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REVIEW ARTICLE

Relationships between motor skills and executive functions in developmental coordination disorder (DCD): A systematic review

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ABSTRACT

Background: Individuals with developmental coordination disorder (DCD) experience motor skill and executive function (EF) difficulties that challenge their daily activities.

Aim/Objective: This systematic review aims to provide an in-depth analysis of the relationships between motor skills and EFs in studies among individuals with DCD.

Material and methods: We conducted a systematic search of eight electronic databases for articles (published 1994–2021) reporting on quantitative studies that estimated relationships between motor skills and EFs when assessing children, adolescents and adults with DCD. Motor skills and EFs were assessed *via* reliable and validated assessment tools. Two reviewers independently screened the articles. We evaluated the quality of the selected articles according to EPHPP guidelines and the methodological quality of the assessments from these studies using the COSMIN checklist and reported results following the PRISMA-P checklist. This systematic review was registered in PROSPERO (CRD42019124578).

Results: A total of 30,808 articles were screened. Eleven articles met the inclusion criteria and were reviewed. Findings from nine studies demonstrated weak to strong correlations between aspects of motor skills and EFs.

Conclusions and significance: Limited evidence supports the relationships between motor skills and EFs among individuals with DCD. Occupational therapists should consider the possibility of this relationship and give more consideration to these components when planning intervention for individuals with DCD.

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Assessment tool; daily function; intervention; occupational therapy; questionnaire

Introduction

Developmental coordination disorder (DCD) is a chronic neurodevelopmental condition that significantly affects an individual's ability to learn and perform essential motor tasks for everyday self-care and academic activities. Consequences of DCD include slowness and inaccuracy in performing daily activities that require motor skills, such as catching, using scissors, handwriting, riding a bike and participating in sports. In addition, poor self-esteem and self-worth, as well as emotional and behavioural problems, have been reported [1].

Children with DCD also show poorer outcomes in scholastic achievements [2] compared to their typically developing peers, especially in reading [3], mathematics [4] and handwriting [5]. There is now greater recognition that, for most individuals with DCD, difficulties persist into adulthood and affect the learning and execution of new motor skills such as driving [6,7]. As in childhood, difficulties extend beyond the motor domain and include problems with attention and anxiety, as well as symptoms of depression and low global self-esteem [8,9]. Difficulties with these widespread daily functions are the main reason that children, adolescents and adults are referred to receive occupational therapy services [10–12].

Barnett et al. [6] described three important components of motor control and everyday functioning that challenge individuals with DCD. The first, balance and postural control, allows individuals to maintain the static, stable body position required for daily tasks. The second, ballistic skills, involves generating and controlling force to project an object (by throwing or kicking). The third, manipulation skills,

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involves receiving and/or moving items within the hand or hands. A wide range of tasks require unimanual (using one hand, as in holding an object) and bimanual (using both hands, as in catching) skills. These essential motor skills are usually executed in a sequence of movements that, when combined, produce smooth, efficient actions to master particular tasks [13]. However, individuals with DCD must exert extra cognitive effort to master and perform everyday motor tasks and to organise themselves, their time and their equipment [14].

The motor difficulties in DCD rarely occur in isolation. The disorder is recognised to have overlapping symptoms and to co-occur with other neurodevelopmental disorders. It is also clinically heterogeneous. Dewey and Bernier [15] suggested that children with DCD manifest developmental variation in brain function, which then results in impaired motor and cognitive behaviour. Several studies have shown that children with DCD have difficulty with tasks involving organisation, planning, decision-making, visualisation, working memory, goal-directed movements and adjustment of movement speed [16–19]. These all involve aspects of executive function (EF).

Executive function is a broad term describing the range of skills required for purposeful and goal-directed activity, socially appropriate conduct and independent regulation of action and affects [20]. The World Health Organisation [21] described EFs as higher-level cognitive functions intimately connected with complex goal-directed behaviour across all life domains. However, over the years, many theorists and researchers have proposed diverse definitions of EFs and developed various neurology, cognitive psychology, developmental psychology or neuropsychology models and frameworks. The lack of a formal definition may have led to some overlap and redundancy in the number of terms used across different approaches [22–24].

Whilst EFs have been conceptualised in different ways in the literature, the most recent evidence supports a model of unity and diversity within EFs [25,26]. This model proposes that EFs consist of separated but interrelated components. The most frequently cited core components of EFs are: (a) inhibition or inhibitory control, including self-control (behavioural inhibition) and interference control (selective attention and cognitive inhibition); (b) working memory; and (c) cognitive flexibility (also called set-shifting, mental flexibility, or mental set-shifting, it is closely linked to creativity). However, other components such as planning and fluency are also included in studies of EF.

