 1. Two reviewers performed the selection of studies independently. After removal of duplicates, the titles were screened, and those that were irrelevant to the review question were excluded. The reviewers read the abstracts of the selected titles to assess each record's eligibility. Studies were selected if they met the following criteria: (1) the participants were aged 3 to 17 years and represented a diagnostic group within NDDs, (2) involved learning a movement task – i.e., the study should have a learning phase, (3) tested a motor learning strategy,; (4) reported on original research – i.e., not a review, and (5) the paper was written in English. Moreover, studies were excluded if they (1) involved a movement task that was not sufficiently complex – e.g., pressing buttons (van Abswoude et al., 2021), (2) focused on instrument validation, or (3) were published study protocols, conference abstracts, or dissertations. The reviewers' selection results were compared, and any inconsistency was resolved through discussion and consensus.

### Charting the Data

Following the JBI protocol for scoping reviews (Peters et al., 2021), the following data were charted: author(s), title, year of publication, study design, aim(s) of the study, participants, motor learning strategy used, settings, measures and outcomes, and main findings. Data extraction was performed by one reviewer and verified by a second reviewer for accuracy.

### Collating, Summarizing, and Reporting the Results

Two reviewers collaboratively collated the data following a framework based on the specific NDD and the types of motor learning strategies that were identified by Kleynen and colleagues (2020). We summarized the results descriptively and report them in the next section.

## Results

As shown in Fig. 1, the electronic search yielded a total of 805 articles. Based on the titles, 220 articles were identified. Following the review of abstracts, we found 25 papers that met our selection criteria. The papers were published between the years of 2010 to 2023. The study designs utilized control groups ($n = 18$) including six randomized controlled trials (RCTs), cohort samples that compared NDD groups with typically developing groups ($n = 4$), and single NDD groups without control ($n = 3$). The main findings are summarized according to specific NDDs and motor learning strategies in Table 1.

### Cerebral Palsy (CP)

Among children with CP, the papers reported on the following motor learning strategies: dual-task learning ($n = 4$), observational learning ($n = 4$), errorless learning ($n = 1$), trial and error ($n = 1$), and movement imagery ($n = 1$). Three of the studies that used dual-task targeted balance and walking performance of the participants (Okur et al., 2022; Tadvalkar & Metgud, 2023; Uysal et al., 2023); one study aimed to improve hand function (Nekar Daekook et al., 2022). All four studies involved interventions in clinical settings that

