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Les fonctions attentionnelles et exécutives chez les enfants et les adolescents ayant un trouble développemental de la coordination et l'influence des troubles comorbides : Une recension systématique des écrits

par Catherine Lachambre

Département de psychologie

Faculté des Arts et des Sciences

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Résumé

Le trouble développemental de la coordination (TDC) est un trouble neurodéveloppemental affectant le développement et l'acquisition des habiletés motrices. Plusieurs études ont soulevé des atteintes des fonctions attentionnelles et exécutives chez les individus vivant avec ce trouble, qui nuiraient encore davantage à leur fonctionnement quotidien. Par ailleurs, la présence de comorbidités neurodéveloppementales est fréquente au sein de cette population et influence certainement le profil cognitif des enfants concernés. Cette recension systématique des écrits vise à identifier les déficits attentionnels et exécutifs des enfants et adolescents ayant un TDC et à mieux comprendre l'influence des troubles comorbides sur ces fonctions au sein de ce trouble. Des études expérimentales traitant des fonctions attentionnelles et/ou exécutives chez les enfants et adolescents ayant un TDC ont été identifiées via les bases de données PubMed/Medline et PsycINFO selon plusieurs critères d'éligibilité préétablis. Trente-huit articles ont ainsi été sélectionnés, abordant au total neuf domaines attentionnels et exécutifs. Les résultats révèlent généralement des faiblesses sur le plan du contrôle inhibiteur, de la mémoire de travail, de la planification, de la fluence non verbale et du fonctionnement exécutif général. La présence de troubles comorbides dans les échantillons d'enfants ayant un TDC pourrait avoir influencé les résultats concernant la mémoire de travail verbale. Ces conclusions permettent de mieux comprendre les atteintes cognitives pouvant faire partie du TDC et de mieux identifier les besoins de ces enfants afin d'optimiser les interventions réalisées auprès d'eux.

Mots-clés : trouble développemental de la coordination, dyspraxie, fonctions exécutives, attention, enfant, adolescent, recension systématique, neuropsychologie clinique

Abstract

Developmental coordination disorder (DCD) is a neurodevelopmental disorder affecting the development and acquisition of motor skills. Several studies have shown impaired attentional and executive functions in individuals with this disorder, which would further impair their daily functioning. In addition, the presence of neurodevelopmental comorbidities is common in this population and certainly influences the cognitive profile of the children concerned. This systematic review of the literature aims to identify the attentional and executive deficits of children and adolescents with DCD and to better understand the influence of comorbid disorders on these functions within this disorder. Experimental studies on attentional and/or executive functions in children and adolescents with DCD were identified through the PubMed/Medline and PsycINFO databases according to several pre-established eligibility criteria. Thirty-eight articles satisfied the inclusion criteria, covering a total of nine attentional and executive domains. The results generally reveal weaknesses in inhibitory control, working memory, planning, nonverbal fluency, and general executive functioning. The presence of comorbid conditions in samples of children with DCD may have influenced the results regarding verbal working memory. These conclusions help to better understand the cognitive impairments that may be part of DCD and to better identify the needs of these children in order to optimize the interventions performed with them.

Keywords: developmental coordination disorder, dyspraxia, executive functions, attention, child, adolescent, systematic review, clinical neuropsychology

Structure de l’essai doctoral

Le présent essai doctoral est composé d’un article, rédigé en anglais afin d’en maximiser l’accessibilité au sein de la communauté scientifique. Des tableaux, figures et appendices à l’article se trouvent à la suite de ce dernier. Un appendice à l’essai doctoral, rédigé en français, a été ajouté à la toute fin, afin de présenter les modèles théoriques pertinents au contexte théorique du présent essai, tout en évitant d’alourdir davantage l’article.

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ABD: Atypical brain development

ASD: Autism spectrum disorder

ADHD: Attention deficit/hyperactivity disorder

AWMA: Automated Working Memory Assessment

BADS-C: Behavioural Assessment of the Dysexecutive Syndrome in Children

CANTAB: Cambridge Neuropsychological Test Automated Battery

CAS: Das-Naglieri Cognitive Assessment System

CL: Catherine Lachambre

CPT: Continuous Performance Test

DCD: Developmental coordination disorder

DD: Developmental dyspraxia

DDL: Developmental dyslexia

D-KEFS: Delis-Kaplan Executive Function System

DSM: Diagnostic and Statistical Manual of Mental Disorders

COVAT: Covert Orienting of Visuospatial Attention Task

IQ: Intellectual quotient

KITAP: Computerized test battery of attention for children

MABC: Movement Assessment Battery for Children

MD: Motor difficulty

MPL: Mélodie Proteau-Lemieux

NEPSY: Developmental Neuropsychological Assessment

NOS: Newcastle-Ottawa Quality Assessment Scale

PRISMA: Prefered Reporting Items for Systematic Reviews and Meta-Analysis

RELD: Mixed receptive expressive language disorder

SL: Sarah Lippé

SLI: Specific language impairment

TD: Typically developing

TDC: Trouble développemental de la coordination

TEA-Ch: Test of Everyday Attention for Children

WCST: Wisconsin Card Sorting Test

WISC-IV: Wechsler Intelligence Scale for Children, Fourth Edition

WMTBC: Working Memory Test Battery for Children

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Attentional and Executive Functions in Children and Adolescents with Developmental Coordination Disorder and the Influence of Comorbid Disorders: A Systematic Review of the Literature

(Article en préparation pour soumission)

Catherine Lachambre[a,b], Mélodie Proteau-Lemieux[c], Jean-François Lepage[c], Eve-Line Bussières[d], Sarah Lippé[a,b]*

a. Department of Psychology, University of Montreal, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, Canada, H3C 3J7
b. Sainte-Justine Hospital Research Center, 3175 chemin de la Côte-Sainte-Catherine, Montreal, Quebec, Canada, H3T 1C5
c. Department of Pediatrics, University of Sherbrooke, 2500 boul. de l'Université, Sherbrooke, Quebec, Canada, J1K 2R1
d. Department of Psychology, University of Quebec at Trois-Rivières, 3351 boul. des Forges, Trois-Rivières, Quebec, Canada, G8Z 4M3

Authors e-mail addresses: catherine.lachambre@umontreal.ca, melodie.proteau-lemieux@usherbrooke.ca, jean-francois.lepage@usherbrooke.ca, eve-line.bussieres@uqtr.ca, sarah.lippe@umontreal.ca

***Corresponding author:**
Sarah Lippé
Department of Psychology, University of Montreal
C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, Canada, H3C 3J7
Tel: (514) 343-6111, ext 46040
e-mail address: sarah.lippe@umontreal.ca

Abstract

Developmental coordination disorder (DCD) is a neurodevelopmental disorder affecting motor skills, but several studies have also revealed attentional and executive impairments in individuals living with this disorder. Moreover, the presence of neurodevelopmental comorbidities is frequent in this population and certainly influences the cognitive profile of the children concerned. This systematic review of the literature aims to identify the attentional and executive deficits present in children with DCD. Presence of tasks' modality (verbal/nonverbal), and the influence of comorbid disorders on attentional and executive profiles are systematically considered. Thirty-eight studies were identified through the PubMed/Medline and PsycINFO databases according to pre-established eligibility criteria. The results revealed statistically significant weaknesses in inhibitory control, working memory, planning, nonverbal fluency, and general executive functioning in children with DCD. The presence of comorbid disorders seemingly contributed to the verbal working memory difficulties findings. This review helps in gaining a better understanding of the cognitive impairments in DCD and of the needs of these children, allowing professionals to optimize interventions.

Keywords: developmental coordination disorder, dyspraxia, executive functions, attention, child, adolescent, systematic review, clinical neuropsychology

1. Introduction

1.1. Developmental Coordination Disorder

Developmental coordination disorder (DCD) is a neurodevelopmental disorder that affects motor skills development in children and influences their ability to perform multiple activities of daily living (Missiuna et al., 2008; Zwicker et al., 2012). According to the Diagnostic and Statistical Manual of Mental Disorders – Fifth Edition (DSM-5; American Psychiatric Association, 2013), DCD is characterized by difficulties in movement acquisition and execution. Criteria include motor abilities that are significantly inferior to those expected given the individual chronological age and learning opportunities, and impairments significantly interfering with daily activities, academic and/or professional accomplishments and hobbies, which emerge during a child's early development and are not better explained by intellectual disability, neurological condition affecting movement or visual impairment. Motor difficulties can be manifested as clumsiness, slowness and inaccuracy in movement execution.

Significant signs of DCD usually emerge during school years, but motor difficulties associated with DCD are developmental and seem to persist into adolescence (Miller et al., 2001) and adulthood (Kirby, 2011). Its prevalence is estimated between 5 and 6% in children aged 5 to 11 years old (American Psychiatric Association, 2013). More boys than girls are affected, with reported ratios of men to women ranging from 1.9:1 to 7.3:1 (Kadesjö & Gillberg, 1999; Lingam et al., 2009). Great variability exists within countries, with prevalence among school-age children ranging from 1.8% in the United-Kingdom (Lingam et al., 2009), 8% in Canada and 19% in Greece (Tsiotra et al., 2006). DCD is present across all cultural, ethnic and socioeconomic groups, but daily living activities and functional impacts of the disorder may vary within these different groups. Thus, these variables should be considered at the time of diagnosis.

DCD has been formerly referred to as *clumsy child syndrome*, and today the terms *specific developmental disorder of motor function* and *dyspraxia* can also be used to describe DCD (American Psychiatric Association, 2013; Kirby et al., 2014). The terms DCD and dyspraxia (or developmental dyspraxia) are the most frequently used terms in the literature. DCD focusses on the observable symptoms, on their functional impacts and manifestations in daily living, and the diagnosis often belongs to occupational therapists or to physiotherapists (Gibbs et al., 2007; Lussier et al., 2017). As for dyspraxia, it is often used as a synonymous to DCD, more widely used and diagnosed in neuropsychology (Dewey, 1995; Gibbs et al., 2007; Lussier et al., 2017; Vaivre-Douret et al., 2011). It is defined as difficulties with organizing, planning, executing and coordinating movement, which leads to impairments in acquisition of complex movements and of movement sequences (Dewey, 1995; Gibbs et al., 2007; Vaivre-Douret, 2007). It relies on a developmental conception of the brain, implying a motor cognition disorder that includes visual and spatial processing problems (Lussier et al., 2017). Children with dyspraxia and DCD typically show visuoperceptual, visuospatial, visuoconstructives and visuomotor deficits (Chaix & Albaret, 2013; Dewey, 1995; Polatajko & Cantin, 2006), further impacting school achievement and daily living.

Several theoretical models of dyspraxia have been proposed over the years to try to explain these deficits. One of the most recent ones was proposed by Vaivre-Douret and her team (2011) and stipulates that dyspraxia involves a deficit of both execution of voluntary gesture and planning/programming of movement. According to this model, when a child intends to perform an action, he first has to formulate a plan to execute that movement, that considers perceptual information, then to build a mental representation of the movement by coding spatiotemporal parameters, and finally to execute the movement while controlling it according to sensorimotor feedback (Vaivre-Douret, 2007; Vaivre-Douret et al., 2011). By conducting neuropsychological, neuro-psychomotor and neuro-visual assessments in children with dyspraxia, the authors showed that the planning and programming processes were the core problems in dyspraxia, and that the execution mechanisms were disturbed only when dyspraxia was comorbid with other neuropsychological disorders (Vaivre-Douret et al., 2011). Therefore, the question arises as to whether children with dyspraxia (or DCD) present only planning impairments on motor tasks, or broader planning and executive functioning deficits.

1.2. Neurodevelopmental Comorbidities

It seems that children who only have DCD are the exception rather than the rule, comorbid disorders being present in most of the cases (King-Dowling et al., 2015; Martin et al., 2010; Visser, 2003). The most frequent comorbid disorder is attention deficit/hyperactivity disorder (ADHD), with approximately 50% of cooccurrence (American Psychiatric Association, 2013; Kadesjö & Gillberg, 1999; Miller et al., 2001; Piek et al., 2007; Tal Saban et al., 2014). Besides, some authors report that DCD and ADHD overlap in their symptoms: children with ADHD frequently demonstrate motor difficulties (Pitcher et al., 2003). Executive dysfunctions and slow processing speed, which are generally inherent characteristics to ADHD, are often found in children with DCD (Piek et al., 2007). It is thus unclear which difficulties are inherent to which disorder, but ADHD and DCD must still be considered as separate disorders since their core deficits are distinct (Goulardins et al., 2015). Learning disorders, including developmental dyslexia (DDL; Iversen et al., 2005; Jongmans et al., 2003), specific language impairment (SLI; Alloway & Archibald, 2008; Flapper & Schoemaker, 2013; King-Dowling et al., 2015), behavioral problems (Dewey et al., 2002; King-Dowling et al., 2015) and autism spectrum disorder (ASD; Green et al., 2002; Kadesjö & Gillberg, 1999) are also common in children with DCD; concomitance between these disorders and DCD reaches up to 30 to 50%. Since deficits in executive and attentional functioning are generally part of these disorders (Castellanos et al., 2006; Henry et al., 2012; Hill, 2004), it seems essential to consider their presence and potential influence on executive and attentional capacities in children with DCD.

1.3. Executive and Attentional Functions

Executive functions are generally conceptualized as a set of general high order control processes (Miyake et al., 2000) working together (Anderson, 2002) to direct and manage cognitive, emotional and behavioral functions, especially during active problem solving (Gioia et al., 2000). A large variety of components seem to define executive functions, typically including: working memory, inhibition, cognitive flexibility/shifting, goal-setting, planning, organization, self-regulation and fluency (Anderson, 2002; Diamond, 2013; Gioia et al., 2000; Miyake et al., 2000; Pennington & Ozonoff, 1996). To this day, however, it is still unclear exactly how many components define executive functions and under which terms they should be grouped (Jurado & Rosselli, 2007). Indeed, several models of executive functions have been proposed in the literature, integrating different components and establishing interactions between them. One of the most integrative and complete models was proposed by Diamond (2013). According to this model, working memory is defined as the ability to hold information in mind for a short period of time while mentally manipulating it to execute a task. It includes verbal and visuospatial subcomponents. Inhibitory control is described as the ability to control attention, behavior, thoughts and emotions to override a dominant, automatic or prepotent response. The author also explains that inhibitory control is divided into two subcomponents:

interference control, combining cognitive and attentional inhibition, and response inhibition, defined as behavioral inhibition. It also encompasses self-regulation, which includes attentional and response inhibition, while focusing primarily on emotional control and regulation. According to Diamond (2013), working memory and inhibitory control support each other: working memory allows one to maintain their goals in their mind along with what they should or should not do, and inhibitory control allows one to stay focused on the important working memory content by inhibiting distractors. When working together, these two executive functions allow cognitive flexibility, defined by Diamond as one's ability to see things from another perspective and to shift between tasks. According to this model, fluency skills are part of cognitive flexibility, since one must be able to shift between different mind sets to be fluent in generating various ideas. Higher-level executive functions are also underpinned by working memory, inhibitory control and cognitive flexibility in this model: reasoning and problem-solving, which are synonymous with fluid intelligence, and planning skills (Diamond, 2013).

Regarding attentional functions, according to Posner and Boies (1971) and Posner and Petersen (1990), they can be divided into three central components. The first one is alertness, which allows individuals to adopt and sustain a state of vigilance and is typically involved in long, boring tasks. The second one is selective attention, which is the ability to selectively process a certain kind of information, while ignoring distractors, and involves filtering mechanisms. The third subfunction of attention is divided attention and concerns the notion of sharing mental processing capacities, which appears necessary when performing two or more tasks simultaneously (Posner & Boies, 1971; Posner & Petersen, 1990). These attentional functions are also closely related to executive functions, particularly to inhibitory control and working memory. Indeed, inhibition capacities allow attentional orienting and control

(Diamond, 2013), while information towards which attentional resources are directed are the ones accessing working memory (Knudsen, 2007).

Executive dysfunction leads to resistance to change, incapacity to modify non-optimal behaviors, a trend towards risk-taking, social difficulties, avolition and learning difficulties (Anderson, 2002; Diamond, 2013; Hofmann et al., 2012). For this reason, executive functions are essential to children's optimal daily functioning and their future quality of life, in their affective, social as well as academic spheres (Diamond, 2013; Lussier et al., 2017).

1.4. Objectives

Several studies have reported impairments in executive and attentional functions in children with DCD (Piek et al., 2004; Querne et al., 2008; Tal Saban et al., 2014; Wilson et al., 2013). Piek et al. (2007) report a generalized executive dysfunction in this population, while other authors report deficits in more specific domains of attentional or executive functioning (Toussaint-Thorin et al., 2013; Wilson et al., 2013) or more largely in nonverbal modalities of executive functioning (Leonard et al., 2015). Consequently, and according to the theoretical model of dyspraxia previously discussed, the question arises as to whether the impairments are only present in visuospatial/nonverbal modalities and on planning tasks, and thus are more linked to the primary deficits found in DCD, or whether difficulties can be found in a broader range of executive functions. This systematic review of the literature aims to answer this question, while considering the influence of comorbid neurodevelopmental disorders combined with DCD on attentional and executive profiles found in these children. Consolidating the results found in previous research appears particularly relevant given that several studies based their conclusions on small samples and thus, supporting supplemental evidence from other studies becomes essential.

On a clinical level, the purpose of this review is to better understand the impairments that can be a part of DCD rather than being explained by the comorbid disorders often observed in DCD, and to better identify the needs of children with DCD considering their potentially complex clinical picture, in order to optimize their assessment and the interventions carried out. This systematic review is the first to focus exclusively on the cognitive profile associated with DCD, and more specifically on the attentional and executive functions in young individuals with this disorder, while explicitly considering the possible influence of cooccurring disorders.

2. Method

This systematic review was performed based on the guidance outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA; Moher et al., 2009).

2.1. Search Strategy and Selection Criteria

A systematic literature research was performed in PubMed/Medline and PsycInfo databases, including articles published between January 1980 and August 2018. Due to the multiple ways of conceptualizing attentional and executive functions in terms of their components, and to be as inclusive as possible, our research was made using all terms previously mentioned that are used to describe these functions. Thereby, research was conducted in English with the following keywords: (1) "developmental coordination disorder" OR "dyspraxi*" OR "motor skills disorder" OR "specific developmental disorder of motor function" OR "clumsiness" OR "clumsy child syndrome"; (2) AND "executive function*" OR "goal setting" OR "set-shifting" OR "shifting" OR "switching" OR "flexibility" OR "planning" OR "inhibit*" OR "working memory" OR "organis*" OR "organiz*" OR "self-regulation" OR "fluency" OR "attention*"; (3) AND "child*" OR "adolescen*" OR "teen*" OR "youth" OR "schoolchild*"

OR “preschool*”. Publications referenced in the included articles were also screened to find additional articles.

Studies were included if (1) their participants were children or adolescents (17 years of age or younger; studies including older participants were excluded), (2) they had a group of participants with a diagnosis of DCD made by a health care professional, by a score at or below the 5th percentile on the *Movement Assessment Battery for Children* (MABC first or second edition), as this score indicates a significant movement difficulty (Brown & Lalor, 2009), or by DSM (IV, IV-TR or 5) criteria for DCD combined with a movement ability measure, in which case a total score at or below the 15th percentile on the MABC was accepted, (3) their participants did not explicitly have any medical condition that could affect their motor or cognitive abilities, (4) they measured one or more attentional or executive functions using performance tests, (5) they used normative data of standardized measures or a control group comprising healthy individuals for results comparison, (6) they were published in French or English in a peer-reviewed journal and (7) they had an empirical research design.

Studies were first selected according to their title. Second, abstracts were read by two authors (CL and MPL) and studies that did not meet the eligibility criteria listed above were excluded. Then the same two authors screened full articles independently to ensure that all eligibility criteria were met. Their disagreements were discussed to reach a consensus and, whenever necessary, another author (SL) settled. The remaining articles were entirely read by the first author.

2.2. Data Extraction

Data extraction from articles that met the selection criteria was made by the first author, with the contribution of MPL. Information was organized in an Excel table and included: title of the article, authors, year of publication, journal in which it was published, aims of the study, groups, their origin and samples size, gender and age of the subjects assessed (mean, standard deviation and range, when available), country in which the study took place, inclusion and exclusion criteria, presence of comorbid disorders in the sample and their nature, information about assessment of motor functions and confounding variables, cognitive functions assessed and tasks used, statistical analysis, results, limitations and commentaries about the paper. Subsequently, the relevant information was analyzed and summarized in Table 1. Components of attentional and/or executive functioning assessed in each included study were determined according to what the study purported to measure. When the same score on a task was reported to assess more than one component of attentional or executive functioning, or to measure different components in different studies, results were reported only in relation to the component it was the most associated with, according to the *Compendium of Neuropsychological Tests* (Strauss et al., 2006) or the task's reference. When several scores were available on the same task and associated with different components of attentional or executive functioning, information provided by each score was considered as a measure of its respective component.

2.3. Quality Assessment of Included Studies

Quality assessment of studies included in this systematic literature review was conducted using a checklist we developed based on the Newcastle-Ottawa Quality Assessment Scale (NOS; Wells et al., 2014). The NOS consists of three domains: "selection of subjects", "comparability of subjects" and "outcome", each domain including two to three items. Since we could not find a tool giving standardized criteria for assessing the quality of neuropsychological and behavioral studies, we adapted the NOS based on the methods used by Wu et al. (2013, 2014, 2016) and Caçola et al. (2017), that were inspired by the NOS and the PRISMA standards.

We developed three to four quality items for each domain of the NOS (selection, comparability and outcome). The result is a 10-item checklist, including: inclusion/exclusion criteria and samples source (for the selection domain), comparability of samples regarding age, gender and IQ (for the comparability domain), and description of outcome measures, adequacy of outcome analysis and discussion (for the outcome domain; see appendix 1 for the complete checklist). Items could be answered by “yes” or “no”, and quality level of evidence was rated as high (8 “yes” or more), medium (6-7 “yes”) or low (5 “yes” or less). The quality assessment was carried out by the first two authors independently and any discrepancy was discussed until they reached a decision by consensus.