Other EF models deal with each of the core EF components. For example, Barkley [27] based a model for children with Attention Deficit Hyperactive Disorder (ADHD) on the understanding that satisfactory development of inhibition is essential for normal performance of four neuropsychological executive abilities: working memory, internalisation of speech, self-regulation of affect-motivation-arousal and reconstitution. Baddeley [28] referred to shifting (the ability to switch between sets, tasks and strategies), selective attention (the ability to focus on a specific task while ignoring irrelevant co-occurring information) and inhibition (the ability to deliberately suppress a dominant response when necessary). Lezak [29] included the abilities of goal formation, planning, carrying out goal-directed plans and effective performance.

To help navigate EF terms, Jones et al. [22] created a map of terminology – a visual tool to help stakeholders understand relationships between some of the most common EF terms and the specific skills to which the terms refer. They conducted a literature review of EF skills, focussing on identifying the similarities and differences between various skills. They organised the EF terms hierarchically into the subcomponents of 'simple skills', which they defined as EFs (i.e. response inhibition, working memory, shifting/flexibility), and 'complex skills', which integrate multiple simple skills (e.g. planning, creativity/fluency) and enable the completion of more complex goals. Jones et al.'s [22] EF-mapping project is an example of an attempt to organise the many and varied definitions of EF components, and their mapping/definition/classification is used in this current systematic review.

Executive function deficits in DCD are a common finding across measures (experimental, questionnaire and real-world behaviour) and are strongly linked to impaired planning and disorganisation in daily life [30,31]. A recent systematic review of the literature revealed weaknesses in inhibitory control, working memory, planning, nonverbal fluency and general executive functioning in children with DCD [32]. However, studies that have explored EFs with DCD populations have focussed mainly on differences between children with and without DCD. For instance, significant group differences were found in handwriting-performance measures and executive-control domains among 64 children aged 10–12 years [5]. Bernardi et al. [33] reported that children with DCD aged 7–11 years demonstrated a range of EF difficulties that persisted over 2 years. Only a few studies have considered adults with DCD, but these indicate that, like children, adults experience difficulties performing complex daily functions involving EFs [9–11,34]. In sum, most of the evidence indicates that individuals with DCD perform poorly in motor skills and in EF components and demonstrate functional difficulties in daily activities [19,35].

The link between EF components and motor skills is reflected in most EF models in which motor behaviour plays a central role. In Barkley's [27] hybrid model, behavioural inhibition permits the effective performance of four executive abilities (working memory, self-regulation of affect/motivation/arousal, internalisation of speech and reconstitution) that then influence the motor system in the service of goal-directed behaviour. Because the effector or motor-output stage depends on the antecedent processing stages, motor behaviour is inextricably linked to EFs. Sergeant's [36] cognitive–energetic model of information processing also links EFs to motor behaviour. Sergeant described a three-tiered information-processing system incorporating the child's energetic state. According to this model, the EF-processing level is responsible for planning, monitoring and correcting errors that influence other computational and state factors, including motor organisation.

Clearly, the motor difficulties of individuals with DCD often accompany various other cognitive and behaviour difficulties, and EFs seems to be an area of particular difficulty in this population. Although motor skills and EFs are linked in many models, relationships between these two areas in DCD are poorly understood. Understanding these relationships may contribute to occupational therapists' clinical thinking when planning intervention for individuals with DCD.

Therefore, the aim of this systematic review, using PICO (population, intervention, comparison, outcomes), was to examine the relationships between motor skills and EF components (outcomes) through an in-depth analysis of the motor and EF assessment (intervention) tools used in studies of individuals with DCD (population). This review does not include a comparison intervention group.

Materials and methods

This systematic review was conducted and reported in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (see PRISMA-P checklist, Table S1). The review was registered on the PROSPERO database (CRD42019124578). No ethical approval was required for the review.

Eligibility criteria

Inclusion criteria for this review were studies that: (1) were published, peer-reviewed journal articles, theses or dissertations; (2) were written in English; (3) addressed motor and EF components with questionnaires and/or performance-based assessments and evaluated linkages between them in individuals with DCD across the lifespan and (4) included participants who were children, adolescents or adults (i.e. from the age of 5 years) with profiles consistent with a DCD diagnosis according to the American Psychiatric Association [1] criteria A, B, C and D in the *Diagnostic and Statistical Manual of Mental Disorders* (*DSM*) 5th edition. If the population in the study included individuals with conditions other than DCD, then an inclusion criterion required at least 30% of that study's participants to have DCD. We also included studies that examined a DCD sample with other co-occurring difficulties (such as communication, attention or learning deficits). An additional requirement was that the assessments employed in each study had been published and were available either for purchase or through a journal article. This was to ensure the content was available for inspection.

Exclusion criteria were studies that: (1) included individuals with known psychiatric or emotional disorders, physical disabilities or neurological diseases; (2) included assessment of only motor components or only EF components but not both; (3) were book chapters, case studies, commentaries, conference abstracts or review articles; (4) referred to a motor or EF subtest that did not stand alone (i.e. without separate scoring); or (5) duplicated other included studies.

