Sensory Processing and Movement Control in Children

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Abstract

Movement control and motor learning depend largely on sensory processing (SP) of different sensory inputs in order to make a relevant perceptual decision that can be expressed as a coordinated and goal-directed movement. The aim of this thesis is to explore the role of SP on perceptual decision-making, movement control and participation among children. The first study aimed to identify and summarise the role of SP on movement abilities among children with movement difficulties, particularly developmental coordination disorder (DCD), through a systematic review. This is due to the literature being replete with studies investigating the role of SP on movement among children with DCD, however, no updated systematic review to synthesise the findings has been published. Furthermore, because there is a paucity of empirical studies considering SP abilities in the context of the relationship between movement control, levels of and preferences for physical activity (PA) among children, the second study aimed to explore the relationship between them using four valid questionnaires. Finally, as limited research was found in the empirical literature that had investigated the effect of multisensory inputs on perceptual decision-making among children, the third study aimed to investigate the effect of multisensory versus unisensory stimuli on two elements contributing to perceptual decision-making (reaction time (RT) and accuracy). The first study showed that the various dimensions of SP significantly contribute to movement abilities in DCD. Moreover, the second study showed that movement abilities, levels of and preferences for PA may be influenced by SP abilities among children. Lastly, the third study showed that multisensory stimuli may enhance the process of decision-making, however, this was found to be more pronounced in older children. These results show clear evidence of the role of SP on movement and emphasise the importance of addressing SP abilities in assessments and intervention programmes.

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A	Auditory
ADHD	Attention-deficit/hyperactivity disorder
ADL	Activities of daily living
Aomax	Maximum area of sway
Aomean	Mean area of sway
AP	Anterior-posterior
APA	American Psychological Association
ASD	Autism spectrum disorder
AUC	Area under the curve
AV	Audio-visual
Beery VMI	Beery-Buktenica Developmental Test of Visual Motor Integration
BMI	Body mass index
BOT	Bruininks-Oseretsky Test of Motor Proficiency
CASP	Critical appraisal skills programme
CNV	Contingent Negative Variation
CoM	Centre of mass
CONST	Constant isometric finger force/torque
CoP	Displacement of the centre of pressure
COVAT	Covert orienting of the visuospatial attention task
D&B	Downs and Black assessment tool
DCD	Developmental coordination disorder
DCD-Q	DCD questionnaire
DLPFC	Dorsolateral prefrontal cortex
DSM	Diagnostic and Statistical Manual of Mental Disorders
DTI	Diffuser tensor imaging
EEG	Electroencephalography
ERP	Event-related potential
ESC	End-state comfort
FA	Fractional anisotropy

fMRI	Functional magnetic resonance imaging
Ƒpeak	Peak frequency
HD	High difficulty
HR-NI	Hand rotation – No instruction
HR-WI	Hand rotation - With instructions
Hz	Hertz
ICE	Invalid cue effect
IDE	Initial directional error
IQ	Intelligence quotient
JND	Just-noticeable difference
KTK-jump	Körper Koördination Test für Kinder-jump
LD	Low difficulty
LOS	Limits of stability
LT	Light touch
LTAS	Light touch after soaking
M-ABC	Movement assessment battery for children
MAD	Median absolute deviation
ML	Mediolateral
ML	Movement length
MSC	Magnitude squared coherence
MSI	Multisensory integration
MT	Movement time
MVT	Maximum voluntary finger force/torque
NJ	Normalised jerk
NT	No touch
PA	Physical activity
PAC	Preferences of Activities for Children
PANESS	Physical and Neurological Examination for Soft Signs
PAQ-C	Physical Activity Questionnaire for Children
PE	positional error

PICOS	Population, Intervention, Comparison, Outcomes, and Study type
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
PROSPERO	International prospective register of systematic reviews
pSW	Positive short wave
RD	Radial diffusivity
RMS	Root mean square
RMSE	Root mean square error
RMT	Rhythmic Movement Test
RQ	Romberg’s quotient
RT	Reaction time
RTCP	Relative time spent in the corrective phase
S1	Encoding phase
S2	Recognition period
SC	Superior sulcus
SDPE	Standard deviation of position error
SOA	Stimulus onset asynchrony
SP	Sensory processing
SP2	Short Sensory Profile2
SPSS	Statistical Package for Social Sciences
TBW	Temporal binding window
TD	Typically developing
Tdrive	Haptic inputs
TPJ	Temporo-parietal junction
TTPV	Time to reach peak velocity
TV	Tracking variability
V	Visual
Var IDE	variability of the IDE
Vdrive	Visual inputs
Vi	Variation index
WISC	Wechsler Intelligence Scale for Children

WJPEBR	Woodcock–Johnson Psycho-Educational Battery-Revised

Chapter 1 Introduction

Coordinated and goal-directed movements are produced in response to sensory processing (SP) of various sensory inputs received from the environment and body (Critz et al., 2015; Fabre et al., 2020). Sensory inputs inform the brain of environmental and task requirements and, hence, guide a movement along its execution (Utley and Astill, 2008). For example, when catching a ball, an internal representation of the body relative to the world and to the ball is primarily formulated and updated in the brain based on SP of the received sensory inputs (Utley and Astill, 2008). Therefore, SP is important for a movement to be produced, enhanced and adjusted in satisfaction and adaptation to environmental demands (Murray and Wallace, 2011; Murray et al., 2019).

SP consists of a dynamic interaction of several cortical stages (Conner et al., 2021) (see Figure 1.1). The first stage comprises *receiving* sensory inputs from various sensory sources such as vision, audition, and tactile (Prochazka and Ellaway, 2012). The second and third stages of SP include *regulating* and *modulating* the received sensory inputs in the brain through the central nervous system (CNS) (Murray and Wallace, 2011; Jorquera-Cabrera et al., 2017). These stages involve discriminating the inputs and organising their intensity in the brain according to their relevance for a task or saliency (Dunn, 1997; Niutanen et al., 2020). Modulation of sensory inputs also refers to the interpretation of the received sensory inputs and determining their characteristics (e.g., a heavy ball) (Galiana-Simal et al., 2020).

Directed by modulation and regulation of sensory inputs, an appropriate perceptual decision is formed leading to the final stage of SP which consists of *executing* behavioural responses that can be generated via movements (Engel-Yeger et al., 2011; Seilheimer et al., 2014). Sensory information are then further compared in the brain with the executed movement for adjustments and enhancements of the movement so it becomes coordinated and meaningful (e.g., efficiently catching a ball and maintaining a grasp on the ball) (Utley and Astill, 2008).

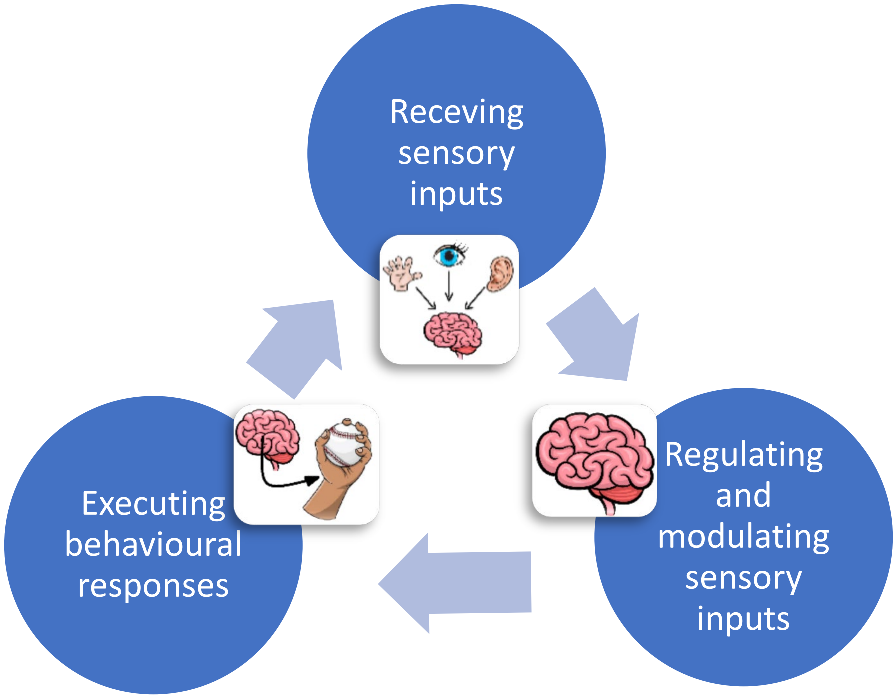


Figure 1.1 Sensory processing involves several cortical stages: sensory inputs are first received by sensory receptors located in various parts of the body such as the eyes (vision), ears (auditory), and skin (tactile). Regulation and modulation of sensory inputs then take place through the central nervous system. Accordingly, a behavioural response is then executed which can be expressed via movement.

Because SP and motor control are believed to interact closely, malfunction in any of these stages is reported in the empirical literature to lead to maladaptive behavioural responses and problems in motor learning which are highly likely to result in movement difficulties (Gal et al., 2010). Movement difficulties, in turn, may affect a person's performance of activities of daily living (ADLs) and participation (Cosbey et al., 2010; Engel-Yeger and Ziv-On, 2011). Dunn (1997) indicates that problems with movement control and motor abilities attributable to deficits in SP are most likely to be due to poor modulation of sensory inputs. Such problems are core deficits of several neurodevelopmental disorders (Critz et al., 2015) including developmental coordination disorder (DCD) (Grove and Lazarus, 2007; Allen and Casey, 2017).

DCD is one of the most prevalent disorders affecting 5-6% of children (King-Dowling et al., 2019; Sit et al., 2019; Delgado-Lobete et al., 2020). Slow and uncoordinated movements are main features of DCD (Schott et al., 2007) which are suggested to lead to delays in developmental milestones (Schott et al., 2007) as well as difficulties in performing ADLs (King et al., 2011; Lingam et al., 2009). However, the mechanism behind movement difficulties in DCD is not yet well understood and cannot be better explained by specific diagnoses (Blank et al., 2019).

Empirical studies indicate that movement difficulties and, hence, low participation levels among children with DCD may be attributed to SP difficulties (Grove and Lazarus, 2007; Allen and Casey, 2017; Delgado-Lobete et al., 2020). Inefficient and slow SP have been reported in studies investigating brain activity while children perform a task (Tsai et al., 2009a; Tsai et al., 2010; Tsai et al., 2012b) and, hence, may account for the slow and atypical movements exhibited by children with DCD (Williams et al., 2008; Fong et al., 2016). Inefficient SP may also explain why motor difficulties are more pronounced with task difficulty in DCD (Elders et al., 2009; Tsai et al., 2012a; Adams et al., 2016; Wade et al., 2016) which could be due to the task requirements exceeding the cognitive capacity for efficient SP and maintaining attention (Wann et al., 1998; Kagerer et al., 2006; Tsai et al., 2009b).

Deficits in visual perception and visuospatial processing which are reported to significantly contribute to movement control and motor learning are also suggested to be most affected in DCD (Wilson and McKenzie, 1998), resulting in problems in motor learning and planning (Wann et al., 1998; Van Waelvelde et al., 2004; Williams et al., 2008; Chen and Wu, 2013; Adams et al., 2016; Debrabant et al., 2016). Other deficits reported in the empirical literature relate to proprioception and tactile processing (Zoia et al., 2002; Wade et al., 2016) as well as kinaesthetic perception (Tseng et al., 2018; Tseng et al., 2019b) in DCD which are also indicated to affect motor coordination (Tran et al., 2022). However, despite all of these indications, a recent review to synthesise the findings of experimental studies regarding the role of SP on motor abilities among children with DCD is yet to be established.

A basic element of movement skill development and motor control is the continuous interaction between the body and the environment (Sugden and Chambers, 2005; Fabre et al., 2020). Sensory inputs received from the environment and body inform the brain about the body position in relation to space and about the force and torque requirements for muscles and joints, respectively, to execute a coordinated movement (Gal et al., 2010). Experiencing and responding to sensory inputs may vary between individuals, resulting in different behavioural outcomes (Dunn, 2007; Murray et al., 2019). Individuals with high neurological thresholds are reported to be slow to detect sensory stimuli, whereas individuals with low thresholds are indicated to be quick to detect sensory stimuli (Dunn, 2014). Moreover, the response to sensory stimuli is suggested to differ between individuals with some relying on passive self-regulation strategies (do not always take action in response to surrounding sensory stimuli), while others rely on active self-regulation strategies (usually reactive to surrounding sensory stimuli) (Dunn, 2014). Dunn (2007) suggested that the two continua (neurological thresholds and self-regulation) interact to form different SP patterns. Each person has a predominant SP pattern that may predict their movement abilities and, hence, participation preferences and behavioural responses (Engel-Yeger, 2008; Ismael et al., 2015; Dunn et al., 2016). The empirical literature is replete with studies confirming the relationship between movement abilities and levels of PA and participation among typically developing (TD) children but there is a paucity of research that has considered the contribution of SP abilities.

Multisensory integration (MSI) entails combining various sensory inputs to form a unified picture of the environment and produce coordinated movement and goal-directed behaviour accordingly (Miller et al., 2009; Evans and Treisman, 2010; Murray and Wallace, 2011; Talsma, 2015). It is well established in the empirical literature that MSI of stimuli that are spatially and temporally congruent results in enhanced cognitive processing such as perceptual decision-making and, hence, improved behavioural performance (Miller et al., 2009). Despite this, limited research has investigated how MSI can enhance perceptual decision-making among TD children and how this may differ between various age groups to identify the developmental trajectory of this cognitive process through childhood.

It is necessary to understand the role of SP on movement abilities to be able to identify the reasons behind motor difficulties and problems with participation in various neurodevelopmental disorders including DCD. Therefore, the aim of the first study of this thesis is to identify and summarise the role of SP on movement abilities among children with DCD. The second study aims to explore the relationship between SP abilities, movement control, levels of and preferences for PA. The third study, on the other hand, aims to investigate the effect of multisensory versus unisensory stimuli on two elements contributing to perceptual decision-making (reaction time (RT) and accuracy).

Chapter 2 Literature review

2.1 Introduction

This chapter provides information about SP including the different stages encountered by the process, the various sensory systems involved, and their relationship with movement abilities. Particular attention is paid to the process of multisensory integration and its effect on perceptual decision-making and behaviour. The consequences and symptoms of atypical SP are then discussed and a section draws upon the commonly used outcome measures. Subsequently, the role of SP on movement abilities among children with neurodevelopmental disorders is presented. Finally, the chapter concludes with a summary of the findings of the empirical literature and the gap in the empirical literature is identified.

2.2 Sensory processing and movement

The ability of an individual to detect and process sensory stimuli is critical to perform ADLs (Allen and Casey, 2017). SP refers to the cognitive capacity to receive sensory inputs from the body and environment, regulate and modulate them, and provide a behavioural response accordingly (Engel-Yeger and Dunn, 2011; Jorquera-Cabrera et al., 2017). Receiving sensory inputs takes place through interoceptors and exteroceptors (Utley and Astill, 2008). To detect the motion of the body, sense muscle stretch and body position, and calculate force required to produce a coordinated movement, proprioception and vestibular sensory inputs are received through various interoceptors including the inner ears, muscle spindles, joint receptors and somatosensory receptors (Prochazka and Ellaway, 2012; Cullen and Zobeiri, 2021). Meanwhile, exteroceptors include visual, auditory, and touch which also receive sensory inputs to sense body position relative to objects or the environment (Griffin, 2012; Prochazka and Ellaway, 2012).

When sensory inputs are received, they need to be accumulated to be detected and noticed by the central nervous system in order to take a response (Dunn, 1997; Groschner et al., 2018). In other words, neurological thresholds within a nerve cell require certain amounts of sensory stimuli for neurons to be triggered and fire an action potential to respond to those sensory stimuli (Krahe and Gabbiani, 2004). Depending on an individual's prior experience and genetics, neurological thresholds for sensory input detection may vary between humans (Dunn, 1997). Individuals with a high neurological threshold are slow to detect and less attentive to surrounding sensory inputs, thus, large amounts of sensory stimuli are required for them to be noticed by such individuals (Dunn, 2014). On the other hand, individuals with a low neurological threshold are quick to detect and more attentive to small amounts of sensory inputs (Dunn, 2014). This has been correlated with brain activity by which sensory sensitivity scores (reflecting sensory detection abilities), as measured using the Sensory Profile (Dunn, 1999), were correlated with brain activity (i.e., low sensitivity scores are associated with low brain activation) (Schauder and Bennetto, 2016).

Studies indicate that the integration and processing of various sensory inputs take place in the superior colliculus (SC) on the posterior midbrain as multisensory neurons have been found in the SC (Wallace et al., 1996). The SC is reported to receive sensory inputs from primary sensory cortices (e.g., visual and auditory) for modulation and regulation of inputs (Gharaei et al., 2020). However, more recent studies reported that SP and integrating various sensory inputs also take place in primary sensory cortices which used to be reported as unisensory areas (Miller et al., 2009; Murray and Wallace, 2011). This may suggest that SP of different sensory inputs takes place early in the processing of sensory information and, therefore, has an immediate influence on behavioural outcomes (Miller et al., 2009; Murray and Wallace, 2011).

The SC is known for its important role in directing behavioural responses in reaction to sensory stimuli (Gharaei et al., 2020). The conversion of sensory signals into behavioural responses can be expressed via controlled movements that occupy environmental demands (Engel-Yeger et al., 2011; Tagliabue and McIntyre, 2014). As such, movement abilities depend largely on SP abilities as they allow a person to develop and learn motor skills and execute coordinated and goal-directed movements (Dunn, 2007). Motor skills and motor learning largely contribute to the performance of various physical activities and participation levels (Shadmehr et al., 2010) which are important for individuals' health, cognitive development and well-being (Brouwer et al., 2019; Lopes et al., 2019).