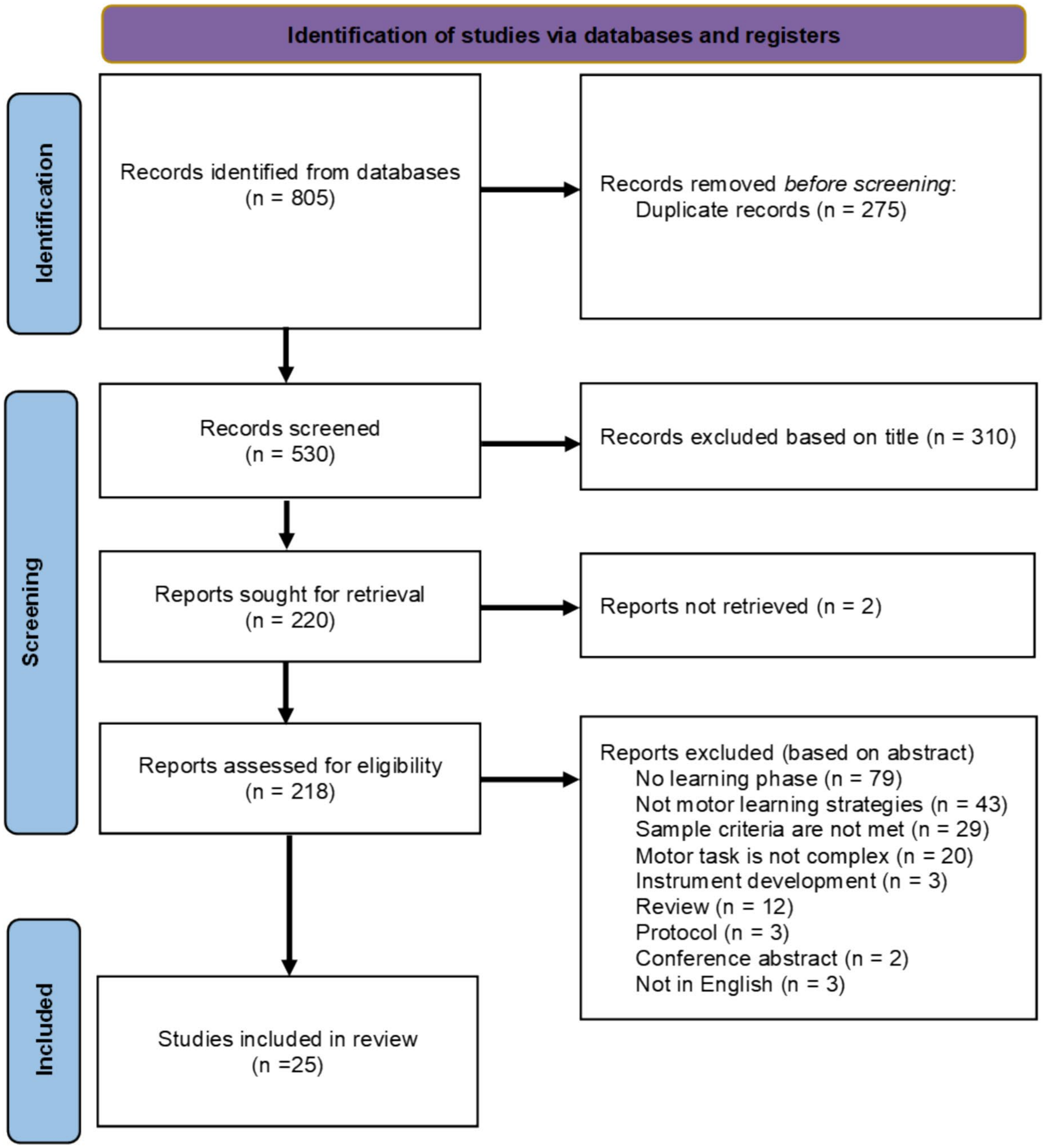


**Fig. 1** PRISMA flow diagram (Page et al., 2021) for article selection

were facilitated by physiotherapists, with one study using a tele-rehabilitation platform (Tadvalkar & Metgud, 2023). All four studies reported improved outcomes following dual-task training, but only one study reported that dual-task training is more advantageous compared to a control group (Uysal et al., 2023). One study reported comparable outcomes between dual-task and control groups (Nekar Dae-kook et al., 2022), whereas two studies did not utilize control groups in their study designs (Okur et al., 2022; Tadvalkar & Metgud, 2023).

Three studies used observational learning, but the findings of one study were reported in two papers (i.e., Simon-Martinez et al., 2020a, 2020b). All three studies focused on upper limb functions (Nuara, et al., 2019; Sgandurra et al., 2013; Simon-Martinez et al., 2020a, 2020b) where therapists facilitated the interventions in clinical contexts, with one study adding the practice of tasks at home (Nuara, et al., 2019). Verbal cues or feedback were provided to the children in two studies (Nuara et al., 2019; Sgandurra et al., 2013). All studies suggested benefits associated with observational

**Table 1** Settings and Main Findings of Motor Learning Studies Involving Samples of Children with Neurodevelopmental Disorders

| NDD | Author/Year | Strategy | Study Design | Setting | Interventions/Tasks | Main findings |
|---|---|---|---|---|---|---|
| CP | Nekar Daekook et al., 2022 | Dual-task | Pretest-Posttest control group design | Clinic-based training in a rehabilitation center; intervention facilitated by physiotherapists. | Basic hand function training (conventional) vs. Basic hand function + visual perception task (dual-task)<br>3 sessions/wk; 4 weeks | Dual-task training and conventional training both improved hand function but only dual-task training improved visual perception ability. |
| | Okur et al., 2022 | Dual-task | Self-controlled clinical design | Clinic-based training in a rehabilitation center; intervention facilitated by physiotherapists. | Balance and walking training (conventional), followed by Balance and walking + cognitive task (dual-task)<br>2 sessions/wk; 8 weeks for each condition | Dual-task in addition to conventional training further improved gait parameters, gross motor function, functional movement skills, and health-related quality of life in children with spastic diplegic CP. |
| | Tadvalkar & Metgud, 2023 | Dual-task | Pretest-Posttest one group design | Telerehabilitation training facilitated by physiotherapists. | Balance and walking exercise + secondary motor task<br>3 sessions/wk; 6 weeks | Dual-task training via telerehabilitation improved balance, coordination, and functional mobility of children with CP at GMFCS levels I and II. |
| | Uysal et al., 2023 | Dual-task | Randomized controlled trial | Clinic-based training in a rehabilitation center with the intervention facilitated by physiotherapists. | Lower limb strengthening (conventional) vs. Balance and walking exercises + cognitive task (dual-task)<br>3 sessions/wk; 12 weeks | Dual-task training was advantageous for balance, fitness, and quality of life of children with CP at GMFCS levels I and II. |
| | Nuara et al., 2019 | Observation | Time series one group design | Home-based training delivered through online videos, facilitated by therapists. | Upper limb movements following a video demonstration + interaction with another child<br>5 consecutive days/wk; 4 weeks | Action observation combined with child-to-child interaction improved hand motor function in unilateral CP. |
| | Sgandurra et al., 2013 | Observation | Randomized controlled trial | Clinic-based training in two child rehabilitation centers with the intervention facilitated by therapists. | Upper limb movements + verbal instructions (control) vs. Upper limb movements + video demonstration (observation)<br>Daily; 15 consecutive days | Action observation training improved upper limb function in daily activities of children with unilateral CP. |