3. Results

3.1. Characteristics of Included Studies

A total of 1001 articles were identified through databases; 631 remained after removing duplicates. Of these, twenty articles (3.2%) had to be discussed between two authors to reach a consensus regarding their inclusion or exclusion, and a third had to settle for five (0.8%) of them. As a result, 38 studies were included in this systematic literature review (see flow diagram in Fig. 1), representing 989 children and adolescents with DCD (or developmental dyspraxia; DD) with or without comorbid disorders, 16 with dyspraxia following preterm birth, 75 with motor difficulties (MD) without DCD, 314 comparison subjects with neurodevelopmental conditions other than DCD, and 1,112 typically developing (TD) controls, for a total of 2,506 subjects. MD groups were composed of children that had been identified with motor difficulties by scoring below the 16th percentile on the MABC-2 (Bernardi et al., 2016, 2017; Leonard et al., 2015) or had a standardized score under 80 on the McCarron Assessment of Neuromuscular

Developmental (McCarron, 1997), without having a diagnosis of DCD (Dyck & Piek, 2010). Some articles used the same tasks in the same sample of participants with DCD, and therefore, whether it was mentioned in the article (Bernardi et al., 2016; Leonard et al., 2015) or obvious (common authors, close in time, same sample size, characteristics and inclusion/exclusion criteria; Alloway, 2007, 2011; Alloway et al., 2009), their samples were considered as one and their participants were counted only once in the reported total participants. The age range for all 38 studies combined is 3 to 16 years old and the mean is 9.6 years old. Results and characteristics of studies included in this review are presented in Table 1. The quality ratings ranged between 5 and 10 out of 10 (see Table 2 for details regarding quality assessment of included studies). Seven studies (18.4%) needed to be discussed between two authors to reach a consensus about their quality level of evidence. It was finally rated as high in 16 studies, medium in 20 studies and low in two studies. The two studies that were rated as low quality were nevertheless included, because they still met the eligibility criteria established by authors. However, they are identified in the sections in which they are discussed in order to nuance their contribution.

No study explicitly assessing organization, self-regulation or goal-setting processes and meeting eligibility criteria established in this review was found. Overall, included studies explored nine dimensions of cognition: three attentional functions (alertness and sustained attention, selective attention, and divided attention) and six executive functions (inhibitory control, working memory, planning, cognitive flexibility, fluency and general executive functioning). A study was considered to discuss general executive functioning when the task they used intentionally assessed multiple executive components, by using an ecological task or a standardized task that did not allow isolating one component of executive functioning. Results are presented in terms of these nine cognitive domains. When several components of attentional and executive functioning were assessed in the same study, the results for each component were reported in their respective section. When it was mentioned in the study, the different modalities (auditory/verbal or visual/nonverbal) used to measure each cognitive function are discussed separately (when available, the modality is identified in Table 1). When it was not possible to isolate the modalities, the general cognitive function of interest is discussed. A summary of attentional and executive functions assessed and their modalities, tasks used, sample size and age group in which they were respectively assessed, along with studies providing results about each cognitive domain, is provided in Appendix 2.

3.2. Attentional Functions

3.2.1. Alertness and sustained attention. Eight articles using independent samples and discussing alertness or sustained attention in children with DCD were included. Among them, three were rated as high-quality studies and five as medium quality. Seven studies assessed alertness or sustained attention in visual modality (Biotteau et al., 2017; Blais et al., 2017; de Castelnau et al., 2007; Kaiser & Albaret, 2016; Querne et al., 2008; Rahimi-Golkhandan et al., 2016; Tsai et al., 2012), totaling 108 children with DCD, 23 with both DCD and DDL, 20 with DDL, 9 with ADHD, and 149 TD controls. One study administered a task in auditory modality (Williams et al., 2013) to 10 children with DCD, 16 with both DCD and ADHD, 14 with ADHD and 18 TD controls. Tasks used to assess alertness and sustained attention in visual modality were the Continuous Performance Test (CPT; omission errors; Conners & Staff, 2000), the Computerized Test Battery of Attention for Children (KITAP; Zimmerman et al., 2002) Alerting test, Go/No No tasks (omission errors; Casey et al., 1997; Ladouceur et al., 2006) and the Visuospatial Working Memory Paradigm (non-delay condition; Muller & Knight, 2002; Tsai et al., 2012). The Test of Everyday Attention for Children (TEA-Ch; Manly et al., 1999) Score! subtest was used in auditory modality. Among the seven studies that assessed alertness and sustained attention in visual modality, four found no significant difference between performances of children with DCD and their TD peers or normative data (Biotteau et al., 2017; Kaiser & Albaret, 2016; Rahimi-Golkhandan et al., 2016; Tsai et al., 2012), while three studies reported that children with DCD had significantly more difficulty than TD children in maintaining their alertness during a long, boring visual task (Blais et al., 2017; de Castelnau et al., 2007; Querne et al., 2008). In auditory modality, the only significant difference Williams et al. (2013) found was between children with both DCD and ADHD and TD controls: children with both disorders had lower scores than their normative peers.

Regarding the presence of comorbid disorders, four studies excluded all neurological or psychiatric comorbidities in their DCD samples (Querne et al., 2008; Rahimi-Golkhandan et al., 2016; Tsai et al., 2012; Williams et al., 2013), one only mentioned excluding children with ADHD or SLI (Biotteau et al., 2017) and three, subjects with ADHD (Blais et al., 2017; de Castelnau et al., 2007; Kaiser & Albaret, 2016; for more details about exclusions and comorbid disorders present in the samples, see Table 1). Thereby, three out of four studies using the purest samples did not find deficits of alertness or sustained attention in children with DCD, while half the studies that may have include subjects with some comorbidities found impairments in this domain in children with DCD. Furthermore, three articles compared the performance of children in different clinical groups on tasks of alertness or sustained attention. It was found that children with DCD, DDL or both DCD and DDL did not differ in their sustained attention capacities (Biotteau et al., 2017), and neither did children with a single diagnosis of DCD or ADHD (Kaiser & Albaret, 2016). In addition, the study by Williams et al. (2013) revealed that children with a single diagnosis of DCD do not exhibit a deficit in auditory sustained attention compared to TD controls, nor did children with a single diagnosis of ADHD, but participants with both diagnoses did have greater difficulty than a normative group in this domain. Thus, there does not seem to be a deficit in alertness or sustained attention specifically associated with DCD, but it appears that the cooccurrence of ADHD might negatively influence these abilities.

3.2.2. Selective attention. Five studies using independent samples and assessing selective attention capacities in children with DCD were included in this section. Quality level of evidence was rated as high in three studies, medium in one study and low in one study. Three studies used only tasks in visual modality (Asonitou & Koutsouki, 2016; Asonitou et al., 2012; Kaiser & Albaret, 2016), totaling 61 children with DCD, 9 with ADHD and 69 TD controls, while one study assessed selective attention only in auditory modality (Toussaint-Thorin et al., 2013) in 13 children with DCD and 14 TD controls. One study assessed both modalities (Barray et al., 2008) in a sample of 32 children with DD and 16 with dyspraxia following preterm birth. Tasks used to assess selective attention in visual modality were the Das-Naglieri Cognitive Assessment System (CAS; Naglieri & Das, 1997) Expressive attention, Number Detection and Receptive Attention tests, the Developmental Neuropsychological Assessment (NEPSY; Korkman et al., 2006) Visual Attention test, and the KITAP Distractibility test (Zimmerman et al., 2002). The task used to assess the auditory modality of this attentional domain was the NEPSY Auditory Attention and Response Set test. Among the four articles that discussed selective attention in visual modality, two reported impairment on this attentional domain in children with DCD (Asonitou & Koutsouki, 2016; Asonitou et al., 2012). The two other studies did not find any significant difference between performance of children with DCD/DD and TD controls or normative data (Barray et al., 2008; Kaiser & Albaret, 2016). However, it seems that children with dyspraxia following preterm birth had significantly poorer scores on a visual attention task than children with DD, a difference that may be due to sequalae related to prematurity rather than dyspraxia (Barray et al., 2008). In addition, both studies that assessed auditive selective attention in DCD found no deficit in these children associated with this attentional component (Barray et al., 2008; Toussaint-Thorin et al., 2013). Even though the results of both studies are consistent, note that the study by Toussaint-Thorin et al. (2013) was the one qualified as low quality and, for this reason, their results should be considered cautiously.

Regarding the management of possible comorbid neurodevelopmental disorders in children composing the DCD groups, two studies excluded children with any other medical, neurological or developmental conditions (Asonitou & Koutsouki, 2016; Asonitou et al., 2012), one only mentioned excluding subjects with ADHD (Kaiser & Albaret, 2016), one included children with ADHD (Toussaint-Thorin et al., 2013), and one did not mention excluding children with comorbid neurodevelopmental or learning conditions (Barray et al., 2008). Thus, since the two studies using the purest samples were the only ones to find deficits of selective attention in children with DCD, these impairments do not appear to be linked to the presence of comorbid conditions. The reasons why studies including children with cooccurring disorders in their DCD sample did not find deficits in this domain may include methodological weaknesses, since the study by Toussaint-Thorin et al. (2013) was rated as low quality, but further research is needed to elucidate this point. Finally, Kaiser and Albaret (2016) compared children with DCD and children with ADHD on this attentional domain, and they found no significant difference between their performances, suggesting that these clinical groups cannot be distinguished based on their selective attention capacities.

3.2.3. Divided attention. Only one article discussing divided attention abilities in children with DCD was included (Kaiser & Albaret, 2016). It was rated as medium quality. The sample consisted of 7 children with DCD, 9 with ADHD and 15 TD controls. The task used was the KITAP Divided Attention test (Zimmerman et al., 2002), combining both visual and auditory modalities. Results showed no impairment on this attentional component in participants with DCD when compared to TD controls, and there was no significant difference between DCD and ADHD groups.

The authors only mention excluding children with ADHD from their DCD sample and thus, it is possible that at least some children presented other comorbid neurodevelopmental conditions or learning difficulties. However, if present, it does not seem that these concomitant disorders might have had a negative influence on the children's divided attention capacities, since no deficits were found.

3.3. Executive Functions

3.3.1. Inhibitory control. Twenty-three articles, using 22 different samples, discussed inhibitory control in children with DCD and were included in this review (Bernardi et al., 2016, 2017; Biotteau et al., 2017; Blais et al., 2017; Chen et al., 2012; de Castelnau et al., 2007; Dyck & Piek, 2010; Gonzalez et al., 2016; Leonard et al., 2015; Mandich et al., 2002, 2003; Pratt et al., 2014; Querne et al., 2008; Rahimi-Golkhandan et al., 2016; Ruddock et al., 2015, 2016; Toussaint-Thorin et al., 2013; Tsai et al., 2010; Tsai, Pan et al., 2009; Tsai, Yu et al., 2009; Wang et al., 2015; Wilson & Maruff, 1999; Wilson et al., 1997), amounting to 592 children with DCD/DD, 75 with poor motor coordination/MD but no DCD, 63 with non-motor neurodevelopmental problems and 652 TD controls. Among these studies, the response inhibition component of inhibitory control was assessed in 14 different samples, and the attentional inhibition component was measured in 10 different samples, since both types of inhibitory control were assessed in two samples.

3.3.1.1. Response inhibition. Overall, response inhibition was assessed in 15 studies using 14 different samples (Bernardi et al., 2016, 2017; Biotteau et al., 2017; Blais et al., 2017; de Castelnau et al., 2007; Dyck & Piek, 2010; Leonard et al., 2015; Mandich et al., 2002, 2003; Pratt et al., 2014; Querne et al., 2008; Rahimi-Golkhandan et al., 2016; Ruddock et al., 2015, 2016; Toussaint-Thorin et al., 2013), amounting to 341 children and adolescents with DCD/DD, 75 with MD but no DCD, 63 with non-motor neurodevelopmental problems and 431 TD controls. They all measured nonverbal response inhibition, and verbal response inhibition was also assessed in three different samples. Regarding the quality level of evidence for all studies discussing response inhibition, two studies were rated as high quality, 11 as medium quality, and two as low quality.

3.3.1.1.1. Nonverbal response inhibition. The 14 samples in which nonverbal response inhibition abilities were assessed (Bernardi et al., 2016, 2017; Biotteau et al., 2017; Blais et al., 2017; de Castelnau et al., 2007; Dyck & Piek, 2010; Mandich et al., 2002, 2003; Pratt et al., 2014; Querne et al., 2008; Rahimi-Golkhandan et al., 2016; Ruddock et al., 2015, 2016; Toussaint-Thorin et al., 2013) regrouped 341 children and adolescents with DCD or DD, 75 with MD but no DCD, 63 with non-motor neurodevelopmental problems and 431 TD controls. Nonverbal measures used to assess response inhibition were the Verbal Inhibition Motor Inhibition test (motor task, total errors and/or completion time; Henry et al., 2012), the CPT (commission errors; Conners & Staff, 2000), Go/No Go tasks (commission errors; Casey et al., 1997; Ladouceur et al., 2006; Mandich et al., 2003; Shue & Douglas, 1992; Wilson & Maruff, 1999), the Simon task (errors; Simon, 1969), the NEPSY Knock-Tap test (Korkman et al., 2006), a modified version of the Double-Jump Reaching task (Ruddock et al., 2015, 2016) and the Paired Images test (Marquet-Doléac, Albaret, & Bénesteau, 1999). Difficulties in children with DCD regarding the ability to inhibit a nonverbal prepotent response when compared to their TD peers were found in nine different samples, especially in terms of correct responses (Bernardi et al., 2016, 2017; Blais et al., 2017; Mandich et al., 2002, 2003; Rahimi-Golkhandan et al., 2016; Ruddock et al., 2015, 2016; Toussaint-Thorin et al., 2013). Rahimi-Golkhandan et al. (2016) specified that the response inhibition deficit in DCD children is only present when stimuli are positively-valenced, and thus more compelling, but not when they are negatively-valenced. Also, five studies using independent samples found no deficit on this ability in participants with DCD or MD compared to normative data or a control group (Biotteau et al., 2017; de Castelnau et al., 2007; Dyck & Piek, 2010; Pratt et al., 2014; Querne et al., 2008).

3.3.1.1.2. Verbal response inhibition. The three samples in which verbal response inhibition abilities were measured (Bernardi et al., 2016, 2017; Pratt et al., 2014) bring a total of 66 participants with DCD, 47 with MD but no DCD and 79 controls. Measures used were the Verbal Inhibition Motor Inhibition test (verbal task, total errors and/or completion time; Henry et al., 2012) and the Stroop task (correct responses; Stroop, 1935). In one of the three samples, the difference between DCD and TD groups was significant on the reduced motor-load task (verbal task), while they were not on the high motor-load task (nonverbal task; Pratt et al., 2014). However, authors explain that results might have been more influenced by the tasks' complexity than by their modality. In the two other samples, no impairment was found on verbal inhibition measures in terms of accuracy (Bernardi et al., 2016, 2017). Nevertheless, Bernardi et al. (2016), being the only research team that used completion time as well as number of errors as outcome measures, found that participants with DCD were significantly slower than their TD peers on the verbal task, even though their accuracy was similar.

To summarize, children with DCD exhibited response inhibition difficulties mostly in the nonverbal modality and fewer evidence of impairment has been found in the verbal modality.

Among the 14 samples included in this subsection, eight were pure DCD samples, participants with any neurodevelopmental or medical comorbid conditions being excluded (Bernardi et al., 2016, 2017; Dyck & Piek, 2010; Pratt et al., 2014; Querne et al., 2008; Rahimi-Golkhandan et al., 2016; Ruddock et al., 2015, 2016). Only ADHD and SLI were mentioned to be excluded in one sample (Biotteau et al., 2017) and only ADHD in three samples (Blais et al., 2017; de Castelnau et al., 2007; Mandich et al., 2002). Children with ADHD were included in one sample (Toussaint-Thorin et al., 2013), and one sample was free of all exclusions (Mandich et al., 2003). Thereby, response inhibition difficulties were found in children with DCD, whether they had comorbid conditions or not. In addition, Biotteau et al. (2017) compared the results of children with DCD with those of children with DDL and found no significant difference between children with DCD only, DCD with comorbid DDL, or DDL only on these capacities. Hence, impairments that were found in most of the studies included in this subsection do not appear to be attributable to the presence of comorbid neurodevelopmental disorders.

3.3.1.2. Attentional inhibition. Overall, 10 studies using independent samples assessed inhibitory control of attention in DCD (Chen et al., 2012; Gonzalez et al., 2016; Mandich et al., 2002, 2003; Tsai et al., 2010; Tsai, Pan et al., 2009; Tsai, Yu et al., 2009; Wang et al., 2015; Wilson & Maruff, 1999; Wilson et al., 1997), totaling 271 subjects with DCD and 241 TD controls. Among these, six were rated as having a high-quality level of evidence and four as having a medium quality one. Two modes of orienting attention were discussed: the endogenous and the exogenous mode. The first mode is defined as a controlled and volitional allocation of attentional resources requiring a cognitive interpretation of stimuli, while the second refers to an automatic and reflexive allocation of attention that has an alerting utility (Wilson & Maruff, 1999; Wilson et al., 1997). The endogenous mode of orienting attention was assessed in six studies (Chen et al., 2012; Mandich et al., 2003; Tsai, Pan et al., 2009; Tsai, Yu et al., 2009; Wilson & Maruff, 1999; Wilson et al., 1997), and the exogenous mode in seven studies (Gonzalez et al., 2016; Mandich et al., 2002; Tsai et al., 2010; Tsai, Yu et al., 2009; Wang et al., 2015; Wilson & Maruff, 1999; Wilson et al., 1997). Tsai, Yu et al. (2009), Wilson and Maruff (1999) and Wilson et al. (1997) discussed both modes. Measures used to assess attentional inhibition were all in visual modality. To assess the endogenous mode of orienting attention, all studies used tasks inspired by the work of Posner (1980, 1988): the Covert Orienting of Visuospatial Attention Task (COVAT; for description of the task, see: Tsai, Pan, et al., 2009; Wilson & Maruff, 1999) or Go/No Go tasks with informative and noninformative central precue conditions (measures of reaction times; Gonzalez et al., 2015; Mandich et al., 2003; Tsai et al., 2010). The COVAT and similar visuospatial attention tasks also allow assessing the exogenous mode of attentional orienting when peripheral precues are presented, and thus such tasks were also used in studies assessing this mode, in addition to the Simon task (measures of reaction times; Simon, 1969).

All six articles that assessed the endogenous mode of orienting attention reported a deficit of endogenous attentional inhibitory control or “disengagement inhibition” of attention in children with DCD, when compared to TD controls (Chen et al., 2012; Mandich et al., 2003; Tsai, Pan et al., 2009; Tsai, Yu et al., 2009; Wilson & Maruff, 1999; Wilson et al., 1997). Among the seven studies discussing the exogenous mode, four found no deficit (Mandich et al., 2002;

Tsai, Yu et al., 2009; Wilson & Maruff, 1999; Wilson et al., 1997), while three reported this mode to be impaired in children with DCD (Gonzalez et al., 2016; Tsai et al., 2010; Wang et al., 2015). It appears that the lack of consistency between these studies and the ones that did not find any impairment might be due to the nature of the precues used in the tasks (eyes) compared to the ones previously used (arrows), which trigger certain different brain areas and neural networks, may be more alerting and involve volitional components of orienting attention as well as automatic components (Tsai et al., 2010; Wang et al., 2015). In summary, the endogenous aspects of attentional control seem to be more largely affected in children with DCD than exogenous aspects of orienting attention, which means they have more difficulty to voluntarily direct and shift their attention toward a stimulus or a task while inhibiting distractors than to automatically shift their attention to peripheral alerting stimuli.

Regarding the presence of comorbid disorders in the DCD samples, seven studies excluded participants with any signs of a comorbid condition (Chen et al., 2012; Tsai et al., 2010; Tsai, Pan et al., 2009; Tsai, Yu et al., 2009; Wang et al., 2015; Wilson & Maruff, 1999; Wilson et al., 1997), two only mentioned excluding children diagnosed with ADHD (Gonzalez et al., 2016; Mandich et al., 2002), and one did not mention any exclusions (Mandich et al., 2003). Thus, since deficits in attentional inhibition were found in children with pure DCD as well as in subjects with possible cooccurring disorders, impairments in this domain seem to be a part of DCD and do not seem to be attributable to disorders associated with DCD.

3.3.2. Working memory. Twelve articles, using 10 different samples of children with DCD, discussed working memory in children with DCD and were included (Alloway, 2007, 2011; Alloway & Archibald, 2008; Alloway et al., 2009; Alloway & Temple, 2007; Bernardi et al., 2017; Biotteau et al. 2017; Dyck & Piek, 2010; Leonard et al., 2015; Piek et al., 2007;

Sumner et al., 2016; Tsai et al., 2012), totaling 297 children with DCD, 23 of whom also had a diagnosis of DDL, 75 children with poor motor coordination/MD but no DCD, 291 children with learning difficulties or neurodevelopmental disorders other than DCD, and 325 TD controls. Among these, visuospatial modality of working memory was measured in six different samples and its verbal modality was assessed in nine different samples. Both modalities were assessed in five samples.

3.3.2.1. Visuospatial working memory. Overall, visuospatial working memory was assessed in six different samples (Alloway, 2011; Alloway & Archibald, 2008; Alloway & Temple, 2007; Bernardi et al., 2017; Leonard et al., 2015; Tsai et al., 2012) totaling 162 children and adolescents with DCD, 47 with MD but no DCD, 189 subjects with neurodevelopmental problems other than DCD, and 105 TD peers. Regarding quality level of evidence, three papers were rated as being high quality studies and five as medium quality ones. Tasks used were the Odd-One-Out, Mr. X and Spatial Span tasks from the Automated Working Memory Assessment (AWMA; Alloway et al., 2004), another version of an Odd-One-Out task (Henry, 2001) and the Visuospatial Working Memory Paradigm (delay condition; Muller & Knight, 2002; Tsai et al., 2012). All six samples of children with DCD showed impairments of visuospatial working, compared to normative data or control groups (Alloway, 2011; Alloway & Archibald, 2008; Alloway & Temple, 2007; Bernardi et al., 2017; Leonard et al., 2015; Tsai et al., 2012). Children with MD but no DCD did not differ from those with DCD: both groups performed more poorly than the TD group (Leonard et al., 2015).