Information sources and search strategy

We performed a preliminary literature search to determine any alternative terms or synonyms for each of the four facets of interest – *DCD*, *executive function*, *motor ability* and *assessment* and created a keyword (free-text word) for each facet (Table S2). Using these terms, we searched eight electronic databases – MEDLINE, Web of Science, CINAHL, PsycINFO, ERIC, Cochrane Database, Scopus and ProQuest Dissertations and Theses Global – for all articles from January 1994 to August 10, 2021. The search was confined to English-language journals. For MEDLINE, CINAHL, PsycINFO, ERIC and Cochrane Database, specific search strategies using medical subject heading (MeSH) terms were developed (Table S3).

Study selection and data extraction

Two reviewers (AB and YF) independently screened titles and abstracts and then full texts using reference-management software (Covidence) with a moderate level of agreement (Cohen's kappa) ($k = .42$). Disagreements between reviewers were resolved in discussion with a third team member (NS or TJ).

As presented in Table 1, the following items were extracted from the 11 included studies: author(s) name, year published, [citation number], article title, country, study aim and study quality as determined according to the Effective Public Health Practice Project (EPHPP) guidelines [46]. Each article was reviewed separately by two authors (AB and YF) through the EPHPP assessment tool for quantitative studies. The EPHPP tool contains six components: selection bias, study design, confounders, blinding, data collection methods, and withdrawals and drop-outs. Each component was rated 1 (*strong*), 2 (*moderate*) or 3 (*weak*) with the support of a detailed dictionary that described each component and rating option. After each reviewer had rated all the articles independently, the ratings were compared. There was a moderate level of agreement between the two authors (AB and YF; $k = .42$). In cases where there was a discrepancy, the reviewers discussed the reasons and collectively made a final decision. The EPHPP final grading is presented in Table 1; the final EPHPP six-component scores are presented in Table S4.

The reported relationships between motor skills and EFs were reviewed, as shown in Table 2. For each included study, the following items were extracted: author(s) name, year published, [citation

Table 1. Summary of articles reviewed.

Author(s), year [citation #]	Article title	Country	Aim of study	Quality
Asonitou et al., 2016 [16]	Cognitive process-based subtypes of developmental coordination disorder (DCD)	Greece	Identify the cognitive subtypes in children with DCD	3
Asonitou et al., 2012 [17]	Motor and cognitive performance differences between children with and without (DCD)	Greece	Investigate probable differences in specific motor and cognitive abilities between children with and without DCD	3
Cunningham et al., 2018 [37]	DCD, psychopathology and IQ in 22q11.2 deletion syndrome	UK	Establish the prevalence of indicative DCD in children with 22q11.2DS; examine associations with IQ, neurocognition and psychopathology	3
Martinez, 2000 [38]	DCD in children: From motor and cognitive perspectives	USA	Define population of children with DCD according to *DSM*-5 criteria; characterise these children in terms of motor and neuropsychological abilities	3
Michel et al., 2011 [39]	Development of cognitive skills in children with motor coordination impairments at 12-mo follow-up	Germany, Switzerland	Investigate development of executive functions (EFs) in 1-yr follow-up in children with motor coordination impairments	3
Omer et al., 2021 [40]	Internalising symptoms in DCD: The indirect effect of everyday EF	UK	Explore an indirect relationship between DCD and internalising symptoms, through everyday EF difficulties	3
Piek et al., 2004 [41]	The relationship between motor coordination, executive functioning and attention in school aged children	Australia, USA	Explore the relationship between EF and motor ability	3
Pratt. et al., 2014 [42]	The effect of motor load on planning and inhibition in DCD	UK	Assess whether the mixed findings regarding EF abilities in DCD could result from the relative motor loads of tasks used to assess EFs in DCD	3
Rigoli et al., 2013 [43]	An 18-mo follow-up investigation of motor coordination and working memory in primary school children	Australia	Examine relationship between motor coordination and visual working memory in children aged 5–11 years	3
Rosenblum, 2015 [44]	Do motor ability and handwriting kinematic measures predict organisational ability among children with DCD?	Israel	Analyse behaviour organisation of children with DCD in varied tasks that require generating and monitoring mental representations related to space and time inputs/requirements	3
Wilson et al., 2020 [45]	Cognitive and motor function in DCD	Australia, UK, Netherlands	Analyse the development of motor skill and EF in school-aged children with and without DCD	3

Note: Quality rating 1 = strong; 2 = moderate; 3 = weak.

Table 2. Relationships between executive functions and motor assessments were reported in the selected studies.