**Table 1** (continued)

| NDD | Author/Year | Strategy | Study Design | Setting | Interventions/Tasks | Main findings |
|---|---|---|---|---|---|---|
| | Simon-Martinez et al., 2020a | Observation | Randomized controlled trial | Day camp model with the intervention facilitated by physiotherapists. | Unimanual upper limb actions + video games + verbal instructions (control) vs. Unimanual upper limb actions + video demonstration (observation)<br>15 sessions over 9 days | Action observation did not differ from control in improving bimanual hand performance, body functions, and manual activity among children with unilateral CP. |
| | Simon-Martinez et al., 2020b | Observation | Randomized controlled trial | Day camp model with the intervention facilitated by physiotherapists. | Unimanual upper limb actions + video games + verbal instructions (control) vs. Unimanual upper limb actions + video demonstration (observation)<br>15 sessions over 9 days | Action observation shortened the movement time for reaching tasks and led to limited benefit in movement patterns. |
| | van Abswoude et al., 2015 | Errorless learning | Pretest-Posttest control group design | School-based training of an aiming task, facilitated by researchers. | Boccia aiming task with gradually increasing size of target (error-strewn) vs. gradually decreasing size of target (errorless)<br>1 practice session | Both errorless and error-strewn learning conditions improved aiming accuracy and stable motor performance of the aiming task in children with CP. Children with low motor proficiency benefited from fewer errors during practice. |
| | Cabral-Sequeira et al., 2016 | Movement imagery | Pretest-Posttest control group design | Laboratory-based study with the experiment conducted by researchers. | Tabletop task of aiming a hand-held pointer towards a target following mental rehearsal (motor imagery) vs. Playing the "tetris" game by manipulating a keyboard (control)<br>Daily; 2 consecutive days | Motor imagery led to improved and stable speed and quality of upper limb movements among adolescents with hemiparetic CP. The addition of physical practice to motor imagery enhanced the learning effects. |
| | Burtner et al., 2014 | Trial and error | Time series cohort design (hemiplegic CP and typical development) | Laboratory-based study with the experiment conducted by researchers. | Coordinated tracking task involving elbow flexion and extension with 100% feedback vs. 62% feedback<br>Daily; 2 consecutive days | More frequent feedback from trial and error led to retention of an upper limb motor skill; lower accuracy and consistency among children with spastic hemiplegic CP compared to those with typical development.<br>Children with CP use feedback from trial error in a manner similar to children with typical development. |