Among the six different samples included in this subsection, subjects with any comorbid neurodevelopmental disorder were excluded from three of the DCD samples (Bernardi et al., 2017; Leonard et al., 2015; Tsai et al., 2012), only children with ADHD or behavioral problems/ASD were mentioned as being excluded from two samples (Alloway, 2011; Alloway & Archibald, 2008), and the remaining paper did not mention any exclusion (Alloway & Temple, 2007). In addition, four studies compared the results of children with DCD on visuospatial working memory measures with those of children with non-motor neurodevelopmental or learning problems. Alloway (2011) and Alloway et al. (2009) found no significant difference between one group of children with DCD and groups of children with ADHD, SLI or ASD. In fact, children with ASD performed better than those with DCD, but the difference was not significant once the nonverbal IQ test's shared motor component was accounted for (Alloway et al., 2009). Furthermore, a study that compared two groups of children with DCD, one in which children had language or nonverbal reasoning difficulties and one in which their disorder was purer, found no difference on visuospatial working memory capacities between the two groups. However, children with a purer DCD performed significantly worse than children with SLI in this study, even when the contribution of receptive language skills was accounted for (Alloway & Archibald, 2008). Also, children with DCD were significantly more impaired than children with general learning difficulties on the visuospatial working memory modality (Alloway & Temple, 2007). Considering these results, visuospatial working memory seems to be a deficit in children with DCD whether their disorder is pure or not, and it appears to be more specific to children with DCD in comparison to children with mild learning impairments or SLI, but not in comparison to children with ADHD or ASD.

3.3.2.2. Verbal working memory. Overall, verbal working memory was measured in nine different samples (Alloway, 2011; Alloway & Archibald, 2008; Alloway & Temple, 2007; Bernardi et al., 2017; Biotteau et al. 2017; Dyck & Piek, 2010; Leonard et al., 2015; Piek et al., 2007; Sumner et al., 2016), comprising 273 children and adolescents with DCD, 75 with poor motor coordination/MD but no DCD, 291 with other neurodevelopmental or learning problems and 295 TD peers. Four studies were rated as having high quality level of evidence, six as medium quality, and one as low quality. Tasks used were the Listening recall, Counting Recall and Backwards Digit Recall tasks from the AWMA (Alloway et al., 2004), the Listening recall task from the Working Memory Test Battery for Children (WMTBC; Pickering & Gathercole, 2001), the Digit Span and Letter-Number sequencing tests from the Wechsler Intelligence Scale for Children, Fourth Edition (WISC-IV; Wechsler, 2003), a Trailmaking/Memory Updating task (Rabbit, 1997) and a combination of the latter with a Goal Neglect task (Duncan et al., 1996). Three samples showed no impairment of verbal working memory in children with DCD when compared to TD controls or normative data (Bernardi et al., 2017; Biotteau et al., 2017; Leonard et al., 2015). Children with MD but no DCD did not differ from children with DCD nor TD children (Leonard et al., 2015). However, six different samples showed difficulties in verbal working memory in this population according to comparisons with control groups or normative data (Alloway, 2011; Alloway & Archibald, 2008; Alloway & Temple, 2007; Dyck & Piek, 2010; Piek et al., 2007; Sumner et al., 2016). Again, children with poor motor coordination without DCD did not differ significantly from children with DCD (Dyck & Piek, 2010). However, the study by Dyck and Piek (2010) was rated as low quality because of the non-comparability of their groups, and thus their results might be explained by a confounding variable. Moreover, two research teams put their results in perspective: Sumner et al. (2016) mentioned they could not conclude to a primary deficit in verbal working memory in children with DCD since their results showed a great heterogeneity across all intelligence domains in these children, and Piek et al. (2007) explained that their results could be attributable to a slower processing speed in children with DCD, but further analysis would be required to confirm it.

Regarding the presence of comorbid disorders, participants diagnosed with any neurodevelopmental or medical comorbid conditions were excluded from four samples (Bernardi et al., 2017; Dyck & Piek, 2010; Leonard et al., 2015; Sumner et al., 2016), only children with ADHD or SLI were mentioned as being excluded from one sample (Biotteau et al., 2017), only children with ADHD or behavioral problems/ASD were mentioned as being excluded from two samples (Alloway, 2011; Alloway & Archibald, 2008), and no exclusions were mentioned in two samples (Alloway & Temple, 2007; Piek et al., 2007). Thereby, two out of three studies that did not find any deficit excluded participants with any other neurodevelopmental disorders from their DCD sample and, among the six different samples in which verbal working memory difficulties were found, all comorbid conditions were excluded from only two samples. Consequently, it seems possible that the impairments found in some studies are at least partially influenced by comorbid disorders. Furthermore, among the 11 articles included in this section, seven compared the results of children with DCD on verbal working memory measures with those of children with non-motor neurodevelopmental or learning problems. Five studies finding at least some difficulties in children with DCD on verbal working memory measures found no difference between children with DCD and children with ADHD, SLI, ASD, mild learning difficulties, RELD or relatively poor language ability (Alloway, 2011; Alloway & Archibald, 2008; Alloway et al., 2009; Alloway & Temple, 2007; Dyck & Piek, 2010), while one found that children with DCD performed significantly poorer than children with ADHD (Piek et al., 2007). Among studies that did not report any impairment on the verbal modality of working memory, one specified that there was no difference between their two groups of DCD subjects, one in which children had a diagnosis of comorbid DDL and one purer group, nor with a group of children with a single diagnosis of DDL (Biotteau et al., 2017). In summary, impairment of verbal working memory in children with DCD is less clear than the visuospatial deficit of working memory, and it does not seem to be very specific to this disorder.

2.3.3. Planning. Eight studies using different samples and assessing planning abilities in children with DCD were included. The quality level of evidence was rated as high in three studies, medium in four studies and low in one study. Two studies compared children's performance on nonverbal and verbal measures (Bernardi et al., 2017; Leonard et al., 2015), counting 40 children with DCD, 47 with MD but no DCD and 55 TD controls, while six considered general planning abilities (Asonitou & Koutsouki, 2016; Asonitou et al., 2012; Barray et al., 2008; Kirby et al., 2010; Pratt et al., 2014; Toussaint-Thorin et al., 2013), regrouping 190 children with DCD or DD, 16 children with dyspraxia following preterm birth and 174 TD controls. One of these studies compared performance in tasks with a high or a low motor-load (Pratt et al., 2014). Measures of planning used were the Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001) Sorting test (number of nonverbal sorts and of verbal sorts for comparison between nonverbal and verbal modalities), the CAS Matching Numbers, Planned Codes, and Planned Connections tests (Naglieri & Das, 1997), the NEPSY Tower task (Korkman et al., 2006), the River Crossing task (Kirby et al., 2010), the Rotational Bar task (Rosenbaum et al., 1990) and the Behavioural Assessment of the Dysexecutive Syndrome in Children (BADS-C; Emslie et al., 2003) 6-Part test. Among the six articles that discussed planning with no regard to the task's modality, one reported no deficit on this ability compared to normative data (Barray et al., 2008), while five reported significantly poorer performance in children with DCD when compared to TD children (Asonitou & Koutsouki, 2016; Asonitou et al., 2012; Kirby et al., 2010; Pratt et al., 2014; Toussaint-Thorin et al., 2013). One of these five studies was however rated as low quality

(Toussaint-Thorin et al., 2013) and thus less weight should be given to it. Pratt et al. (2014) specify that the task's motor-load did not affect performance on the planning measures since subjects with DCD showed significant difficulties in both tasks, even when the effect of perceptual reasoning was accounted for. Also, the two studies that compared performance on nonverbal and verbal measures found different results. Leonard et al. (2015) found no difference between groups of children with DCD, MD and TD controls on the verbal measure and that only children in the MD group had significantly poorer performance than the TD group on the nonverbal measure. Bernardi et al. (2017) reported that children with DCD, as well as children in the MD group, performed more poorly than TD controls on the nonverbal measure of planning, but they found no significant difference in the verbal planning measure. Thus, in all children with motor problems, planning might be impaired on a nonverbal measure, but not on a verbal one.

Regarding the presence of comorbid disorders in DCD samples of studies included in this section, five excluded children with any other diagnosed medical, neurological or developmental conditions (Asonitou & Koutsouki, 2016; Asonitou et al., 2012; Bernardi et al., 2017; Leonard et al., 2015; Pratt et al., 2014), one excluded participants with learning disorders but included those with ADHD symptoms (Kirby et al., 2010), one included children with ADHD (Toussaint-Thorin et al., 2013), and one did not mention excluding children with comorbid neurodevelopmental or learning conditions (Barray et al., 2008). Thus, among the six articles that reported at least some impairment of planning in children with DCD, four used pure samples, whereas among the two that did not report any deficit, one used a sample free of comorbid disorders. Therefore, impairments found do not seem to be attributable to the presence of comorbid disorders, and these do not appear to influence planning abilities in children with DCD.

3.3.4. Cognitive flexibility. Four studies using different samples and exploring cognitive flexibility were included. Three of them were rated as medium quality studies and one as low quality. Once again, two compared children's performance on nonverbal and verbal measures (Bernardi et al., 2017; Leonard et al., 2015), counting 40 children with DCD, 47 with MD but no DCD and 55 controls, while two assessed general cognitive flexibility (Piek et al., 2007; Toussaint-Thorin et al., 2013), representing 31 children with DCD, 39 with ADHD and 152 controls. Nonverbal and verbal measures between which performance has been compared were respectively the Cambridge Neuropsychological Test Automated Battery (CANTAB; Cambridge Cognition, 2006) Intra-/Extra-Dimensional Shift task and the D-KEFS Trail Making test (Delis et al., 2001). Measures of general cognitive flexibility used were a Visual Inspection Time task (set-shifting trial; Anderson, 1988) and the Trail Making test A and B for Children (Reitan, 1958). Among the two articles that discussed general cognitive flexibility, one found no deficit on this ability (Toussaint-Thorin et al., 2013), while the other reported significantly worse performance in children with DCD than in controls (Piek et al., 2007). Note however that the study that found no deficit was the one rated as low quality and thus more weight should be given to the study by Piek et al. (2007). In regards to the two studies that compared performance on nonverbal and verbal measures, Leonard et al. (2015) found no difference between groups of participants with DCD, MD without DCD and TD controls in both nonverbal and verbal measures, while Bernardi et al. (2017) reported that children with DCD performed more poorly than TD controls on the nonverbal measure of cognitive flexibility, without any difference between the MD and the TD groups. Cognitive flexibility was thus impaired only in children with DCD, only on the nonverbal measure. Note however that both studies used a Trail Making test as a measure of cognitive flexibility, which is a graphomotor task, and it is thus possible that the impairment found by Bernardi et al. (2017) is at least partly attributable to the primary motor deficits of children with DCD.

Regarding the presence of comorbid disorders among DCD samples, two studies excluded participants with other diagnosed neurodevelopmental disorders from their DCD sample (Bernardi et al., 2017; Leonard et al., 2015). One article did not mention excluding participants with comorbid disorders (Piek et al., 2007) and one included children with ADHD (Toussaint-Thorin et al., 2013). Thereby, one out of two studies that used a pure sample found impairments in cognitive flexibility, specifying that difficulties are only present on a nonverbal measure. One study that included children with comorbid conditions did not find any difficulties, while the other found some. Furthermore, one study compared the performance of children with DCD with that of children with ADHD and found that the firsts were more impaired than the seconds on a general cognitive flexibility measure (Piek et al., 2007). Thus, no specific cognitive flexibility profile seems to be associated with DCD since the results are heterogeneous, but more difficulty on nonverbal flexibility tasks might be present. In addition, comorbid disorders do not seem to have a notable influence on this ability in this clinical group.

3.3.5. Fluency. Four articles using different samples and exploring fluency in children with DCD were included (Barray et al., 2008; Bernardi et al., 2017; Leonard et al., 2015; Toussaint-Thorin et al., 2013), summing up to 85 subjects with DCD/DD, 16 with dyspraxia following preterm birth, 47 with MD but no DCD and 69 TD controls. One study only used a nonverbal measure of fluency, one only assessed the verbal modality and two assessed both modalities.

2.3.5.1. Nonverbal fluency. Overall, nonverbal fluency ability was assessed in three studies using different samples (Barray et al., 2008; Bernardi et al., 2017; Leonard et al., 2015), regrouping 72 children with DCD, 16 with dyspraxia following preterm birth, 47 with MD but no DCD and 55 TD children. Quality level of evidence was rated as high in one study and as medium in two studies. Tasks used were D-KEFS (Delis et al., 2001) and NEPSY (Korkman et al., 2006) Design Fluency tasks. All three studies reported difficulties on these tasks for children with DCD, compared to normative data or control group (Barray et al., 2008; Bernardi et al., 2017; Leonard et al., 2015). Children with MD but no DCD did not differ from children with DCD: they also had poorer performance than TD children (Leonard et al., 2015). Furthermore, there seems to be no difference between children with DCD and children with dyspraxia following preterm birth on nonverbal fluency, but Barray et al. (2008) pointed out that the difficulties of these clinical groups on a design fluency task may be attributable to graphomotor demands of the task. Indeed, these children, given the very nature of their disorder, exhibit rather poor graphic skills (Barray et al., 2008).

Regarding the presence of comorbid disorders among the DCD samples, two excluded children with a diagnosis of neurodevelopmental disorders (Bernardi et al., 2017; Leonard et al., 2015) and one did not mention excluding subjects with neurodevelopmental comorbidities (Barray et al., 2008). Thereby, whether neurodevelopmental comorbidities are excluded or not, nonverbal fluency capacities appear to be impaired in children with DCD.

2.3.5.2. Verbal fluency. Verbal fluency was also discussed in three articles using different samples (Bernardi et al., 2017; Leonard et al., 2015; Toussaint-Thorin et al., 2013) and assessed in 53 children with DCD/DD, 47 with MD but no DCD and 69 TD children. Quality level of evidence was rated as medium in two studies and as low in one study. Tasks used were the D-KEFS (Delis et al., 2001) and NEPSY (Korkman et al., 2006) Verbal Fluency tasks. Among the three studies, two found no deficit on verbal fluency in children with DCD/DD compared to control group (Leonard et al., 2015; Toussaint-Thorin et al., 2013), while Bernardi et al. (2017) found that children with DCD performed more poorly than controls. However, since the study by Toussaint-Thorin et al. (2013) was the one rated as low quality, their results should be considered with parsimony.

Regarding the presence of comorbid disorders among the children with DCD/DD, two studies excluded participants with neurodevelopmental comorbidities (Bernardi et al., 2017; Leonard et al., 2015) while Toussaint-Thorin et al. (2013) included children with ADHD. Thus, inclusion or exclusion of ADHD did not seem to influence the results about verbal fluency capacities.

3.3.6. General executive functioning. Two studies using independent samples and assessing general executive functioning were included, regrouping 52 subjects with DCD/DD and 53 TD controls. These articles were considered as discussing general executive functioning since the tasks used assessed multiple components of executive functioning. One study was rated as high quality and the other as low quality. One study used an ecological cooking task known to assess executive functions and multitasking abilities (Toussaint-Thorin et al., 2013). The other study used a computerized version of the Wisconsin Card Sorting Test (WCST; Beijing Haisiman Technology Development Company, 1999), a neuropsychological test assessing generalization, working memory, attention and cognitive flexibility capacities (Zhu et al., 2012). Both studies reported that children had significantly poorer performance than a control group composed of healthy individuals. On the WCST, children with DCD were impaired on most measures (Zhu et al., 2012) and on the cooking task, children in the DCD group made more errors, exhibited difficulties in respecting the task's guidelines and were more dependent, suggesting impairments in problem solving abilities (Toussaint-Thorin et al., 2013). However, since the last study is considered as a low-quality study, more research using ecological tasks is needed to confirm their conclusions.

One study included in this section used a rather pure sample (Zhu et al., 2012), while Toussaint-Thorin et al. (2013) included children with ADHD in their DCD sample. Thus, children with DCD seem to exhibit difficulties in tasks integrating multiple components of executive functioning, whether they also have ADHD or not.

3.4. Developmental Considerations

The effect of age on cognitive functions has been studied in visual sustained attention, response inhibition, working memory, planning, cognitive flexibility and fluency abilities.

Regarding visual sustained attention, in a cross-sectional study, de Castelnau et al. (2007) found that this capacity improved with age in both their sample of children with DCD and their TD group, but the discrepancy between the two groups remained, from 8-9 years old to 12-13 years old. These results suggest that difficulties in sustained attention persist with age in children with DCD.

Four studies considered the effect of years passing on response inhibition capacities. Three studies using a cross-sectional design found that nonverbal response inhibition capacities were better in older participants with DCD than in younger children with the disorder (de Castelnau et al., 2007; Ruddock et al., 2015, 2016), so that these capacities in children with DCD approached those of TD children as they got older (Ruddock et al., 2015, 2016). The other study, using a longitudinal design, found no improvement in nonverbal response inhibition in a DCD sample after a two-year follow-up, and the differences originally found between their DCD group and their TD group persisted two years later (Bernardi et al., 2017). These results indicate that the impairment found in nonverbal response inhibition in children might be due to a delay in the development of this cognitive function rather than a primary deficit, but given the heterogeneity of results across studies, more research would be necessary to confirm it. Regarding verbal response inhibition capacities, Bernardi et al. (2017) reported no improvement after two years in their DCD sample, but they also found no deficit on this ability compared to their TD group at both time points.

Additionally, among the functions that they found to be impaired in children with DCD in their longitudinal study, Bernardi et al. (2017) reported a significant improvement of visuospatial working memory, nonverbal planning, nonverbal cognitive flexibility and nonverbal and verbal fluency over time in children with DCD. They also mention that improvements in their TD group were similar, so that the deficit found in these domains in children with DCD, in comparison to TD children, persisted after a two-year follow-up (Bernardi et al., 2017).

In summary, attentional and executive functions seem to improve with age in children with DCD, as well as in TD controls, but studies found that discrepancies between performance of children with DCD and that of TD children persist over time on most executive tasks.

4. Discussion

4.1. Summary of Findings

The 38 articles included in this systematic review, totalizing a sample of 989 children and adolescents with DCD, repeatedly reported significant impairment of nonverbal response inhibition, attentional inhibition, visuospatial and verbal working memory, planning, nonverbal fluency and general executive functioning in children with DCD. Studies assessing cognitive flexibility are divided in half: one study, with a quite small sample size (17 subjects with DCD), found a deficit only on a nonverbal measure, while another study, with 23 subjects with DCD, did not find any impairment. Similarly, two out of three studies measuring verbal response inhibition found some impairment in this area, but one study mentioned it only affects completion time. Regarding studies exploring alertness and sustained attention, selective attention, divided attention and verbal fluency, most found no deficit in these areas in children with DCD when compared to a TD control group or normative data. No studies investigating organization and self-regulation skills were included in this systematic review as none met the inclusion criteria.

In light of these results, there is no evidence of an obvious attentional deficit in children with DCD. However, executive functions are widely impaired. Yet difficulties are not limited to domains that are expected to be affected considering the nature of their disorder (e.g. nonverbal planning), since deficits were found in inhibitory control, on both modalities of working memory, in general planning abilities and on ecological tasks integrating multiple components of executive functions. In summary, executive functions are more impaired on a nonverbal/visuospatial modality than on a verbal modality, and results suggest that a broad executive deficit is present in children with DCD.

A few studies also explored the possible differences between a group of children with DCD and a group of children with MD without DCD. As previously described, these groups were composed of children whose motor difficulties have been objectified but who did not have a diagnosis of DCD. It is interesting to note that most results showed no difference between these groups and DCD groups in terms of executive impairments and thus, executive difficulties seem to be present independently of motor impairments severity. Consequently, the results highlighted in this review appear to generally apply to both children diagnosed with DCD and those with motor difficulties without a diagnosis of such disorder.

4.2. Influence of Comorbid Disorders

Among the cognitive functions that were impaired in most studies, the presence of comorbid disorders did not seem to have a notable influence on inhibitory control (both response and attentional inhibition), visuospatial working memory, planning, cognitive flexibility, nonverbal fluency and general executive functioning capacities. Thus, the profiles described in these domains do not appear to be attributable to cooccurring disorders. These results suggest that cognitive impairments are genuine to DCD, which is surprising since DCD is a primary motor disorder and the definition does not include executive functioning problems (American Psychiatric Association, 2013; Missiuna et al., 2008; Zwicker et al., 2012). However, not all studies addressed the issue of comorbidities in the same way: some studies based their exclusion criteria only on comorbid disorders that had been diagnosed in children, while others measured and confirmed their presence in children composing their sample. In most samples in which response inhibition, visuospatial working memory, planning, cognitive flexibility, nonverbal fluency and general executive functioning were assessed, children with cooccurring disorders were excluded based on previously diagnosed disorders, without their diagnoses being confirmed by the research teams. The presence of children's difficulties linked to comorbid disorders was confirmed by authors in most samples in which attentional inhibition was assessed. Therefore, it is particularly clear that deficits in attentional inhibition are part of DCD. However, since most studies allowing us to conclude that comorbid disorders have no influence on the executive functioning profile of children with DCD did not confirm the presence of cooccurring disorders, it is possible that children in their DCD sample suffered from additional neurodevelopmental disorders that were not diagnosed yet and that authors are consequently not aware of. Considering this, more thorough large sample studies are needed to conclude on the influences of comorbidities on executive functions in DCD.

Nevertheless, comorbid conditions could have had at least some influence on verbal working memory capacities. Indeed, among the six samples in which verbal working memory difficulties were found, all comorbid disorders were excluded from only two samples (Dyck & Piek, 2010; Sumner et al., 2016). Although, two other samples were free of ADHD and behavioral problems/ASD (Alloway, 2011; Alloway & Archibald, 2008), and thus the impairments found in these samples do not seem to be attributable to one of these disorders. It could however be influenced by the possible presence of language or learning difficulties, since these were not excluded from four samples that showed verbal working memory difficulties (Alloway, 2011; Alloway & Archibald, 2008; Alloway & Temple, 2007; Piek et al., 2007). Moreover, among the three samples in which verbal working memory abilities were preserved, two were pure DCD samples and one was free of comorbid ADHD or SLI. In summary, when at least the cooccurrence of SLI is excluded, impairments in verbal working memory are less probable in children with DCD. Therefore, deficits in this area do not seem to be part of the DCD profile per se, but may appear when cooccurring difficulties, especially in terms of language, are present.