The empirical literature suggests that individuals differ in terms of their reaction to sensory stimuli (Dunn, 2007; Murray et al., 2019). Individuals who usually react to surrounding sensory inputs, such as moving away from sensory distractors (e.g., noise) to maintain focus, are indicated to use active self-regulation strategies (Dunn, 2014). On the other hand, individuals who are not usually responsive to surrounding sensory stimuli and do not always take actions, such as working in a room without removing sensory distractors (e.g., turning off the TV), are suggested to use passive self-regulation strategies (Dunn, 2014).

Dunn (1997) proposed a SP framework that consists of an interaction between the two continua of dealing with the received sensory inputs: neurological threshold to detect sensory stimuli and self-regulation strategies. The interaction then forms different SP patterns that are reported to reflect individuals' SP abilities and shape their motor abilities, personalities, and preferences for physical activities (PA) (Engel-Yeger, 2008; Ismael et al., 2015; Dunn et al., 2016; Roberts et al., 2018). For instance, an individual with a high neurological threshold and active self-regulation is reported to be seeking large sensory inputs to maintain arousal and satisfaction such as participation in sports activities (Engel-Yeger and Ziv-On, 2011). However, despite this association having been established, little is known about how SP abilities may determine movement abilities among typically developing (TD) children and consequently affect their levels of and preferences for PA.

2.3 Multisensory integration

Multisensory integration (MSI) refers to the ability to combine various sensory inputs (auditory, visual, vestibular, etc.) to form a unified picture representing the body and the environment and accordingly produce coordinated and meaningful movements (Evans and Treisman, 2010; Talsma, 2015). Human behavioural responses are suggested to be directed based on an interconnection between MSI and perceptual decision-making (Bizley et al., 2016; Renton et al., 2021). Therefore, it is well-established in the empirical literature that MSI of inputs that are spatially and temporally aligned results in enhanced perceptual decision-making and, hence, behavioural performance (Barutchu et al., 2011; Parker and Robinson, 2018). These can be observed as faster responses and higher detection rates of sensory inputs (Miller et al., 2009).

However, several factors are suggested to influence the process of MSI and, in turn, affect perceptual decision-making (Seilheimer et al., 2014). The process of attention to select the relevant sensory input to be processed and responded to while ignoring irrelevant inputs is suggested to be a key ‘top down’ element contributing to MSI and decision-making (Miller et al., 2009; Seilheimer et al., 2014; Rungratsameetaweemana and Serences, 2019; Franzen et al., 2020). Attention is also suggested to mature gradually throughout childhood and may continue to do so until adolescence (Lustig and Meck, 2011; Abundis-Gutiérrez et al., 2014).

Some studies indicate that certain sensory modalities (e.g., vision) dominate and attenuate the presence of other sensory inputs when multisensory stimuli are presented, thereby influencing attention (Barnhart et al., 2018). It has been reported that modality dominance changes during development (Barnhart et al., 2018; Parker and Robinson, 2018) with the auditory being dominant in infants, while children aged 6 to 7 years and older tend to shift to visual dominance (Curtindale et al., 2007; Gori et al., 2012; Nava and Pavani, 2013; Barnhart et al., 2018; Broadbent et al., 2018a). However, some ‘bottom-up’ factors that are suggested to be stimulus driven may contribute to the attention to the presented sensory inputs and, hence, influence modality dominance (Shea, 2015). These include the saliency effects of the visual inputs which are believed to be delivered to sensory organs more quickly (i.e., ‘light arrives before sound’) (Murray and Wallace, 2011). Furthermore, the intensity of the sensory input presented, its location, and the duration for which it was presented may affect modality dominance (Gori et al., 2008; Shea, 2015). For instance, more meaningful and intense inputs (e.g., faces) are faster to be detected and processed than simple/familiar visual stimulus (e.g., a flash) (Murray and Wallace, 2011; Talsma, 2015).

Another factor that is suggested to affect attention and, consequently, MSI is the temporal synchrony of sensory stimuli presentation (Gohil et al., 2017). Murray and Wallace (2011) argue that the strength of MSI effects will be optimal if neuronal responses triggered by sensory inputs of different modalities are within a small temporal proximity. A strong body of evidence indicates that this temporal binding window develops gradually among children and does not become fully mature before adolescence (Gori et al. 2008; Nardini et al. 2008; Hillock-Dunn et al. 2016). Given this, the ability to integrate different sensory inputs is suggested to follow a developmental trajectory, as indicated by their behavioural performance in multisensory contexts when compared to adults (Ayres, 1979; Gori et al., 2008; Brandwein et al., 2011; Seilheimer et al., 2014). These differences might be particularly prominent when there is stimulus onset asynchrony (SOA) (i.e., a temporal gap between the presentations of sensory inputs) (Gohil et al., 2017). In accordance with this, studies investigating brain activity indicate that multisensory neurons are not fully mature in young children (Miller et al., 2009).

2.4 Atypical sensory processing

Deficits in SP are indicated to take place in any of the SP stages and, thus, may affect detecting and receiving sensory inputs, modulating or regulating them, or providing responses relative to the sensory inputs (Engel-Yeger et al., 2011). Problems with SP may be presented as a mismatch between environmental demands and the internal representation of the body (Miller et al., 2001). Thus, as SP largely interfere with the production and control of movement, a malfunction in any of the various aspects of SP may result in movement difficulties (Ayres, 2005; Jorquera-Cabrera et al., 2017). The effects of atypical SP may be more prominent in complex movements as they require greater processing of sensory inputs from the environment and body to maintain movement control and stability (Prochazka and Ellaway, 2012).

Although it is indicated that quantifying SP in measurements remains a challenge for researchers (Stevenson et al., 2014; Dieuleveult et al., 2017), a number of outcome measures have been used and reported in the empirical literature to assess SP abilities. SP assessments entail structured behavioural assessments or parent report questionnaires with the Sensory Profile (Dunn, 1999) being most widely utilised in research (Dunn et al., 2016). Symptoms of atypical SP reported in the empirical literature include extreme SP patterns such as being hypersensitive or hyposensitive to the received sensory inputs (Schulz and Stevenson, 2019). These may lead to difficulties performing ADLs and participating in leisure and PA (White et al., 2007). Such SP challenges may appear independently or as a comorbidity to various diagnoses (Critz et al., 2015). The prevalence of SP challenges among children without specific diagnoses ranges from 10% to 55%, while the range of such problems among children with various diagnoses ranges from 40% to 88% (Critz et al., 2015).

One of the neurodevelopmental disorders that is believed to encounter problems with SP is developmental coordination disorder (DCD) (Grove and Lazarus, 2007; Allen and Casey, 2017; Delgado-Lobete et al., 2020; Tran et al., 2022). DCD is a common neurodevelopmental disorder affecting 5-6% of the child population (Smits-Engelsman et al., 2015). Children with DCD may exhibit movement difficulties and motor delay which may have an impact on their physical, social and emotional wellbeing (Zwicker et al., 2018). Understanding the underlying mechanisms of DCD is of great importance to better model assessments and treatments and prevent secondary complications.

2.5 Conclusion

SP consists of several stages including receiving various sensor inputs, modulating and regulating them, and providing a behavioural response accordingly. Behavioural responses can be expressed via movements to occupy environmental demands. Movement abilities are the basic elements for performing any physical activity and participation and leisure activities. For a coordinated and meaningful movement to take place, an interplay occurs between MSI and perceptual decision-making. A dysfunction in any of the SP stages can lead to various difficulties. The consequences of problems with SP are indicated to be presented as movement difficulties which are the core deficits of several neurodevelopmental disorders such as DCD.

The primary aim of this thesis was to explore the role of SP on perceptual decision-making, movement control and participation among children. The first study identifies and summarises the role of SP on movement abilities among children with movement difficulties, particularly DCD. This is due to the empirical literature being replete with studies measuring the role of SP on movement among children with DCD whilst there are no recent systematic reviews summarising the findings that have been published. Moreover, the second study of this thesis explores the relationship between SP abilities, movement control, levels of and preferences for PA. This was sought to build on previous research which investigated the relationship between movement skills and levels of PA and participation among TD children but overlooked SP abilities. It is imperative to understand the attributes of movement abilities and the factors leading to low and high levels of PA among TD children as this may predict the level of PA in adulthood. In addition, exploring how SP abilities interfere with movement skills and levels of participation and PA may help to recognise the mechanism behind movement difficulties and low participation levels among various neurodevelopmental disorders such as DCD. Furthermore, to better understand children's behavioural responses and identify potential advantages to maturing sensory systems, the third study investigates the effect of multisensory versus unisensory inputs on two elements contributing to perceptual decision-making (RT and accuracy). This investigation involved older and younger children as there is limited research in the empirical literature measuring how MSI contributes to decision-making among TD children and the trajectory of the development of this interaction remains unclear.

Chapter 3 Study one: Systematic review of the effect of sensory processing on movement in children with DCD

3.1 Introduction

3.1.1 Background

As established in previous chapters, SP involves receiving and interpreting sensory inputs derived from various sensory modalities, such as vision, haptic, auditory and proprioception (Miller et al., 2009). It consists of several stages including the ability to detect sensory stimuli, regulate and interpret them, and provide a behavioural response accordingly (Parker and Robinson, 2018). Several interacting perceptual-motor systems are engaged to process sensory information and produce a coordinated motoric reaction (Utley and Astill, 2008). Thus, SP plays a significant role in determining the ability to learn new motor skills and control a movement.

According to the DSM-V, DCD is characterised by motor difficulties occurring at an early developmental stage and leading to behavioural, social and academic problems (APA, 2013; Wilson et al., 2017b). These motor difficulties are not attributed to any other known medical condition (APA, 2013). Given that the aetiology of DCD is not yet understood (van Hoorn et al., 2020) it has been suggested that deficits in SP might account for the delay in motor abilities among children with DCD (Allen and Casey, 2017). A relationship between SP deficits and neurodevelopmental disorders has previously been noted (Ayres and Robbins, 2005; Beyer et al., 2019) and is consistently reported in the research concerning DCD (Wilson and McKenzie, 1998; Sugden and Chambers, 2005; Elbasan et al., 2012). Studies that have investigated the neurophysiology of perceptuomotor deficits in DCD suggest that it may be due to atypical activity patterns in brain regions or reduced connectivity between somatosensory motor areas (Gomez and Sirigu, 2015).

While many studies have sought to measure the effect of the different aspects of SP on the ability of children with DCD to produce task specific movement, these studies differed in their aims and, hence, the methods employed to explore the role of SP are diverse. Studies that aimed to investigate visual and kinaesthetic processing among children with DCD indicate that visuospatial processing is largely compromised in DCD and, thus, these disruptions explain the difficulties evidenced in terms of their motor abilities (Adams et al., 2014). Such deficits can be presented as disturbances in motor programming and motor control mechanisms, such as feedforward and feedback control, in addition to deficits in executive functioning and internal modelling (Adams et al., 2014; Ferguson et al., 2015). Further difficulties related to SP were reported regarding the ability of children with DCD to integrate multisensory information (Delgado-Lobete et al., 2020) which is suggested to contribute to their motor performance. With the majority of studies exploring the effects of visual stimuli combined with other sensory modalities, atypical motoric responses to adapt to changes in the simultaneous presentation of various sensory stimuli were reported among children with DCD (Bair et al., 2012; Wade et al., 2016).

Nevertheless, some researchers found that perceptuomotor skills in children with DCD tend to improve as the children grow older (Zoia et al., 2002; de Castelnau et al., 2007), and that the difference between DCD and TD children gets smaller with chronological age. Other studies have indicated that difficulties in perceptuomotor abilities experienced among children with DCD are evidenced to be associated with task complexity such as increased constraints and cognitive involvement (de Castelnau et al., 2008; Schott et al., 2016).

Despite the plentiful literature concerning the effect of SP on movement skills and motor control among children with DCD, a recent coherent synthesis evaluating the quality of the existing literature has yet to be established. Therefore, the aim of the current review is to identify and summarise the role of SP on movement abilities among children with DCD. Understanding the impact of SP on the behavioural and motoric responses of children with DCD will hopefully help to recognise the mechanisms behind DCD and, hence, better diagnose and tailor treatment programmes. It was hypothesised that the various dimensions of SP, such as visuospatial, kinaesthetic and proprioception processing, have a significant effect on movement abilities among children with DCD.

3.1.2 Review question

What is the role of sensory processing on movement abilities in children with DCD?

3.2 Methods

The guidelines recommended by the Centre of Reviews and Dissemination (2009) were followed when compiling this literature review. The protocol of the systematic review was registered in the international prospective register of systematic reviews (PROSPERO) with the registration number CRD42020193264.

3.2.1 Search strategy

A pilot search, with the following search terms: sensory processing, children, developmental coordination disorder, DCD, was conducted in May 2020 using the PubMed database to search the evidence base to focus the review question and the inclusion and exclusion criteria. Consequently, a search protocol was written and agreed upon by the research team members which included the finalised research question and the search strategy that was to be used.

The PICOS framework (population, intervention, comparison, outcomes, and study type) (Moher et al., 2009) was modified and used to identify the review question. The population was defined as children aged between 5-12 years; the intervention (modified to interest) as DCD (and other forms of the term; see below); comparison was defined as DCD compared to TD children; outcomes as motoric performance; and study type defined as observational case-controlled studies. The inclusion and exclusion criteria are discussed in a later section below.

A formal search was conducted in May 2020 to first check and ensure a similar review had not previously been published and then to look for and include relevant studies (see table 3.1 for search terms used). The search was run using the following databases: CINAHL, EBSCOhost, Cochrane, Ovid/PsychINFO, PubMed/Medline, Scopus, PsychARTICLES, PEDRO, and ERIC (EMBASE). These databases were selected because they deal with various aspects of research concerning movement in children and DCD. The search was modified to suit each database according to their specific requirements (see Table 3.1).

It was recommended by the recent international clinical practice guidelines of DCD to use the term ‘DCD’ or ‘developmental coordination disorder’ in research publications (Blank et al., 2019). This name was officially given to the disorder following the London Consensus (1994) (Polatajko et al., 1995)(Polatajko et al., 1995). Therefore, the search terms used were as follows (with the Boolean operator to combine them): developmental coordination disorder*, 'OR' developmental co-ordination disorder*, 'OR' DCD, 'AND' sensory, 'OR' multisensory, 'OR' multi-sensory, 'AND' children, 'NOT' donation. The term 'donation' was excluded from the search because many of the studies found in the preliminary search dealt with donation, especially 'donation after cardiac death (DCD).'

Table 3.9: Search strategy summary and findings of databases

Research question	The effect of sensory processing on movement in children with DCD		
Information sources	CINAHL, EBSCOhost, Cochrane, Ovid/PsychINFO, PubMed/Medline, Scopus, PsychARTICLES, PEDro, ERIC (EMBASE)		
Search terms used for all the databases with the use of Boolean operators: children [Abstract/ Title] AND DCD [Abstract/ Title] OR developmental coordination disorder* [Abstract/ Title] OR developmental co-ordination disorder [Abstract/ Title] AND sensory [Abstract/ Title] OR multisensory [Abstract/ Title] OR multi-sensory [Abstract/ Title] NOT donation [all text]			
Date of search	**Information sources**	**Search strategy**	**Search hits**
28.05.2020	**CINAHL**	Limited to English , journal articles, humans, age group 2-12 years, include related words to search terms, publication year 1995-2020	**540**
28.05.2020	**Cochrane**	Limited to publication year 1995-2020	**29**
29.05.2020	**ERIC (EMBASE)**	Limited to English, journal articles, age group 1-12 years, publication year 1995-2020	**50**
29.05.2020	**AMED**	Limited to publication year 1995-2020	**14**
29.05.2020	**Medline (Ovid)**	Limited to English, humans, age group 0-18 years, publication year 1995-2020	**53**
29.05.2020	**PsycINFO**	Limited to English, humans, age group 0-12 years, publication year 1995-2020	**47**

29.05.2020	**PubMed**	Limited to English, humans, age group 0-18 years, publication year 1995-2020	**757**
29.05.2020	**Scopus**	Limited to English, publication year 1995-2020	**126**
29.05.2020	**PEDro**	Limited to peadiatrics, publication year (since 1995)	**44**

Moreover, Google Scholar was also utilised to search for further relevant studies. In addition, a citation chain of *backward* and *forward* searching was conducted which involved going through the references of key papers and looking into the studies that have cited these papers (Boland et al., 2017).

3.2.2 Inclusion and exclusion criteria

Due to the limited resources available for translation, only English language journal articles were included. The publication year of the selected studies was limited to those published between 1995 and 2020, following the London Consensus Statement (1994) in the diagnosis of DCD. In addition, the target population of this review was children with DCD between the ages of 5-12 years. This aligns with the developmental changes in sensory processing, executive function and motor skills that take place within this age range as noted in Chapter Two. Furthermore, the minimum age of 5 years was chosen because that is the youngest age at which it is recommended to give an official diagnosis of DCD (Blank et al., 2019). Moreover, only studies involving age-matched TD children as the control group were included to ensure that valid comparisons and interpretations were reached in the selected studies (Portney and Watkins, 2009).

Studies indicate that using different assessment tools to diagnose children with DCD might result in different scores and, hence, different diagnoses (Lee et al., 2019). To achieve comparable outcomes from the selected articles, the review team members agreed to include only studies that used the movement assessment battery for children (M-ABC) (Henderson and Sugden, 1992) and its second version (M-ABC2) (Henderson et al., 2007) to diagnose DCD, given these are the ‘gold standard' tools recommended to identify a DCD (see Chapter Two).