**Table 1** (continued)

| NDD | Author/Year | Strategy | Study Design | Setting | Interventions/Tasks | Main findings |
|---|---|---|---|---|---|---|
| ID | Mikolajczyk & Jankowicz-Szymanska, 2015a | Dual task | Pretest-Posttest control group design | School-based training facilitated by researchers. | Postural stability exercise + upper limb motor task (dual-task)<br>No information about control<br>3 sessions/wk; 12 weeks | Dual-task training led to improved postural stability in adolescents with moderate ID. |
| | Mikolajczyk & Jankowicz-Szymanska, 2015b | Dual task | Pretest-Posttest control group design | School-based training facilitated by physiotherapists. | Postural stability exercise + upper limb functional activity (dual-task) vs. No intervention (control)<br>3 sessions/wk; 12 weeks (continuation of earlier study) | The extended dual-task training improved the static balance of adolescents with moderate ID. |
| | Capio et al., 2013 | Errorless learning | Pretest-Posttest control group design | School-based training facilitated by researchers. | Overhand throwing task with a gradually increasing target size (error-strewn) vs. gradually decreasing target size (errorless)<br>1 session/wk; 4 weeks | Errorless learning improved movement form, and increased throwing activity during free play to a greater extent than error-strewn learning among children with ID. |
| | Capio & Eguia, 2021 | Errorless learning | Pretest-Posttest control group design | School-based training facilitated by researchers. | Object control skills (throw, roll, catch, kick, dribble, strike) with gradually increasing task difficulty (errorless) vs. Waitlist (control)<br>1 session/wk; 8 weeks | Errorless learning led to significant improvements in object control skills proficiency of children with ID. |
| | Hemayattalab & Movahedi, 2010 | Movement imagery | Pretest-Posttest control group design | School-based training facilitated by researchers. | Basketball free throw with Movement imagery vs. Physical practice vs. Physical practice followed by Movement imagery vs. Movement imagery followed by Physical practice vs. No practice (control)<br>Daily; 24 consecutive days | All practice conditions led to improved skill performance; movement imagery followed by physical practice led to the greatest improvement among adolescents with ID. |
| ASD | Heidari et al., 2021 | Observation | Pretest-Posttest control group design | Laboratory-based study with the experiment conducted by researchers. | Overarm throw with video demonstration + physical practice (observation) vs. no intervention (control)<br>Daily; 3 consecutive days | Observational learning led to improvements in throwing accuracy, visual search behaviour, and duration of quiet eye among children with and without ASD. |

**Table 1** (continued)

| NDD | Author/Year | Strategy | Study Design | Setting | Interventions/Tasks | Main findings |
|---|---|---|---|---|---|---|
| | Saber Sotoodeh & Taheri-Torbati, 2021 | Observation | Pretest-Posttest two-arm cohort design (ASD and typical development) | Laboratory-based study with the experiment conducted by researchers. | Underarm throw with Video demonstration + physical practice vs. Point light display model + physical practice<br>Daily; 2 consecutive days | Observational learning using point-light display led to better skill performance compared to observational learning using video demonstration among both children with ASD and with typical development. |
| | Taheri-Torbati & Sotoodeh, 2018 | Observation | Pretest-Posttest two-arm cohort design (ASD and typical development) | Laboratory-based study with the experiment conducted by researchers. | Underarm throw with Video demonstration + physical practice vs. Live demonstration + physical practice<br>Daily; 2 consecutive days | Observational learning using video or live demonstration both led to improved skill performance among male children with ASD and with typical development. |
| | Tse & Masters, 2019 | Analogy | Pretest-Posttest control group design | Laboratory-based study with the experiment conducted by researchers. | Basketball shooting with visual analogy vs. verbal analogy vs. explicit instructions vs. no instruction (control)<br>1 practice session | Verbal and visual analogy learning were comparable with explicit learning in improving basketball shooting performance in children with ASD; visual analogy learning led to sustained performance during transfer tasks. |
| DCD | Inacio et al., 2023 | Dual task | Time series cohort design (DCD and typical development) | School-based training facilitated by researchers. | Rhythmic stepping task + cognitive task<br>2 sessions/wk; 7 weeks | Rhythmic stepping with dual-task demands led to improvements in step timing in children with probable DCD that is comparable to typically developing children. |
| | Jahanbakhsh et al., 2020 | Dual task | Pretest-Posttest control group design | Laboratory-based study with the experiment conducted by researchers. | Balance and walking exercise (single-task) vs. Balance and walking exercise + cognitive task (dual-task) vs. No exercise (control)<br>3 sessions/wk; 8 weeks | Dual-task training improved the balance performance of children with DCD, more than the single-task training. |

**Table 1** (continued)

| NDD | Author/Year | Strategy | Study Design | Setting | Interventions/Tasks | Main findings |
|---|---|---|---|---|---|---|
| | Scott et al., 2023 | Movement imagery + Observation | Pretest-Posttest control group design | Home-based training facilitated by parents who received training on the intervention. | Practice of activities of daily living following Mental practice of the hand movements (motor imagery) while watching a Video demonstration (observation) vs. Playing a computer game (control)<br>1 session/wk; 4 weeks | Combined observation and motor imagery learning led to greater improvements in shoelace tying and cup stacking, relative to the control condition, among children with DCD. |
| DCD + ADHD | Izadi-Najafabadi et al., 2022 | Discovery | Randomized controlled trial | Clinic-based training in a hospital rehabilitation department with the intervention facilitated by occupational therapists. | Cognitive Orientation to Occupational Performance (CO-OP) consisting of Goal-Plan-Do-Check strategy to discover strategies to perform motor tasks (discovery) vs. Waitlist (control)<br>1 session/wk; 10 weeks | CO-OP which included discovery learning led to improvements in self-perceived motor performance and movement quality among children with DCD and those with DCD + ADHD. |
| DS | Büyükçelik et al., 2023 | Dual task | Randomized controlled trial | Clinic-based training in a hospital rehabilitation department with the intervention facilitated by physiotherapists. | Balance exercise + cognitive task (dual-task) vs. No intervention (control)<br>2 sessions/wk; 8 weeks | Dual-task training led to improved balance and functional independence in self-care among children with DS. |