Author(s), year [citation #]	Assessment: Motor	Assessment: EF	Correlation type	Sample	EF–motor skills relationship in DCD	Correlation level
Asonitou et al., 2016 [16]	MABC: MD, BS, BAL BOT-2: Running speed and agility	CAS: A. Planning B. Attention C. Simultaneous	Pearson	DCD: 54 (18 F) 5- and 6-yr-olds ($M = 66.48$ mo, $SD = 4.6$) TD: 54 (18 F), 5- and 6-yr-olds ($M = 66.48$ mo, $SD = 4.6$)	DCD: MABC: MD & A ($r = -.592$, $p < .01$) C ($r = -.601$, $p < .01$)	Strong Strong
Asonitou et al., 2012 [17]	MABC: MD, BS, BAL, total BOT-2: Running speed and agility	CAS: A. Planning B. Attention C. Simultaneous	NP	24 DCD (11 F) + 18 TD (3 F) 5-yr-olds; 30 DCD: (7 F) 6-yr-olds TD: 36 (14 F)	DCD: MABC: MD & C ($r = -.28$, $p < .05$) MABC: total & C ($r = -.31$, $p < .05$) TD: MABC MD & C ($r = -.32$, $p < .05$) MABC BAL & A ($r = -.31$, $p < .05$) MABC total & A ($r = -.27$, $p < .05$) MABC total & C ($r = -.33$, $p < .05$)	Weak Moderate Moderate Moderate Weak Moderate
Cunningham et al., 2018 [37]	MABC2 DCDQ	(1) CANTAB (2) WCST	NP	22q11.2DS: 70 (29 F), age $M = 11.2$ yr, $SD = 2.2$ 32 unaffected siblings (18 F), age $M = 11.5$ yr, $SD = 2.1$	NS between DCDQ and spatial planning or spatial working memory from the CANTAB NS between DCDQ and WCST (set shifting and total errors)	None None
Martinez, 2000 [38]	MABC total	(1) Digit Span (WISC-R) (2) WCST (3) Trail Making test A and B	NP	DCD: 12 (2 F) 9–11 ($M = 10.1$ yr) Borderline DCD: 16 (3 F) 9–11 ($M = 10.4$ yr) 14 TD (5 F) 9–11 ($M = 10.7$ yr) matched by sex, age, handedness, vocabulary ability, height, and weight	Both groups together: NS between motor and EF measures MABC and Digit Span Backward ($r = -.37$, $p < .016$)	Moderate
Michel et al., 2011 [39]	MABC2: MD, BS, BAL, total	1. Cognitive Flexibility task 2. Fruit Stroop task 3. Backwards Colour Recall	NP	Young (5 yr) impaired: 23 (4 F) Older (6 yr) impaired: 24 (9 F) Young (5 yr) TD: 23 (12 F) Older (6 yr) TD: 24 (14 F)	MABC2: MD and (3) ($r = .40$, $p < .01$) NS between EFs and motor measures	Moderate
Omer et al., 2021 [40]	DCDQ	BRIEF	Pearson	DCD: 32 (7 F) ($M = 12.45$ yr, $SD = 2.08$) TD: 51 (23 F) ($M = 11.98$ yr, $SD = 2.39$)	DCDQ: BRIEF GEC ($r = .84$, $p < .05$) BRIEF BRI ($r = .79$, $p < .05$) BRIEF MCI ($r = .82$, $p < .05$)	Strong
Piek et al., 2004 [41]	MAND	1. GNG task 2. Trail Making/ Memory Updating task 3. (3) GNT	NP	Overall sample: 238 children aged 6.67–14.83 yr ($M = 10.58$ yr, $SD = 2.26$) Risk of DCD: 28 (8 F) TD: 210 (103 F);	DCD and TD groups together: MAND: NDI and: (2) Trail 1 *M* time ($r = -.262$, $p < .01$) (2) Trail 1 (*SD*) ($r = -.222$, $p < .01$) (2) Trail 2 *M* time ($r = -.222$, $p < .01$) (2) Trail 2 (*SD*) ($r = -.155$, $p < .05$) (3) ($r = .134$, $p < .05$)	Weak Weak Weak Weak Weak
Pratt et al., 2014 [42]	MABC2: MD, AC, BAL, total	1. NEPSY Tower task	Spearman/ Bonferroni corrections	DCD: 26 (4 F) 6.1–14.11 yr ($M = 9.11$ yr) TD: 26 (11 F) 7.2–14.7 yr ($M = 9.7$ yr)	NS between motor and EF tasks in DCD group or TD group	None

(*continued*)

Table 2. Continued.