Additionally, in accordance with the Leeds Consensus Statement (2006) recommendations, the inclusion of articles was limited to those using a ≤ 5^{th} percentile cut-off of the overall performance score for the diagnostic test (M-ABCs) to identify participants with DCD. Furthermore, because motor difficulties are considered a significant problem in DCD (Wilson et al., 2012), only studies measuring the effect of SP on movement performance were included. Finally, only observational case-control studies were included in order to draw meaningful comparisons using the objective data provided by the selected studies.

3.2.3 Study selection

After searching all of the relevant databases, each of the articles found was exported to EndNote X9 library to remove duplicates. The titles and abstracts were then screened as the first step to exclude studies that were deemed irrelevant. Next, the eligibility of the remaining studies was tested by reading the full text, and, hence, excluding the irrelevant ones. A summary of the screening process is demonstrated in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Page et al., 2021) figure below (see Figure 3.1).

3.2.4 Data extraction

Relevant data from each of the included studies were presented in tables alongside a narrative synthesis of the findings. The descriptive and analytical data extracted from the studies included the following: the authors, year and country of publication, age range and gender of the participants, sample size, inclusion criteria to diagnose DCD, study paradigm and type of sensory stimuli being employed, outcome measures used, and the results of the studies.

3.2.5 Categorising the studies

The studies were categorised into groups based on their primary objectives, the outcome measures used, and the type of sensory stimulus involved in the experiment. The categories were adopted from Wilson and McKenzie (1998) and modified to suit the research question of the current review. There were four main categories: (i) visual processing, (ii) perceptual processing, (iii) motor control, and (iv) motor skill.

The first category (visual processing) included studies that sought to measure visuospatial skills in children with DCD. In other words, visual stimuli were manipulated in different spatial settings and behavioural responses were measured accordingly. The second category (perceptual processing) had two subcategories: (a) kinaesthetic perception and (b) cross-modal perception. The first subcategory (kinaesthetic perception) involved measuring the perception of limb movement and limb position in response to various sensory environments, whilst the second subcategory (cross-modal perception) involved measuring movement abilities with regard to integrating sensory stimuli presented through different modalities.

In the third category (motor control), movement planning and executive function were measured in response to different contexts involving sensory inputs. This category was also divided into two subcategories: (a) chronometrics and (b) kinematics. The chronometrics subcategory involved measuring motor programming parameters and cognitive performance such as reaction times, movement times and selection accuracy. Meanwhile, the kinematics subcategory involved measuring the spatiotemporal features of movement such as speed, trajectory, movement accuracy and variability. Finally, the motor skill category entailed using standardised motor assessment tools in different sensory environments. Figure 3.2 illustrates the categories and subcategories of the studies.

3.2.6 Quality assessment

The quality assessment tool was initially approved by the three members of the review team using the Downs and Black (D&B) (Downs and Black, 1998). This was agreed upon because the tool has been widely used in the empirical research and has been reported as being suitable for quantitative studies (Feast et al., 2016; Harris-Fry et al., 2017; Smith et al., 2019). In addition, it has the same item criteria when used for different study designs (Hootman et al., 2011) making it easier to be employed.

Two of the review team members (SS and LB) piloted the use of the D&B tool and the quality assessment was undertaken on three of the included studies. Consequently, the review team discussed the outcome and agreed that many of the questions provided in the D&B assessment tool needed to be amended to suit the designs and methods of the studies included. For instance, several questions in the D&B focus on controlling for confounding factors that may affect the outcome of an intervention such as the duration of the training/treatment programme, which is not applicable to the studies included in the current review as they were mostly case-control studies.

As a result, the review team suggested piloting the use of the critical appraisal skills programme (CASP) (CASP, 2018) tool for quality assessment. The CASP tool has a variety of checklists to suit different study designs (Purssell, 2019) that could help to identify the strengths and weaknesses of the study (Voss and Rehfuess, 2013). Moreover, unlike some alternative tools, the CASP is reported to assess the generalisability of studies (Hannes et al., 2010) which is considered advantageous for researchers and clinicians.

The quality assessment process was repeated for the three selected articles using the CASP assessment tool and the outcome revealed that CASP is better suited to the designs of the articles included in this systematic review. A specifically designed study checklist for case-controlled studies was used that included questions that were applicable to the study design of the articles included in this review, which primarily focused on assessing the validity and generalisability of the results.

Eleven questions were included in CASP and divided into three sections; the first and second sections assess the validity and reliability of the results, respectively, whilst the third measures the generalisability of the outcome. Choices of answers of ‘yes’, ‘no’, and ‘can’t tell’ are given to all the questions in the checklist, except questions 7,8, and 9. However, similar to other reviews (Shanks et al., 2010; Wilson et al., 2017b), the CASP was modified and specific scores were given to the answers in the checklist; ‘yes’ and ‘no’ were given scores of 2 and 0, respectively, whereas ‘can’t tell’ was given a score of 1. This was also applied to questions 7, 8 and 9 in which choices of answers were not provided. In addition, after piloting the use of CASP, the team members agreed to combine the two sub-sections (6.a and 6.b) of question six as one question exploring the effect of confounding factors on the study results, because similar responses were reported for the two sub-sections. This was also applied in previous research (Wilson et al., 2017b). Moreover, a grading system adapted from previous research (Wilson et al., 2017b) was employed in the current review to offer a scale of: ‘low’ for total scores below 11; ‘moderate’ for total scores between 12 and 18; and ‘high’ for total scores between 19 and 22.

Subsequently, the methodological quality of the remaining articles was assessed independently by two members of the review team (SS and LB) using the CASP assessment tool, scoring and grading system. Cohen's Kappa coefficient was then calculated, using windows Statistical Package for Social Sciences (SPSS) version 28 (SPSS Inc., Chicago, Illinois), to measure the inter-rater reliability, which is the agreement between the two raters' CASP scores for all of the studies (Landis and Koch, 1977). As Landis and Koch (1977) suggest, a Kappa value above 80% represents an 'excellent' level of agreement, above 60% represents a 'substantial' level, between 40-60% represents a 'moderate' level, and below 40% is for a 'poor' level of agreement. Furthermore, when disagreements occurred during the quality assessment process, a consultation with a third team member (SA) was conducted until a consensus was reached.

3.2.7 Data analysis/synthesis

Because the studies were heterogeneous in the methods employed, a quantitative meta-analysis was unsuitable, and the studies were categorised to help in reaching a meaningful analysis. As a result, a narrative synthesis was applied to analyse the results of the studies.

3.3 Results

3.3.1 Study selection

The preliminary literature search identified 1,660 studies from the nine selected databases. After exporting the articles into EndNote and removing 428 duplicates, the titles and the abstract of the remaining studies were screened against the inclusion criteria which resulted in 1,114 irrelevant studies being excluded. Then the full text of 118 studies was screened for possible inclusion in the systematic review. Of these, 85 were excluded, mainly due to the use of outcome measures other than M-ABC or the use of a cut-off total score above the 5th percentile to identify participants with DCD (see figure 3.1). In addition, 17 relevant articles were added from sources other than the databases such as Google Scholar and hand searching, which led to a final number of 46 studies to be included in the systematic review.

The study selection process alongside the different reasons for exclusion are specified in the PRISMA (Page et al., 2021) figure below (see Figure 3.1).

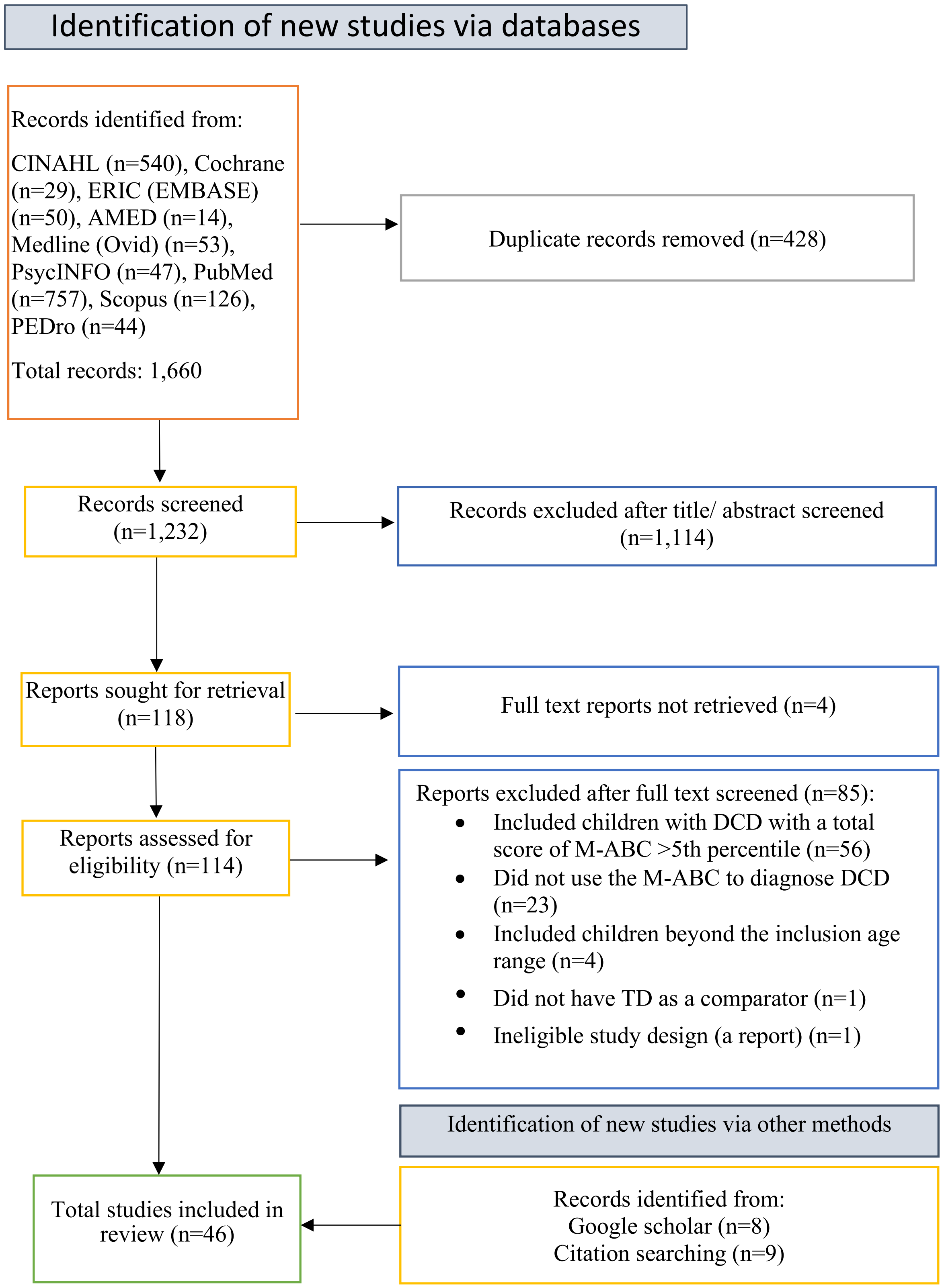


Figure 3.1 PRISMA study selection flowchart (Page et al., 2021)

3.3.2 Study characteristics

The characteristics and findings of the articles are presented in the sections below for each category including the study design and setting, authors and year of publication, sample size, age range and gender of the participants, the inclusion criteria of the DCD group, and the obtained score for methodological quality. The study paradigms of the articles were then discussed considering the type of sensory stimuli employed and the outcome measures used. After that, the results of the studies were illustrated, and a summary of the findings is included below each category.

Based on the primary objectives of the articles, along with the outcome measures and type of sensory stimulus involved, sixteen studies were included in the visual processing category, whereas three and six studies were included in the subcategories kinaesthetic and cross-modal of the perceptual processing category, respectively. Moreover, three and five studies were included in the chronometrics and kinematics subcategories of the motor control category, respectively, and thirteen studies were included in the motor skills category (see Figure 3.2).

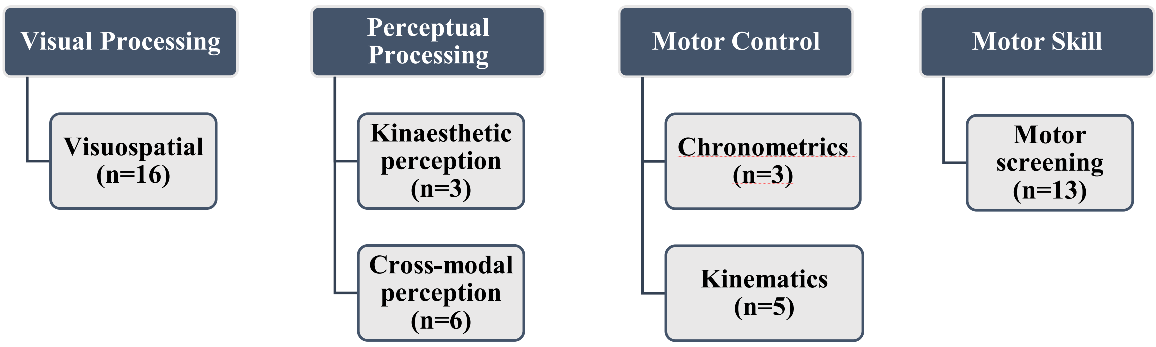


Figure 3.2 Categorising of studies adapted from Wilson and McKenzie (1998).

All of the studies were observational case-control studies except for those of Bonney et al. (2017), Diz et al. (2018), Smits-Engelsman et al. (2015), Tsai (2009), and Tsai et al. (2012b) in which an experimental study design was employed and sensory processing effects on movement were measured before and after a specific training period. However, to focus on the question posed in the current review, we were only interested in analysing the pre-intervention data. In addition, the setting of the included studies ranged from 39% based in Taiwan, 13% in the US, 11% in South Africa, 11% in Belgium, 7% in the UK, 4% in Italy, 4% in Canada, and 2% in each of Korea, Australia, Brazil, Hong Kong, and Denmark. The sample size of the included studies ranged from 6 to 66 participants with a mean of 26 in the DCD group and 6 to 105 participants with a mean of 31 in the TD group. The age range of the participants was 5-12 years for the DCD group and 4-12 years for the TD, with a mean age of 9 years for both groups. Moreover, the proportion of male to female participants was 57% in the DCD group and 55% in the TD.

3.3.3 Methodological quality

The inter-rater agreement between the assessors evaluating the methodological quality was found to be 'substantial' (Cohen's Kappa: 0.726) as calculated using CASP scores for all of the included studies. This indicates that 73% of agreement was achieved between the assessors (Landis and Koch, 1977; McHugh, 2012) The results for the CASP scores for methodological quality are presented in Table 3.2. The mean score for the methodological quality of all the studies was 20 (high level).

Table 3.2: CASP scores of included studies

	Q.1	Q.2	Q.3	Q.4	Q.5	Q.6	Q.7	Q.8	Q.9	Q.10	Q.11	Total
Adams et al. (2016)	Yes	Yes	Yes	Yes	Yes	Can't tell	Can't tell	Yes	Yes	Can't tell	Yes	19
Bair et al. (2012)	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Can't tell	Yes	Can't tell	Can't tell	18
Biancotto et al. (2011)	Yes	Yes	Can't tell	Yes	Can't tell	No	Yes	Yes	Yes	Can't tell	Yes	17
Bo et al. (2008)	Yes	Yes	Can't tell	Yes	Yes	Can't tell	Yes	Yes	Yes	Can't tell	Yes	19
Bonney et al. (2017)	Yes	Yes	Yes	Yes	Can't tell	No	Can't tell	Can't tell	Yes	yes	Can't tell	16
Chen et al. (2019)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Chen and Tsai (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Chen et al. (2015)	Yes	Yes	Can't tell	Yes	Yes	Can't tell	Yes	Yes	Yes	Can't tell	Yes	19
Chen and Wu (2013)	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	Yes	21
Chen et al. (2011)	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Can't tell	Yes	Yes	Can’t tell	19

Chen et al. (2012)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Chung and Stoffregen (2011)	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	Can’t tell	Yes	Can't tell	Yes	19
Debrabant et al. (2013)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Debrabant et al. (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Diz et al. (2018)	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	20
Elders et al. (2010)	Yes	Yes	Can't tell	Yes	Yes	Yes	Can't tell	Can't tell	Yes	No	Yes	17
Ferguson et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Can’t tell	Yes	Can’t tell	Yes	20
Fong et al. (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Gheysen et al. (2011)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	20
Kagerer et al. (2006)	Yes	Yes	Can't tell	Can't tell	Yes	Yes	Yes	Can't tell	Yes	No	Yes	17
King et al. (2011)	Yes	Yes	Can't tell	Can't tell	Yes	Yes	Yes	Yes	Yes	No	Yes	18

Mon-Williams et al. (1999)	Yes	Yes	Can't tell	Can't tell	Yes	Yes	Yes	Can't tell	Yes	Can't tell	Yes	18
Przysucha and Taylor (2004)	Yes	Yes	Can't tell	Can't tell	Yes	Can't tell	Yes	Yes	Yes	No	Yes	17
Przysucha et al. (2008)	Yes	Yes	Can't tell	Can't tell	Yes	Can't tell	Yes	Can't tell	Yes	No	Yes	16
Roche et al. (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Can’t tell	Yes	Yes	Yes	21
Sartori et al. (2020)	Yes	Yes	Yes	Can't tell	Can't tell	No	Yes	Can't tell	Yes	Yes	Yes	17
SmitsEnglesman et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Speedtsberg et al. (2017)	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	20
Tsai et al. (2010)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Tsai and Wu (2008)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Tsai (2009)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Tsai et al. (2012a)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22

Tsai et al. (2009a)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Tsai et al. (2009b)	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	Yes	21
Tsai et al. (2012b)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22
Tsai et al. (2008)	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	Yes	21
Tsai et al. (2009c)	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	Yes	21
Tseng et al. (2019a)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	21
Tseng et al. (2018)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	21
Tseng et al. (2019b)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	21
Van Waelvelde et al. (2006)	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	Yes	21
Van Waelvelde et al. (2004)	Yes	Yes	Yes	Yes	Yes	No	Yes	Can’t tell	Yes	Yes	Yes	19
Wade et al. (2016)	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Can't tell	Yes	Yes	Yes	20

Wann et al. (1998)	Yes	Yes	Can't tell	Can't tell	Yes	No	Yes	Can't tell	Yes	No	Yes	15
Williams et al. (2008)	Yes	Yes	Yes	Yes	Yes	Can't tell	Can’t tell	Can’t tell	Yes	Yes	Yes	19
Zoia et al. (2002)	Yes	Yes	Yes	Yes	Yes	No	Yes	Can't tell	Yes	Yes	Yes	19

No: 0; Can’t tell: 1; Yes: 2

3.3.4 Visual processing (visuospatial)

Sixteen studies explored the effect of manipulating the spatiotemporal characteristics of visual stimuli on movement performance, including the Posner paradigm (Tsai, 2009; Tsai et al., 2009a; Tsai et al., 2009c; Tsai et al., 2010; Chen et al., 2012; Tsai et al., 2012b), prism adaptation (Kagerer et al., 2006), the 'moving room' paradigm (Wann et al., 1998; Chung and Stoffregen, 2011) and other validated visuospatial attentional (Gheysen et al., 2011; Tsai et al., 2012a) and motor imagery (Williams et al., 2008) tasks. Further studies included in this category used real objects employed as visual stimuli and manipulated them spatially to assess visuospatial processing (Van Waelvelde et al., 2004; Chen et al., 2013; Adams et al., 2016; Debrabant et al., 2016). This category included fourteen studies with a 'high' level of methodological quality and two of a 'moderate' level (see Table 3.3).