Finally, it seems that difficulties found in measures of visuospatial and verbal working memory were frequent but not specific to children with DCD, since they were not significantly different than those found in children with certain non-motor neurodevelopmental disorders, as ADHD, SLI, RELD, ASD and learning difficulties. In fact, impairments in these domains could be a general sign of an atypical cognitive development, without however being specific to a disorder nor systematically present in children with neurodevelopmental conditions.

4.3. Brain Correlates

Studies on neural correlates in DCD contribute to our understanding of the results highlighted in this review. Indeed, these studies revealed implications of corpus callosum, basal ganglia, inferior parietal cortex, thalamus and cerebellum in DCD, and of connections between these structures (Biotteau et al., 2016; Lundy-Ekman et al., 1991; Querne et al., 2008; Zwicker et al., 2009). Abnormalities have also been noted in frontal cortex functioning and in white matter maturation and composition in individuals with DCD (de Castelnau et al., 2008; Peters et al., 2013; Querne et al., 2008; Zwicker et al., 2009). Therefore, given the variety of brain areas involved in this disorder, the hypothesis of an Atypical Brain Development (ABD) has been proposed and stipulates that brain dysfunctions underlying deficits found in various developmental disorders are rather diffuse than localized (Gilger & Kaplan, 2001; Visser, 2003). ABD is not a precise disorder, but could rather manifest itself in different forms, such as motor, attentional and/or reading disorders (Kaplan et al., 1998; Visser, 2003). Given the strong overlap between symptoms of DCD and ADHD and the generalized disorder that seems to underly attentional and motor difficulties (Visser, 2003), the umbrella term *Deficit in Attention, Motor control and Perception* (DAMP) was also formerly proposed and defined as a combination of DCD and ADHD (Gillberg & Kadesjö, 2003; Kadesjö & Gillberg, 1999). The authors insisted on the importance of a term acknowledging both attentional and motor control problems in clinical practice, stipulating that these symptoms have strong common background factors and that the prognosis of children with DAMP was poorer than that of children with either DCD or ADHD (Gillberg & Kadesjö, 2003).

Several authors have also hypothesized that children with DCD could have an automatization deficit, related to a cerebellar dysfunction (Visser, 2003). Although possibly greater or more obvious in children with DCD than in children with ADHD and/or DDL, this deficit does not appear to be specific to any clinical population but is rather common in developmental disorders in general (Puyjarinet, 2018; Visser, 2003). Those two conditions could therefore explain the high prevalence of comorbidities among neurodevelopmental disorders and the non-specificity of the cognitive impairments found amongst them (Gilger & Kaplan, 2001; Nicolson & Fawcett, 2011).

The fact that frontal cortex, basal ganglia, cerebellum and parietal cortex are especially implicated in attentional and executive functioning (Jurado & Rosselli, 2006; Knudsen, 2007; Miller & Cohen, 2001) and that these brain structures do not operate optimally in individuals with DCD, as previously described, might explain the attentional and executive impairments highlighted in this review. Additionally, an atypical hemispheric lateralization for attention and inhibitory functions has been revealed in children with DCD along with a reduced efficiency of cerebral network involved in inhibitory control (Querne et al., 2008). Evoked potential studies have also reported that children with DCD allow fewer resources than TD controls for spatial locations comparison and response retrieval and selection (Tsai et al., 2012), and that they may have less mature anticipatory and executive processes, reduced interhemispheric and cognitive-to-motor transfer speeds as well as an atypical neural activity associated with attentional control (Tsai et al., 2010; Tsai, Pan et al., 2009; Wang et al., 2015). Given this set of cerebral abnormalities implicating abilities that are necessary to adequately perform attentional and executive tasks, our results showing impairments in most executive domains in children with DCD are not surprising.

4.4. Strengths and Limitations of the Current Review

This systematic review of the literature has several strengths as well as limitations. On a methodological level, the facts that we used a broad variety of research terms for executive functions and that we included studies using different types of performance tasks, from experimental tasks to standardized neuropsychological tests, allow our review to be more inclusive and thus our results are more representative of the variety of studies that explored attentional and executive functions in children and adolescents with DCD. The inclusion of studies using more ecological tasks is also a strength since our results contribute to a better understanding and representation of these children's daily difficulties. In addition, this review is the first to explicitly discuss the influence of disorders concomitant with DCD on attentional and executive processes. The fact that we included studies that used DCD samples with comorbid disorders, as well as the fact that the included studies recruited their DCD sample from various sources, makes our results more generalizable to the population of children with DCD.

Regarding methodological limitations, the lack of search and inclusion of grey literature and nonpublished studies may bring a publication bias. Furthermore, a standardized quality assessment tool for neuropsychological studies could not be found, so we developed our own quality assessment checklist based on the NOS and the PRISMA standards. By this mean, we also raised the limitations of included studies that compromised their quality and thus, the quality of this review. One of these important limitations was the small sample size of some studies, which ensures that, even when grouped together, the number of participants remains small and the results lack statistical power. This applies especially for results regarding auditive alertness/sustained attention, divided attention, comparisons between verbal and nonverbal planning and between verbal and nonverbal cognitive flexibility, and verbal fluency. Similarly, some of the attentional and executive components discussed in this review have been explored in a small number of studies, particularly selective attention, divided attention, cognitive flexibility, fluency and general executive functioning. Thereby, we must be more cautious when considering the conclusions regarding these domains, in which more studies are necessary to replicate the results found in this review. Another important limitation of studies included in this review is the inconsistency regarding the clarity of exclusion criteria in DCD samples. As the presence of comorbid disorders was not always rigorously documented nor confirmed, it is possible that the results highlighted in this review are more attributable to the presence of comorbid disorders than we can know.

Other factors are to be considered when interpreting the conclusions of this systematic review. Firstly, we presented our results according to nine attentional and executive components to reduce the heterogeneity of the construct evaluated in each section. However, on a conceptual level, it seems that attentional and executive functions, although dissociable, are also united and interrelated (Diamond, 2013; Knudsen, 2007; Lehto et al., 2003; Miyake et al., 2000). Similarly, all tasks require the implication of more than one cognitive function, and in certain cases, it might be difficult to isolate one attentional or executive component. As a matter of fact, some studies using the same assessment tools reported their results in relation to different cognitive domains. Hence, the results described might be partially due to impairment in other cognitive areas than those purportedly assessed. Also, several tasks used to measure cognitive functions require a motor component. Children with DCD could perform more poorly on these tasks not because of an attentional or executive impairment, but because of their primary motor deficit associated with their disorder. Secondly, no study explicitly assessing organization, self-regulation or goal-setting processes were included since none met the eligibility criteria established in this review and because few tasks assessing these components of executive functions exist. Therefore, this systematic review does not allow discussing the integrity of these executive functioning components. Thirdly, even though eligibility criteria allowed including studies with subjects up to 17 years old, the most often studied ages were 8 to 12 years old. Given the considerable development of executive functions through childhood and adolescence (Best & Miller, 2010; Diamond, 2013; Jurado & Rosselli, 2007), it would be incorrect to generalize the results of this review to children and adolescents of all ages. Fourthly, it was previously mentioned that impairments found in the domains of visuospatial and verbal working memory were not specific to children with DCD, since children with ADHD or ASD shared these difficulties. Yet children with ADHD and ASD also often share sensorimotor deficits with children with DCD (Goulardins et al., 2015; Pitcher et al., 2003; Wisdom et al., 2007). Given the overlap between symptoms that seems to be present, there is a limitation to the comparisons that can be made between these clinical groups. Finally, there is great heterogeneity among children with DCD (Alloway & Archibald, 2008; Biotteau et al., 2017; Sumner et al., 2016; Visser, 2003) that could explain the variability of results found in certain cognitive areas and compromises the generalizability of results to all the DCD population.

4.5. Directions for Future Research

Additional studies using larger samples and replicating the results of these studies are needed, especially in domains of alertness/sustained attention, divided attention, verbal and nonverbal planning, verbal and nonverbal cognitive flexibility, and verbal fluency. Likewise, a small number of studies have explored selective attention, divided attention, cognitive flexibility, fluency and general executive functioning in children in DCD, and more research on these cognitive functions is also needed to confirm the results highlighted in this review. Since no studies discussing organization, self-regulation and goal-setting skills and meeting our eligibility criteria were found, more rigorous studies exploring these executive functions are needed. Future studies should also focus on children under 8 years old and over 12 years old. Considering the development of attentional and executive functions during childhood and adolescence, and the variability of developmental trajectories among the different components of executive functioning (Best & Miller, 2010), cross-sectional and longitudinal studies comparing different age groups and following children through several years would be important in order to determine whether children with DCD present a lasting executive deficit or whether their difficulties are due to a developmental delay that catches up with time. In addition, to improve results generalization and comparison between studies, future research should avoid selecting their sample only in specialized clinical settings in order to obtain samples that are more representative of the population of children with DCD. Furthermore, given the fact that cooccurring disorders may have an influence on some executive functions, especially on verbal working memory, future studies should document and verify the presence of comorbid condition in their sample. More studies should also compare attentional and executive functioning profiles of children with DCD without any other developmental or neurological problem, with that of children with other neurodevelopmental disorders and of children with multiple diagnoses to explore the possible distinction between these groups. Lastly, future research should allow better understanding of the overlap between executive functions and motor skills. To do so, the choice of tasks should be judicious and make possible a better comparison of children's performance on tasks requiring motor and visuospatial skills with their performance on tasks requiring no such abilities. In addition, given the overlap between DCD, ADHD and ASD previously discussed, a dimensional approach could be useful to go beyond group comparisons and allow a better understanding of cooccurring motor and cognitive difficulties. With more studies using larger samples, a meta-analytic approach would be relevant and could control for such confounding variables.

5. Conclusion

This systematic review of the literature revealed that children and adolescents with DCD show impairments mostly on tasks of inhibitory control, working memory, planning, nonverbal fluency and general executive functioning. Alertness and sustained attention, selective and divided attention and verbal fluency capacities appear more intact, whereas results regarding cognitive flexibility are divided. More evidence supports the presence of a deficit in nonverbal executive tasks, without the impairments being exclusive to this modality. Cooccurring disorders might influence impairments found on verbal working memory capacities in children with DCD.

These results contribute to a better understanding of the cognitive profile associated with DCD and have several implications. On a conceptual level, we must consider that executive impairments are common in DCD and, although they may be partly explainable by the underlying visuospatial and motor deficits they are not entirely so, especially in areas of working memory, planning abilities and general executive functioning. When evaluating executive functioning in children with DCD, clinicians should still be aware of the possible contribution of visuospatial and motor deficits in their results, and impairments on executive tasks that do not require visuospatial or motor skills should be found before concluding to an executive deficit in a child with DCD. Since a few studies have identified similar difficulties in children with

DCD to children with less severe motor difficulties that did not have a diagnosis of DCD, clinicians must keep in mind that children with motor difficulties that have not been diagnosed with DCD may present the same set of executive difficulties. Furthermore, when clinicians do conclude to executive deficits in a child with DCD, they must keep in mind that attentional and executive impairments may be part of the disorder itself. While it is important that children benefit from appropriate interventions to help them with their difficulties, professionals should also be parsimonious in diagnosing concomitant disorders. Indeed, it appears possible that the high prevalence of comorbid disorders found in children with DCD is due to cognitive dysfunction related to DCD itself, without necessarily being specific to this disorder, rather than to an additional disorder. In all cases, professionals intervening with children and adolescents with DCD should expect them to be impulsive and to be easily distracted by task-irrelevant stimuli. They should also adapt their interventions to try to avoid overloading their working memory and support them in developing their planning skills.

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Declarations of interest:

The authors declare no conflict of interest.

Appendix 1

Quality assessment:

Adaptation of the Newcastle-Ottawa Quality Assessment Scale

Cohort studies

Selection

1. The study mentions how diagnoses in all clinical groups were made and inclusion criteria for each group.
2. The study mentions exclusion criteria for each group.
3. The study mentions the sample sources of every group.
4. All groups are drawn from the same community.

Comparability

5. All groups are age-matched.
6. All groups are gender-matched.
7. All groups are IQ-matched or the study controls for IQ.

Outcome

8. The study mentions neuropsychological tests and/or clearly describes experimental tasks used to assess attentional/executive functioning, and references about them are provided.
9. Outcome analysis is adequate (statistical measures, conclusions according to results).
10. The study presents a clear discussion considering implications and limitations of outcomes.

Answer items by “yes” or “no”.

8 “yes” or more = high quality level of evidence

6-7 “yes” = medium quality level of evidence

5 “yes” or less = low quality level of evidence

Appendix 2

Summary of attentional and executive functions assessed, age ranges, sample sizes and tasks used among studies

	Attentional or executive functions studied	Ages of DCD groups in which function was assessed (years) Range (mean)	Total DCD sample size in which function was assessed	Tasks used to assess attentional or executive function	Studies Authors (years)
Attentional functions	Alertness and sustained attention	7-16 (10.5)	157		
	○ Visual	7-16 (10.7)	131	CPT-II (omission errors)	Biotteau et al. (2017)
					Blais et al. (2017)
				CPT double version (correct responses)	de Castelnau et al. (2007)
				KITAP: Alerting	Kaiser & Albaret (2016)
				Go/No Go task (omission errors)	Querne et al. (2008)
				Go/No Go task with positively and negatively valenced stimuli (omission errors)	Rahimi-Golkhandan et al. (2016)
				Visuospatial Working Memory Paradigm (non-delay condition)	Tsai et al. (2012)
	○ Auditive	7-12 (8.8)	26	TEA-Ch: Score!	Williams et al. (2013)
	Selective attention	5-12 (8.0)	160		
	○ Visual	5-12 (7.5)	93	CAS: Expressive attention, Number Detection, Receptive Attention	Asonitou & Koutsouki (2016)
					Asonitou et al. (2012)

				NEPSY: Visual attention	Barray et al. (2008)
				KITAP: Distractibility	Kaiser & Albaret (2016)
	○ Auditive	5-12 (9.6)	45	NEPSY: Auditory attention and Response set	Barray et al. (2008)
					Toussaint-Thorin et al. (2013)
	Divided attention	8-12 (9.9)	7	KITAP: Divided attention	Kaiser & Albaret (2016)
Executive functions	Inhibitory control	3-16 (10)	592		
	Response inhibition	3-16 (10.1)	341		
	○ Nonverbal	3-16 (10.1)	341	Motor VIMI (total errors)	Bernardi et al. (2017)
					Leonard et al. (2015)
				Motor VIMI (total errors and completion time)	Bernardi et al. (2016)
				CPT-II (commission errors)	Biotteau et al. (2017)
					Blais et al. (2017
				CPT double version (commission errors)	de Castelnau et al. (2007)
				Go/No Go task (commission errors)	Dyck & Piek (2010)
					Querne et al. (2008)
				Go/No Go task with informative and uninformative precue conditions (initiation and failure-to-inhibit errors)	Mandich et al. (2003)
				Go/No Go task with positively and negatively valenced stimuli (commission errors)	Rahimi-Golkhandan et al. (2016)
				Visual Simon task (failure-to-inhibit errors)	Mandich et al. (2002)
				NEPSY: Knock-Tap task	Pratt et al. (2014)

			Double-Jump Reaching task – Modified version	Ruddock et al. (2016)
				Ruddock et al. (2015)
			The Paired Images test	Toussaint-Thorin et al. (2013)
○ Verbal	6-14 (10.6)	66	Verbal VIMI (total errors)	Bernardi et al. (2017)
				Leonard et al. (2015)
			Verbal VIMI (total errors and completion time)	Bernardi et al. (2016)
			Stroop task	Pratt et al. (2014)
Attentional inhibition	7-12 (9.7)	271		
○ Endogenous mode	7-12 (9.8)	188	COVAT	Chen et al. (2012)
				Tsai, Yu et al. (2009)
				Wilson & Maruff (1999)
				Wilson et al. (1997)
			Endogenous Posner paradigm	Tsai, Pan et al. (2009)
			Go/No Go task with both informative and uninformative precue conditions (reaction times)	Mandich et al. (2003)
○ Exogenous mode	7-12 (9.8)	123	COVAT	Wilson & Maruff (1999)
				Wilson et al. (1997)
			Visuospatial Attention task cued and non-cued conditions	Gonzalez et al. (2016)
			Visuospatial Attention (eye-gaze cueing) paradigm	Tsai et al. (2010)
				Wang et al. (2015)

			Visual Simon task (reaction times)	Mandich et al. (2002)
				Tsai, Yu et al. (2009)
Working memory	3-14 (9.6)	297		
○ Visuospatial	5-14 (10.2)	162	AWMA: Odd-One-Out, Mr. X, Spatial Span	Alloway (2007)
				Alloway (2011)
				Alloway & Archibald (2008)
				Alloway et al. (2009)
				Alloway & Temple (2007)
			Odd-One-Out test	Bernardi et al. (2017)
				Leonard et al. (2015)
			Visuospatial Working Memory Paradigm (delay condition)	Tsai et al. (2012)
○ Verbal	3-14 (9.5)	273	AWMA: Listening Recall, Counting Recall, Backwards Digit Recall	Alloway (2007)
				Alloway (2011)
				Alloway & Archibald (2008)
				Alloway et al. (2009)
				Alloway & Temple (2007)
			WMTBC: Listening Recall	Bernardi et al. (2017)
				Leonard et al. (2015)
			WISC-IV: Digit Span, Letter-number Sequencing	Biotteau et al. (2017)

				Sumner et al. (2016)
			Trailmaking/Memory Updating task, Goal Neglect task	Dyck & Piek (2010)
				Piek et al. (2007)
Planning	5-14 (9.0)	230		
○ Nonverbal	7-14 (11.0)	40	D-KEFS: Sorting test (nonverbal sorts)	Bernardi et al. (2017)
				Leonard et al. (2015)
○ Verbal	7-14 (11.0)	40	D-KEFS: Sorting test (verbal sorts)	Bernardi et al. (2017)
				Leonard et al. (2015)
○ General	5-14 (8.4)	190	CAS: Matching Numbers, Planned Codes, Planned Connections	Asonitou & Koutsouki (2016)
				Asonitou et al. (2012)
			NEPSY: Tower task	Barray et al. (2008)
				Pratt et al. (2014)
				Toussaint-Thorin et al. (2013)
			River Crossing task	Kirby et al. (2010)
			Rotational Bar task	Pratt et al. (2014)
			BADS-C: 6-Part test	Toussaint-Thorin et al. (2013)
Cognitive flexibility	6-14 (10.2)	54		
○ Nonverbal	7-14 (11.0)	23	CANTAB: Intra-/Extra-Dimensional Shift	Bernardi et al. (2017)
				Leonard et al. (2015)
○ Verbal	7-14 (11.0)	23	D-KEFS: Trail Making test	Bernardi et al. (2017)
				Leonard et al. (2015)

○ General	6-14 (9.5)	31	Visual Inspection Time task	Piek et al. (2007)
			Trail Making test A and B for Children	Toussaint-Thorin et al. (2013)
Fluency	5-14 (10.3)	68		
○ Nonverbal	5-14 (10.4)	55	NEPSY: Design Fluency	Barray et al. (2008)
			D-KEFS: Design Fluency	Bernardi et al. (2017)
				Leonard et al. (2015)
○ Verbal	7-14 (10.7)	36	D-KEFS:Verbal Fluency	Bernardi et al. (2017)
				Leonard et al. (2015)
			NEPSY: Verbal Fluency	Toussaint-Thorin et al. (2013)
General executive functioning	6-12 (9.1)	52	Ecological assessment: cooking task	Toussaint-Thorin et al. (2013)
			Wisconsin Card Sorting Test	Zhu et al. (2012)

Note: CPT-II = Continuous Performance Test, Second Edition; KITAP = computerized test battery of attention for children; TEA-Ch = Test of Everyday Attention for Children; CAS = Das-Naglieri Cognitive Assessment System; NEPSY = Developmental Neuropsychological Assessment; VIMI = Verbal Inhibition Motor Inhibition test; COVAT = Covert Orienting of Visuospatial Attention Task; AWMA = Automated Working Memory Assessment; WMTBC = Working Memory Test Battery for Children; WISC-IV = Wechsler Intelligence Scale for Children, Fourth Edition; D-KEFS = Delis-Kaplan Executive Function System; BADS-C = Behavioural Assessment of the Dysexecutive Syndrome in Children; CANTAB = Cambridge Neuropsychological Test Automated Battery.