learning in children with unilateral CP. One study did not have a control group in their study design (Nuara et al., 2019), while one study that compared video observation with watching computer games found clear advantages associated with observational learning (Sgandurra et al., 2013). One other study added observational learning with constraint-induced movement therapy (CIMT) and found the outcomes were comparable with using CIMT alone (Simon-Martinez et al., 2020a). They further reported that adding observational learning to CIMT led to faster task performance, – i.e., shortened movement time (Simon-Martinez et al., 2020b).

One study used trial and error in a laboratory and involved practicing discrete arm movements using a computer-based task, where children had to move a lever to replicate a movement trajectory displayed on a screen and receive feedback on their errors (Burtner et al., 2014). They found that trial and error led to improved motor performance in children with CP but with lower accuracy and consistency compared to children who are typically developing. In contrast, a school-based experiment compared errorless learning with an error-strewn approach when practicing an aiming task (van Abswoude et al., 2015). They reported that committing fewer errors during practice was associated with greater performance improvements and greater automaticity of movement. Thus, they suggested that minimizing errors could be a suitable strategy for children with CP. Finally, a laboratory study evaluated the effects of movement imagery training followed by physical practice among adolescents with CP who were learning an aiming task (Cabral-Sequeira et al., 2016). Compared to the control group who played a computer game, those who engaged in movement imagery displayed greater improvements in movement performance, which were stable at retention.

### Intellectual Disability (ID)

Among children with ID, dual-task learning (n = 2), errorless learning (n = 2), and movement imagery (n = 1) were examined. Two studies by a group of researchers utilized a dual-task strategy to improve postural balance in school-based settings. In both studies, both tasks were motor in nature, such as combining a balancing task (i.e., sitting on an exercise ball) and a reaching task (Mikolajczyk & Jankowicz-Szymanska, 2015a) and combining balance exercises with activities of daily living (Mikolajczyk & Jankowicz-Szymanska, 2015b). Both studies reported benefits to postural stability following dual-task interventions. Two studies by another group of researchers utilized errorless learning in school-based programs that targeted the object control skills of children with ID. The first study focused on the overhand throwing task and they found that children with ID improved their movement skills while displaying the ability to multitask (Capio et al., 2013). A second study applied errorless learning across a range of object control skills, such as catching and kicking, and reported significant and large improvements among the participants (Capio & Eguia, 2021). Finally, a school-based study tested movement imagery among adolescents with ID who were learning basketball free throws (Hemayattalab & Movahedi, 2010). They found that all practice conditions, whether physical practice, movement imagery, or combinations of physical practice and movement imagery in sequence led to significant improvements among the adolescents with ID. However, the greatest gains were found when movement imagery was followed by physical practice.

### Autism Spectrum Disorder (ASD)

In children with ASD, the motor learning strategies that have been examined include observational learning (n = 3) and analogy learning (n = 1). Two of the studies that used observational learning were laboratory-based, involved throwing tasks, and facilitated observation through videos (Heidari et al., 2021; Saber Sotoodeh & Taheri-Torbati, 2021). A third study compared the effects of video and live observations, also in a throwing task (Taheri-Torbati & Sotoodeh, 2018). All the studies reported that video observation was beneficial for children with ASD, but only one study utilized a control group (Heidari et al., 2021). No difference was found in the beneficial effects of video and live observation (Taheri-Torbati & Sotoodeh, 2018), but a point-light display (i.e., irrelevant information was removed) was more advantageous than video observation (Saber Sotoodeh & Taheri-Torbati, 2021) among both children with ASD and children with typical development.

One school-based study facilitated the practice of a basketball shooting task using verbal (i.e., *"Shoot the ball as if you are trying to put cookies into a cookie jar on a high shelf"*) and visual (i.e., picture of a child putting cookies into a cookie jar) analogies, which were compared with explicit biomechanical instructions and no-instruction control (Tse & Masters, 2019). Movement performance improved for all children except those in the no-instruction control group. Only those who were given visual analogy displayed stable performance one day after learning (i.e., retention) and when the hoop distance was increased (i.e., transfer).