Study sample

- Sample characteristics

None of the studies included in this category conducted a *priori* sample size calculation and the sample size ranged from 6-66 participants (see Table 3.3). In addition, all of the studies involved participants from a broad distribution (different clinical and educational settings), thereby helping to reach a more representative sample (Portney and Watkins, 2009), except for the studies of Adams et al. (2016), Chen et al. (2013), Chen et al. (2012), and Wann et al. (1998), in which the participants were recruited from one setting. The study by Tsai et al. (2012a), on the other hand, did not mention the recruitment setting. Moreover, a gender imbalance was evident in several studies by which the ratio of boys to girls ranged from 2:1 to 9:1 (see Table 3.3).

- DCD eligibility criteria

The DSM criteria were explicitly reported to be followed by Adams et al. (2016) (followed the DSM -V) and by Tsai et al. (2010) (followed the DSM-IV), however, the methods used to confirm the criteria were not reported in Tsai et al. (2010). Of the DSM-V, criterion A was fulfilled by all of the studies by which the motor assessments of the M-ABC1 or MABC2 were used to identify movement problems and only children with an overall of $\leq 5^{th}$ percentile were included. In addition, Tsai et al. (2009a) used both the M-ABC1 and Bruininks-Oseretsky Test of Motor Proficiency, second edition (BOT-2-SF) (Bruininks and Bruininks, 2005) to confirm motor difficulties.

Criterion B was fulfilled by five studies by which parents' and/or teachers' reports or the M-ABC2 checklist were used to confirm the impact of motor difficulties on activities of daily living (ADLs) and academic performance (Tsai, 2009; Gheysen et al., 2011; Tsai et al., 2012b; Adams et al., 2016; Debrabant et al., 2016) (see Table 3.3). Meanwhile, criterion C was only fulfilled by Adams et al. (2016) by indicating that some participants recruited in their study were as young as 6 years of age, which presumably indicates that DCD symptoms appeared at an early developmental stage. However, the onset of DCD symptoms among the older age group of the recruited children was not referred to.

The majority of the included studies met criterion D by using various methods (see Table 3.3) to screen the participants against any neurological problems (Williams et al., 2008), intellectual problems (Chen et al., 2013) or both (Wann et al., 1998; Van Waelvelde et al., 2004; Kagerer et al., 2006; Tsai, 2009; Tsai et al., 2009a; Tsai et al., 2009c; Tsai et al., 2010; Gheysen et al., 2011; Chen et al., 2012; Tsai et al., 2012a; Tsai et al., 2012b; Adams et al., 2016; Debrabant et al., 2016). The only exception was the study by Chung et al. (2011) which did not report the assessment of such problems.

- Confounding factors

Given that the heterogeneity of DCD is reported in the empirical literature (Sugden, 2007), controlling for differences in individual characteristics could be imperative to aid in reaching a valid outcome. Therefore, to reduce the heterogeneity of the included participants, some studies mentioned that there was no statistically significant difference in terms of the individual characteristics among the participants (such as age, gender, weight, height, body mass index (BMI) and intelligence quotient (IQ)) between both the TD and the DCD groups (Tsai et al., 2009a; Tsai et al., 2009c; Tsai et al., 2010; Gheysen et al., 2011; Chen et al., 2012; Tsai et al., 2012a; Tsai et al., 2012b; Chen et al., 2013; Debrabant et al., 2016). In addition, to further control for extraneous confounding factors, all the studies in this category involved a control group of a similar age as the DCD group, with less than six-months difference between the groups. Moreover, because Tsai et al. (2012a) were interested in measuring the neurophysiology behind task performance, and as handedness is reportedly associated with cerebellar asymmetry and brain lateralisation (Annett, 2013), the authors of Tsai et al. (2012a) ensured that both the TD and DCD group were right-handed to help reach matched groups and reliable results.

The co-occurrence of ADHD and DCD is highly evidenced in the empirical literature (Blank et al., 2019). Additionally, children with DCD alone are likely to perform differently than when combined with ADHD (Alloway, 2011; Kaiser et al., 2015). Therefore, excluding children presenting with such disorders could help to control internal validity and ensure that motor difficulties are not attributed to other neurodevelopmental disorders, as stated in criterion D of the DSM-V. Thus, participants with ADHD were excluded in several studies in this category using different screening tools. All of the studies by Tsai et al. used the brief behavioural scale based on the DSM-IV (DSM-IV-RS), whereas the ADHD rating scale (ADHD-RS) (DuPaul, Power, Anastopoulos, & Reid, 1998) was used by Chen et al. (2013). Gheysen et al. (2011), on the other hand, did not specify the exclusion criteria used.

Table 3.3: Characteristics and settings of the included studies - visual processing (visuospatial) category

Reference, study design & country	**Sample size & gender**	**Age range (mean±SD)**	**DCD eligibility criteria**	**Quality score**
Adams et al. (2016) Case control South Africa	DCD: 30 20 boys, 10 girls TD: 90 50 boys, 40 girls	DCD: 6-10 years (8.53±1.20) TD: 6-10 years (8.03±1.26)	DSM-V: crit. (A) M-ABC2 ≤5th %tile, crit. (B) teacher report, crit. (C) age range (6-10 years), crit. (D) Parents and teacher report confirms no medical or intellectual problem	19
Chen and Wu (2013) Case control Taiwan	DCD: 24 12 boys, 12 girls TD: 24 12 boys, 12 girls	DCD: 11-12 years (11.22±0.44) TD: 11-12 years (11.43±0.48)	M-ABC2 ≤5th %tile, excluded ADHD using ADHD-RS	21
Chen et al. (2012) Case control Taiwan	DCD: 66 25 boys, 41 girls TD: 36 24 boys, 12 girls	DCD-M: 9-10 years (9.6±0.3) DCD-S: 9-10 years (9.6±0.4) TD: 9-10 years (9.7±0.3)	M-ABC1 ≤5th %tile, excluded neurodevelopmental and intellectual disorders	22
Chung and Stoffregen (2011) Case control Korea	DCD: 10 4 boys, 7 girls TD: 10 6 boys, 3 girls	DCD: 10-11 years (10.4±0.5) TD: 10-11 years (10.9±0.6)	M-ABC1 ≤5th %tile	19
Debrabant et al. (2016) Case control Belgium	DCD: 21 18 boys, 3 girls TD: 20 16 boys, 4 girls	DCD: 8-10 years (9.2±0.10) TD: 8-10 years (9.4±0.7)	M-ABC2 ≤5th %tile, excluded neurodevelopmental disorders by neurological examination, confirmed motor difficulties interference with ADLs and academic performance using M-ABC2-checklist, excluded intellectual difficulties (IQ≤85) using WISC3	22

Gheysen et al. (2011) Case control Belgium	DCD: 18 14 boys, 4 girls TD: 20 12 boys, 8 girls	DCD: 8-12 years (10±1.1) TD: 8-11 years (9.10±1.1)	M-ABC2 ≤5th %tile, excluded intellectual difficulties (IQ>85) using WISC3-short form, excluded ADHD, excluded diagnosed NDD, confirmed motor difficulties interference with ADLs and academic performance	20
Kagerer et al. (2006) Case control USA	DCD: 10 9 boys, 1 girl TD: 10 9 boys, 1 girl	DCD: 6-9 years (8.2±1.5) TD: 7-9 years (8.5±1.1)	MABC1 ≤5th %tile, independent DCD diagnosis by a paediatrician using PANESS, excluded intellectual difficulties using WJPEBR	17
Tsai (2009) Experimental Taiwan	DCD: 27 TD: 16 *Gender NR*	DCD: 9-10 years (9.5±0.3) TD: 9-10 years *Mean age NR*	M-ABC1 ≤5th %tile, excluded neurodevelopmental and intellectual disorders using parent/ teacher report, excluded ADHD using DSM-IV-RS, confirmed motor difficulties interference with ADLs and academic achievement using parents/teacher report	22
Tsai et al. (2009a) Case control Taiwan	DCD: 28 12 boys, 16 girls TD: 26 12 boys, 14 girls	DCD: 9-10 (9.5±0.4) TD: 9-10 (9.5±0.4)	M-ABC1 ≤5th %tile, BOT-2-SF ≤10th, excluded neurodevelopmental disorders, and intellectual disorders (IQ 85-125) using the WISC-R, excluded ADHD using DSM-IV-RS	22
Tsai et al. (2009c) Case control Taiwan	DCD: 36 19 boys, 17 girls TD: 36 19 boys, 17 girls	DCD: 9-10 years (9.9± 0.6) TD: 9-10 years (9.8 ±0.6)	M-ABC1 ≤5th %tile, M-ABC1 (balance sub-test) ≤10th, excluded neurodevelopmental disorders, excluded ADHD using DSM-IV-RS, IQ (within normal) using WISC-R	21
Tsai et al. (2010) Case control Taiwan	DCD: 30 15 boys, 15 girls TD: 30 15 boys, 15 girls	DCD: 9-10 years (9.6±0.4) TD: 9-10 years (9.7±0.2)	DSM-IV (methods not specified), M-ABC1 ≤5th %tile, excluded neurodevelopmental disorders, excluded intellectual difficulties (IQ 85-125) using WISC-R, excluded ADHD using the DSM-IV-RS	22

Tsai et al. (2012a) Case control Taiwan	DCD: 24 12 boys, 12 girls TD: 30 15 boys, 15 girls	DCD: 11-12 years (11.6±0.4) TD: 11-12 years (11.7±0.5)	M-ABC2 ≤5th %tile, excluded neurodevelopmental disorders, excluded intellectual difficulties (IQ 85-115) using WISC-R, excluded ADHD using DSM-IV-RS, only included right-handed using Edinburgh Inventory	22
Tsai et al. (2012b) Experimental Taiwan	DCD: 30 18 boys, 5 girls TD: 21 12 boys, 9 girls	DCD: 9-10 years (9.5±0.37) TD: 9-10 years *Mean NR*	M-ABC1 ≤5th %tile, excluded neurodevelopmental disorders, IQ (within normal range) using WISC, excluded ADHD using DSM-IV-RS, confirmed motor difficulties interference with ADLs using parents and teacher report	22
Van Waelvelde et al. (2004) Case control Belgium	DCD: 36 22 boys, 14 girls TD: 36 22 boys, 14 girls	DCD: 9-10 years (10±0.6) TD: 9-10 years (10.1±0.7)	M-ABC1 ≤5th %tile, excluded neurodevelopmental disorders by school doctor, IQ<70	19
Wann et al. (1998) Case control UK	DCD: 6 5 boys, 1 girl TD: 6 Gender NR	DCD: 10-12 years TD: 10-12 years *Means NR*	M-ABC1 ≤5th %tile, excluded neurodevelopmental disorders and intellectual; difficulties (within normal range of IQ)	15
Williams et al. (2008) Case control Australia	DCD: 21 9 boys, 12 girls TD: 21 9 boys, 12 girls	DCD: 7-11 years (9.4±0.7) TD: 7-11 years (9.4±1.3)	M-ABC1 ≤5th %tile, excluded neurodevelopmental disorders	19

%tile, percentile; ADHD, attention deficit hyperactivity disorder; ADHD-RS, ADHD-rating scale; BOT-2-SF, Bruininks-Oseretsky Test of Motor Proficiency, second edition; crit., criterion; DSM-IV-RS, ADHD rating scale based on DSM-IV; IQ, intelligence quotient; NR, not reported; PANESS, Physical and Neurological Examination for Soft Signs; SD, standard deviation; WISC, Wechsler Intelligence Scale for Children; WJPEBR, Woodcock–Johnson Psycho-Educational Battery-Revised

Apparatus and methodological procedures

Covert orienting of the visuospatial attention task (COVAT) was employed in six studies of this category (Tsai, 2009; Tsai et al., 2009a; Tsai et al., 2009c; Tsai et al., 2010; Chen et al., 2012; Tsai, 2012b) based on the Posner paradigm (Posner, 1980; Posner, 1988). The Posner paradigm requires a motoric action to take place in response to visual target cues presented at different locations on a screen. These target cues are presented with preceding visual stimuli (pre-cues) that either contradict (invalid) or predict (valid) the location of the target cues. A child's capability for inhibitory control or the invalid cue effect (ICE) is usually explored in studies investigating the Posner paradigm by measuring the time required to prevent the unwanted movement response that follows attentional disengagement to the invalid cues (Mandich et al., 2003).

Two modes of attention are involved in COVAT tasks and are suggested to be related to different visuospatial attention systems (Tsai et al., 2009a). The first of these is the endogenous (or top-down) attention mode which consists of pre-cues that are not always informative or attractive, such as pre-cues with dim colours or low sounds, presented centrally or away from the target cues. Therefore, engagement with the endogenous pre-cues is voluntary, involving intention at a cognitive level and internal knowledge, and therefore subsequent responses depend on the strength of the attentional benefits of the pre-cue (Kurtz et al., 2017; Fernández et al., 2021). The other type is the exogenous (or bottom-up) attention mode which consists of pre-cues that are salient and attention shifting, such as pre-cues with bright light, loud sound, or sudden onset of presentation, displayed peripherally or at the target cue. Therefore, engagement with the exogenous pre-cues is reflexive or involuntary due to the nature of the pre-cue and, hence, responses are stimulus-driven (Kurtz et al., 2017; Fernández et al., 2021).

All six studies focused on investigating children's perceptual abilities in visuospatial attentional disengagement and inhibitory control by measuring the reaction time (RT), along with the strength of inhibitory control (or invalid cue effect) which was determined by calculating the difference between the mean RT of the valid (congruent) and invalid (incongruent) conditions. In addition, perceptual abilities are better explained in terms of anticipatory and executive functioning when examining the RT in relation with the accuracy of responses (Dmochowski and Norcia, 2015). Therefore, the accuracy was also measured by calculating the number and percentage of errors, including delay errors (responses later than the time interval given before the next trial), anticipatory errors (responses sooner than the time interval between trials), and orientation errors (inaccurate responses).

Chen et al. (2012), Tsai (2009), and Tsai et al. (2009a) examined the endogenous mode of attention by employing a digitally presented arrow (pre-cue) that either pointed towards (valid) or away (invalid) from the location of the target cue. These studies were similar in that the participants were asked to press one of two buttons using the index finger (for targets presented on the left) and middle finger (for targets presented on the right) of the dominant hand, regardless of the pre-cue. The experiments involved mostly valid trials to increase the facilitatory effect and investigate inhibitory control (Lim et al., 2019), as reported by the authors (Tsai, 2009; Tsai et al., 2009a).

Varying the stimulus-onset asynchrony (SOA), the time period between the pre-cue and the target stimulus, was shown to affect the RT and, hence, could represent a child's ability in temporal attention and attentional shifts (Chen et al., 2012; Lawrence and Klein, 2013). The SOA was the same for the two studies by Tsai et al. (350ms), whereas Chen et al. (2012) compared children's responses under two SOAs (350ms and 800ms). However, the response accuracy (i.e., number and percentage of errors) was measured by both Tsai (2009) and Tsai et al. (2009a) but not by Chen et al.

Chen et al. (2012) conducted a subgroup-analysis to compare the responses of children with DCD between those who were classified as severe and moderate (< 1st vs 5th percentile in the total score of the M-ABC1 test), which was not considered in the other two studies. Moreover, Tsai et al. (2009a) measured brain activity using an electroencephalogram (EEG) while the participants performed the COVAT task. The EEG data were then analysed relative to the behavioural responses.