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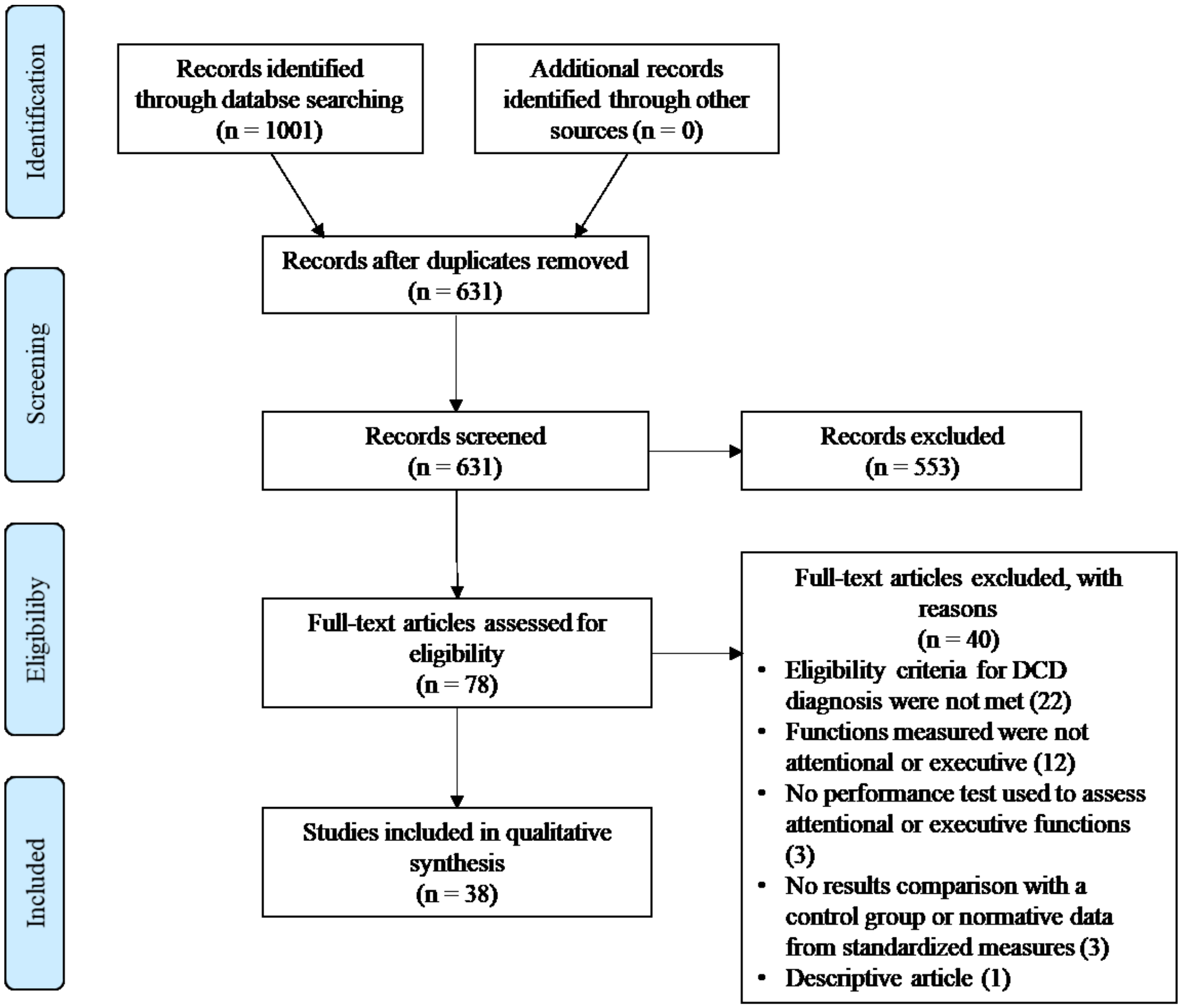

Figure 1. PRISMA flow chart illustrating articles identification and selection process.

Table 1

Studies included in the systematic review

Studies Authors (year)	Groups (sample size) *Origin*	Gender Number of males (%)	Age (years) M (SD)	Presence of a comorbid disorder to DCD	Attentional or executive function studied	Task(s) used to assess attentional or executive functions	Summary of results
Alloway (2007)	DCD (55; same sample as Alloway, 2011 and Alloway et al., 2009) *Schools, referred by health care professio-nals*	44 (80.0%)	8.8 (1.6)	No mention of exclusion.	Working memory (verbal) Working memory (visuospatial)	AWMA: Listening Recall, Counting Recall, Backwards Digit Recall Odd-One-Out, Mr. X, Spatial Span	49% of sample obtained standard scores of less than 85 on the verbal WM measures. 60% of sample obtained scores of less than 85 on the visuospatial WM measures. The difference between performance on visuospatial and verbal WM measures was not significant.
Alloway (2011)	DCD (55; same sample as Alloway, 2007 and Alloway et al., 2009) ADHD (50) TD (50) *Schools, referred by health care professio-nals*	44 (80.0%) 43 (86.0%) 30 (60.0%)	8.8 (1.6) 9.8 (1.0) 9.9 (1.0)	Exclusion of children diagnosed with behavioral or attentional problems.	Working memory (verbal) Working memory (visuospatial)	AWMA: Listening Recall, Counting Recall, Backwards Digit Recall Odd-One-Out, Mr. X, Spatial Span	The DCD and ADHD groups performed more poorly than the TD group on both verbal and visuospatial WM measures. Children with DCD showed deficits on both modalities compared to TD controls. Their WM profile did not differ significantly compared to that of children with ADHD.

Alloway & Archibald (2008)	DCD only (11) DCD unselected (12) SLI (11) *Schools, referred by health care professio-nals*	8 (72.7%) 8 (66.7%) 7 (63.6%)	8.9 (1.4) 8.5 (1.6) 8.8 (1.4)	Exclusion of children diagnosed with ADHD or ASD. Inclusion of children with language or nonverbal reasoning difficulties (DCD unselected group).	Working memory (verbal) Working memory (visuospatial)	AWMA: Listening Recall, Counting Recall, Backwards Digit Recall Odd-One-Out, Mr. X, Spatial Span	The two DCD groups did not significantly differ on their WM profiles. Their performance was more than 1.25 SD below the standardized mean on most tasks. Children in the DCD only group performed significantly worse than children with SLI on the visuospatial WM measures, even when the contribution of receptive language skills was accounted for. Their verbal WM skills were similar. Thus, children in DCD groups had deficits in both WM modalities, whereas those in SLI group only had verbal WM deficits.
Alloway et al. (2009)	DCD (55; same sample as Alloway, 2007, 2011) SLI (15) ADHD (83) AS (10) *Schools, referred by health care professio-nals*	44 (80.0%) 9 (60.0%) 71 (85.5%) 8 (80.0%)	8.8 (1.6) 9.2 (1.7) 9.1 (1.1) 8.8 (1.5)	Exclusion of children diagnosed with behavioral problems.	Working memory (verbal) Working memory (visuospatial)	AWMA: Listening Recall, Counting Recall, Backwards Digit Recall Odd-One-Out, Mr. X, Spatial Span	Children with DCD had significantly lower scores than children with AS on visuospatial WM measures, but the difference was attributable to the motor component of the tests. There were no significant differences when comparing with the other clinical groups. On verbal WM measures, there were no differences between groups.
Alloway & Temple (2007)	DCD (20) MLD (20) *Schools, referred by health care professio-nals*	14 (70.0%) 15 (75.0%)	9.8 (1.4) 9.8 (1.4)	No mention of exclusion.	Working memory (verbal) Working memory (visuospatial)	AWMA: Listening Recall, Counting Recall, Backwards Digit Recall Odd-One-Out, Mr. X, Spatial Span	Mean standard scores of children with DCD on all WM tasks were less than 85. Performances of children with DCD were poorer than that of children with MLD on all WM measures. Children with DCD showed significant deficits in visuospatial WM, while MLD group performed within age-expected level

							in this domain. On measures of verbal WM, both groups were impaired. Thus, impaired visuospatial WM seems to be more specific to children with DCD when compared to children with MLD.
Asonitou & Koutsouki (2016)	DCD (54) TD (54) *General population*	36 (66.7%) 36 (66.7%)	Total of 42 5-year-olds and 66 6-year-olds: 5.5 (0.4)	Exclusion of children with any other medical or neurological condition, or identified intellectual disability.	Selective attention (visual) Planning	CAS: Expressive Attention, Number Detection, Receptive Attention Matching Numbers, Planned Codes, Planned Connections	A significant proportion of children with DCD were impaired on planning and attention measures. Globally, children with DCD had more difficulties than TD children in all measured domains, and difficulties in planning were greater than those in attention.
Asonitou et al. (2012)	DCD (54) 5-year-old (24) 6-year-old (30) TD (54) 5-year-old (18) 6-year-old (36) *General population*	36 (66.7%) 13 (54.2%) 23 (76.7%) 37 (68.5%) 15 (83.3%) 22 (61.1%)	42 5-year-olds: 5.2 (0.3) 66 6-year-olds: 5.8 (0.2)	Exclusion of children diagnosed with emotional or behavioral disorder, with a history of pre- or existing developmental disorder (such as ADHD), or with an intellectual disability (IQ < 70).	Selective attention (visual) Planning	CAS: Expressive Attention, Number Detection, Receptive Attention Matching Numbers, Planned Codes, Planned Connections	Children with DCD performed more poorly than TD children on all tasks, indicating difficulties in terms of both attention and planning when compared to healthy controls. Also, more severe motor impairment seems to be associated with poorer planning abilities.
Barray et al. (2008)	DD (32) AP (16) *Learning disorders centers*	24 (75.0%) 6 (37.5%)	9.1 (2.3) 9.0 (2.1)	Exclusion of children with probable personality disorder, social conduct disorder, or verbal IQ < 80.	Selective attention (visual) Selective attention (auditive) Planning Fluency (nonverbal)	NEPSY: Visual Attention Auditory Attention and Response Set Tower task Design Fluency	Children with DD performed significantly better than those with AP only on the Visual attention task. All children had difficulties in the Design Fluency task that seemed to be the most difficult task for them. Performances on the other tasks were globally within the normative range.

Bernardi et al. (2017)	DCD (17) MD (17) TD (17) *General population*	6 (35.3%) 8 (47.1%) 13 (76.5%)	12.0 (1.2) 10.5 (0.6) 11.3 (1.0)	Exclusion of children diagnosed with ADHD, ASD, reading, language and IQ < -2 SD, or any medical condition.	Working memory (verbal) Working memory (nonverbal) Fluency (verbal) Fluency (nonverbal) Response inhibition (verbal) Response inhibition (nonverbal) Planning (verbal) Planning (nonverbal) Flexibility (verbal) Flexibility (nonverbal)	WMTBC: Listening Recall Odd-One-Out test D-KEFS: Verbal Fluency D-KEFS: Design Fluency Verbal VIMI (total errors) Motor VIMI (total errors) D-KEFS: Sorting test (verbal sorts) D-KEFS: Sorting test (nonverbal sorts) D-KEFS: Trail Making test CANTAB: Intra-/Extra-Dimensional Shift	Children with DCD performed significantly more poorly than TD children on all nonverbal measures and on the verbal fluency task at both time points (2-year follow-up). Children with MD also had poorer performance on all nonverbal measures, except the flexibility one. At time 2, only nonverbal WM and nonverbal fluency differences remained between MD and TD groups. Improvement over time was significant for verbal and nonverbal WM, fluency and flexibility, and for nonverbal planning. It was not significant for verbal and nonverbal inhibition and verbal planning. Changes over time were similar between each group.
Bernardi et al. (2016)	DCD (23) MD (30) TD (38) (Same sample as Leonard et al., 2015) *General population*	16 (69.6%) 17 (56.7%) 17 (44.7%)	10.0 (1.1) 8.9 (1.2) 9.3 (1.0)	Exclusion of children diagnosed with any other neurodevelopment-tal disorder, including ADHD.	Response inhibition (verbal) Response inhibition (nonverbal)	Verbal VIMI (total errors and total completion time) Motor VIMI (total errors and total completion time)	On the motor inhibition task, children with DCD or MD had difficulties performing accurately. On the verbal inhibition task, they took significantly more time than TD children, but the accuracy between groups was similar. Inhibition impairments in DCD and MD groups thus appear to affect accuracy when a motor response is required and completion time when the response is given verbally. There were no

							significant differences between DCD and MD groups.
Biotteau et al. (2017)	DCD (22) DCD+ DDL (23) DDL (20) *Referred by a learning disability center or health care profession-nals*	16 (72.7%) 16 (69.6%) 12 (60.0%)	9.7 (1.6) 9.9 (1.2) 10.2 (1.3)	Exclusion of children with intellectual disability, SLI or ADHD, according to DSM-IV-TR criteria. Presence of DDL, excluding surface dyslexia, in DCD+DDL group.	Sustained attention (visual) Response inhibition (nonverbal) Working memory (verbal)	CPT-II (omission errors) CPT-II (commission errors) WISC-IV: Digit Span and Letter-Number Sequencing	All children had mean scores within or slightly above the normal range on the CPT-II. Variations between groups were not significant. WM index was within the normal range in the three groups. Having a dual diagnosis did not lead to a cumulative impact on cognitive abilities.
Blais et al. (2017)	DCD (10) TD (10) *Hospital*	7 (70.0%) 3 (30.0%)	13.5 (1.4) 13.5 (1.8)	Exclusion of children with a history of head trauma or epilepsy, an intellectual disability or ADHD according to DSM-5 criteria.	Sustained attention (visual) Response inhibition (nonverbal)	CPT-II (omission errors) CPT-II (commission errors)	Children with DCD performed significantly worse than TD children. Their average percentages of commission, omission and perseveration errors were significantly greater than those of control individuals. There was no difference between groups for reaction times.
Chen et al. (2012)	SDCD (20) MDCD (46) TD (36) *Research database*	9 (45.0%) 16 (34.8%) 24 (66.7%)	9.5 (0.3) 9.6 (0.3) 9.7 (0.3)	Exclusion of children with any signs of neurolo-gical of physical impairments, developmental disorders or intellectual disability, accor-ding to a rehabi-litation physician.	Attentional inhibition (endogenous mode of orienting attention)	COVAT	The capacity of children with DCD, both severe and moderate, to intentionally disengage their attention from invalid cued location when the delay between precue and target stimulus was longer was reduced. This suggests a deficit of attentional control in DCD, more specific to the endogenous mode of orienting attention and referring to the process of disengagement inhibition.
de Castelnau et al. (2007)	DCD (24) TD (60) *Hospital*	18 (75.0%) 30 (50.0%)	3 age groups: 8-9 years, 10-11 years and	Exclusion of children with ADHD, according to a brief neuropsychological	Sustained attention (visual)	CPT double version (correct responses) CPT double version	Children with DCD had significantly less correct responses than TD children, but it increased with age. They omitted significantly more responses than controls. However,

			12-13 years. 8 children with DCD and 20 TD children in each of them.	examination and DSM-IV criteria, and with an IQ < 80.	Response inhibition (nonverbal)	(commission errors)	there was no significant difference in number of commission errors between groups, and these decreased with age. In conclusion, children with DCD had poorer attentional capacities than TD children, but they were not more impulsive, and their capacities improved with age.
Dyck & Piek (2010)	DCD (20) RELD (21) PLA (22) PMC (28) *Referred by health care profession-nals*	13 (65.0%) 16 (76.2%) 14 (63.6%) 17 (60.7%)	8.4 (2.1) 7.1 (1.8) 7.5 (1.6) 8.8 (3.1)	Exclusion of children diagnosed with any other comorbid disorders.	Response inhibition (nonverbal) Working memory (verbal)	Go/No Go task (commission errors) Trailmaking/Me-mory Updating task, Goal Neglect task	Children with DCD had scores within the normal range on the response inhibition task. Their performances were within the low normal range for WM tasks. Differences with children with PMC were not significant. Scores of children in the RELD group were lower on the response inhibition and WM tasks, indicating greater difficulties in this group.
Gonzalez et al. (2016)	DCD (10) TD (12) *Specialized clinic*	7 (70.0%) 8 (66.7%)	10.1 (1.0) 10.0 (1.1)	Exclusion of children diagnosed with ADHD.	Attentional inhibition (exogenous mode of orienting attention)	Visuospatial attention task cued and non-cued conditions	Children with DCD made more inhibition errors (saccades to the cue) than TD children, indicating poor inhibitory control. These inhibition difficulties resulted in inappropriate allocation of visual attention.
Kaiser & Albaret (2016)	DCD (7) ADHD (9) TD (15) *Specialized school, referred by health care profession-nals*	Not mentioned	9.9 (0.9) 10.2 (1.3) 9.6 (1.3)	Exclusion of children with a dual diagnosis of DCD and ADHD, and with an IQ < 70.	Selective attention (visual) Alertness (visual) Divided attention	KITAP: Distractibility Alerting Divided Attention	Results of children with DCD on KITAP tasks were not significantly different from results of children with ADHD or of TD children. Thus, the three groups cannot be discriminated based on their performance on the KITAP.
Kirby et al. (2010)	DCD (11) TD (28) *Research database*	8 (72.7%) 13 (46.4%)	9.9 10.2 (SDs not available)	Exclusion of children with severe learning difficulties or low cognitive ability, according to teachers.	Planning	River Crossing task	Significant differences between groups were seen in children's planning strategies. Children with DCD tended to add mats, but not modify their placement of mats, whereas TD children were more

				Inclusion of children with ADHD symptoms.			likely to change spacing of mats. This suggests that initial mat placement plan of TD children was more effective than that of children with DCD. This indicates that children with DCD may have difficulty to elaborate a plan as efficiently as TD children and may also not know how to improve it.
Leonard et al. (2015)	DCD (23) MD (30) TD (38) (Same sample as Bernardi et al., 2016) *General population*	16 (69.6%) 17 (56.7%) 17 (44.7%)	10.0 (1.1) 8.9 (1.2) 9.3 (1.0)	Exclusion of children diagnosed with ASD or ADHD, and of children with IQ, language or reading skills more than two SD below the mean.	Working memory (verbal) Working memory (nonverbal) Fluency (verbal) Fluency (nonverbal) Response inhibition (verbal) Response inhibition (nonverbal) Planning (verbal) Planning (nonverbal) Flexibility (verbal) Flexibility (nonverbal)	WMTBC: Listening Recall Odd-One-Out test D-KEFS: Verbal Fluency D-KEFS: Design Fluency Verbal VIMI (total errors) Motor VIMI (total errors) D-KEFS: Sorting test (verbal sorts) D-KEFS: Sorting test (nonverbal sorts) D-KEFS: Trail Making test CANTAB: Intra-/Extra-Dimensional Shift	For nonverbal WM, fluency and inhibition tasks, children with MD or DCD scored significantly lower than TD children. For nonverbal planning, only the MD group (not the DCD group) differed significantly from the TD group. There were no significant differences between groups on flexibility tasks or on any of the verbal measures. In summary, children with DCD or MD had more difficulties on nonverbal tasks compared to TD children.
Mandich et al. (2002)	DCD younger + older (20)	Not mentioned	Younger: 8.6 (0.8) Older: 10.6 (0.7)	Exclusion of children diagnosed with ADD.	Response inhibition (nonverbal)	Visual Simon task (failure-to-inhibit errors)	Children with DCD seem to have no deficit regarding the time needed to suppress an incorrect response and this ability appears to develop at the

	TD younger + older (20) *Specialized clinic*		Younger: 8.5 (0.7) Older: 10.8 (0.8)		Attentional inhibition (exogenous mode of orienting attention)	Visual Simon task (reaction times)	same rate in both groups. However, children with DCD had a reliably smaller rate of correct responses in the incompatible trials compared to TD children. Overall, children with DCD exhibited an inhibitory dysfunction regarding manual response inhibition, manifesting itself in terms of error rate.
Mandich et al. (2003)	DCD (18) TD (18) *Specialized clinic*	Not mentioned	9.9 (1.5) 9.8 (1.4)	No mention of exclusion.	Response inhibition (nonverbal) Attentional inhibition (endogenous mode of orienting attention)	Go/No Go task with both informative and uninformative precue conditions (anticipation and failure-to-inhibit errors) Go/No Go task with both informative and uninformative precue conditions (reaction times)	Children with DCD did not commit more anticipation errors than TD children, but they produced about twice as many failure-to-inhibit errors. Children with DCD may have impaired inhibitory control, since they needed more time to intentionally disengage their attention from the cued position (disengagement inhibition). They also exhibited difficulty to inhibit the unwanted movement of attention urged by precues. Thus, they exhibited more difficulties than controls in restraining both their manual and attentional movements.
Piek et al. (2007)	DCD (18) ADHD-I (20) ADHD-C (19) TD (138) *Referred by health care profession-nals*	12 (66.7%) 16 (80.0%) 15 (78.9%) 59 (42.8%)	8.8 (2.0) 10.8 (1.8) 10.7 (2.3) 10.3 (2.2)	Exclusion of children with an estimated IQ < 80.	Working memory (verbal) Flexibility	Trailmaking/Memory Updating task, Goal Neglect task Visual Iinspection Time task	On the Goal Neglect task, children with DCD made more errors than the three other groups. On the Trailma-king/Memory Updating task, children in the DCD group were significantly slower than those in other groups but did not commit more errors. They were also slower than the other groups on the set-shifting task. Thus, performance of children with DCD was significantly poorer than that of ADHD and TD children on all measures of EF, and there was no

							significant difference between ADHD and TD children.
Pratt et al. (2014)	DCD (26) TD (24) *General population*	22 (84.6%) 13 (54.2%)	9.9 (2.5) 9.6 (2.0)	Exclusion of children with any other disorder, such as ADHD, ASD or dyslexia.	Planning (reduced motor-load) Planning (high motor-load) Response inhibition (reduced motor-load/verbal) Response inhibition (high motor-load/nonverbal)	NEPSY: Tower task Rotational Bar task Stroop task NEPSY: Knock-Tap task	Children with DCD performed significantly more poorly than TD children on both the high motor-load and reduced motor-load planning tasks. They also had significantly lower scores than TD children on the reduced motor-load inhibition task, but differences in performance on the high motor-load inhibition task were not significant. Results might have been influenced by the tasks' complexity.
Querne et al. (2008)	DCD (9) TD (10) *Hospital*	7 (77.8%) 7 (70.0%)	9.9 (1.8) 10.0 (1.1)	Exclusion of children with a history of neurological or psychiatric disorders.	Sustained attention (visual) Response inhibition (nonverbal)	Go/No Go task (omission errors) Go/No Go task (commission errors)	Children with DCD did not make more commission errors than TD children, but they made significantly more omission errors. Thus, children with DCD seem to be as effective as TD children in inhibiting a prepotent motor response, but to have more difficulties with sustained attention.
Rahimi-Golkhan-dan et al. (2016)	DCD (12) TD (24) *Schools, general population*	4 (33.3%) 10 (41.7%)	9.8 (1.4) 10.3 (1.6)	Exclusion of children diagnosed with intellectual disability, or neurological or psychiatric disorders such as ADHD.	Sustained attention (visual) Response inhibition (nonverbal)	Go/No Go task with positively- and negatively-valenced stimuli (omission errors) Go/No Go task with positively- and negatively-valenced stimuli (commission errors)	Children with DCD were more impulsive than TD children with happy faces stimuli, as they made more commission errors. The difference between groups for sad faces was not significant. There was no significant difference between the two groups for omission errors. Overall, results showed a deficit of inhibitory control in the DCD group when the no-go stimulus was a compelling, positively-valenced cue, which shows a deficit in 'hot' executive functions.