Author(s), year [citation #]	Assessment: Motor	Assessment: EF	Correlation type	Sample	EF–motor skills relationship in DCD	Correlation level
		2. Rotational Bar task 3. Stroop task 4. NEPSY Knock-Tap task				
Rigoli et al., 2013 [43]	MAND: fine motor, gross motor	CogState Brief Battery: One-Back task, reaction time and accuracy	Cross-lagged correlation (baseline, follow-up)	Overall sample: 59 children aged 5.7–11.4 yr ($M = 8.56$ yr, $SD = 1.46$) Movement difficulty: 18 (7 F) assessed at baseline and 18-mo follow-up	MAND: fine motor baseline and Follow-up reaction time ($r = -.582$, $p < .05$) Follow-up accuracy ($r = .715$, $p < .01$). MAND fine motor follow-up and baseline accuracy ($r = .473$, $p < .05$) MAND gross motor follow-up and baseline accuracy ($r = .508$, $p < .05$)	Strong Strong Moderate Strong
				TD: 41 (27 F)	MAND fine motor follow-up & Baseline accuracy ($r = .320$; $p < .05$) Baseline reaction time ($r = -.369$; $p < .05$).	Moderate Moderate
Rosenblum, 2015 [44]	MABC total	QASOA-T	Regression	DCD: 21 (8 F), $M = 9.9$ yr, $SD = 1$ mo Controls: 21 (8 F), $M = 9.8$ yr, $SD = 1.3$ mo	Regression analysis, both groups together: MABC total accounted for 67% variance in (1) ($\beta = .83$, $p < .001$)	
Wilson et al., 2020 [45]	MAND: fine motor, gross motor	GMLT	χ^2	Overall sample: 186 (100 F) children aged 6–11 yr ($M = 8.5$ yr, $SD = 1.6$) DCD: 52 (25 F) TD: 134 (25 F)	DCD: χ^2 (df 1) $= 1.92$, $p = 0.166$ DCD + EF χ^2 (df 1) $= 2.75$, $p = 0.097$ TD χ^2 (df 1) $= 58.47$, $p < 0.001$	Weak Weak Strong

Notes: AC: aiming and catching; BAL: balance; BOT-2: Bruininks-Oseretsky Test of Motor Proficiency; BRIEF: Behaviour Rating Inventory of Executive Function; BRI: BRIEF Behaviour Regulation Index; BS: ball skills; CANTAB: Cambridge Neuropsychological Test Automated Battery; CAS: Cognitive Assessment System; DCD: developmental coordination disorder; DCDQ: DCD questionnaire; EF: executive function; F: female participants; GEC: BRIEF Global Executive Composite; GMLT: Groton Maze Learning Test; GNG: Go/No-Go; GNT: Goal Neglect task; *M*: mean; MABC: Movement Assessment Battery for Children; MABC2: MABC: 2nd ed.; MAND: McCarron Assessment of Neuromuscular Development; MCI: BRIEF Metacognitive Index; MD: manual dexterity; NDI: neurodevelopmental index; NP: not provide correlation; QASOA-T: Questionnaire for Assessing Students' Organisational Abilities-teachers' version; *SD*: standard deviation; TD: participants with typical development; WCST: Wisconsin Card Sorting Test; WISC-R: Wechsler Intelligence Scale for Children.
Correlation values: strong = 0.50–1.00; moderate = 0.30–0.49; weak = 0–0.29.

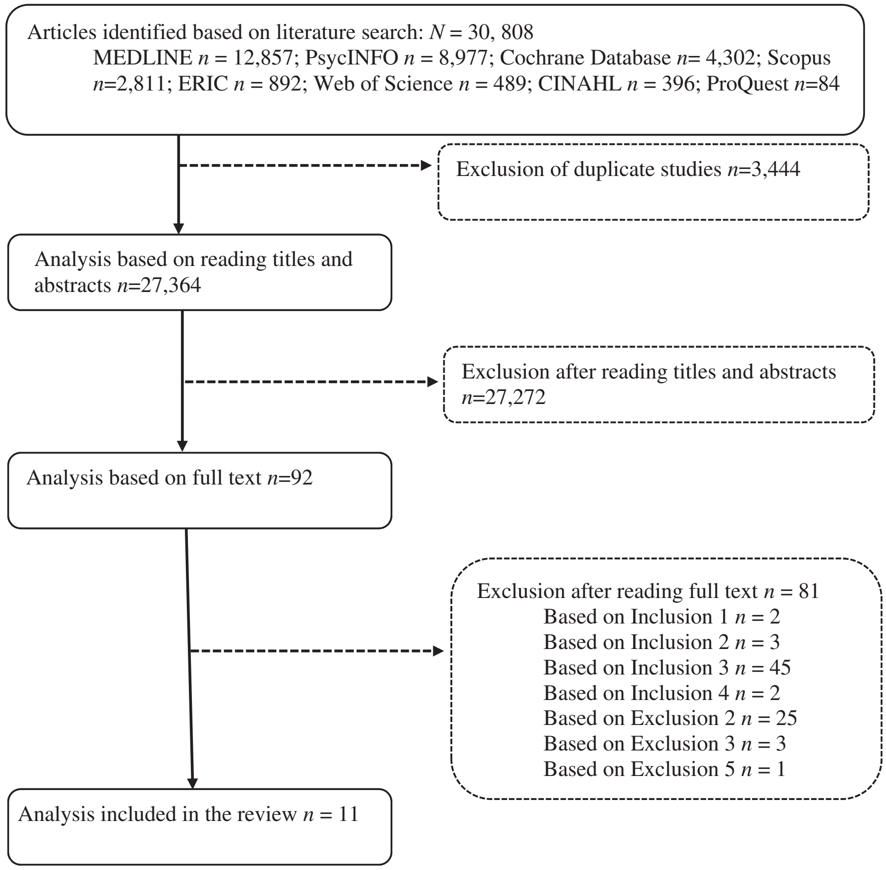

Figure 1. PRISMA flow chart of study selection.

number], motor assessment, EF assessment, type of correlation, study sample, motor and EF relationships reported in the DCD sample and correlation levels. Correlation values of 0.50–1.00 were considered strong, 0.30–0.49 as moderate, and 0–0.29 as small [47].