The exogenous mode of attention was investigated by Tsai et al. (2010) and Tsai et al. (2012b) to measure children's perceptual abilities in decision-making and visuospatial attention. The task involved a digitally displayed eye-gazed stimulus (pre-cue) that pointed towards (valid) or away from (invalid) a yellow asterisk (target cue) with a fixed SOA (500ms). Unlike the endogenous mode studies, children were asked to step on pedals (right or left) using both lower limbs to indicate the location of the visual target stimuli. In both studies, the anticipatory, delay and orientation errors were measured along with collecting EEG data while children performed the task to identify the neural basis of any behavioural differences.

Inhibitory control and visuospatial attention were explored by Tsai et al. (2009c) who investigated both the endogenous and exogenous modes of attention among children with DCD. Two tasks were employed and involved examining the dominant and non-dominant upper and lower limbs. The two tasks were first applied to the lower limbs and after 6 months, they were repeated for the upper limbs. Task one (endogenous) consisted of two different visual pre-cues (single or double arrows) which were presented in short (150ms) or long (850ms) SOAs. Target cues were then presented at the sides (left or right) and, accordingly, the participants were asked to either press or step on the right or left button or pedal, respectively. The endogenous task of Tsai et al. (2009c) also involved mostly valid trials to investigate facilitatory effects, as in the abovementioned studies. Task two (exogenous), on the other hand, consisted of red or green circular pre-cues being displayed as visual stimuli with 500ms- or 1,000ms-long appearance (SOAs) in the left or right direction. Participants were asked to press/step the right button/pedal for green circles and left button/pedal for red circles, regardless of their location. Therefore, congruent trials consisted of a green circle in the right box or a red circle in the left box, whereas incongruent trials consisted of a green circle in the left box or a red circle in the right box.

Tsai et al. (2012a) examined visuospatial attention and working memory by employing a task that involved the presentation of matched and mismatched visual stimuli that were either presented simultaneously (non-delay attention task) or at different timings (3- or 6-second delay working memory task). The visual stimuli were presented at two stages; the first one was the encoding stage (S1) in which a single rectangle was presented and the second one was the recognition stage (S2) in which two matched or mismatched rectangles were presented. Participants had to press a button with their index or middle finger of their dominant hand to indicate the congruency of the stimuli (the pair of rectangles). In addition to examining the behavioural performance by measuring RT and response accuracy, brain activity was measured using EEG.

Visuospatial attention among children with DCD was also investigated in Gheysen et al. (2011) by employing a validated serial RT task. It involved visual stimuli that were systematically presented at different locations on a screen through five blocks with identical sequence of the location presentation. The participants were asked to respond using the index and middle fingers of both hands to press a button that corresponds to the location of the visual stimuli; the left index and middle fingers were used for stimuli presented on the left side, whereas the right index and middle fingers were used for stimuli presented on the right side. The RT and response accuracy were measured in Gheysen et al. (2011). The authors also sought to measure the perceptuomotor learning effect in children by comparing their motoric performance on the five blocks of the fixed sequence presentation with a sixth block of a random presentation of the visual stimuli. However, the frequency of the stimuli presentation was kept the same as the fixed sequence blocks. The authors noted that the paradigm was designed like this to determine if the learning effect was due to learning the sequence of the stimuli presentation in the different locations or due to the frequency of presentation of each location (Gheysen et al., 2011).

Visuospatial attention has been shown to have a significant role in internal modelling and motor imagery which is the ability to update the mental representation of movements and position of the body and limbs according to the encountered changes of sensory stimuli to adapt the motoric responses (Adams et al., 2014). Williams et al. (2008) sought to examine motor imagery among children with DCD and explore its relationship with their movement difficulties. The task employed in their study consisted of visual stimuli with a picture of a left or right hand or a raised arm with a whole body that were presented in 45° steps of rotations. The participants were asked to respond by pressing one of two buttons to indicate whether the hand or arm raised in the whole-body picture was a right or left limb.

Although the study of Williams et al. (2008) did not mention which hand was used for responding (dominant vs non-dominant), the participants’ hands were covered so as not to facilitate their response by looking at their hands. Additionally, to obtain baseline measurements, the participants were first asked to perform the hand task with no guidance given for performance (HR-NI). In the following trials for both the hand and whole-body tasks, the participants were advised to guide their answers by imagining their own hand (HR-WI) or themselves in the position of the stimulus. Furthermore, Williams et al. (2008) compared the results of participants having severe DCD (<5th percentile of M-ABC) with those having moderate DCD (between 5th and 15th percentiles of M-ABC). However, to answer the research question of this review, a focus on the data of the severe DCD was made.

Motor imagery and internal modelling were also considered in Adams et al. (2016). Here they were interested in measuring their effect on motor planning and proprioception (position sense) among children. This was achieved by examining the end position of their arm movement after performing a goal-directed task that involved spatially manipulated visual stimuli. The end-state comfort (ESC) of the arm is suggested to reflect children's anticipation and motor planning in goal-directed tasks (Wilson et al., 2012). Three tasks were employed by Adams et al. (2016): a position sense task, a sword task, and a bar task. The position sense task involved measuring proprioceptive abilities in the elbow joint because it is suggested that this joint is primarily used in the other tasks employed in this study. The sword and bar task consisted of a sword or bar being placed in different rotated positions requiring the arm to start in an uncomfortable position to grasp the rotated object and place it in a fixed slot, finishing the task with an ESC of the arm. The positions (rotations) that the objects (sword or bar) were placed in were either non-critical (control), whereby no arm rotation was required when grasping the object, or critical, in which the participants had to start the grasp in an uncomfortable position (rotated arm). The scores for the ESC were analysed and correlated with the scores for the M-ABC to measure the effect of motor planning on movement abilities among children with DCD.

The prism adaptation paradigm was employed by Kagerer et al. (2006) to measure children's abilities to update their internal model (visuospatial adaptation) and assess their motor planning. In this study, children were asked to reach for visual targets presented at different locations on a screen using a digital pen (with the vision of the moving hand occluded throughout the experiment) and real-time or distorted feedback of the pen's movement was displayed. The distorted feedback was either presented gradually or abruptly. To explore the effect of visuospatial adaptation, Kagerer et al. examined movement kinematics before, during and after exposure to the feedback by measuring the root mean square error (RMSE), initial directional error (IDE), normalised jerk (NJ), and movement length (ML).

Visuospatial adaptation was also measured by Chung and Stoffregen (2011) and Wann et al. (1998) who employed the 'moving room' paradigm. The two studies utilised similar age groups and small sample sizes but they employed different experimental procedures. Chung and Stoffregen performed a covaried movement of the walls of the room between the amplitudes of 1cm or 2cm with room oscillation frequencies of 0.1Hz, 0.2Hz, or 0.3Hz. Meanwhile, Wann et al. measured the foot length of each participant to estimate the amplitude of the wall's movement which was set at and beyond their limits: low (40%), medium (80%), and high (120%) of average subjects' foot length. In addition, the wall's movement was controlled with a fixed frequency of 0.17Hz in Wann et al.'s study.

Both Chung and Stoffregen (2011) and Wann et al. (1998) had the same number of trials (n=6) including all conditions of covaried amplitudes and frequencies which were randomly distributed. However, Wann et al. had 2 more trials; one with eyes closed during the trial and one with no wall movement to obtain the baseline measurements of the participants' standing sway. Coupling motion between postural sway and the movement of the walls of the rooms was measured by Chung and Stoffregen by examining the anterior-posterior (AP) displacement of the centre of pressure (CoP), whereas Wann et al. measured it using only head movement. Both studies sought to calculate the relative phase (between body sway and room motion) and magnitude squared coherence (MSC), and Chung and Stoffregen measured maximum spectrum as well.

Debrabant et al. (2016) and Van Waelvelde et al. (2004) assessed children's visual perception and visuomotor abilities by tracing and copying tasks of geometric forms that are spatially different using the Beery-Buktenica Developmental Test of Visual Motor Integration (Beery VMI) (Beery, 1997). Perceptuomotor abilities were assessed by examining the participants' movement accuracy when performing the tasks.

In Debrabant et al. (2016), functional magnetic resonance imaging (fMRI) and diffuser tensor imaging (DTI) were used during children's performance of the Beery VMI test to measure their brain activity and in particular the sensorimotor white matter tracts. The behavioural performance in the Beery VMI task was then correlated with their neural activity. Van Waelvelde et al. (2004), on the other hand, compared the results of the Beery VMI with standardised gross motor assessments which were a ball-catching task and Körper Koördination Test für Kinder-jump (KTK-jump) to measure the relationship between visual-motor abilities (Beery VMI) and standardised motor skills (jumping and ball catching). Additionally, a visual timing task was employed by Van Waelvelde et al. (2004) to measure children's visual perceptual-motor abilities. The children were required to press a button when a digitally moving visual stimulus was presented with different speeds reaching a specific target. Performance accuracy (number of errors) was assessed and compared with their Beery VMI scores and the standardised motor tests.

The effect of visual perception on movement and visuo-motor integration were also explored by Chen and Wu (2013) who examined participants' postural control when performing golf putting towards a spatially manipulated hole. The authors measured CoP displacement in the AP and mediolateral (ML) axes while participants putted a golf ball (directing a golf ball towards a hole). The task consisted of easy and hard conditions, depending on the distance between the ball and the hole. Performance accuracy was investigated by measuring the distance between the putted ball (when it came to a stop) and the centre of the hole. Chen and Wu (2013) also measured children's visual perceptual abilities by asking them to estimate the size of the hole by drawing it while being 1m away. The role of visual perception on movement was explored by Chen et al. (2013) by which the relationship between children's putting performance (distance between the putted ball and the hole), children's visual perception (perceived hole size), and their postural control (CoP displacements in the AP and ML) while performing the task was explored.

Table 3.4: Paradigm and outcome measures of included studies - visual processing (visuospatial) category

Reference	Paradigm	Conditions and Procedure	Outcome measures
Adams et al. (2016)	Grasp a rotated sword or bar to place it in fixed slot	**Conditions** Critical: start with an uncomfortable arm rotation to grasp the object (bar or sword) Control: start with an uncomfortable arm rotation was not required to grasp the object (bar or sword) Position sense: ipsilateral remembered: match angle position of the same arm contralateral matching: match the angle position between the two arms **Procedure** Sword task: 6 rotations x 3 rep. (18 trials; 4 critical rotations) Bar task: 8 rotations x 2 sides of bar x 2 rep. (32 trials; eight critical rotations) Randomly presented Dominant hand	**ESC (%)** **Position sense (°)**
Chen and Wu (2013)	Putt a golf ball into a spatially manipulated hole	**Conditions** Hard: golf ball placed 0.76m away from hole Easy: golf ball placed 1.98m away from hole **Procedure** 20 trials; 10 easy and 10 hard Randomly presented	**Putting performance (cm):** distance between putted ball and hole **Perceived hole size (cm)** **CoP displacement (cm):** AP & ML axes
Chen et al. (2012)	Press a button according to the location of the target-cues (preceded by pre-cues presentation)	**Conditions** Valid pre-cue: target cue appearing on the arrow-pointer side	**RT (ms)**

		<u>Invalid pre-cue:</u> target cue appearing opposite to arrow-pointer side <u>No cue:</u> presentation of fixation cross only **Procedure** 120 trials in a single session.; 72% valid cue, 18% invalid cue, 10% no cue 500ms → + → 1000ms → Pre-cue (yellow arrow pointing to left or right) → 350 or 800ms SOA → target cue appeared on the left or right side → response → 1000ms → next trial Press left button with index finger for target-cue appearing in left box, and right button with middle finger for right box (dominant hand) Randomly presented Instructed to respond as quickly as possible	**Strength of inhibitory control (ICE) (ms)**
Chung and Stoffregen (2011)	Maintain postural control with imposed optic flow 'moving room'	**Conditions** <u>6 conditions (combination of amplitudes and frequencies):</u> Amplitudes of wall movement: 1 or 2 cm Oscillation frequencies of wall movement: 0.1, 0.2, or 0.3 Hz **Procedure** 6 trials x 60 sec. each Participants' positions were monitored by which they had to maintain their feet position on markers placed on the floor and their gaze at a picture placed in the front wall	Force plate (sampled at 100 Hz) for measurements **CoP displacement (cm)** **Relative phase between room motion and COP displacements (°)** **Coherence (NU)** **Maximum spectrum (NU)**
Debrabant et al. (2016)	Perform a copy and trace task using different geometric forms/ behavioural performance correlated with brain activity	**Conditions** <u>Beery VMI:</u> tracing task, copy task, visual discrimination **Procedure** fMRI used to collect brain activity data while participants performed Beery VMI	**Beery VMI- score of correct figures (NU)**

	Additional measures	Performance of the Beery VMI correlated with IQ scores	
Gheysen et al. (2011)	Press a button according to the location of visual stimuli	**Conditions** Sequence blocks: identical sequence of visual stimuli presentation Random block: random presentation of visual stimuli **Procedure** 6 blocks x 100 trials Press a button with index and middle finger of both hands according to location of the visual stimuli Instructed to respond as fast and as accurately as possible	**Percentage of errors (%)** **RT (ms)**
	Additional measures	Effect of practice, sequence learning and sequency awareness	
Kagerer et al. (2006)	Reach visual targets presented at different location using a digitized pen, with a real- or distorted feedback	**Conditions** Gradual: presentation of distorted visual feedback was in steps of 10°, up to a total of 60° (21 trials per step) Abrupt: presentation of distorted visual feedback as a 60° rotation from the beginning of the exposure condition Pre-exposure (baseline trials): normal visual feedback of pen's movement Exposure condition: feedback of pen's movements distorted (rotated) Post-exposure (after-effects): normal visual feedback of pen's movement after exposure **Procedure** 30 trials pre-exposure, 126 trials exposure, 9 trials post exposure Vision of hand movement occluded	**RMSE (cm)** **IDE (°)** **NJ (NU)** **ML (cm)**

		Randomly presented Dominant hand Instructed to move as straight and fast as possible	
Tsai et al. (2010)	Step on a pedal according to the location of target-cues (preceded by pre-cues) / behavioural performance correlated with brain activity	**Conditions** Valid: target cue appearing on the eye gaze side Invalid: target cue appearing opposite to the eye gaze side Neutral: no pre-cue Catch trials: no target cue, to reduce the automatic response **Procedure** 255 trials (3 sets of 85): 33 valid, 33 invalid, 22 neutral, and 3 catch trials 1000ms → + → 1000ms → eye-gazed visual stimuli (pre-cue) → 500ms SOA → yellow asterisk appeared at either sides of the eye-gazed visual cue → 500 or 3000ms → response → 1500ms → next trial Step on right or left pedal depending on location of target-cue (using both lower limbs) Randomly presented Instructed to respond as quickly and accurately as possible Adjustable equipment Eye fixation monitored	**Number and percentage of errors (%)** **Error rate (%)** (anticipatory error + delay error + orientation error)/number of trials) **RT (ms)** **Strength of inhibitory control (ICE) (ms)**
Tsai (2009)	Press a button according to the location of target-cues (preceded by pre-cues)	**Conditions** Valid pre-cue: target cue appearing on the arrow-pointer side	**Number and percentage of errors (%)**

		Invalid pre-cue: target cue appearing opposite to arrow-pointer side No cue: presentation of fixation cross only **Procedure** 180 trials in a single session (2 sets of 90 trials); 60% valid cue (54 trials), 30% invalid cue (27 trials), 10% no cue (9 trials). White fixation cross located in the middle of two boxes → 1000ms → yellow arrow (pre-cue) → 350ms SOA → green circular target cue appeared in one of the two boxes → response → 1500ms → next trial Press left button with index finger for target-cue appearing in left box, and right button with middle finger for right box (dominant hand) Randomly presented Instructed to respond as quickly and accurately as possible Adjustable equipment Eye fixation monitored	**Error rate (%)** (anticipatory error + delay error + orientation error)/number of trials) **RT (ms)** **Strength of inhibitory control (ICE) (ms)**
	Additional measures	Measurements repeated after 10-weeks of table tennis training	
Tsai et al. (2012a)	Press a button to indicate whether visual stimuli (presented simultaneously or at different timings) were matched or mismatched/ behavioural performance correlated with brain activity	**Conditions** Attention task (non-delay): 1000ms → + → visual stimuli (matched or mismatched) presented together (180ms) → feedback → 1000ms → next trial Memory task (delay): 1000ms → + → encoding S1 (first visual stimuli) (180ms) → 3000 or 6000ms → recognition S2 (second visual stimuli)(500ms) → + → feedback → + → next trial **Procedure** 108 trials x 3 blocks (324 trials each)	**Percentage of correct responses (%)** **RT (ms)**

		Press a button for matched with index finger and mismatched with middle finger Randomly presented Dominant hand Instructed to press a button as quickly as possible, with feedback provided after every trial Adjustable equipment Eye-fixation monitored	
Tsai et al. (2009a)	Press a button according to the location of target-cues presented digitally (preceded by pre-cues) / behavioural performance correlated with brain activity	**Conditions** Valid pre-cue: target cue appearing on the arrow-pointer side Invalid pre-cue: target cue appearing opposite to arrow-pointer side No cue: presentation of fixation cross only **Procedure** 180 trials in a single session (2 sets of 90 trials); 60% valid cue (54 trials), 30% invalid cue (27 trials), 10% no cue (9 trials). White fixation cross located in the middle of two boxes → 1000ms → yellow arrow (pre-cue) → 350ms SOA → green circular target cue appeared in one of the two boxes → response → 1500ms → next trial Press left button with index finger for target-cue appearing in left box, and right button with middle finger for right box (dominant hand) Instructed to respond as quickly and accurately as possible Adjustable equipment Eye fixation monitored	**Number and percentage of errors (%)** **Error rate (%)** (anticipatory error + delay error + orientation error)/number of trials) **RT (ms)** **Strength of inhibitory control (ICE) (ms)**