Ruddock et al. (2016)	DCD (62) 6 years (7) 7 (13) 8 (11) 9 (11) 10 (15) 11 (5) TD (109) 6 years (28) 7 (21) 8 (21) 9 (18) 10 (15) 11 (5) 12 (1) *Schools, general population*	35 (56.5%) 3 (42.8%) 9 (69.2%) 9 (81.8%) 7 (63.6%) 6 (40.0%) 1 (20.0%) 48 (44.0%) 9 (32.1%) 7 (33.3%) 10 (47.6%) 12 (66.7%) 7 (46.7%) 2 (40.0%) 1 (100.0%)	6.4 (0.6) 7.5 (0.3) 8.6 (0.4) 9.5 (0.3) 10.6 (0.3) 11.3 (0.2) 6.4 (0.4) 7.5 (0.3) 8.4 (0.3) 9.5 (0.3) 10.3 (0.3) 11.4 (0.2) 12.3 (0.0)	Exclusion of children with a history of developmental (ASD, ADHD), physical and/or neurological condition reported in a parent/teacher pre-screening questionnaire.	Response inhibition (nonverbal)	Double-Jump Reaching task – Modified version	Until 10-11 years old, children with DCD performed slower and with more variability than TD children. Therefore, in general, they were less efficient than controls, but the developmental lag in their performance seemed to lessen in later childhood. Performance of both groups improved with age, but the growth curve was different.
Ruddock et al. (2015)	DCD (42) 6-7 years (10) 8-9 (16) 10-12 (16) TD (87) 6-7 years (26) 8-9 (38) 10-12 (23) *Schools, general population*	22 (52.4%) 5 (50.0%) 11 (68.8%) 6 (37.5%) 34 (39.1%) 9 (34.6%) 15 (39.5%) 10 (43.5%)	7.3 (0.7) 8.9 (0.6) 11.1 (0.4) 7.2 (0.5) 8.9 (0.6) 10.7 (0.5)	Exclusion of children for whom any developmental, neurological and/or physical condition was reported, which was confirmed by the child's school health officer.	Response inhibition (nonverbal)	Double-Jump Reaching task – Modified version	Children with DCD were generally slower than TD children and they made significantly more anticipation errors, indicating difficulties in inhibitory control. Moreover, only the differences between younger children and the two other groups were significant; mid-aged and older children did not significantly differ in their anticipation error rate. Thereby, initiation inhibition capacities are poorer in children with DCD than in TD children, but the gap between them lessen when they get older.
Sumner, Pratt, & Hill (2016)	DCD (52) TD (52) *General population*	36 (69.2%) 36 (69.2%)	9.2 (2.2) 9.3 (1.5)	Exclusion of children diagnosed with any other developmental disorder (ADHD, ASD, dyslexia),	Working memory (verbal)	WISC-IV: Digit Span, Letter-Number Sequencing	Scores of children with DCD were significantly lower than TD children on the WM index. Children with DCD performed significantly worse than TD children on the Digit span task, but not on the Letter-number

				neurological condition, or other medical condition that could explain motor impairment.			sequencing task. Almost 30% of children with DCD had scores of more than 1 SD below the population mean on the Digit span. Thus, the results showed some indication of difficulties in WM.
Toussaint-Thorin et al. (2013)	DD (13) TD (14) *Hospital*	11 (84.6%) 8 (57.1%)	10.1 (1.4) 10.4 (1.3)	Exclusion of children with possible associated dyslexia and with a verbal IQ < 70. Inclusion of children with ADHD.	Selective attention (auditive) Flexibility Planning Response inhibition (nonverbal) Fluency (verbal) General executive functioning	NEPSY: Auditory Attention and Response Set Trail Making test A and B for Children NEPSY: Tower task, BADS-C: 6-Part test The Paired Images test NEPSY: Verbal Fluency Ecological assessment: cooking task	No deficits were found on measures of attention, flexibility and fluency. Almost half of children with DD had a score in the clinical range on the inhibition task. Three children with DD had a pathological score on the tower task, but planning appeared to be more impaired on the 6-Part test, the strategy score being particularly affected. Thus, children with DD exhibited deficits of nonverbal planning and inhibition. On the cooking task, children with DD made significantly more errors than TD children and they were not able to inhibit their verbalizing behavior, despite the task's guidelines. They were also significantly more dependent than TD children, suggesting a limited capacity to find strategies or solutions to face a problem.
Tsai et al. (2012)	DCD (24) TD (30) *General population*	12 (50.0%) 15 (50.0%)	11.6 (0.3) 11.7 (0.4)	Exclusion of children with ADHD according to DSM-IV criteria, with any known neurological disorder, behavioral problems, pervasive developmental disorders or special educational needs,	Alertness (visual) Working memory (visuospatial)	Visuospatial Working Memory Paradigm (non-delay condition) Visuospatial Working Memory Paradigm (delay condition)	Children with DCD performed less accurately than TD children in the conditions with delays, but not in the non-delay condition. This indicates difficulty in WM tasks, but not in the attentional task. EEG results showed that children with DCD allocated fewer resources to compare spatial locations. Overall, a deficit in retrieval of spatial information was found in children with DCD through

				or an IQ < 85 or > 115.			EEG measures, which seemed to impair their WM performance.
Tsai et al. (2010)	DCD (30) TD (30) *General population*	15 (50.0%) 15 (50.0%)	9.5 (0.3) 9.6 (0.2)	Exclusion of children with ADHD according to DSM-IV, any definite signs of neurological disorders, behavioral problems or pervasive development disorders, special needs in education, or an IQ < 85 or > 125.	Attentional inhibition (exogenous mode of orienting attention)	Visuospatial attention (eye-gaze cueing) paradigm	There were no significant differences between groups on error rates. Children with DCD responded significantly slower than TD children in all conditions. This suggests a reduced alertness to the imminent appearance of the target. Results showed a deficit in reflexive/automatic (exogenous) orienting of visual attention.
Tsai, Pan et al. (2009)	DCD (28) TD (26) *General population*	12 (42.9%) 12 (46.2%)	9.5 (0.3) 9.5 (0.3)	Exclusion of children with ADHD according to DSM-IV, any definite signs of neurological disorders or behavioral problems, special needs in education, or an IQ < 85 or > 125.	Attentional inhibition (endogenous mode of orienting attention)	Endogenous Posner Paradigm	Children with DCD responded more slowly than TD children, but there was no significant difference on the error rate. They had more difficulties than TD controls to move their attention when it has been primed to a falsely indicated location. Thus, they exhibited an inhibition deficit in the endogenous mode of orienting attention.
Tsai, Yu et al. (2009)	DCD-LEs (36) TD (36) *General population*	19 (52.8%) 19 (52.8%)	9.9 (0.5) 9.8 (0.5)	Exclusion of children with ADHD according to DSM-IV, special educational needs, physical or behavioral problems, or evident neurological damage.	Attentional inhibition (endogenous mode of orienting attention) Attentional inhibition (exogenous mode of orienting attention)	COVAT Visual Simon task (reaction times)	Children with DCD took longer than TD children to respond to neutral trials, indicating a reduced alertness to the imminent appearance of the target. Results showed a deficit in DCD children associated with only the intentional disengagement of attention (endogenous mode) but not the automatic/reflexive dislocation of attention (exogenous mode).
Wang et al. (2015)	DCD (23) TD (23)	12 (52.2%) 12 (52.2%)	9.4 (0.5) 9.3 (0.5)	Exclusion of children with	Attentional inhibition	Visuospatial attention (eye-	There were no significant differences between groups on error rates.

	General population			ADHD according to DSM-IV criteria, with any definite signs of neurolo-gical disorders, behavioral problems or special educational needs, or an IQ < 85 or > 125.	(exogenous mode of orienting attention)	gaze cueing) paradigm	Children with DCD responded significantly slower than TD children in all conditions. They had a poorer general attentional orienting capacity and a difficulty to effectively alter a planned action after their attention had been incorrectly oriented.
Williams et al. (2013)	DCD (10) DCD+ ADHD (16) ADHD (14) TD (18) *Schools, hospital or referred by health care professio-nals*	6 (60.0%) 14 (87.5%) 8 (57.1%) 10 (55.6%)	8.5 (1.2) 9.1 (1.7) 10.1 (1.4) 10.2 (1.3)	Exclusion of children with ADHD or DCD in other groups than the ones they are supposed to be in, with any physical or neurological condition that could contribute to motor impairment, or with an IQ < 70.	Sustained attention (auditive)	TEA-Ch: Score!	Children in the DCD+ADHD group had significantly more difficulty in the sustained attention task compared to the TD children. Scores in the DCD group were also lower than in the ADHD group, but the differences were not significant. There were no other differences between other groups.
Wilson & Maruff (1999)	DCD (20) TD (20) *General population*	10 (50.0%) 10 (50.0%)	10.3 10.6	Exclusion of children with current or history of neurological diseases, including head injury, psychiatric disorders, including ADHD, or an estimated IQ < 80.	Attentional inhibition (endogenous and exogenous modes of orienting attention)	COVAT	Within each group, responses were significantly faster for valid than invalid cues, but the effect was much greater for children with DCD. Even when the delay between the cue and the target was longer, these children still had difficulty to shift their attention as efficiently as TD children. Results showed a deficit in the endogenous disengagement of attention in children with DCD, while the exogenous orienting mode was not affected.
Wilson et al. (1997)	DCD (20) TD (20)	18 (90.0%) 18 (90.0%)	9.8 9.7	Exclusion of children with current or past	Attentional inhibition (endogenous	COVAT	Children with DCD responded slower than TD children and increasing delay between the cue and the

	General population			history of neurological diseases, including head injury, psychiatric disorders, including ADHD, or as estimated IQ < 80.	and exogenous modes of orienting attention)		stimulus did not help them as it did for TD children. They were able to complete attentional orienting as efficiently as TD children when the delay was brief. Reaction time was also significantly greater in the DCD group for invalid cues, compared with the TD group. These results showed a deficit in the disengagement of attention in children with DCD. Thus, they have a deficit in the endogenous mode of orienting attention, but not in the exogenous mode.
Zhu et al. (2012)	DCD (39) TD (39) *Hospital*	28 (71.8%) 28 (71.8%)	8.1 (0.5) 8.0 (0.7)	Exclusion of children with any comorbid neurological diseases, mental and neurodevelopmental disorders, according to detailed physical and psychiatric examinations.	General executive functioning	Wisconsin Card Sorting Test	Children with DCD committed significantly more errors, perseverative responses and perseverative errors than TD children. They also needed more trials to complete the first category. Results indicated difficulties in executive functioning in children with DCD.

Note: M = mean; SD = standard deviation; DCD = developmental coordination disorder; DSM = Diagnostic and Statistical Manual of Mental Disorders (-IV-TR = Fourth Edition, Text Revision; -5 = Fifth Edition); MABC = Movement Assessment Battery for Children; AWMA = Automated Working Memory Assessment; WM = working memory; ADHD = attention-deficit/hyperactivity disorder (-I = impulsive; -C = combined); TD = typically developing; SLI = specific language impairment; ASD = autism spectrum disorder; AS = Asperger syndrome; IQ = intellectual quotient; MLD = mild learning difficulties; CAS = Das-Naglieri Cognitive Assessment System; DD = developmental dyspraxia; AP = dyspraxia following preterm birth; NEPSY = Developmental Neuropsychological Assessment; MD = motor difficulties (without DCD); WMTBC = Working Memory Test Battery for Children; D-KEFS = Delis-Kaplan Executive Function System; VIMI = Verbal Inhibition Motor Inhibition test; CANTAB = Cambridge

Neuropsychological Test Automated Battery; DDL = developmental dyslexia; CPT-II = Continuous Performance Test, Second Edition; WISC-IV = Wechsler Intelligence Scale for Children, Fourth Edition; SDCD = severe developmental coordination disorder; MDCD = moderate developmental coordination disorder; COVAT = Covert Orienting of Visuospatial Attention Task; RELD = mixed receptive expressive language disorder; PLA = relatively poor language ability; PMC = relatively poor motor coordination; KITAP = computerized test battery of attention for children; MAND = McCarron Assessment of Neuromuscular Development; BADS-C = Behavioural Assessment of the Dysexecutive Syndrome in Children; BOT-2-SF = Short Form Bruininks-Oseretsky Test of Motor Proficiency, second edition; DCD-LEs = DCD on lower extremities; TEA-Ch = Test of Everyday Attention for Children.

Table 2

Quality assessment of studies included in the systematic review

Studies Authors (year)	Quality items										
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	# of "yes" Quality level
Alloway (2007)	Yes	No	Yes	NA	NA	NA	Yes	Yes	Yes	No	8 High
Alloway (2011)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	8 High
Alloway & Archibald (2008)	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	7 Medium
Alloway et al. (2009)	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	6 Medium
Alloway & Temple (2007)	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	7 Medium
Asonitou & Koutsouki (2016)	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	9 High
Asonitou et al. (2012)	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	8 High
Barray et al. (2008)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	8 High
Bernardi et al. (2017)	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	7 Medium
Bernardi et al. (2016)	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No	6 Medium
Biotteau et al. (2017)	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	8 High
Blais et al. (2017)	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	No	6 Medium
Chen et al. (2012)	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	No	6 Medium
de Castelnau et al. (2007)	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	No	6 Medium
Dyck & Piek (2010)	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	5 Low
Gonzalez et al. (2016)	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	7 Medium
Kaiser & Albaret (2016)	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	6 Medium

Kirby et al. (2010)	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	7 Medium
Leonard et al. (2015)	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No	6 Medium
Mandich et al. (2002)	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	No	6 Medium
Mandich et al. (2003)	Yes	No	Yes	No	Yes	No	Yes	Yes	Yes	No	6 Medium
Piek et al. (2007)	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No	6 Medium
Pratt et al. (2014)	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	7 Medium
Querne et al. (2008)	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	7 Medium
Rahimi-Golkhan-dan et al. (2016)	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	8 High
Ruddock et al. (2016)	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	7 Medium
Ruddock et al. (2015)	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	7 Medium
Sumner et al. (2016)	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	8 High
Toussaint-Thorin et al. (2013)	Yes	Yes	No	No	Yes	No	No	Yes	No	Yes	5 Low
Tsai et al. (2012)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	10 High
Tsai et al. (2010)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	9 High
Tsai, Pan et al. (2009)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	8 High
Tsai, Yu et al. (2009)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	9 High
Wang et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	9 High
Williams et al. (2013)	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	7 Medium
Wilson & Maruff (1999)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	9 High
Wilson et al. (1997)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	9 High
Zhu et al. (2012)	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	8 High

Note: NA = Non-applicable; was counted as “yes” to avoid penalizing studies for criteria that did not apply to them.

Highlights

- The 38 studies included revealed impairments in most executive functions in DCD.
- Attentional functions appear more intact in children with this disorder.
- Comorbid disorders affect particularly alertness and verbal working memory in DCD.
- Selective attention and working memory profiles do not seem specific to DCD.

Appendice I

Présentation des modèles théoriques

Les fonctions cognitives et motrices altérées dans le TDC incluent des déficits praxiques et exécutifs (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). Une description des modèles théoriques de ces domaines cognitifs apparaît donc nécessaire pour bien comprendre les profils des enfants touchés par ce trouble. Par ailleurs, malgré que les termes dyspraxie et TDC soient maintenant utilisés comme synonymes, le diagnostic d'une dyspraxie était jusqu'à récemment plus fréquent que celui du TDC et appartient davantage à la neuropsychologie, alors que le TDC est plus souvent diagnostiqué par les ergothérapeutes et physiothérapeutes (Gibbs, Appleton, & Appleton, 2007; Lussier, Chevrier, & Gascon, 2017). Pour ces raisons, des modèles théoriques de la dyspraxie seront d'abord présentés, et ceux des fonctions exécutives seront discutés par la suite.

Modèles théoriques de la dyspraxie

De multiples modèles théoriques de la dyspraxie ont vu le jour depuis les années 1970, tentant d'expliquer les déficits liés à ce trouble (pour un résumé de plusieurs modèles théoriques, voir Lussier et al., 2017). L'un des premiers modèles à avoir été proposé est celui de l'intégration sensorielle, proposé par Ayres (Ayres, 1971) et discuté par plusieurs auteurs par la suite (notamment : Dewey, 1995; Lane et al., 2019; Smith Roley et al., 2007; Vaivre-Douret, 2014). Ayres émet plusieurs postulats concernant le développement sensoriel et moteur typique, ainsi que concernant les liens unissant ces deux sphères. Smith Roley et ses collègues (2007) expliquent d'abord que, selon l'auteure, l'apprentissage moteur dépend des sensations perçues, et que les différents systèmes sensoriels se développent de manière interreliée. En effet, le développement d'une conscience des sens et des sensations perçues permettrait à l'enfant d'acquérir une représentation de son corps. Celle-ci favoriserait à son tour le développement des capacités d'intégration sensorielle, permettrait d'acquérir un contrôle postural, reposant sur les systèmes visuel, vestibulaire, proprioceptif et moteur, et de planifier des séquences de mouvements à réaliser (Ayres, 1972; Dewey, 1995; Smith Roley et al., 2007). La recherche a confirmé que le système vestibulaire, particulièrement, permet le contrôle de l'équilibre, tant en mouvement qu'en position statique, la coordination bilatérale et la perception spatiale nécessaire à la navigation efficace du corps dans l'espace. Il joue également un rôle important dans la régulation de l'attention en permettant de conserver un champ visuel stable par le contrôle des mouvements oculaires, et en maintenant le niveau d'éveil (Lane et al., 2019), ce qui favorise la disponibilité de l'enfant aux apprentissages (Smith Roley et al., 2007). Lane et ses collègues (2019) expliquent également que le touché et la proprioception, constitutifs du système somatosensoriel, permettent l'intégration du mouvement de son propre corps, de la stabilité de la posture et de l'orientation spatiale du corps. Ainsi, les systèmes sensoriels apparaissent essentiels aux praxis, comprenant la conceptualisation des actions (idéation), la planification et l'exécution des mouvements (Lane et al., 2019). Ayres s'est donc intéressée aux liens entre les difficultés praxiques et les dysfonctions des systèmes sensoriels. À travers la réalisation de plusieurs études par analyses factorielles, elle a documenté l'existence de six patrons de dysfonctions de l'intégration sensorielle, dont un faisant référence à la dyspraxie développementale (Smith Roley et al., 2007). Son modèle en découlant stipule que les enfants atteints de la dyspraxie présentent un système d'intégration sensorielle déficitaire, qui ne leur permet pas d'évaluer adéquatement la nature des informations sensorielles perçues, particulièrement sur les plans tactile, visuel et vestibulaire, ce qui nuit à la planification des mouvements et à la capacité de ces enfants à s'ajuster en cours d'action selon la rétroaction fournie par les sens (Smith Roley et al., 2007; Vaivre-Douret, 2014). En effet, Ayres, Mailloux et Wendler (1987) ont établi des corrélations entre le dysfonctionnement du traitement visuel et tactile et les difficultés praxiques chez les enfants. De ce fait, comme la perception sensorielle est du moins partiellement altérée chez les enfants dyspraxiques, et étant donné l'influence de celle-ci sur les fonctions praxiques, ces enfants éprouvent des difficultés de planification des mouvements, qui influencent leur exécution, ainsi que des difficultés à s'ajuster en cours d'exécution en fonction de la rétroaction envoyée par les sens (Ayres et al., 1987; Lane et al., 2019; Smith Roley et al., 2007; Vaivre-Douret et al., 2014).

En 1985, Cermak propose un modèle de la dyspraxie se basant sur la conceptualisation de l'apraxie chez l'adulte proposée par Roy (1978) et reprise par Roy et Square (1985). Ces auteurs stipulent que les apraxies peuvent être classées en deux catégories, soit les apraxies de planification et les apraxies exécutives. Les premières dépendent d'un système conceptuel, regroupant les connaissances sur les objets nécessaires pour exécuter des gestes, sur les gestes eux-mêmes et sur le séquençage des gestes nécessaires pour accomplir une action (Roy, 1978; Roy & Square, 1985). Roy (1978) distingue deux sous-types d'apraxies de planification : l'apraxie de planification primaire, dans laquelle l'organisation conceptuelle des mouvements requis pour effectuer une séquence est affectée, et l'apraxie de planification secondaire, dans laquelle les déficits de planification motrice sont plutôt dus à un traitement altéré de l'information sensorielle (Cermak, 1985). En ce qui concerne les apraxies exécutives, elles dépendent plutôt d'un système de production, responsable de programmer l'action sur le plan sensorimoteur et d'activer les muscles nécessaires pour l'exécuter en s'adaptant à l'environnement. Les patients atteints d'une apraxie exécutive sont donc en mesure de conceptualiser les mouvements, mais éprouvent des difficultés à transposer leur planification en un patron cohérent de mouvements (Cermak, 1985; Roy & Square, 1985).

Ainsi, selon Cermak (1985), deux types de dyspraxie existent également, soit le trouble de planification motrice et le trouble d'exécution des mouvements. Tout d'abord, l'auteure décrit des difficultés d'organisation qui ont été observées par des cliniciens dans plusieurs sphères chez les enfants dyspraxiques, notamment sur le plan de l'organisation du matériel, et qui appuieraient l'hypothèse selon laquelle certains enfants présentent des déficits d'organisation conceptuelle qui seraient à la source de leurs difficultés motrices. Ces enfants s'inscrivent donc dans la catégorie de ceux touchés par une dyspraxie de planification primaire. Ensuite, pour Cermak, le modèle de l'intégration sensorielle proposé par Ayres réfère à la dyspraxie de planification secondaire, dans laquelle le système somatosensoriel serait déficitaire et ne permettrait donc pas l'élaboration d'une représentation du corps adéquate, essentielle pour une planification motrice efficace. Enfin, Cermak (1985) explique que, parmi un groupe d'enfants présentant des difficultés motrices, des cliniciens ont pu identifier un sous-groupe d'enfants qui savaient comment procéder pour accomplir une tâche motrice, mais qui se montraient particulièrement maladroits dans son exécution. Selon l'auteure, ces enfants sont ceux présentant une dyspraxie exécutive (Cermak, 1985).