The motor and EF assessments used in the studies are presented in Tables S5 and S6 respectively. The tables show the assessment used, authors(s) name, year published, [citation number], description of the task involved and description of scoring. The EF assessments are organised according to the EF-mapping project [22] and are presented as simple or complex skills.

To assess the methodological quality of the assessments included in the reviewed articles, we applied the Consensus-Based Standards for the Selection of Health Measurement Instruments (COSMIN) checklist [48]. The checklist consists of nine domains that refer to methodological standards for studies on measurement properties: (a) internal consistency; (b) reliability (including test-retest reliability, inter-rater reliability and intra-rater reliability); (c) measurement error (absolute measures); (d) content validity (including face validity); (e) structural validity; (f) hypotheses testing; (g) cross-cultural validity; (h) criterion validity and (i) responsiveness. Items are scored on a 4-point scale representing *poor* (0), *fair* (+), *good* (++) or *excellent* (+++) quality. The overall quality score of each psychometric property was defined as the lowest score of any item within the box, following the 'worst score counts' method (Tables S7 and S8).

Results

Study selection

The review identified 30,808 articles, which was reduced to 27,364 following the removal of duplicates across the eight databases. After screening titles and abstracts, 92 studies were initially selected for full-text analysis (Figure 1). After exclusions, 11 studies — 10 journal articles and one doctoral thesis – met the inclusion criteria.

Characteristics of included articles

Table 1 summarises the characteristics of the 11 studies. All were published after 1994 (which was when the term DCD was endorsed in the International

Consensus Meeting in London on Canada, in 1994) [30] and were conducted across eight countries. In six studies, the children included in the study were screened for DCD with motor assessments during the study process [16,17,37–39,43]; in the other five studies, the children who were recruited to the studies had already been diagnosed with DCD. One study reported comorbidity with the genetic disorder, 22q11.2. That is, the participants were diagnosed with DCD in addition to this other primary diagnosis (however, the 22q11.2 did not explain the motor difficulties) [37]. Another study [41] considered comorbidity with ADHD and indicated that motor abilities significantly accounted for variance in tasks measuring the speed of performance, whereas inattention appeared to influence performance variability. The other studies did not report the comorbidities of the participants. Participant ages in the 11 studies ranged from 5 to 15 years, and all studies compared a group of typically developing children to the study group with DCD.

A review of the articles' aims revealed two items of interest. First, in defining the study's specific purpose, only three [40,41,49] specifically aimed to examine relationships between EFs and motor skills. Second, when presenting EF definitions, six articles referred to the term *executive function* [37,39–42,45]; three used the terms *cognitive* or *neurocognitive skills* [16,17,38]; and two referred to specific terms for EF components, such as *working memory* and *organisation in time and space* [43,44].

Quality of articles

The EPHPP was used to assess the quality of the articles in the current review. Six articles [16,17,37,40,42,43] received moderate ratings for selection-bias components, and five articles [38,39,41,44,45] received weak ratings. The study-design component is generally a good indicator of the extent of bias. Both reviewers rated all the articles as case-control studies. No article in the current review included an intervention procedure, so the reviewers' ratings were similar for all articles (i.e. moderate). The reviewers rated only one article [38] as strong regarding the 'confounders' component. Within this article, there seemed to be no important differences between groups prior to the study. In the other 10 articles, it was unclear as to how the researchers controlled possible confounding variables (e.g. education, SES).

Blinding refers to masking the assessors' awareness of the group status of participants and the participants' own awareness of the research question. No reviewed article clearly reported the extent of blinding in the study. Therefore, the articles received weak ratings on this component. The data-collection method component refers to the reliability and validity of the assessment tools used in the articles. All articles received strong ratings because they used assessments judged to have high reliability and validity.

The EPHPP rating related to withdrawals and drop-outs was not applicable to most of the studies because there was only one assessment point. Of the three studies that did include a follow-up assessment, one [43] described both the number and reasons for withdrawals and drop-outs at the 18-month follow-up. In the other two studies [39,45], it was difficult to determine the percentage of participants who completed the study. In the total quality-of-the-article score according to the EPHPP, only two articles were rated as moderate (i.e. with one weak rating); the others were rated as weak (i.e. two or more weak ratings).

Characteristics of included assessment tools

Four performance-based motor skill assessments and one motor questionnaire were used in the 11 studies reported; all five assessments had good psychometric properties. A further 16 performance-based assessments and two questionnaires were used to examine EF. In light of this wide range of EF measures, we mapped the assessment tools according to Jones et al.'s [22] EF-mapping project. This mapping demonstrated 15 tools that classified 'simple' skills such as response inhibition; the others classified 'complex' skills such as planning (see Tables S5 and S7).