### Developmental Coordination Disorder (DCD)

The motor learning strategies that have been examined in children with DCD include dual-task learning (n = 2), discovery learning (n = 1), observational learning (n = 1), and movement imagery (n = 1). Two studies examined the use of dual-task learning. One study was school-based and utilized a combination of motor and cognitive auditory tasks (Inacio et al., 2023). Children with DCD and a comparison group of typically developing children practiced stepping with a concurrent auditory Stroop task, and displayed improvements in step timing following the training period, which were retained five weeks later. The other study was laboratory-based and utilized a combination of motor and cognitive tasks (Jahanbakhsh et al., 2020). The dual-task training group practiced balance activities while engaging in cognitive tasks such as counting and memory games. Compared to groups that performed only the balance activities (i.e., single task) and that did not receive any training (i.e., control), the dual-task group displayed greater improvements in both static and dynamic balance.

The study that used discovery learning was conducted in a clinical setting facilitated by occupational therapists, where discovery learning was used in the context of the Cognitive Orientation to Occupational Performance (CO-OP) (Izadi-Najafabadi et al., 2022). The participants included children with DCD and those with cooccurring ADHD. Compared with participants in the waitlist control group, those who participated in CO-OP displayed greater improvements in self-perceived and therapist-rated motor performance. Improvements in neural connectivity, however, were not observed among those who were concurrently diagnosed with ADHD. Finally, one study investigated the efficacy of a home-based and parent-led intervention that combined observational learning and movement imagery for learning daily movement tasks (Scott et al., 2023). Compared with those in the control group, those in the training group displayed greater improvements in the shoelace tying and cup stacking tasks, but not in the shirt buttoning and cutlery tasks. In particular, the study recommended that combined observational learning and movement imagery is useful for movement tasks that are completely novel for children.

### Down Syndrome

One study investigated the effects of a dual-task balance training delivered by physiotherapists for children with DS (Büyükçelik et al., 2023). Postural and balance motor tasks (e.g., sit to stand, standing on one leg) were combined with cognitive tasks (e.g., naming animals, identifying colors). When compared to a control group, the dual-task group displayed significantly better balance and functional performance following the training period.

The summary in Table 2 shows that the use of motor learning strategies has been most examined in children with CP (n = 11). The other NDDs for which motor learning strategies had been applied included ID (n = 5), DCD (n = 4), ASD (n = 4), ADHD (n = 1) and Down syndrome (DS, n = 1). The most commonly used motor learning strategies were dual task (n = 9) and observational learning (n = 7). Fewer studies have examined errorless learning (n = 3) and movement imagery (n = 3). Only one study each used analogy learning, discovery learning, and trial and error.

## Discussion

In this scoping review, we aimed to contribute to translating research to practice by mapping the research that examined motor learning strategies as a means to acquire motor skills among specific diagnostic groups of NDDs. Guided by a framework for neurorehabilitation (Kleynen et al., 2020) and focused on functional motor skills rather than simple tasks such as pressing of buttons or following sequences, we identified three main findings. First, most evidence of motor learning strategies has been generated for children with CP. Among the diagnoses under the umbrella of NDDs (American Psychiatric Association, 2022), CP might be considered to have primarily motor impairments. The updated definition

**Table 2** Number of studies found for each motor learning strategy and diagnostic group

| Strategy | Diagnostic Group | | | | | |
|---|---|---|---|---|---|---|
| | CP | ASD | ADHD | DCD | ID | DS |
| Analogy | | 1 | | | | |
| Discovery | | | 1* | 1* | | |
| Dual-task | 4 | | | 2 | 2 | 1 |
| Errorless | 1 | | | | 2 | |
| Observational | 4 | 3 | | 1** | | |
| Trial and error | 1 | | | | | |
| Movement Imagery | 1 | | | 1** | 1 | |
| Total | 11 | 4 | 1 | 4 | 5 | 1 |

*Note:* *One study in the corresponding motor learning strategy involved two diagnostic groups and **one study involved two motor learning strategies; hence the overall total based on the total per diagnostic group is larger than the actual total of reviewed studies. Diagnostic groups: cerebral palsy (CP), autism spectrum disorder (ASD), attention deficit – hyperactivity disorder (ADHD), developmental coordination disorder (DCD), intellectual disability (ID), Down syndrome (DS) of CP specifies that it is characterized by impaired development of movement and posture (Sadowska et al., 2020). While impairments in other domains (e.g., socioemotional, cognitive) may also be apparent in children with CP, the primacy of motor impairments probably generates strong interest among motor learning researchers. Research involving other NDDs is also emerging, including for those where the primary issues are not motor impairments – i.e., ID, ASD. Second, most studies delivered interventions in real-life settings over several weeks (as opposed to one to two days in the laboratory), which could lead to programs that could be implemented in practice. However, many interventions were still delivered by researchers, which suggests the transfer of knowledge to practitioners (e.g., occupational therapists, physiotherapists, and trainers) could still be limited. Finally, while majority of the studies used control groups, fewer than a quarter of them were randomized controlled trials. This suggests that more robust evidence is needed to support the use of motor learning strategies in facilitating motor skills acquisition among children with NDDs.