Au cours des années 1990, Dewey (1995) propose un modèle neuropsychologique de la dyspraxie stipulant qu'il s'agit d'un trouble de la performance gestuelle. Dewey et Kaplan (1994) ont procédé à des analyses par grappes dans une tentative de préciser les mécanismes sous-jacents à ce trouble, et elles ont identifié quatre groupes d'enfants se distinguant par la nature de leurs déficits moteurs. Un premier groupe d'enfants présentait des difficultés d'exécution motrice, soit d'équilibre, de coordination et d'exécution des mouvements, sans que leurs habiletés de planification motrice ne soient compromises. Un second groupe présentait le profil inverse, manifestant plutôt un déficit de planification des mouvements, objectivées par des difficultés à organiser des séquences motrices, sans montrer de problèmes particuliers à exécuter des gestes isolément. Un troisième groupe d'enfants présentait des déficits sévères de toutes les habiletés motrices, tant liées à la production des gestes qu'à leur planification, indiquant que certains enfants présentent des atteintes généralisées des fonctions motrices. Le dernier groupe étaient composés d'enfants ne présentant pas de difficultés motrices (Dewey & Kaplan, 1994). La distinction entre les deux premiers groupes indique une dissociation entre les habiletés d'exécution des gestes et la planification de ceux-ci, ce qui va, selon les auteures, à l'encontre de l'hypothèse suggérant que les déficits de performance gestuelle résultent d'un déficit de planification motrice (Dewey & Kaplan, 1994), tel qu'impliquait le modèle d'Ayres. Leur modèle ne nie toutefois pas l'impact potentiel des fonctions perceptuelles sur les habiletés praxiques. En effet, le troisième groupe d'enfants identifié par Dewey et Kaplan (1994) présentait des difficultés d'intégration visuomotrice significativement plus importantes que le deuxième groupe, et les auteures concluent donc que le dysfonctionnement des fonctions visuomotrices ne serait qu'un facteur parmi d'autres menant aux difficultés de planification motrice identifiées chez certains enfants (Dewey, 1995; Dewey & Kaplan, 1994).

Un autre facteur important, au cœur de leur modèle, est selon eux un déficit de conceptualisation abstraite qui, dans le cas des enfants dyspraxiques, affectent leur performance gestuelle. En effet, Dewey et Kaplan (1992) ont montré que les enfants éprouvent davantage de difficulté à exécuter des gestes selon une demande verbale que par imitation, que leurs difficultés augmentent avec la complexité des séquences motrices demandées et qu'ils performent moins bien des gestes transitifs (mimant la manipulation d'un objet qui serait nécessaire pour réaliser l'action réelle) qu'intransitifs. Ainsi, les difficultés sont augmentées dans les contextes où les enfants doivent davantage se représenter les gestes mentalement. D'ailleurs, il semble que les enfants dyspraxiques présentent également des difficultés de conceptualisation langagière. En effet, les résultats de Dewey et Kaplan (1992) suggèrent que les habiletés praxiques, et particulièrement la performance de gestes transitifs, sont corrélées aux habiletés de langage réceptif, exigeant aussi une capacité d'abstraction. Ce déficit commun des habiletés de conceptualisation abstraite pourrait ainsi être à la source de la fréquente cooccurrence entre les troubles moteurs et verbaux (Dewey, 1995; Dewey & Kaplan, 1992). En ce qui concerne la dyspraxie, Dewey (1995) conclut donc que les difficultés motrices retrouvées chez les enfants présentant ce trouble sont en grande partie attribuables à des difficultés de conceptualisation abstraite des gestes qui, tel qu'observé par Dewey et Kaplan (1992), influencent tant l'exécution de gestes représentationnels, soit les gestes qui ont une signification, non représentationnels, soit les gestes sans signification, que la production de séquences gestuelles.

En résumé, les modèles d'Ayres, de Cermak et de Dewey précédemment présentés ne sont pas incompatibles. Selon Ayres, les déficits moteurs des enfants dyspraxiques sont attribuables à des déficits d'intégration sensorielle, principalement du système somatosensoriel. Cermak considère que ces déficits sont sous-jacents à un sous-type de dyspraxie, soit la dyspraxie de planification secondaire, mais stipule aussi l'existence d'une dyspraxie de planification primaire et d'une dyspraxie exécutive, dans laquelle seule l'exécution des gestes est affectée, sans que leur planification ne le soit. Les travaux de Dewey et Kaplan (1994) ont montré que des difficultés de planification du geste pouvaient exister chez les enfants dyspraxiques, mais, selon le modèle découlant de ces travaux et proposé par Dewey (1995), c'est davantage la conceptualisation abstraite des mouvements qui serait affectée et perturberait tant la planification des mouvements que leur exécution.

Le modèle présenté par Vaivre-Douret (2007) et Vaivre-Douret et ses collègues (2011) discuté dans l'article constituant le présent essai doctoral constitue un modèle plus intégratif de la dyspraxie (Fig. 1). En effet, il emprunte certains éléments à chacun des modèles préalablement décrits et les combine afin de leur donner un sens à travers quatre étapes nécessaires à la réalisation d'un mouvement. Ce modèle propose également des bases neuronales assez spécifiques à chaque fonction motrice, ayant été identifiées par imagerie par résonance magnétique (Vaivre-Douret et al., 2011). Les auteurs proposent que la première étape nécessaire à la réalisation d'un mouvement consiste à avoir une intention motrice, soit le désir de réaliser un geste, qui est orienté vers un but et découle d'une prise de décision et de la motivation de l'individu. Ce processus dépend du cortex limbique, du thalamus et du cortex préfrontal. La seconde étape consiste à planifier le mouvement. Pour y arriver, l'enfant doit considérer les informations perçues par ses sens dans son environnement, notamment tactiles, visuelles et auditives, et par rapport à son propre corps, soit les informations proprioceptives et vestibulaires. L'intégration des indices sensoriels prend place dans les ganglions de la base et le thalamus, qui envoient ensuite l'information traitée au cortex préfrontal, pariétal et temporo-occipital. La troisième étape est celle de programmation du mouvement. L'enfant doit alors être en mesure de conceptualiser le mouvement pour se créer une représentation interne de ses différents paramètres spatiotemporels. Les ganglions de la base et le thalamus sont impliqués dans ce processus également, mais celui-ci est aussi sous-tendus par le cortex prémoteur et moteur ainsi que le néocervelet. La quatrième et dernière étape consiste à exécuter le mouvement en considérant la rétroaction sensorielle et motrice fournie en cours d'exécution,

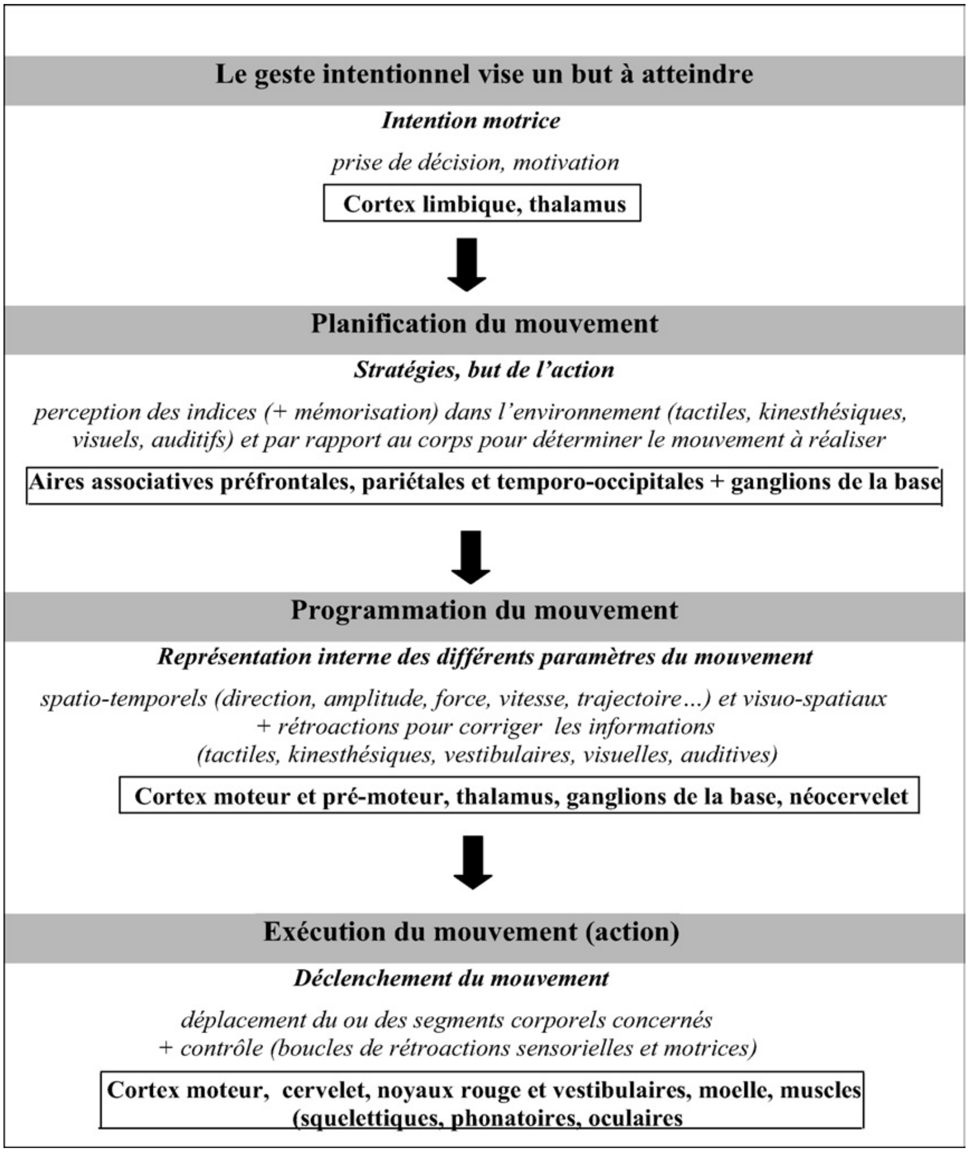

Figure 1. Modèle intégratif de l'organisation de l'action dans les dyspraxies développementales (Vaivre-Douret, 2007).

afin d'adapter les gestes réalisés aux paramètres spatiotemporels, qui changent en cours d'action. L'activation adéquate des muscles pour effectuer le mouvement désiré, planifié et programmé est le résultat de l'activité du cervelet, des noyaux rouge et vestibulaires, du cortex moteur et de la moelle épinière (Vaivre-Douret, 2007; Vaivre-Douret et al., 2011).

Les résultats des évaluations neuropsychologique, neuropsychomotrice et neurovisuelle réalisées par Vaivre-Douret et son équipe (2011) suggèrent que ce seraient principalement les étapes de planification et de programmation du mouvement qui seraient perturbées chez les enfants présentant une dyspraxie. Ces difficultés seraient attribuables à une dysfonction du circuit cervelet-thalamus-ganglions de la base. Les mécanismes d'exécution des mouvements seraient par ailleurs intacts chez les sous-groupes d'enfants présentant une dyspraxie pure, mais des difficultés sur ce plan seraient présentes chez des enfants dyspraxiques également atteints de comorbidités ayant des impacts au niveau du circuit moteur cortical. Les auteurs concluent donc que la dyspraxie est un trouble du geste intentionnel dirigé vers un but, dans lequel la planification et la programmation du mouvement est perturbée en lien avec des dysfonctions sous-corticales et cérébelleuses. De plus, selon leur modèle, un déficit d'intégration sensorimoteur et spatiotemporel serait également sous-jacent aux difficultés objectivées (Vaivre-Douret et al., 2011).

Ainsi, ce modèle concorde avec les modèles d'Ayres, de Cermak et de Dewey. En effet, comme Ayres, Vaivre-Douret et ses collègues (2011) stipulent qu'un déficit d'intégration sensorielle contribuerait aux difficultés des enfants dyspraxiques. De plus, leur conclusion selon laquelle ce sont principalement les étapes de planification et de programmation motrice qui sont atteintes dans cette population est compatible tant avec le concept de dyspraxie de planification de Cermak (1985) qu'avec celui de déficit de conceptualisation abstraite du mouvement proposé par Dewey (1995). Seul le concept de dyspraxie purement exécutive n'est pas discuté dans ce modèle intégratif.

Modèles théoriques des fonctions exécutives

Les fonctions exécutives ont fait l'objet de multiples recherches, ont été traitées par un grand nombre d'auteurs et plusieurs modèles théoriques de ces fonctions ont été proposés à travers les années. Seuls les modèles ayant été utiles à l'élaboration de la définition des fonctions exécutives proposée dans l'article constituant le présent essai doctoral seront ici présentés.

En 1974, Baddeley et Hitch proposent un modèle théorique établissant des liens entre les fonctions exécutives et attentionnelles et dans lequel la mémoire de travail occupe une place centrale. Selon ce modèle, la mémoire de travail réfère au système permettant de maintenir des informations en tête en les manipulant de façon à effectuer des tâches cognitives complexes, telles que comprendre, raisonner et apprendre (Baddeley, 2010). Baddeley et Hitch (1994) la définissent comme un système se divisant en trois sous-composantes : deux sous-systèmes de stockage, soit la boucle phonologique et le calepin visuospatial, et un sous-système central appelé l'exécutif central.

La boucle phonologique permet de maintenir en mémoire durant une courte période de temps l'information verbale et de la manipuler pour exécuter une tâche (Baddeley & Hitch, 1994). Quatre évidences principales supportent son existence et son fonctionnement. Tout d'abord, il existerait un effet de similarité phonologique influençant son efficacité. En effet, Conrad et Hull (1964) ont constaté que le rendement en rappel sériel immédiat est plus faible lorsque les items présentés sont phonologiquement similaires, probablement car ils deviennent alors plus difficiles à discriminer sur le plan du code articulatoire sous lequel ils sont encodés. Ensuite, un effet de discours non pertinent est relevé : le matériel verbal entendu par l'individu, mais qu'il lui est mentionné d'ignorer, affecte les capacités de rappel verbal sériel immédiat, puisque les stimuli non pertinents semblent corrompre la trace mnésique (Colle & Welsh, 1976).

Des processus phonologiques pourraient être impliqués dans cet effet, puisque des distracteurs phonétiquement proches des stimuli-cibles auraient un plus grand impact sur le rendement (Salamé & Baddeley, 1982). Un autre effet soulevé en est un de suppression articulatoire, soit de facilitation du rappel sériel immédiat par la répétition mentale (ou vocale) de l'information à rappeler. En effet, lorsqu'il est demandé aux sujets de prononcer un son non pertinent durant le rappel, empêchant ainsi la répétition, le rendement au rappel est plus faible (Baddeley, Lewis, & Vallar, 1984). Enfin, le dernier effet relevé appuyant l'existence de la boucle phonologique est l'effet de longueur des mots. Baddeley, Thomson et Buchanan (1875) ont effectivement observé que l'augmentation de la longueur des items présentés résultait systématiquement en une réduction de l'empan mnésique immédiat. Baddeley et Hitch (1994) expliquent cet effet par la suppression articulatoire; lorsque les items à mémoriser sont plus longs, le rythme de répétition est ralenti, de même que le rythme auquel l'information peut être rafraîchie en mémoire. De ce fait, des informations peuvent être perdues avant d'avoir pu être répétées. Bref, ces éléments supportent l'existence et les mécanismes sous-jacents de la boucle phonologique.

En ce qui concerne le calepin visuospatial, il sert quant à lui à stocker l'information visuelle et spatiale nécessaire pour effectuer une activité sur une courte période de temps (Baddeley & Hitch, 1994). Il serait également affecté par un effet d'interférence, mais dont les mécanismes d'action sont moins clairs que pour la boucle phonologique. En effet, Baddeley et Lieberman (1980) ont constaté qu'une tâche spatiale sans composante visuelle (tâche de poursuite spatiale auditive) affecte le rappel d'énoncés décrivant des localisations spatiales, mais l'interférence au cours de cette dernière tâche serait moindre lorsque la tâche d'interférence en est une visuelle sans composante spatiale (jugement de la brillance de diapositives vides). Baddeley et Hitch (1994) expliquent que ces résultats impliquent l'utilisation d'un système spatial sans composante visuel et soulèvent la possibilité que le calepin visuospatial puisse être à son tour divisé en deux sous-composantes, l'une spécialisée dans la rétention de la localisation spatiale et l'autre, d'informations concernant l'identité visuelle.

Quant à l'exécutif central, il assume plusieurs fonctions et serait, selon Baddeley (1996), l'entité sous-jacente à d'autres fonctions exécutives, considérées comme distinctes dans d'autres modèles qui seront présentés subséquemment. Notamment, l'exécutif central permettrait de coordonner l'activité des deux systèmes de stockage de la mémoire de travail afin de réaliser deux tâches simultanément (Baddeley & Hitch, 1994). En effet, en 1986, Baddeley, Logie, Bressi, Sala, et Spinnler ont montré, par l'évaluation de patients atteints de la maladie d'Alzheimer, une dissociation entre la boucle phonologique et le calepin visuospatial ainsi que l'exécutif central, par le biais du rendement lors d'une situation de double-tâche. Dans ce contexte, les patients arrivaient à exécuter les tâches faisant appel aux deux systèmes de stockage séparément, mais éprouvaient des difficultés importantes à les réaliser simultanément, indiquant un dysfonctionnement de l'exécutif central dans cette population (Baddeley, 1996; Baddeley et al., 1986). L'exécutif central permettrait aussi d'alterner entre différentes stratégies afin de générer du matériel demandé aléatoirement, mais serait de capacité limitée, ce qui freinerait ce processus. Baddeley (1996) explique que, plus le débit de génération est rapide, moins le matériel généré est aléatoire. De la même façon, plus il y a de réponses possibles répondant aux critères de génération, plus lent est le débit de génération aléatoire. Ensuite, l'exécutif central serait, selon ce modèle, en charge de sélectionner les stimuli à traiter en inhibant les distracteurs, faisant ainsi référence à l'attention sélective. En effet, en coordonnant la boucle phonologique et le calepin visuospatial, l'exécutif central a la responsabilité d'orienter ces deux sous-systèmes vers les stimuli pertinents à un certain moment et d'en assurer la rétention, par les mécanismes de stockage (Baddeley, 1996; Baddeley & Hitch, 1994). Enfin, Baddeley (1996) mentionne que l'exécutif central ferait appel à la mémoire à long terme lorsque pertinent. Il explique que ce serait particulièrement le cas lorsque les stimuli à traiter impliquent leur compréhension, par exemple dans le cas d'une histoire racontée. En effet, la compréhension requière la formation d'un modèle mental, qui nécessite l'implication des deux sous-systèmes de stockage, mais qui ferait également appel à des connaissances sémantiques. Celles-ci constituant des éléments de la mémoire à long terme, c'est dans ce contexte que cette dernière serait impliquée dans une tâche de rappel immédiat (Baddeley, 1996). Néanmoins, en retravaillant son modèle, Baddeley (2000, 2010) y a ajouté un troisième sous-système de stockage, le tampon épisodique, qui permettrait de retenir des tronçons d'information multidimensionnelle, combinant les informations provenant des différents sens. Il explique que c'est plus précisément par ce tampon épisodique que les différentes informations contenues en mémoire de travail interagiraient entre elles ainsi qu'avec les connaissances sémantiques, tant visuelles que verbales, et donc avec la mémoire à long terme (Baddeley, 2000, 2010).

L'idée proposée par Baddeley stipulant que la mémoire de travail comporte des composantes verbale et visuospatiale est généralement acceptée dans la littérature traitant des fonctions exécutives. Cependant, lorsque discutée en lien avec d'autres composantes exécutives, la mémoire de travail est souvent traitée comme une seule entité. D'ailleurs, elle fait partie des trois fonctions exécutives généralement reconnues dans la littérature, les deux autres étant la flexibilité cognitive et l'inhibition. Plusieurs chercheurs ont réalisé des études par analyses factorielles afin de spécifier dans quelle mesure ces trois fonctions exécutives sont unitaires ou séparables. C'est le cas de Miyake et ses collègues (2000), qui ont étudié la question auprès d'une population de jeunes adultes. Les auteurs définissent la flexibilité comme l'habileté à alterner entre des tâches ou des états mentaux et l'inhibition comme celle à volontairement inhiber une réponse dominante, automatique ou prépondérante lorsque requis. En ce qui concerne la mémoire de travail, ils font référence à une fonction de mise à jour de l'information, qui contrôle l'information retenue en mémoire de travail durant une brève période de temps. Miyake et ses collègues (2000) ont ainsi considéré la possibilité de modèles à trois facteurs, convenant le mieux si les trois fonctions exécutives ciblées étaient séparables, à deux facteurs, qui conviendraient si deux des fonctions ciblées dépendaient du même construit sous-jacent, et à un facteur, correspondant aux résultats si les trois fonctions exécutives ciblées reposaient toutes sur le même construit et n'étaient donc pas réellement dissociables. Leurs résultats révèlent que c'est un modèle à trois facteurs qui correspond le mieux à la conceptualisation de ces trois fonctions exécutives. De ce fait, il semble que la flexibilité, la mémoire de travail et l'inhibition soient des construits séparables. Cependant, les auteurs ont aussi calculé des corrélations entre les résultats aux tâches mesurant les différentes fonctions et ont trouvé que, bien que distinguables, les trois fonctions exécutives ne sont pas indépendantes. En effet, des corrélations modérées ont été relevées entre les trois facteurs. Les auteurs concluent donc que ces fonctions exécutives sont à la fois unitaires et dissociables (Miyake et al., 2000).