Tsai et al. (2012b)	Step on a pedal according to the location of target-cues (preceded by pre-cues) / behavioural performance correlated with brain activity	**Conditions** Valid: target cue appearing on the eye gaze side Invalid: target cue appearing opposite to the eye gaze side Neutral: no pre-cue Catch trials: no target cue, to reduce the automatic response **Procedure** 255 trials (3 sets of 85): 33 valid, 33 invalid, 22 neutral, and 3 catch trials 1000ms → + → 1000ms → eye-gazed visual stimuli (pre-cue) → 500ms SOA → yellow asterisk appeared at either sides of the eye-gazed visual cue → response → 1500ms → next trial Step on right or left pedal depending on location of target-cue (both lower limbs) Randomly presented Instructed to respond as quickly and accurately as possible Adjustable equipment Eye fixation monitored	**Number and percentage of errors (%)** **RT (ms)** **Strength of inhibitory control (ICE) (ms)** **Error rate (%)** (anticipatory error + delay error + orientation error)/number of trials)
	Additional measures	measurements after 10-weeks of soccer training.	
Tsai et al. (2009c)	Step on a pedal or press a button according to the location of target-cues (preceded by pre-cues)	**Task one endogenous:** **Conditions** Valid (congruent): a single arrow pre-cue and target cue appearing on the same side of arrow	**Number of errors (NU)** **RT (ms)** **Strength of inhibitory control (ICE) (ms)**

		<u>Invalid</u> (incongruent): a single arrow pre-cue and target cue appearing on the opposite side of the arrow <u>Neutral</u>: double arrow pre-cue with equal probability of the location of the target-cue (left or right box) <u>Catch:</u> no target cue **Procedure** 120 trials x 3 blocks 26 valid trials (65%), 7 invalid (18%), 4 neutral (10%), three catch (7.5%) 1000ms → + → 750ms → double or single arrow → 150 or 850ms SOAs → target cue on the left or right → response → 1000ms → next trial Randomly presented **Task two exogenous:** **Conditions** <u>Congruent:</u> colour of target matches the direction <u>Non-congruent:</u> colour of target does not match the direction **Procedure** 120 trials x 3 blocks 20 congruent, 20 non-congruent 1000ms → white fixation cross in the middle of two boxes → 1000ms → red or green circle pre-cues presented in one of the boxes for 500ms or 1000ms SOA → target cues as green (requires right button regardless of location) and red circle (requires left button/ pedal) → 1000ms → next trial	

		Randomly presented Adjustable equipment Eye fixation monitored	
Van Waelvelde et al. (2004)	Perform a copy and trace task using different geometric forms and correlating performance with standardized motor skills	**Visual timing task** 30 trials Press a button when a digitally moving visual stimulus reached a specific target zone Time for the ball to reach the target zone was between 1200 and 1700ms Randomly presented Feedback provided after each trial **Beery VMI** Tracing task Copy task Visual discrimination	**Visual timing task: absolute error (ms); systematic error (ms); error variance (ms)** **Beery VMI (NU):** number of correct figures
	Additional measures	Correlation between Beery VMI, KTK-jump, ball-catching task, and timing task	
Wann et al. (1998)	Maintain postural control with imposed optic flow 'moving room'	**Conditions** (combination of amplitudes and frequencies): Amplitude of wall movement: 40% (low), 80% (medium), and 120% (high) of subject foot size Oscillation frequency of wall movement: 0.17 Hz **Procedure** 2 baseline trials (one with no wall swinging and one with eyes closed)	Electromagnetic tracker used to measure head movement (sampled at 60 Hz) **Postural sway (cm)** **MSC (NU)** (between room motion and postural sway) **Mean gains (NU)**

		6 trials x 16 sec. each Randomly presented Excluded all trials in which participants stumbled or stepped forward	**Phase lag/lead (rad)**
Williams et al. (2008)	Press a button to indicate the side of the limb that is visually presented	**Conditions** HR-NI (baseline measurements): hand rotation task with no imagery instructions (no guidance on how to perform the task) HR-WI: hand rotation task with imagery instructions (children were guided to imagine themselves in the position of the picture to perform the task) Whole body task: whole body with right or left arm raised (children were guided to imagine themselves in the position of the picture to perform the task) **Procedure** 40 trials Pictures rotated in steps of 45° Participants hands were covered Instructed to respond as quickly and accurately as possible	**Response time (ms)** **Accuracy (% of correct responses)** **Slope (learning) (NU)** **Intercept (RT on angle) (NU)**

%, percentage; +, white fixation cross; AP, anterior-posterior; cm, centimetre; CoP, centre of pressure; ESC, end-state comfort; Hz, hertz; ICE, invalid cue effect; KTK-jump, Körper Koördination Test für Kinder-jump; m, metre; ML, mediolateral; ms, milliseconds; MSC, magnitude squared coherence; NU, no unit; rad, radians rep., repetitions; sec., seconds; SOA, stimulus onset asynchrony

Results

Studies examining visuospatial attention in children with DCD through COVAT have arrived at different conclusions. Of the studies that explored endogenous attentional control, Chen et al. (2012) found that there was no significant difference in performance between the severe (M-ABC <1st) and moderate (M-ABC <5th) DCD groups in all conditions. Moreover, despite the DCD groups being slower across all trials compared to TD, there was no significant difference in the RT among the three groups (moderate DCD, severe DCD, and TD) (p=.075) in the valid conditions (see Table 3.5). However, Chen et al. (2012) reported a significantly larger RT in the DCD groups (moderate and severe) compared to the TD group (p=.018) in the invalid conditions (specifically in the long SOA) (see Table 3.5). This was also supported by the significantly larger inhibitory control (ICE) in the DCD groups compared to TD, yet this was again only noticed in the long SOA condition (p=.007).

On the other hand, Tsai and colleagues (2009; 2009a; 2010; 2012b) reached similar findings. All studies found no significant difference between the TD and DCD groups with respect to the error rate (see Table 3.5). However, children with DCD had significantly larger RT and ICE in all experimental conditions (valid, invalid, and neutral) compared to TD children. Data for the brain recordings of the studies by Tsai et al. (2009a; 2010; 2012b) are reported in Section 5.3.8.

Tsai et al. (2009c) reported similar findings to the abovementioned studies, however, in the valid conditions of the task involving the endogenous mode of visuospatial attention, children with DCD performed with significantly larger RT compared to TD only in the lower extremity trials (step on a pedal) (p=.040) and not in the upper extremity trials (press a button) (p=.057) (see Table 3.5). Similarly, in the exogenous attentional control tasks in Tsai et al.'s (2009c) study, children with DCD only had significantly more response errors when responding using the lower extremities (p=.020).

Both Gheysen et al. (2011) and Tsai et al. (2012a) reported that the DCD group had significantly more errors and longer RT than the TD group. However, in Tsai et al.'s study, the differences in accuracy and RT between the DCD and TD groups were only found in terms of the memory conditions (3- and 6-second delay) ($p<0.001$ for accuracy and $p=0.022$ for RT) but not in the non-delay condition (see Table 3.5). The electrophysiological data of Tsai et al. (2012a) are reported in Section 5.3.8. Likewise, Gheysen et al. (2011) reported that children with DCD were not able to retain the location sequence of the visual stimuli presented in the sequence block (see Table 3.5). This was concluded because the DCD group performed similarly between all blocks ($p=.30$), whereas the TD group had significantly higher RT in the random block compared to the sequence blocks ($p<.001$).

With regard to the studies that investigated motor imagery and internal modelling among children with DCD, Williams et al. (2008) found that the DCD group had significantly longer RT than the TD group in the HR-NI at all angles except for 180° (see Table 3.5). However, there was no significant difference in response accuracy between the groups ($p=.051$). On the other hand, the RT of children with DCD was significantly decreased in the HR-WI and was evidenced to be similar to that of the TD (see Table 3.5), yet a significant difference in response accuracy was observed between the groups in the HR-WI ($p=.001$). In the whole-body task of Williams et al. (2008), there was no significant difference in the RT between the DCD and TD groups (see Table 3.5). Nevertheless, the DCD group was significantly less accurate compared to the TD group $p<.001$ and exhibited a significantly larger deterioration in performance (larger RT) as angular rotations were away from the upright picture.

In a similar way, Adams et al. (2016) found that the significant difference in ESC between DCD and TD was only apparent in the critical trials of the sword task ($p=0.025$), whereas no significant difference was reported in the non-critical trials ($p=0.928$). In addition, there was no significant difference between the groups in the bar task (see Table 3.5). The authors also looked into proprioceptive abilities by employing a position sense test and found that there was no significant difference in position sense error between the groups (see Table 3.5). Moreover, there were no significant correlations between the ESC, in either the sword or the bar grasping task, and the position sense error, nor did the position sense error correlate with the total scores of the M-ABC2.

Studies investigating visuospatial adaptation agreed that children with DCD did not show systematic deficits in updating their internal mapping and were able to adapt to specific situations of visuospatial changes. For instance, in Kagerer et al.'s (2006) study, children with DCD were able to adapt similarly to TD children when the distorted online feedback of movement was provided within the abrupt conditions. However, there was a significant difference between the groups in the gradual perturbations in Kagerer et al. (2006); the after-exposure effects of the gradual condition show that the movement paths of DCD were significantly less accurate compared to the TD group but the p-value to show the difference was not reported (see Table 3.5).

Furthermore, Chung and Stoffregen (2011) found that children with DCD were able to act similarly to TD children in response to motion changes of room walls. However, the two groups had different outcomes when the amplitude and frequency of wall movement were increased to 2cm and 0.2Hz, respectively ($p<.02$); children with DCD showed significantly increased CoP displacement, whereas TD children displayed a significant decrease. Nevertheless, the p-values to show the statistical difference between the groups were not reported for several dependent variables in Chung and Stoffregen's research (see Table 3.5).

Wann et al. (1998) found that children with DCD displayed significantly greater standing sway than TD in the eyes-closed condition ($p<.001$) and in the eyes-open condition, however, in the latter, the statistical p-value to show the difference was not mentioned. With regard to the visually induced sway in Wann et al.'s study, unlike Chung and Stoffregen's (2011), the DCD and TD groups did not differ significantly. Nevertheless, inferential statistics indicating the differences between the groups were not reported for several dependent variables by Wann et al. (see Table 3.5).

Visual perception and visual-motor integration were reported to be compromised among children with DCD in the studies of Chen and Wu (2013), Debrabant et al. (2016), and Van Waelvelde et al. (2004). In Chen and Wu's study, the perception of the size of the hole was significantly smaller in the DCD group than in the TD group ($p<.05$). This is indicated to result in significantly inferior putting performance and more body movement (in the AP axis) in the DCD group compared to the TD group in both the easy and hard conditions ($p<.05$), with a greater deterioration in DCD than TD children in the difficult conditions compared to the easy conditions. This is similar to the findings of Williams et al.'s (2008) study, in which movement difficulties among children with DCD were more pronounced for complex tasks.

Both Van Waelvelde et al. (2004) and Debrabant et al. (2016) concluded that the DCD group had significantly lower scores than the TD for all tests of the Beery VMI ($p<.0001$ and $p<.001$, respectively). In addition, heterogenous results were found for the DCD group in Wann et al. (1998) and Van Waelvelde et al.'s studies, in which some children had better scores than the TD group in the employed tasks. However, Van Waelvelde et al. overlooked measuring the RT in the visual timing task, which might help to better understand the attributes of their erroneous responses. The findings for the fMRI of Debrabant et al. are discussed in Section 5.3.8.

Table 3.5: Results of the included studies - visual processing (visuospatial) category

Reference	Outcome	Condition	Results Mean (±SD), ES, p-value
Adams et al. (2016)	ECS (%)	Sword – critical	**DCD** 66.11% sig. less than **TD** 81.11%, ES(r)=.21, ***p*=.025**
		Sword – non-critical	**DCD** 83.89% not sig. different from **TD** 84.17%, ES(r)=.03, ***p*=.928**
		Bar – critical	**DCD** 45.83% not sig. different from **TD** 44.93%, ES(r)=.003, ***p*=.973**
		Bar -non-critical	**DCD** 80.63% not sig. different from **TD** 86.04%, ES(r)=.17, ***p*=0.065**
	Joint position sense (°)	Relative position sense	No sig. difference between groups, ***p*=0.77,** *NOVR*
		Absolute position sense	No sig. difference between groups, ***p*=0.63,** *NOVR*
	Additional measures		No sig. correlation found between ESC, joint position sense outcome, and the M-ABC2 scores
Chen and Wu (2013)	Perceived hole size (cm)		**DCD** 8.01 cm (±0.47) sig. smaller than **TD** 9.28 cm (±0.64), ***p*<.05**
	Putting performance (distance between ball and hole)	Easy	**DCD** sig. longer than **TD**, ***p*<.05,** *NOVR*
		Hard	**DCD** sig. longer than **TD**, ***p*<.05,** *NOVR*
	CoP – ML (cm)	Easy and hard	No sig. difference between groups, *p-values NOVR*

	CoP-AP (cm)	Easy	**DCD** sig. more than **TD**, ***p*<.05**
		Hard	**DCD** sig. more than **TD**, ***p*<.05**
	Additional measures	For both groups: Sig. +ve correlation between putting performance and perceived hole size, r=–.66, ***p*<.05** Sig. -ve correlation between body movement and putting performance for AP axis, r=–0.59, ***p*<.05** and ML axis, r=–0.50, ***p*<.05** Sig. -ve correlation between body movement and perceived hole size for AP axis, r=–0.68, ***p*<.05** and for ML axis, r=–0.50, ***p*<.05**	
Chen et al. (2012)	RT (ms)	350ms SOA-valid cue	**TD** 349.0 ms (±68.7), **MDCD** 350.2 ms (±71.2), **SDCD** 367.9 ms (±79.9), no sig. difference between the groups, *p-value NR*
		350ms SOA-invalid cue	**TD** 458.0 ms (±88.6), **MDCD** 476.3 ms (±83.9), **SDCD** 503.1 ms (±141.5), no sig. difference between groups, *p-value NR*
		800ms SOA-valid cue	**TD** 347.5 ms (±64.4) **MDCD** 358.0 ms (±64.3) **SDCD** 368.8 ms (±74.9), no sig. difference between groups, *p-value NR*
		800ms SOA-invalid cue	**SDCD** 439.1 ms (±147.4) sig. longer than **TD** 352.1 ms (±57.3), ***p*=.018** **SDCD** 439.1 ms (±147.4) not sig. different from **MDCD** 408.1 ms (±84.8), *p-value NR*
	Strength of inhibitory control (ICE) (ms)	350ms SOA	**TD** 109.0 ms (±64.0) **MDCD** 126.1 ms (±83.4) **SDCD** 135.9 ms (±87.5), no sig. difference between groups, ***p*=.428**
		800ms SOA	**MDCD** 50.1 ms (±74.8) and **SDCD** 70.3 ms (±129.2) sig. larger than **TD** 4.6 ms (±48.5), **p<.007**, No sig. difference between **SDCD** and **MDCD**, ***p*=.34**
	Additional measures	No significant correlation between ICE values at each SOA and M-ABC scores for both groups, *p-value NR*	

Chung and Stoffregen (2011)	CoP (cm)	Sig. Frequency x Group Interaction, *p*<.02, *NOVR*	
	Relative phase (°)	0.1 Hz room movement	Mean for both groups: 60.98°(±57.98), *NOVR*
		0.2 Hz room movement	Mean for both groups: 59.28°(±81.98), *NOVR*
		0.3 Hz room movement	Mean for both groups: 137.98°(±65.38), *NOVR*
		1 cm room movements	Mean for both groups: 105.78°(±75.28), *NOVR*
		2 cm room movements	Mean for both groups: 66.28°(±61.58), *NOVR*
	Coherence (NU)	1 cm room movements	Mean for both groups: 0.28(±0.19), *NOVR*
		2cm room movements	Mean for both groups: 0.30(±0.28), *NOVR*
	Maximum spectrum (NU)	2cm and 0.2 Hz room movements	**DCD** sig. different from **TD**, ***p*<.02**, *NOVR*
	Additional measures	Postural activity (qualitative measure; CoP)	**DCD** postural movement was as an inverted-U vs **TD** U-shaped postural activity in response to increase of oscillations frequency
		Postural activity (qualitative measure; Max. spectrum)	Smaller room motion: **DCD** response was U-shaped vs **TD** an inverted-U response Larger room motion: **DCD** response was an inverted-U shaped vs **TD** was U-shaped response
		copy task	**DCD** sig. lower than **TD**, ***p*<.0001,** *NOVR*

Debrabant et al. (2016)	Beery VMI – score of correct figures (NU)	visual discrimination task	**DCD** sig. lower than **TD**, ***p*<.0001,** *NOVR*
		Trace task	**DCD** sig. lower than **TD, *p*<.0001,** *NOVR*
	Additional measures	No sig. correlation between IQ and the Beery VMI scores in **DCD** group Sig. +ve correlation between IQ and Beery VMI in **TD** group Brain recordings are in section 5.3.8	
Gheysen et al. (2011)	Error rate (%)	*Not specified*	**DCD** 5.65%(±2.15) sig. more than **TD** 3.94%(±2.50), ***p*<.05**
	RT (ms)	Sequence blocks	**DCD** sig. slower than **TD**, ***p*<.01,** *NOVR*
		DCD: no sig. difference between random and sequence block, ***p*=.30,** *NOVR* **TD**: sig. difference between random and sequence block, ***p*<.001,** *NOVR*	
Kagerer et al. (2006)	*All dependent variables, specific values for each variable were NR*	Exposure effect for abrupt and gradual conditions (95% CI):	No sig. difference between groups, ***p*>.2**
	RMSE (*cm*)	Gradual post-exposure effect (95% CI):	**DCD** 4.58 cm (±5.48) vs **TD** 9.35 cm (±4.73), *p-value NR* Between-subjects p-values: **TD *p*=.001**, **DCD *p*>.05**
	IDE (°)		**DCD** 0.36°(±0.57) vs. **TD** 3.74°(±1.66), *p-value NR* Between-subjects p-values: **TD *p*<.001**, **DCD *p*>.05**
	NJ (NU)		**DCD** 3.01(±2.23) vs **TD** 6.62(±6.27), *p-value NR*