In translating motor learning research to practice, we focused on children with NDDs to address their need for effective management of impairments in motor control and coordination. Research involving children with NDDs have focused on those with CP who are typically referred to physiotherapy for early intervention, where motor learning strategies are considered of great importance (Gordon & Magill, 2017). Our findings suggest that research on motor learning strategies for children with CP tends to veer toward practice contexts with clinical interventions delivered by therapists to address daily activities such as balance and hand function. While the reviewed studies generally show that dual-task strategy is suitable for children with CP, the learner's characteristics and the complexity of the tasks at hand should be considered. The concept of dual-task strategy entails the concurrent execution of two distinct tasks – either cognitive or motor – each characterized by varying degrees of difficulty (Kleynen et al., 2020). In children with CP, the level of challenge associated with motor tasks that are deemed automatic, such as walking, could vary according to their tone (i.e., spasticity) or affectation (e.g., diplegia, hemiplegia). Introducing an additional cognitive or motor load may pose an excessive challenge, potentially resulting in a decline in their overall task performance (Roostaei et al., 2021).

Therapists and trainers of children with CP likely integrate observational learning into practice through demonstrating the tasks themselves. Our reviewed studies suggest observational learning could be integrated into therapist-led training programs in a clinic, via telehealth, or in a day camp model in the form of video demonstrations. Together with emerging technologies, we might consider that observational learning by children could be facilitated by video games or virtual reality. For instance, virtual reality has been seen as a promising platform for improving the balance and motor skills of children and adolescents with CP (Ravi et al., 2017), but motor learning principles need to be integrated better when such systems are used (Demers et al., 2021). Future studies could explore digital technology-enabled observational learning, especially given the recent exponential growth in generative artificial intelligence.

While the definition of ID does not specify motor impairments and describes it to be characterized by impairments in functioning and adaptive behaviors (Schalock et al., 2021), it has been shown that the severity of ID is positively associated with problems in manual dexterity and balancing skills (Vuijk et al., 2010). It is promising that researchers have explored the use of motor learning strategies for children with ID. Errorless motor learning was proposed as a suitable strategy for children with ID because the relative lack of reliance on cognitive resources associated with this approach accommodates the cognitive impairments of children with ID (Capio et al., 2013). In contrast, a dual-task strategy that typically imposes concurrent cognitive and motor tasks (Kleynen et al., 2020) could exacerbate the difficulties that children with ID experience associated with their cognitive deficits. However, the studies that tested a dual-task strategy for children with ID used two concurrent motor tasks (Mikolajczyk & Jankowicz-Szymanska, 2015a, 2015b). As this is not consistent with how dual-task strategy is typically delivered (i.e., concurrent motor and cognitive tasks), there does not seem to be support for the use of dual-task strategy for children with ID. Considering the impairments of children with ID, a relatively less reliance on cognitive resources such as that in errorless motor learning could be considered by practitioners.

Children with DCD typically display impaired execution of coordinated motor actions that lead to slow, clumsy, or inaccurate movements (Biotteau et al., 2020), and so would benefit from effective motor learning strategies. A DCD diagnosis tends to be established when children reach school age (Vens et al., 2022), as the impairments affect school functions such as handwriting and performance in physical education. Hence, opportunities for early intervention tend to be rare, and interventions when they are provided tend to be focused on functional motor skills associated with school activities. As DCD impairments are not associated with cognitive deficits, motor learning strategies that require cognitive resources could be suitable in this condition. For instance, dual-task strategy appears promising, especially when the secondary task is designed to reinforce the primary motor task (Inacio et al., 2023; Jahanbaksh et al., 2020). They can also engage in discovery learning in the context of CO-OP (Izadi-Najafabadi et al., 2022), and in motor imagery combined with observational learning (Scott et al., 2023). These motor learning strategies appear to be important for learning complex motor tasks that involve multiple discrete movements performed in a sequence, which are particularly difficult for children with DCD (Cantin et al., 2014). While further studies are needed to establish robust evidence, the identified strategies appear to match the characteristics and needs of children with DCD.