Lehto, Juujärvi, Kooistra et Pulkkinen (2003) ont répliqué ces résultats chez des enfants en adoptant une définition de la mémoire de travail plus près de celle de Baddeley, la décrivant comme comportant des processus de stockage temporaire et de contrôle de l'information. Comme Miyake et al. (2000) avant eux, Lehto et ses collègues (2003) ont réalisé des analyses factorielles leur permettant de mettre en lumière la séparabilité des trois fonctions exécutives étudiées, mais également des corrélations modérées entre elles. Ils stipulent donc que les fonctions exécutives sont des construits dissociables mais reliés, et ajoutent quelques considérations développementales. Selon leurs résultats, la mémoire de travail et la flexibilité seraient des habiletés qui deviennent plus matures avec l'âge. En ce qui concerne l'inhibition, les auteurs n'ont pas trouvé de corrélation significative entre la performance des enfants dans les tâches la mesurant et leur âge, résultat qu'ils attribuent à la difficulté élevée de l'une des tâches sélectionnées pour évaluer l'inhibition. Dans une autre étude par analyses factorielles réalisée auprès d'enfants, St Clair-Thompson et Gathercole (2006) ont inclut dans leurs analyses factorielles les mêmes construits que Miyake et al. (2000), soit la flexibilité, la mise à jour de l'information en mémoire de travail et l'inhibition, mais ont obtenu des résultats légèrement différents. En effet, les résultats obtenus suggèrent que la mise à jour de l'information en mémoire de travail et l'inhibition sont non seulement dissociables, mais aussi non reliées, puisqu'aucune corrélation significative n'a été trouvée entre les tâches mesurant ces deux composantes. De plus, cette étude ne permet pas d'identifier un troisième facteur constituant la flexibilité, différence que les auteurs expliquent potentiellement par le paradigme adopté pour tester cette fonction (St Clair-Thompson & Gathercole, 2006).

Bref, ces études permettent de confirmer que la mémoire de travail, ou la mise à jour de l'information qui y est traitée, et l'inhibition sont des composantes distinctes des fonctions exécutives, tant chez les adultes que chez les enfants. La dissociation de la flexibilité de ces deux autres fonctions apparaît moins unanime, mais des évidences existent tout de même concernant sa distinction. Enfin, il semble que, bien qu'elles soient dissociables, ces fonctions exécutives sont aussi généralement liées entre elles. C'est notamment les liens unissant ces trois fonctions exécutives que tentent d'expliquer les modèles théoriques subséquents, tout en considérant l'existence d'autres processus exécutifs.

En 2000, Gioia, Isquith, Guy, et Kenworthy ont mis sur pied un questionnaire visant à évaluer les manifestations comportementales des fonctions exécutives chez les enfants dans leur vie quotidienne, le *Behavior Rating Inventory of Executive Function* (BRIEF), qui se base sur un modèle à plusieurs composantes. Les auteurs définissent d'abord les fonctions exécutives comme un ensemble de processus qui seraient particulièrement impliqués durant une résolution de problème active ou vis-à-vis une nouvelle situation. Ces processus sont, selon les auteurs, responsables de guider, diriger et coordonner les différentes fonctions cognitives, comportementales et émotionnelles des individus. Ainsi, ils affirment que les différentes composantes de ces processus incluent les habiletés à inhiber des stimuli ou des impulsions, à modifier et adapter ses stratégies de résolution de problème lorsque nécessaire, à retenir des informations en mémoire de travail pour résoudre un problème en plusieurs étapes, à initier des actions, à planifier et s'organiser pour atteindre les buts fixés et à réguler et évaluer ses comportements et émotions (Gioia et al., 2000). Afin de bâtir leur questionnaire, les auteurs ont conduit des analyses factorielles dans des échantillons normatifs et cliniques afin de mieux statuer sur la séparabilité des composantes. Ils ont conclu à un modèle à deux facteurs, les différentes composantes proposées se regroupant sous deux grandes dimensions, qu'ils ont libellées comme étant la régulation comportementale et les fonctions métacognitives. La première regroupe trois composantes des fonctions exécutives, soit l'inhibition, la flexibilité et le contrôle émotionnel, alors que cinq composantes sont regroupées pour former la seconde dimension, soit l'initiative, la mémoire de travail, la planification/organisation, l'organisation du matériel et l'autorégulation (Gioia et al., 2000). D'autres études par analyses factorielles ont ensuite vérifié le modèle théorique sur lequel se base le questionnaire (Egeland & Fallmyr, 2010; Gioia, Isquith, Retzlaff, & Epsy, 2002). Ces études ont conclu qu'un modèle à trois facteurs seraient plus représentatif des huit composantes des fonctions exécutives proposées. En effet, selon les auteurs, la composante d'autorégulation se diviserait en deux sous-composantes, l'une faisant référence à la gestion de ses comportements et l'autre à la gestion d'une tâche. Ainsi, ils proposent que trois dimensions principales des fonctions exécutives existeraient : la régulation comportementale, la régulation émotionnelle et la métacognition (Egeland & Fallmyr, 2010; Gioia et al., 2002). Selon le modèle établi par Gioia et ses collègues (2002), la première inclut l'inhibition et l'autorégulation comportementale, la seconde inclut le contrôle émotionnel et la flexibilité, et la troisième est composée des habiletés d'initiation de l'action, de mémoire de travail, de planification/organisation, d'organisation du matériel et de gestion d'une tâche. Les auteurs relèvent aussi des corrélations élevées significatives entre les trois dimensions, révélant d'importantes interactions entre les différents facteurs constituant les fonctions exécutives, malgré qu'elles apparaissent distinctes (Gioia et al., 2002).

Parallèlement, Anderson (2002) a proposé un modèle théorique combinant fonctions exécutives et attentionnelles chez les enfants. L'auteur considère d'abord les résultats de plusieurs études ayant réalisé des analyses factorielles à partir de résultats d'enfants à des batteries de tests mesurant les fonctions exécutives, et ayant démontré l'existence d'un facteur lié à la planification, un lié au contrôle des impulsions, un autre au raisonnement conceptuel et un lié à la vitesse de réponse (Kelly, 2000; Levin et al., 1991; Welsh, Pennington, & Groisser, 1991). En combinant ces résultats et ses connaissances en neuropsychologie clinique, Anderson (2002) propose un modèle dans lequel figurent quatre domaines exécutifs distincts, soit le contrôle attentionnel, le traitement de l'information, la flexibilité cognitive et la fixation de buts (Fig. 2). En s'inspirant des travaux d'Alexander et Stuss (2000), l'auteur explique que ces domaines sont distincts, mais fonctionnent également de manière interreliée et interdépendante,

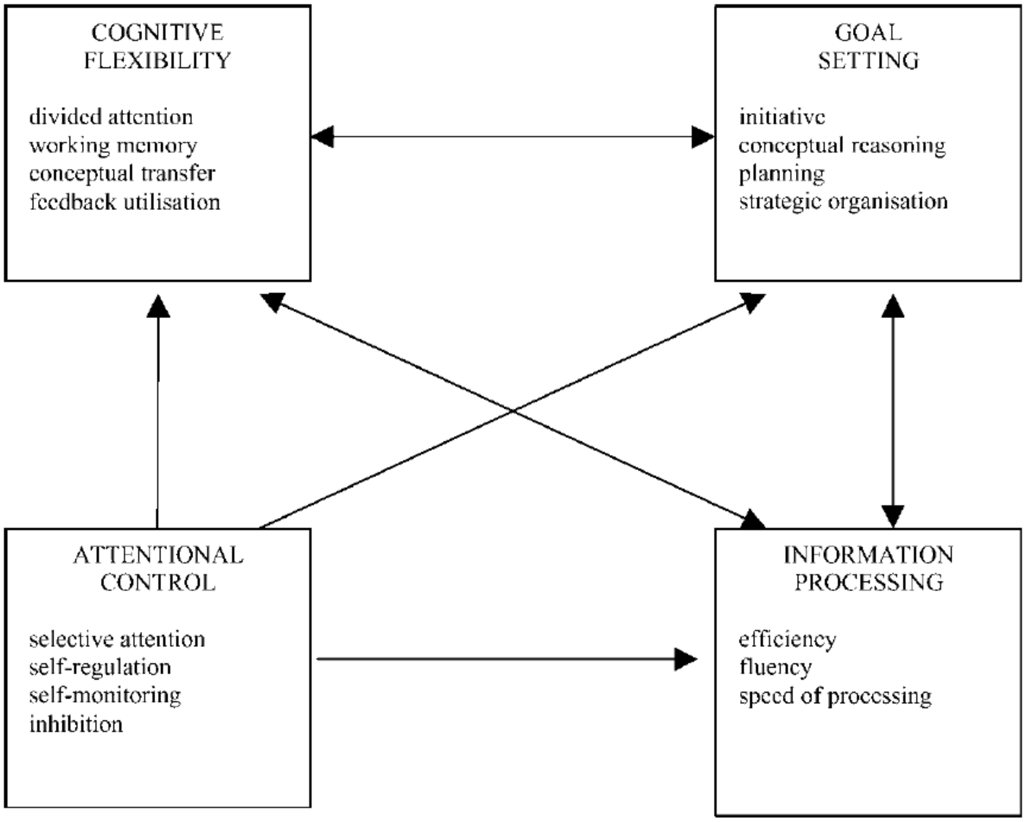

Figure 2. Modèle des fonctions exécutives proposé par Anderson (2002).

de sorte qu'ils constituent ensemble un système de contrôle général, à la tête duquel se trouve le contrôle attentionnel. Celui-ci inclut la capacité de diriger l'attention vers des stimuli spécifiques et ce, durant une longue période de temps, en plus des capacités d'autorégulation, de contrôle des actions et d'inhibition. Les processus de traitement de l'information incluent les habiletés de fluence, d'efficience et de rapidité, et ceux de fixation des buts réfèrent à l'habileté de prendre des initiatives, de planifier et de réfléchir à des concepts et à des stratégies permettant de s'organiser pour atteindre les objectifs fixés. En ce qui concerne la flexibilité cognitive, elle consiste en la capacité d'alterner entre des demandes, de partager les ressources attentionnelles en traitant plusieurs informations simultanément, d'intégrer les connaissances conceptuelles et la rétroaction fournie par l'environnement afin de générer différentes stratégies et d'éviter de répéter des erreurs déjà commises, et inclut également la mémoire de travail (Anderson, 2002). Ainsi, le contrôle attentionnel influence la mise en action des trois autres processus, puisqu'il permet de sélectionner, selon la tâche à accomplir, l'information à traiter et les processus exécutifs nécessaires à mettre en application pour fournir une réponse adéquate.

En bref, plusieurs modèles théoriques existent et, bien qu'aucun ne soit totalement incompatibles, leurs auteurs ne s'entendent pas tous sur le nombre de composantes des fonctions exécutives, sur la mesure dans laquelle elles se distinguent ou sous quelles appellations elles devraient être regroupées. Dans cette optique, Diamond (2013) a proposé un modèle intégratif des fonctions exécutives s'appliquant tant aux enfants qu'aux adultes, faisant également des liens avec les fonctions attentionnelles et expliquant les interactions entre les différentes composantes (Fig. 3). Ce modèle a été présenté dans l'article constituant le présent essai doctoral car il apparaît comme étant le plus complet, mais il sera ici davantage approfondi. Les différentes composantes des fonctions exécutives selon ce modèle seront d'abord décrites et définies, puis les liens entre elles seront ensuite mis de l'avant.

Tout d'abord, Diamond (2013) définie les fonctions exécutives comme une famille de processus mentaux descendants nécessaires à la concentration et aux situations dans lesquelles l'instinct ou les automatismes sont inadéquats ou insuffisants, et dont l'utilisation demande un effort. À la tête de son modèle se trouvent les trois fonctions exécutives identifiées par Lehto et al. (2003) et Miyake et al. (2000), soit la mémoire de travail, le contrôle inhibiteur et la flexibilité cognitive. Selon l'auteure, la mémoire de travail réfère à l'habileté de retenir des informations en tête en les manipulant mentalement dans le but de compléter une tâche. De manière plus concrète, elle explique que cette habileté est nécessaire pour comprendre le langage, puisqu'au minimum plusieurs éléments d'une même phrase doivent être gardés en tête et compris pour assurer une compréhension plus globale. De même, faire des liens entre différents concepts et organiser ses idées, par exemple, sont des tâches nécessitant l'implication de la mémoire de travail. De plus, la conceptualisation de Diamond concorde avec celle de Baddeley, puisque l'auteure affirme que cette composante se sépare en sous-composantes verbale et non-verbale (Diamond, 2013).

En ce qui concerne le contrôle inhibiteur, Diamond (2013) le définit comme la capacité à contrôler l'attention, les comportements, les pensées et les émotions dans le but de freiner une réponse prédominante et de la remplacer par une réaction plus appropriée au contexte. Celui-ci se compose donc de deux sous-composantes, l'une chargée du contrôle de l'interférence et l'autre, de l'auto-contrôle. Dans le contrôle de l'interférence est incluse l'inhibition sur le plan attentionnel, aussi appelée attention exécutive, qui permet de sélectionner les stimuli auxquels porter attention en ignorant les distracteurs, ainsi que l'inhibition sur le plan cognitif, qui permet d'inhiber des pensées ou des souvenirs. La sous-composante référant à l'auto-contrôle se définit quant à elle par la capacité à contrôler ses émotions et comportements et implique donc la gestion de l'impulsivité, la capacité de résister à la tentation et de s'imposer et de respecter une discipline dans le but d'atteindre un objectif. De plus, l'auteure du modèle explique que l'inhibition et l'autorégulation sont des fonctions se chevauchant, puisque la dernière réfère au contrôle et à la régulation des émotions, et permet le maintien d'un niveau d'éveil émotionnel, motivationnel et cognitif optimal pour la tâche à accomplir.

Par ailleurs, Friedman et Miyake (2004) ont réalisé une étude par analyses factorielles afin d'identifier dans quelle mesure l'inhibition d'une réponse prédominante, à laquelle le

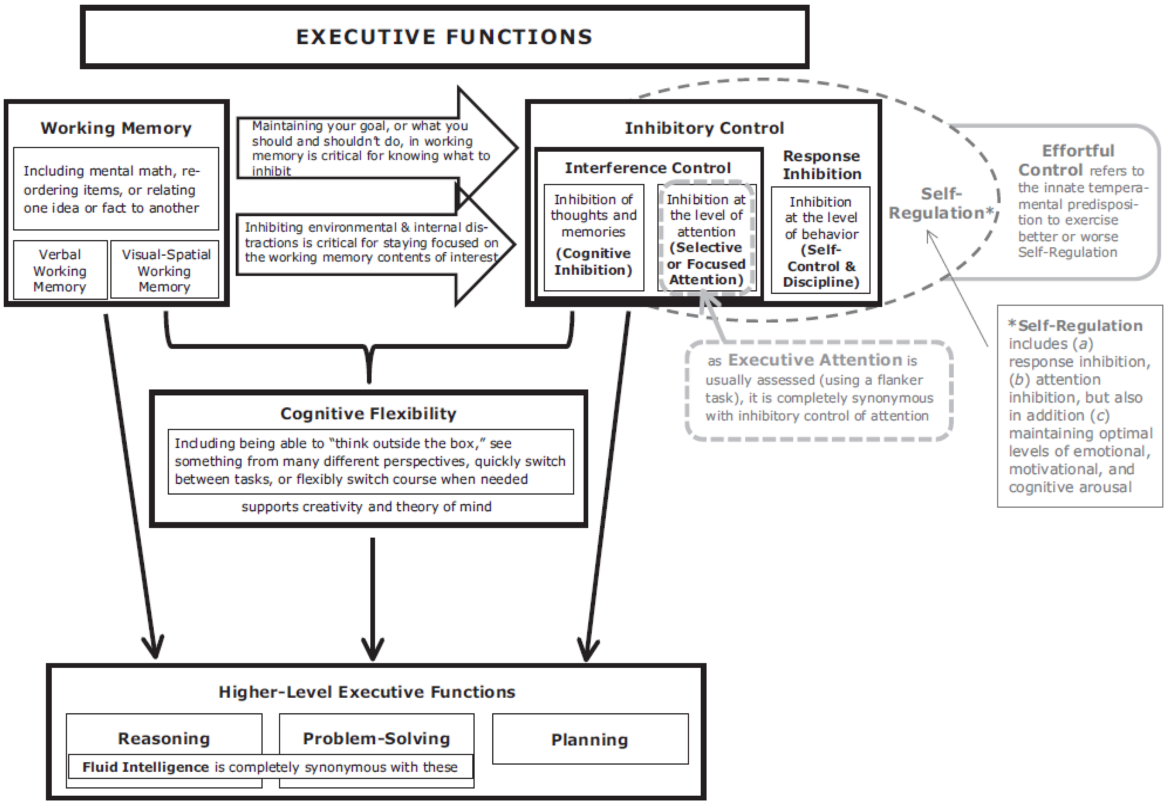

Figure 3. Modèle des fonctions exécutives proposé par Diamond (2013).

concept d'auto-contrôle de Diamond réfère, l'inhibition de l'attention, et l'inhibition à l'interférence proactive, correspondant au concept d'inhibition cognitive de Diamond, sont distinctes ou appartiennent au même construit. Les auteurs concluent que les deux premiers types d'inhibition sont étroitement liés puisqu'ils relèvent d'un seul facteur, mais sont indépendants du troisième (Friedman & Miyake, 2004). Ainsi, il semble adéquat de regrouper l'inhibition d'une réponse prédominante et celle de l'attention en un même construit, soit celui du contrôle inhibiteur dans le modèle de Diamond (2013), mais la conception de l'auteure selon laquelle l'inhibition cognitive appartient également au même construit pourrait être critiqué.

Enfin, Diamond (2013) inclut dans la définition de la flexibilité cognitive l'habileté à changer de perspective, tant perceptuelle qu'interpersonnelle, à s'ajuster à des demandes changeantes et à des imprévus, à alterner entre différentes tâches ou exigences, et à générer des stratégies, faisant référence aux habiletés de fluence. Elle résume la définition de cette composante en affirmant qu'elle constitue l'opposé de la rigidité cognitive (Diamond, 2013).

Bien que distincts, la mémoire de travail, le contrôle inhibiteur et la flexibilité cognitive sont, selon le modèle de Diamond (2013), interreliés et interdépendants, tout comme le stipulent Lehto et al. (2003) et Miyake et al. (2000). Tout d'abord, l'auteure explique que la mémoire de travail et le contrôle inhibiteur ont besoin l'un de l'autre pour fonctionner et agissent souvent de pair. En effet, la mémoire de travail est essentielle aux capacités d'inhibition puisque, durant une tâche requérant ces dernières, la mémoire de travail permet de garder en tête les consignes de la tâche et le but de celle-ci en même temps qu'elle est exécutée, afin de respecter les contraintes d'inhibition. Inversement, pour garder en mémoire de travail seulement les informations pertinentes à une tâche, il est nécessaire d'inhiber les distracteurs et les informations non pertinentes à la tâche. L'auteure spécifie tout de même que ce n'est pas toutes les tâches requérant l'une de ces deux fonctions qui nécessitent l'autre. En effet, l'influence de l'une ou l'autre peut être minimisée dans certains contextes, par exemple en ne mentionnant qu'une consigne à la fois, ce qui réduit l'implication de la mémoire de travail, ou en offrant un environnement et une tâche épurée de toute distraction, réduisant ainsi l'implication du contrôle inhibiteur (Diamond, 2013).

Quant à la flexibilité cognitive, elle a besoin des capacités de mémoire de travail et du contrôle inhibiteur pour être optimale. En effet, Diamond (2013) explique que, pour être en mesure de changer de perspective, il est nécessaire d'inhiber la perspective adoptée antérieurement et de garder en mémoire de travail les éléments constitutifs ou nécessaires à la nouvelle perspective. De la même façon, on peut facilement s'imaginer que la mémoire de travail ait un rôle à jouer lorsqu'il est nécessaire d'alterner entre plusieurs exigences, puisque celles-ci doivent être gardées en tête pour répondre adéquatement à la demande. Dans ce contexte, le contrôle inhibiteur permettrait aussi d'inhiber les réponses conformes à une exigence lorsque c'en est une autre qui doit être respectée.

Les trois fonctions exécutives principales du modèle de Diamond (2013) permettent le fonctionnement de fonctions exécutives de plus haut niveau. En se basant sur les travaux de Collins et Koechlin (2012), mettant en évidence des composantes du fonctionnement exécutif nécessaires à la prise de décision, Diamond (2013) identifie trois fonctions exécutives de plus haut niveau. Les deux premières sont les habiletés de raisonnement et de résolution de problème. Elle explique que celles-ci sont équivalentes à l'intelligence fluide, des corrélations élevées ayant été relevées entre des mesures de ce construit et des mesures des fonctions exécutives (Conway, Kane, & Engle, 2003; Kyllonen & Christal, 1990; Roca et al., 2009). La troisième fonction exécutive de plus haut niveau identifiée par Diamond (2013) est la planification. L'auteure fournit peu d'explication quant aux raisons motivant son intégration dans son modèle, mais cet ajout concorde avec les modèles d'Anderson (2002) et de Gioia et al. (2000), qui incluent également une composante liée à la planification.

Pour conclure, et tel que souligné précédemment, de nombreux modèles théoriques des fonctions exécutives figurent dans la littérature. La plupart se base sur des études ayant réalisé des analyses factorielles, permettant de se positionner quant à la possibilité de distinguer ou non certaines composantes et quant aux liens les unissant. Malgré tout, les différentes études n'arrivent pas toutes aux mêmes conclusions et différents facteurs sont parfois postulés, différences qui peuvent être explicables notamment par l'âge des participants inclus dans les études ainsi que par les tâches utilisées pour mesurer les différentes fonctions exécutives. Ainsi, on peut conclure que l'existence de trois fonctions exécutives principales est généralement reconnue, soit l'inhibition, la mémoire de travail et la flexibilité, qui sont des composantes distinctes mais interreliées des fonctions exécutives. En revanche, il est plus difficile d'établir un consensus sur les autres composantes du fonctionnement exécutif. C'est d'ailleurs pour cette raison que les différents termes employés à travers les différents modèles théoriques ont tous été inclus dans les mots-clés utilisés pour la recherche documentaire à la base de la recension des écrits constituant le présent essai doctoral, l'objectif étant de dénicher un maximum d'articles traitant du sujet visé et ce, peu importe le modèle théorique ayant été adopté par les auteurs des études.

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