			Between-subjects p-values: **TD *p*<.05**, **DCD *p*>.05**
	ML (cm)		**DCD** 1.00 cm (±1.43) vs **TD** 10.47 cm (±9.07) *p-value NR* Between-subjects p-values: **TD *p*<.05**, **DCD *p*>.05**
	RMSE (cm)	Abrupt post-exposure effect (95% CI):	**DCD** 7.94 cm (±6.86) vs. **TD** 12.08 cm (±6.89), *p-value NR* Between-subjects p-values: **TD *p*=.001**, **DCD *p*<.05**
	IDE (°)		**DCD** 1.62°(±1.56) vs **TD** 3.96°(±2.12) *p-value NR* Between-subjects p-values: **TD *p*=.001**, **DCD *p*=.057**
	NJ (NU)		**DCD** 3.38(±4.73) vs **TD** 4.91(±4.83) *p-value NR* Between-subjects p-values: **TD *p*<.02**, **DCD *p*<.05**
	ML (cm)		**DCD** 4.01 cm (±3.13) vs. **TD** 12.19 cm (±14.10), *p-value NR* Between-subjects p-values: **TD *p*>.05**, **DCD *p*<.02**
Tsai et al. (2010)	Anticipatory error (%)	*Not specified*	**DCD** 0.67%(±0.76) not sig. different from **TD** 0.50%(±0.86**), *p*=.221**
	Delay error (%)	*Not specified*	**DCD** 0.80%(±1.22) not sig. different from **TD** 0.433%(±0.55), ***p*=.073**
	Response error (%)	*Not specified*	**DCD** 1.77%(±2.67) not sig. different from **TD** 1.07%(±1.05**), *p*=.694**
	Error rate (%)	*Not specified*	No sig. difference between groups, ***p*=.209**

	RT (ms)	Congruent	**DCD** 490.39 ms (±73.65) sig. longer than **TD** 364.30 ms (±49.23), ***p*<.001**
		Incongruent	**DCD** 529.63 ms (±68.53) sig. longer than **TD** 382.15 ms (±58.14), ***p*<.001**
		Neutral	**DCD** 529.99 ms (±80.97) sig. longer than **TD** 393.13 ms (±64.35), ***p*<.001**
	Strength of inhibitory control (ICE) (ms)	*Not specified*	**DCD** 39.24 ms (±30.25) sig. larger than **TD** 17.86 ms (±28.51), ***p*=.007**
	Additional measures	Brain recordings are in section 5.3.8	
Tsai (2009)	error rate (%)	*Not specified*	**DCD** 5.79%(±4.231) not sig. different from **TD** 6.18%(±7.3), ***p*=.675**
	RT (ms)	Valid (congruent)	**DCD** 437.00 ms (±69.01) sig. longer than **TD** 336.01 ms (±60.10), ***p*<.001**
		Invalid (incongruent)	**DCD** 535.90 ms (±83.40) sig. longer than **TD** 395.66 ms (±60.54), ***p*<.001**
	Strength of inhibitory control (ICE) (ms)	*Not specified*	**DCD** sig. larger than **TD, *p*=.031**
	Additional measures	No significant difference between the **DCD** and **TD** group in error rate after training, ***p*=.097** Sig. smaller strength of inhibitory control in **DCD** training group only, ***p*=.005**	
	Accuracy (NU)	3- sec. delay	**DCD** 0.78(±0.08) sig. less than **TD** 0.87(±0.05), ***p*<.001**

Tsai et al. (2012a)		6-sec. delay	**DCD** 0.70(±0.08) sig. less than **TD** 0.82(±0.06), ***p*<.001**
		Non-delay	**DCD** 0.85(±0.07) vs **TD** 0.88(±0.06) no sig. difference, *p-value NR*
	RT (ms)	3-sec. delay	**DCD** 885.53 ms (±57.86) sig. longer than **TD** 831.01 ms (±53.22), ***p*=.001**
		6-sec. delay	**DCD** 868.41 ms (±52.11) sig. longer than **TD** 830.79 ms (56.21), ***p*=.015**
		Non-delay	**DCD** 586.14 ms (±92.68) vs. **TD** 571.85 ms (±63.86), no sig. difference, *p-value NR*
	Additional measures	Brain recordings are in section 5.3.8	
Tsai et al. (2009a)	Anticipatory error (%)	*Not specified*	No sig. difference between groups, ***p*=.274**
	Orientation errors (%)	*Not specified*	**DCD** 13.34%(±20.87) not sig. different from **TD** group 8.73%(±13.98), ***p*=.211**
	Delay errors (%)	*Not specified*	Occurred rarely, with a median=0 for both groups, *NOVR*
	Error rate (%)	*Not specified*	No sig. difference between groups ***p*=.218**
	RT (ms)	Valid	**DCD** 422.78 ms (±75.86) sig. longer than **TD** 348.66 ms (±66.84), ***p*<.0001**
		Invalid	**DCD** 530.08 ms (±113.29) sig. longer than **TD** 407.50 ms (±67.32), ***p*<.0001**

		Non-cued	**DCD** 594.55 ms (±134.36) sig. longer than **TD** 481.89 ms (±90.81), ***p*<.0001**
	Strength of inhibitory control (ICE) (ms)	*Not specified*	**DCD** 107.29 ms (±69.55) sig. larger than **TD** 58.84 ms (±34.94), ***p*=.002**
	Additional measures	Brain recordings are in section 5.3.8	
Tsai et al. (2012b)	Error rate (%)	*Not specified*	**DCD** 1.06%(±0.71) not sig. different from **TD** 0.62%(±0.60), ***p*=.233**
	RT (ms)	Congruent (valid)	**DCD** 454.25 ms (±92.20) sig. longer than **TD** 349.80 ms (±46.45), ***p*<.001**
		Incongruent (invalid)	**DCD** 510.54 ms (±79.53) sig. longer than **TD** 359.64 ms (±42.70), ***p*<.001**
	Strength of inhibitory control (ICE) (ms)	*Not specified*	**DCD** sig. larger than **TD**, ***p*=.002**
	Additional measures	No sig. difference in error rate between groups after training, ***p*=.142** Significantly smaller strength of inhibitory control for **DCD** group after training, ***p*=.006** Brain recordings are in section 5.3.8	
Tsai et al. (2009c)	Anticipatory error (NU)	Endogenous-LE	**DCD** 0.06(±0.23) not sig. different from **TD** 0.08(±0.28), ***p*=.649**
		Exogenous-LE	**DCD** 0.11(±0.32) not sig. different from **TD** 0.17(±0.38), ***p*=.502**

		Endogenous-UE	**DCD** 0.10(±0.31) not sig. different from **TD** 0.09(±0.30), ***p*=.935**
		Exogenous-UE	**DCD** 0.20(±0.41) not sig. different from **TD** 0.16(±0.37), ***p*=.659**
	Error rate (%)	Endogenous-LE	**DCD** 2.67%(±1.78) not sig. different from **TD** 2.57%(±1.62), ***p*=.813**
		Exogenous-LE	**DCD** 3.09%(±1.27) sig. more than **TD** 2.44%(±1.03), ***p*=.020**
		Endogenous-UE	**DCD** 2.67%(±1.84) not sig. different from **TD** 2.58%(±1.48), ***p*=.820**
		Exogenous-UE	**DCD** 2.95%(±1.91) not sig. different from **TD** 2.39%(±1.05), ***p*=.149**
	RT (ms)	Invalid-endogenous (LE)	**DCD** 733.91 ms sig. longer than **TD** 610.88 ms, ***p*<.001**
		Invalid-endogenous (UE)	**DCD** 654.19 ms sig. longer than **TD** 526.92 ms, ***p*=.001**
		Valid-endogenous (LE)	**DCD** 543.19 ms sig. longer than **TD** 472.67 ms, ***p*=.040**
		Valid-endogenous (UE)	**DCD** 459.60 ms not sig. different from **TD** 391.22 ms, ***p*=.057**
		Neutral-endogenous (LE)	**DCD** 545.45 ms sig. longer than **TD** 480.50 ms, ***p*=.024**
		Neutral-endogenous (UE)	**DCD** 480.22 ms sig. longer than **TD** 396.35 ms, ***p*=.007**
		Endogenous (UE)	**DCD** 190.72 ms sig. larger than **TD** 138.21 ms, ***p*<.001**

	Strength of inhibitory control (ICE) (ms)	Endogenous (LE)	**DCD** 193.76 ms sig. larger than **TD** 136.48 ms, ***p*<.001**
	Additional measures	Responses to catch trials (NU)	LE conditions- **DCD** 0.11(±0.32) vs. **TD** 0.08(±0.28), no sig. difference, ***p*=.696** UE conditions- **DCD** 0.07(±0.25) vs. **TD** 0.06(± 0.25), no sig. difference ***p*=.948**
Van Waelvelde et al. (2004)	Beery-VMI (score; NU)	Tracing task	**DCD** 19.03(±3.33) sig. lower than **TD** 21.94(±3.10), ES(d)= –0.89, ***p*<0.001**
		Copy task	**DCD** 17.11(±2.58) sig. lower than **TD** 21.22(±2.92), ES(d)= –1.48, ***p*<0.001**
		Visual discrimination task	**DCD** 18.81(±2.66) sig. lower than **TD** 22.06(±3.29), ES(d)= –1.07, ***p*<0.001**
	Visual timing-systematic error (ms)	**DCD** –32.89 ms (±59.40) not sig. different from **TD** –20.66 ms (±25.18), ES(d)=–.027, ***p*=.259**	
	Visual timing-Absolute error (ms)	**DCD** 92.52 ms (±48.16) sig. longer than **TD** 52.78 ms (±17.50), ES(d)= 1.09, ***p*<0.001**	
	Visual timing-Error variance (ms)	**DCD** 116.93 ms (±71.86) sig. longer than **TD** 65.21 ms (±35.55), ES(d)= 0.90, ***p* <0.001**	
	Additional measures	**DCD**: sig. -ve correlation between each of ball catching, tracing task, and VMI copy task with M-ABC scores; sig. -ve correlation between visual timing task and ball-catching task; sig. +ve correlation between VMI copy task and tracing task	

		TD: sig. -ve correlation between KTK-jump and M-ABC scores, sig. +ve correlation between tracing task and each of VMI copy task and visual discrimination task	
Wann et al. (1998)	Postural sway/ without room motion (cm)	Eyes open	**DCD** 7.37 cm (±2.06) sig. greater than **TD** 3.5 cm (±0.50), *p-value NR*
		Eyes closed	**DCD** 9.03 cm (±0.84) sig. greater than **TD** 3.56 cm (±0.34), ***p*<.001**
	Postural sway (cm)	With room motion	Induced sway displayed in 76% of **DCD** trials vs. 72% of **TD** trials, no sig. difference, *p-value NR*
	MSC (NU)	Low (40% Zf)	**DCD** 0.620(±0.048) vs **TD** 0.541(±0.056), *NOVR*
		Medium (80% Zf)	**DCD** 0.701(±0.060) vs **TD** 0.550(±0.059), *NOVR*
		High (120% Zf)	**DCD** 0.701(±0.029) vs **TD** 0.648(±0.066), *NOVR*
	Mean gains (NU)	*Not Specified*	No sig. difference between groups, *p-value NR*
	Phase lag/ lead (rad)	Low (40% Zf)	**DCD** -0.176 rad (±0.195) not sig. different from **TD** -0.979 rad (±0.396), *p-value NR*
		Medium (80% Zf)	**DCD** -0.421 rad (±0.192) not sig. different from **TD** -0.537 rad (±0.448), *p-value NR*
		High (120% Zf)	**DCD** -0.672 rad (±0.462) not sig. different from **TD** -0.628 rad (±0.464), *p-value NR*
	Intercept (RT on angle) (NU)	HR-NI (baseline)	**DCD-S** 1660.89(±762.95) and **DCD-M** 1312.27(±248.05) sig. larger than **TD** 1023.12(±343.54), ***p*=.001**

Williams et al. (2008)	Slope (learning) (NU)		**DCD-S** 8.55(±5.55) and **DCD-M** 9.25(±4.80) not sig. different from **TD** 10.61(±3.75), ***p*=.18**
	RT (ms)		**DCD-S** sig. slower than **TD** at specific angles (0°, ***p*=.002**; 45**°, *p*<.001**; 90°, ***p*<.001**; 135°, ***p*=.026**, 180°, ***p*=.923**)
	Accuracy (%)		**DCD-S** 80.45%(19.51) not sig. different from **TD** 91.60%(13.55), ***p*=.051**
	Intercept (RT on angle) (NU)	HR-WI	**DCD-S** 1439.94(±566.76) and **DCD-M** 1203.82(±416.29) not sig. different from **TD** 1081.32(±469.44), ***p*=.070**
	Slope (learning) (NU)		**DCD-S** 7.36(±5.47) and **DCD-M** 8.26(±3.26) not sig. different from **TD** 9.66(±4.18), ***p*=.12**
	RT (ms)		All groups had longer RT with angle increase, no between-group sig. difference, ***p*=.751**
	Accuracy (%)		**DCD-S** 81.04%(20.43) sig. less than **TD** 95.75%(5.38), ***p*=.001**
	Intercept (NU)	Whole-body task	**DCD-S** 1974.96(±834.65) and **DCD-M** 2196.47(±849.55) sig. less than **TD** 2771.68(±965.12), ***p*=.005**
	Slope (learning; NU)		**DCD-S** 3.31(±5.25) and **DCD-M** 2.68(±4.34) sig. more than **TD** 0.00(5.82), ***p*=.005**
	RT (ms)		No sig. difference between the three groups, ***p*=.193**
	Accuracy (%)		**DCD-S** sig. less than **TD**, ***p*<.001**

-ve, negative; +ve, positive; °, degrees; AP, anteroposterior; cm, centimetre; CoP, centre of pressure; DCD-M, moderate DCD (≤15th %tile M-ABC score); DCD-S, severe DCD (≤5th %tile M-ABC score); ESC, end state comfort; HD, high difficulty; HR-NI, hand rotation task-no instruction; HR-WI, hand rotation task-with instructions; ICE, invalid cue effect; LD, low difficulty; LE, lower extremity; Max., maximum; MDCD, moderate DCD (≤5th %tile M-ABC score); ML, mediolateral; ms, milliseconds; MSC, magnitude squared coherence; NOVR, no other values reported; NR, not reported; NU, no unit; RT, reaction time; SDCD, severe DCD (≤1st %tile M-ABC score); sec. second; sig. significant; UE, upper extremity

Conclusion

With mostly high level of methodological quality, studies investigating visuospatial attention skills among children with DCD indicate that a deficit in the speed of their sensory processing might play a significant role in their erroneous responses. In addition, these studies suggest that motor difficulties in DCD may be related to task complexity, involving mental workload and high cognitive demand. These findings were also supported by the studies that explored motor imagery and internal modelling in DCD which also had high methodological quality level.

With several limitations in the studies that examined visuospatial adaptation among children with DCD, and with some studies with moderate methodological quality level, they concluded that both the DCD and TD groups were able to update their internal mapping and adapt to the visuospatial modifications of the visual inputs. However, performance of children with DCD was evidenced to show high intra-group variations and heterogeneity by which some children were not able to show similar performance to TD children and others were able to perform similarly to TD children.

Other studies, with high methodological quality, sought to measure the impact of visual perception on movement also reported that a deficit in visual perception may be the reason behind the motor difficulties experienced by children with DCD. Moreover, these studies also reported heterogeneity and large variations in the motoric responses of the DCD group.

3.3.5 Perceptual processing

3.3.5.1 Kinaesthetic perception

Three studies assessed kinaesthetic (proprioceptive) abilities in different joints among children with DCD under various sensory environments. Tseng et al. (2018) specifically measured kinaesthetic perception in wrist joints, whereas Tseng et al. (2019b) were interested in both the elbow and wrist. Mon-Williams et al. (1999), on the other hand, took general measurements of both upper limbs, without specifically measuring each joint individually. This category included one study with a ‘moderate’ level of methodological quality and two with a ‘high’ level (see Table 3.6).

Study sample

- Sample characteristics

None of the studies performed *a priori* sample calculations and all had relatively small sample sizes in the DCD group (n=8-20) (see Table 3.6). In addition, Mon-Williams et al. (1999) had an unbalanced distribution of participants between the DCD and TD groups (n=8 vs. n=32) (see Table 3.6). However, all of the studies recruited children from more than one educational setting to achieve a more representative sample. Moreover, Mon-Williams et al. reported five of the DCD group and two of the TD group had strabismus.

- DCD eligibility

Only Tseng et al. (2018) reported following the DSM criteria to recruit participants with DCD, by which the DSM-V was followed. However, criterion A of the DSM-V criteria was followed by all of the studies by including children with a total score of $\leq 5^{th}$ percentile in the M-ABC1 motor assessment test. Criterion B was considered by Mon-Williams et al. (1999) and Tseng et al. (2018) who used the M-ABC1 and M-ABC2 checklists to confirm how movement difficulties interfere with ADLs and academic achievement. Criterion C was only considered by Tseng et al. (2018) who used teachers' reports to confirm that DCD symptoms appeared at a younger age. Criterion D, on the other hand, was fulfilled by Tseng et al. (2018) and Tseng et al. (2019b) by excluding neurological and intellectual conditions without specifying the methods used to do so.