Relationships between motor skills and EF

All 11 studies examined relationships between motor skills and EF. The MABC and its second edition were the most common assessments used in the studies to assess motor skills, and most significant correlations with EF (from strong to weak) were found using these assessments [16,17,38,39,44]. Among the results, no significant relationships were found using the BOT-2 [16,17] or with the one article that used the DCD Questionnaire [37]. Articles [37] and [42] reported no significant correlations between motor skills and EF. Article [44] reported regression analyses following strong correlations in both groups but provided no information specifically about the correlations.

A more in-depth analysis of the correlations in the DCD groups showed that the total MABC test score was significantly related to EF components, including creativity/fluency (CAS: Simultaneous) [17,18], working memory (Digit Span, Backwards Colour Recall) [38] and organisation (QASOA-T) [44]. Interestingly, it also revealed that manual dexterity from the MABC and fine motor skills from the MAND had many significant correlations with EF assessments. The manual dexterity from the MABC had significant moderate to strong correlations with planning and creativity/fluency components [16,17] and with working memory (Backward Colour Recall) [39]. The fine and gross motor scores on the MAND were found to have, respectively, moderate and strong correlations with working memory from the One-Back task (CogState Brief Battery) reaction time and accuracy [43].

According to the MAND assessment, the total score had a significant weak correlation with the working memory (Trail Making/Memory Updating task) [41] and planning (GNT) [41] EF components. However, the total MAND score presented significant strong correlations with working memory components assessed by the GMLT in the group with typical development but not in the group with DCD. Although the DCDQ did not correlate with EF components such as working memory and shifting [37], significant strong correlations were found between the DCDQ and the BRIEF questionnaire [40].

Discussion

This systematic review synthesises findings from 11 studies and provides evidence of weak to strong relationships between motor skills and EFs among individuals with DCD. Motor skills, such as aiming, catching and manual dexterity, which are basic skills for performing goal-directed everyday activities, were significantly correlated with different simple and complex EF components. The results are supported by common EF models, such as Barkley's [27], which explains the relationships between EF components such as inhibition or working memory and motor control. Some articles in this review demonstrated these relationships with strong correlations. For example, Asonitou et al. [16] stated that movement is not a single factor because movement includes cognitive and perceptual processes that precede the movement response. Rigoli et al. [43] also found strong correlations suggesting the importance of fine motor performance in predicting working memory performance (and vice versa) for children with movement difficulties. Strong positive correlations were also found in Omer et al.'s [40] study. They indicated that EF deficits in children with DCD might affect the children's ability to use adaptive coping strategies.

The occupational therapy literature has supported this relationship and highlights that daily functional activity among individuals with DCD may be more challenging through higher cognitive demands [e.g. 50]. This implies that early EF and motor difficulties identification is essential for improving learning, academic, and other daily functioning.

However, most relationships between motor skills and EF found in this systematic review were only moderate to weak and the authors of the studies included in this review attempted to explain these results. For example, Wilson et al. [45] explained the weak correlation among children with persisting DCD over a two-year period that showed improvement in EF but significantly below their peers. They suggested that children with DCD develop their EF skills at a rate similar to that of their peers with typical development but do not necessarily reach the same absolute level of performance.

Piek et al. [41] examined comorbidity using Sergeant's [36] model to explain the weak correlations. They argued that the first level in the model is a set of lower-level cognitive processes, including encoding, central processing and response organisation, which are implicated in a motor organisation [51]. The second level is the energetic pools, consisting of arousal, activation and effort; children with ADHD display deficits in this level. The third level consists of the management or EF system that reviews performance and corrects errors. In goal-directed behaviour, the management or EF-processing level is responsible for planning, monitoring and correcting errors that influence the other computational and state factors, including motor organisation [36]. These explanations indicate that which of these levels is measured in each study can affect the correlations obtained.

Martinez [38] suggested that an increase in the cognitive challenge of motor tasks (such as the stepping accuracy tasks in their study) leads to a decrease in task performance. Martinez [38] argued that the children with DCD most likely did not have the psychomotor or working memory capacities to manage the increasing task demands of foot-eye coordination in the stepping task compared to eye-hand coordination in the manual task. She concluded that whereas children with DCD did not differ in nonmotor-dependent cognitive measures, such as vocabulary and executive functioning, they performed significantly worse than typically developing children on neuropsychological measures that included significant working memory or psychomotor components.

In Michel et al.'s [39] explanation of their results, they indicated that children with poor motor abilities showed slower performance in cognitive tasks, but not due to the motor demands of the task, which were minimal (i.e. press a button). Instead, they claimed that the children performed slower due to the increased complexity of the task demands.

These findings suggest that the EF task's nature and the level of task complexity may partly explain the different levels of correlations found between EF and motor skills. The relationship between motor coordination and EFs appeared to be weak to moderate and thus left a substantial amount of unexplained variance of motor-coordination performance. Pratt et al.'s [42] study found no significant relationships between motor skills and EF. In addition to referring to the impact of task complexity, and the component skills required in EF tasks, they argued that the relationship of EFs with motor abilities possibly changes with development and that the varied ages of the samples across the studies may explain the different findings. Arguably, the low number of studies examining the relationships can be evidence of the challenges in exploring relationships between motor skills and EFs.