ASD is characterized by social communication impairments, restricted interests, and a tendency for repetitive behaviors (Hodges et al., 2020). Despite motor impairments not being a defining factor in ASD, there has been growing evidence that motor deficits are, in fact, pervasive in children with ASD (Bhat, 2021; Odeh et al., 2022). As such, research in motor learning strategies for children with ASD is warranted. Thus far, only observational learning (Heidari et al., 2021; Saber Sotoodeh & Taheri-Torbati, 2021; Taheri-Torbati & Sotoodeh, 2018) and visual analogy (Tse & Masters, 2019) have been explored. However, these motor learning strategies are both heavily reliant on processing of visual input and could be challenging for children with ASD who often have impaired visuospatial abilities (Nejati et al., 2021). Given that all the reviewed studies were laboratory-based, there is currently limited evidence to identify practicable motor learning strategies for children with ASD.

### Recommendations for Future Research

Our review shows that the majority (72%) of the studies evaluated motor learning strategies in the context of clinic or school interventions that were delivered over several weeks. This suggests that most of the study designs enable the translation of research to practice, where motor learning strategies may be integrated to functional training programs. Only the studies involving children with ASD were limited to laboratory contexts, indicating a relatively bigger gap between research findings and practice. In contrast, previous reviews of motor learning research showed that studies were mostly in laboratory settings that involved short practice (e.g., one day) of simple tasks (e.g., Eguia et al., 2023; van Abswoude et al., 2021). However, our current review also shows that despite the contexts being mostly in practice settings, less than half (48%) of the interventions were delivered by therapists. Except for the case of children with CP, the interventions in our reviewed studies were mostly researcher-led. This may suggest an insufficient alignment between research designs and practitioners' needs which often leads to passive dissemination of evidence that is known to be ineffective (Shato et al., 2024). We therefore recommend that future studies should aim to engage practitioners in designing, delivering, and evaluating motor learning strategies in children with NDDs.

While RCT is considered the highest level of evidence of intervention effectiveness (Wallace et al., 2022), our review found only six RCTs most of which were conducted in children with CP. With growing evidence of sensorimotor issues in ID and ASD (Bhat, 2021; Odeh et al., 2022; Vuijk et al., 2010) and the deficits in complex movement planning in DCD (Cantin et al., 2014), RCTs are critically needed to identify suitable and effective motor learning strategies that will address the needs of children with these NDDs. Moreover, to facilitate uptake in practice, implementation science studies are also recommended to understand how practitioners could embed effective motor learning strategies into their real-world clinical contexts (Moir, 2018).

### Limitations

In searching for studies that specifically applied motor learning strategies in groups of children with NDD, we were guided by the neurorehabilitation framework for motor learning proposed by Kleynen and colleagues (2020). However, we note that there may be other motor learning strategies that were left out of our review by following the terminology of our adopted framework. For example, a number of studies have used attentional focus strategies for children with NDDs (Eguia et al., 2023), but attentional focus is considered a means of delivering the elements of instruction and feedback rather than a specific motor learning strategy. Considering the recently proposed Optimizing Performance through Intrinsic Motivation and Attention for Learning (OPTIMAL) theory (Wulf & Lewthwaite, 2016, 2021), which suggests that an external focus of attention contributes to the effectiveness, efficiency, and automaticity of movement, we may consider that further synthesis of evidence related to motor learning strategies should include research on the use of attentional focus. Given our purpose, we adopted a scoping review protocol which does not include a quality assessment of the reviewed studies. Nevertheless, we noted whether the mapped studies in this review adopted elements of robust study designs such as the use of control groups, the nature of the interventions (i.e., clinical, school, laboratory), and testing procedures. Moving forward, a systematic review and meta-analysis may be considered to evaluate publication bias and assess the quality of the evidence.

## Conclusion

In this scoping review, we identified that research on motor learning strategies for children with NDDs have so far focused on CP, with studies that include RCTs and delivered clinical interventions that addressed upper limb functions, balance, and locomotion. Practitioners may consider the use of dual-task strategies and observational learning for children with CP. There is emerging interest in applying motor learning strategies for children with ID, ASD and DCD but further research is needed to generate more robust evidence. Combined with careful consideration of individual learner characteristics, practitioners can explore motor learning strategies to address sensorimotor issues of children with NDDs. Future studies could also strengthen the involvement of practitioners and generate knowledge to support successful integration of motor learning strategies in real-life programs.

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