Methodological considerations, limitations and implications

The current systematic review highlights some challenges that may also be interpreted as study limitations. First, the literature lacked consensus as to precise EF components because EF is a multifaceted construct [e.g. 24,52,53]. This situation challenges policymakers, educators and other stakeholders to accurately identify the most important skills to target and to discover research findings associated with those skills or outcomes of interest [22]. Specifically, Josman and Meyer [49] suggested that a general definition should include components that best reflect the occupational scope among children and adolescents. They indicated that an appropriate EF definition may assist occupational therapists to choose the tools best suited to each individual and create an appropriate evaluation process to define intervention goals, including those directed at improving EFs. Mapping the assessment tools found in this review aimed to clarify the challenge of unifying EF research relative to DCD. The mapping demonstrated how complex it can be to find uniformity in EF assessment tools, which makes it difficult to compare results across studies. The use of Jones et al.'s [22] classification into simple and complex components may prompt researchers in the future to define more precisely what they want to assess and then select appropriate assessment tools.

Second, based on the results of the review, no one EF assessment tool was used more widely than others. Additionally, apart from the QASOA-T questionnaire [54] and the BRIEF inventory [40], all other assessment tools used in the 11 studies were mostly neuropsychological assessment tools that examine EF components according to a bottom-up approach. Bottom-up assessments tend to examine small, separate components of a client's skills or occupational performance components. They focus primarily on the body-structure-(impairment) and function-(impairment) levels of the International Classification of Functioning, Disability and Health [21]. Moreover, bottom-up assessments are frequently administered in contrived, standardised contexts that may not be meaningful to the client and often are isolated from relevant daily life contexts. The current review reinforces the need for future research to incorporate assessments into a top-down approach with a global perspective and focus on clients' participation in their living contexts to determine what is important and relevant to them [55]. Because occupational therapists can adopt a bottom-up, a top-down or a mixed-direction approach to clients' assessment, it is important to be cognisant of both assessment approaches and the implications associated with each to examine relationships between motor skills and EF components through a combination of assessment tools.

Third, 45 articles were excluded from this systematic review because, although they used assessments of both motor skills and EF components, they did not examine the relationships between them according to the purpose of this review. This result highlights that although the EF components are widely investigated among individuals with DCD, the relationship with motor skills is lacking in studies. It reinforces the point that future studies need to analyse these relationships to strengthen researchers' and clinicians' knowledge.

Fourth, the 11 studies in this review are diverse; thus, it is challenging to draw a clear picture of the findings. The various researchers used a range of statistical analyses (e.g. Pearson and Spearman correlations) depending on the distributions in their data. Additionally, there was variability in how the researchers analysed the relationships between motor and EF skills. Some [38,41,44] examined relationships between variables for all participants (i.e. for the DCD group and typically developing group combined), whereas others examined each group individually. Because correlation analyses with both groups may increase the range of scores and thus increase the chance of stronger relationships among variables, it is difficult to reach clear conclusions about the relationships from these studies.

Fifth, although the literature referred to the high level of comorbidity of DCD with ADHD, the EF deficits may also be implicated in the motor-coordination deficit. Only one study in this systematic review considered this issue [41]. Future research exploring DCD and ADHD should control for the presence of comorbid and possibly confounding symptomatology.

Lastly, all studies extracted for this systematic review received weak quality scores according to the EPHPP guidelines; thus, the findings should be interpreted with caution. The major weakness in most articles was in not describing possible confounders and blinding of assessments. Despite this weakness, the evaluation of the articles indicated the high quality of the assessment tools used in the various studies, showing good levels of reliability and validity.

Conclusions

The purpose of this systematic review was to provide an in-depth analysis of the relationships between motor skills and EFs used in studies of individuals with DCD. Although the included studies presented weak to strong correlations, they highlighted some important issues for researchers and clinicians. The level of EF development, the types of assessment used and their cognitive demands, as well as comorbidity issues in each study, should be considered. Researchers should continue to examine EF and motor skills to gain a better theoretical and clinical understanding of the relationships between them and their effects on daily functions among individuals with DCD.

Occupational therapy practitioners should consider possible relationships between motor skills and EFs and use a range of assessment tools to evaluate individuals with DCD. As Rigoli et al. [43] indicated, when children are referred to occupational therapy for potential cognitive difficulties, it is also important to consider the children's level of motor functioning. Similarly, if children present with movement difficulties, it may be important to assess their performance in cognitive areas such as working memory. Rigoli et al. [43] suggested that interventions in the motor domain also may support cognitive development and vice versa. Using accurate assessments will assist occupational therapists in creating relevant intervention goals and developing unique occupation-based intervention protocols for individuals with DCD.

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Data availability statement

All data generated or analysed during this study are included in this published article.

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