- Confounding factors

The exclusion of participants with ADHD was only reported by Tseng et al. (2018) to reach homogeneity in the DCD group. Moreover, given that all of the methods used in the studies involved the upper limbs, handedness was considered in the three studies and the dominant hand was used for the purpose of test application. This might be important as the empirical literature reports that different performance may be reached by the dominant and non-dominant upper limbs in behavioural studies (Tsai et al., 2009c). Additionally, age-matched controls with less than one month difference were recruited in these studies.

Table 3.6: Characteristics and settings of the included studies - perceptual processing (kinaesthetic perception) category

Reference, study design & country	**Sample size & gender**	**Age range (mean ± SD)**	**DCD eligibility criteria**	**Quality score**
Mon-Williams et al. (1999) Case control UK	DCD: 8 6 boys, 2 girls TD: 32 *Gender NR*	DCD: 5-7 years TD: 5-7 years *Mean age NR*	M-ABC1 ≤5th %tile, M-ABC1 checklist	18
Tseng et al. (2018) Case control Taiwan	DCD: 20 9 boys, 11 girls TD: 30 14 boys, 16 girls	DCD: 10-11 years (10.4±0.3) TD: 10-11 years (10.5±0.3)	DSM-V: crit. (A) M-ABC2 ≤5th %tile, crit. (B) M-ABC2 checklist, crit. (C) teachers' report, crit. (D) parents' report, neurodevelopmental disorders excluded, IQ<85 excluded	21
Tseng et al. (2019b) Case control Taiwan	DCD: 20 9 boys, 11 girls TD: 30 14 boys, 16 girls	DCD: 9-11 years (10.4±0.3) TD: 9-11 (10.5±0.3)	M-ABC2 ≤5th %tile, neurodevelopmental disorders excluded, IQ<85 excluded	21

%tile, percentile; crit., criterion; IQ, intelligence quotient; NR, not reported

Apparatus and methodological procedure

Similar validated tasks were employed by Tseng et al. (2018) and Tseng et al. (2019b). The tasks of Tseng et al. (2018) included ipsilateral joint position matching tasks and psychophysical discrimination threshold test for the wrist joint, whereas Tseng et al. (2019b) employed ipsilateral and contralateral joint position matching tasks for both the wrist and elbow. The two studies only examined the dominant upper limb. The ipsilateral matching task of both studies consisted of covering participants' eyes and positioning their dominant limb into a reference angle and then returning it to a neutral position. Children were then asked to position the same limb as in the reference position. On the other hand, the contralateral matching task in Tseng et al.'s (2019b) study required children's non-dominant limb to be moved to a reference position and the participants were asked to match this position with their dominant hand.

Because perceptual acuity is commonly measured by examining position sense bias and precision (Holst-Wolf et al., 2016), the two studies by Tseng et al. were interested in measuring the two aspects of perceptual acuity. Position sense bias is measured by examining the positional error (PE) which represents the systematic error or positional bias. PE refers to the degree to which the sensed limb position matches with the reference limb position. The position sense precision, on the other hand, is measured by examining the standard deviation of position error (SDPE) which represents the random error or precision. It represents response consistency of participants or how much their repeated responses agree with each other.

The psychophysical discrimination threshold task was also employed by Tseng et al. (2018), in which the limb was randomly positioned into two different angles: reference and comparison. Children then verbally indicated which position was larger in angular amplitude. The discrimination threshold was measured through the just-noticeable difference (JND) which was determined by measuring the angular difference at the 75% correct response level. In addition, both studies by Tseng et al. examined the correlation between proprioceptive abilities (joint positions sense) and motor function (scores of the M-ABC2) to assess the effect of kinaesthetic abilities on movement.

Mon-Williams et al. (1999), on the other hand, conducted two experiments which entailed children matching the dominant upper (visible or non-visible) limb similarly in position to the non-dominant (visible or non-visible) limb (see Table 3.7). As in the studies of Tseng et al., the authors of Mon-Williams et al. measured the PE and position bias of arm movement in relation to the body and the other limb, in addition to measuring the RMSE.

Table 3.7: Paradigm and outcome measures of the included studies - perceptual processing (kinaesthetic perception) category

Reference	Paradigm	Conditions and Procedure	Outcome measures
Mon-Williams (1999)	Position a visible/non-visible dominant upper limb similarly to the other visible/non-visible non-dominant upper limb	**Conditions** **Experiment 1** <u>VP:P:</u> Point with the unseen dominant index finger (placed under the table) to the visible non-dominant index finger (placed above the table) <u>V:P:</u> Point with the unseen dominant index finger (placed under the table) to a visible location (placed above the table) with the non-dominant hand being visible but placed on the lap <u>P:P:</u> Point with the unseen dominant index finger (placed under the table) to the unseen non dominant index finger (placed above the table) **Experiment 2** <u>VP2:P2</u>**:** Position the visible dominant hand to the unseen non-dominant hand (placed in a box) <u>P2:P2:</u> Position the unseen dominant hand to the unseen non-dominant hand (placed in a box) **Procedure** 5 x trials for each condition Fixed order of tasks (from simple to hard) Dominant hand Eye closure monitored	Motion trackers used for kinaesthetic measurements **RMSE (cm)** **PE (mm)** **Positional bias (NU)**
Tseng et al. (2018)	Position a non-visible dominant wrist to a reference position	**Conditions** <u>Ipsilateral joint position matching:</u> Dominant wrist moved from neutral position to reference 20° flexion position (held for 3 sec.),	Bimanual manipulandum and optical encoders were used for kinaesthetic measurements

		then moved back to neutral position. Participants had to position wrist as in reference position (5x trials) <u>Psychophysical discrimination threshold:</u> Dominant hand moved to two random positions (held for 2 sec.): 1. reference position (20° wrist flexion) 2. comparison position (20.5–40°; steps of 0.5°). Participants had to verbally indicate the wrist position with larger amplitude (20 x trials) **Procedure** Dominant hand Adjustable equipment Vision-occluding goggles worn for all tasks	**PE (°)** **SDPE (°)** **JND (°)**
Tseng et al. (2019b)	Position a non-visible dominant upper limb (wrist or elbow) to a reference position or similarly to the other non-visible upper limb	**Conditions** <u>Ipsilateral matching (elbow and wrist):</u> Dominant limb moved from neutral position to reference position (3 sec.), then moved back to neutral position. Participant then positions limb as in reference position (5x trials) Wrist reference position: 20° flexion Elbow reference position: 60° flexion <u>Contralateral matching (elbow and wrist):</u> Non-dominant limb moved from neutral to reference position. Participant then place dominant limb as in the reference position (5x trials) **Procedure** Randomly presented Dominant hand Adjustable equipment Vision-occluding goggles worn for all tasks	Bimanual manipulandum and optical encoders were used for kinaesthetic measurements **PE (°)** **SDPE (°)** Data were normalised by dividing each value over the respective reference position (wrist: 20°; elbow: 30°). Therefore, PEnorm and SDPEnorm were measured to compare data

°, degrees; cm, centimetre; JND, just noticeable difference threshold; NU, no unit; PE, positional error; RMSE, root mean square errors; sec., seconds; SPDE, standard deviation of positional error

Results

The PE was found to be similar between the DCD and TD groups in both Tseng et al. (2018) (p=.72) and Tseng et al. (2019b) (p>.05), indicating no differences in position sense bias. However, the SDPE showed that the responses of the DCD group were significantly more variable in their estimation of angles when compared to the TD group (p<.05 in Tseng et al. (2018) and p<.001 in Tseng et al. (2019b)), indicating lower position sense precision in the DCD group.

The psychophysical discrimination threshold task in Tseng et al.'s (2018) study showed that children with DCD had significantly larger position sense JND thresholds compared to the TD group (p<.001). Furthermore, neither study found a significant relationship between joint position sense measures and motor function (M-ABC2) in the DCD and TD groups (see Table 3.8). However, Tseng et al. (2018) found that balance sub-scores of the M-ABC2 were significantly and negatively associated with the JND (p=0.032) in the TD group only.

In both experiments by Mon-Williams et al. (1999), children with DCD performed with significantly more PE in all of the tasks compared to TD children. In addition, significantly more errors were noted in the DCD group in the tasks that involved more constraints, such as when both limbs were covered and less information was available. Similarly, the results when measuring the directional bias in limb position revealed that the DCD group positioned the limb away from the body or matched with the other limb only in the tasks that involved one of the limbs being visible and not in the task when both limbs were occluded (see Table 3.8). In contrast, the TD group positioned the limb away from the body or matched with the other limb in almost all of the tests. However, many of the data collected were not reported in the two experiments by Mon-Williams et al. (1999) (see Table 3.8). Moreover, the authors indicate that large variability in performance was noticed among the DCD group, as in the studies by Tseng et al. (2018; 2019b), yet the SD was not reported by Mon-Williams et al. (see Table 3.8).

Table 3.8: Results of the included studies - perceptual processing (kinaesthetic perception) category

Reference	**Outcome**	**Condition**	**Results** **Mean (±SD), effect size (ES), p-value**
Mon-Williams et al. (1999)	RMSE (cm)	Experiment 1	**DCD** not sig. different from **TD**, *p-value and mean NR*
	PE (mm)		**DCD** larger than **TD** for three tasks of experiment 1, ***p*<.001,** *NOVR*
	RMSE (cm)	Experiment 2	*No numerical data reported*
	PE (mm)		**DCD** larger than **TD** for two tasks of experiment 2, ***p*<.01,** *NOVR*
	Additional measures	DCD had equivalent errors on the VP:P and P:P tasks but sig. more errors in the harder task, V:P task, between-subjects *p*<0.01, and more errors when limbs were visible than when they were covered, albeit with high variability, *mean values NR* No sig. difference found between strabismic and non-strabismic groups, *NOVR* Examination of limb position directional bias: Experiment 1: DCD sig. positioned the limb away from body in VP:P and V:P, within-subjects *p*<0.01, but not sig. away in P:P, *p*=0.07 vs TD sig. positioning the limb away from the body in all tests, within-subjects *p*<0.01 Experiment 2: DCD sig. positioned the dominant limb above the non-dominant limb, within-subjects *p*<.01 and away from the body, within-subjects *p*<.01 for VP:P, but not sig. higher (*p*=0.1) or sig. away (*p*=0.6) in P:P vs TD sig. positioning the dominant limb above the non-dominant limb in all tests, within-subjects *p*<0.01, but sig. positioning the limb away from body only in P:P, within-subjects *p*<0.01, and not in V:P, within-subjects *p*=0.06 Performance (errors) bias: DCD sig. more errors in contralateral side in all tests, within-subjects *p*<0.05 vs TD sig. more errors in the contralateral side in V:P and P:P only, within-subjects *p*<.05, but not in VP:P	
	PE (°)		**DCD** not sig. different from **TD**, ***p*=0.72,** *NOVR*

<table>
<tr><td rowspan="3">Tseng et al. (2018)</td><td colspan="2">SDPE (°)</td><td>DCD 2.12°(±1.03) sig. more than TD 1.48°(±0.74), ES(d)=.71, p<.05</td></tr>
<tr><td colspan="2">JND thresholds (°)</td><td>DCD 3.96°(±1.74) sig. higher than TD 2.32°(±1.00), ES(d)=1.16, p<.001</td></tr>
<tr><td>Additional measures</td><td colspan="2">Correlation between wrist proprioception position sense acuity measures and motor function (M-ABC2): DCD: no sig. correlation between proprioceptive measures and MABC-2 sub-scores, p's>.05. TD: MABC-2 balance scores and JND thresholds were sig. and -ve correlated, r=−0.40, p=0.032, no other sig. correlations</td></tr>
<tr><td rowspan="9">Tseng et al. (2019b)</td><td rowspan="4">PEnorm (%)</td><td>Wrist (contralateral)</td><td>DCD 18.89%(±13.67) not sig. different from TD 20.26%(±13.96), p>.05</td></tr>
<tr><td>Wrist (ipsilateral)</td><td>DCD 13.35%(±7.78) not sig. different from TD 12.59%(±6.99), p>.05</td></tr>
<tr><td>Elbow (contralateral)</td><td>DCD 26.41%(±11.63) not sig. different from TD 24.67%(±12.21), p>.05</td></tr>
<tr><td>Elbow (ipsilateral)</td><td>DCD 9.41%(±3.87) not sig. different from TD 9.63%(±4.79), p>.05</td></tr>
<tr><td rowspan="4">SDPEnorm (%)</td><td>Wrist (contralateral)</td><td>DCD 10.39%(±5.16) sig. larger than TD 7.51%(±3.44), p<.002</td></tr>
<tr><td>Wrist (ipsilateral)</td><td>DCD 10.61%(±5.15) sig. larger than TD 7.39%(±3.69) p=.002</td></tr>
<tr><td>Elbow (contralateral)</td><td>DCD 6.00%(±3.55) sig. larger than TD 4.79%(±1.97), p=.045</td></tr>
<tr><td>Elbow (ipsilateral)</td><td>DCD 8.15%(±4.29) sig. larger than TD 6.69%(±2.39), p=.045</td></tr>
<tr><td>Additional measures</td><td></td><td>No sig. relationship between joint position sense measures and M-ABC2 scores for both DCD and TD, p>.05</td></tr>
</table>

cm, centimetre; Exp., experiment; norm, normalised value; NOVR, no other values reported; NR, not reported; PE, positional error; RMSE, root mean square errors; sig., significant; -ve, negatively

Conclusion

With different levels of methodological quality (high and moderate), the studies in this category arrived at similar conclusions; children with DCD acted similarly to TD in terms of position sense bias, however, the DCD group displayed lower position sense precision that was illustrated as higher error variability. In addition, performance deterioration was reported in tasks with a higher complexity, such as when both hands being covered and not visible. Moreover, children with DCD had a significantly higher joint position sense JND threshold. Additionally, no relationship was found between motor assessment scores and the performance of joint precision in the DCD group.

3.3.5.2 Cross-modal perception

Six studies examined motor performance under the effect of combining various sensory inputs such as auditory and visual stimuli (King et al., 2011; Sartori et al., 2020), visual and haptic stimuli (Zoia et al., 2002; Bair et al., 2012), or haptic and proprioceptive (Tseng et al., 2019a; Wade et al., 2016). Three of the studies were deemed to be of a 'high' methodological quality level, whilst three were of a 'moderate' level (see Table 3.9).

Study sample

- Sample characteristics

None of the six studies performed a *priori* power calculation to estimate the required sample size, with some having a relatively small sample size for the DCD group (see Table 3.9). In addition, there was an unbalanced distribution of the number of participants in the groups between DCD and TD in the studies of Bair et al. (2012) and Zoia et al. (2002) (see Table 3.9). However, most of the studies recruited children from a broad distribution of clinical or educational settings to ensure that they achieved a more representative sample of DCD (Bair et al. 2012; Sartori et al. 2020; Tseng et al. 2019a; Zoia et al. 2002).

- DCD eligibility

Three studies reported following the recommended DSM criteria to identify participants with DCD (Bair et al. 2012; Sartori et al. 2020; Tseng et al. 2019a) but some did not state how each criterion of the DSM was fulfilled (see Table 3.9). However, criterion A was fulfilled by all of the studies using the M-ABC1 and M-ABC2 motor assessment tests, whereas criteria B and C were only explicitly reported to be attained by Sartori et al. using the M-ABC2 checklist and a parental questionnaire, respectively. Furthermore, criterion D was fulfilled by all except Wade et al. (2016) by excluding neurological and intellectual disorders (see Table 3.9).

- Confounding factors

As previously mentioned, controlling for individual differences might be important in the heterogenous population of DCD. Therefore, Wade et al. (2016) measured the statistical difference between participants of both groups and ensured that there was no significant difference between them in terms of BMI or IQ. Moreover, Bair et al. (2012) only recruited children with a score of ≤15 for the M-ABC balance subsection (i.e., indicating a better balance performance) in order to detect balance deficits elicited using their experimental paradigm.

Excluding children with ADHD was only reported in the studies by Sartori et al. (2020) and Tseng et al. (2019a) in which participants with a confirmed diagnosis of a neurodevelopmental disorder (such as cerebral palsy, ADHD, autism spectrum disorder (ASD)) were excluded, which might also help to meet criterion D of the DSM-V. In addition, as the tasks applied in the studies of King et al. (2011), Tseng et al. (2019a), and Wade et al. (2016) involved upper limb function, the authors ensured that tasks were performed using the participants' dominant side. This might lead to more meaningful outcomes because, as previously mentioned, hand preference and differences in performance between the dominant and non-dominant limbs have been reported among children in the empirical literature (Tsai et al., 2009c). Finally, to draw valid comparisons between the groups, the performance of DCD was compared to age-matched controls (with less than one month difference between the groups) in all of the studies.

Table 3.9: Characteristics and settings of the included studies - perceptual processing (cross-modal perception) category

Reference, study design & country	**Sample size & gender**	**Age range (mean±SD)**	**DCD eligibility criteria**	**Quality score**
Bair et al. (2012) Case control USA	DCD: 21 17 boys, 3 girls TD: 41 21 boys, 20 girls	DCD: 6.6-11.8 years (9.2±1.6) TD: 4.2 -10.8 years (7.5±1.9)	DSM-IV (*methods NR),* M-ABC1 ≤5th %tile, neurodevelopmental disorders excluded using PANESS, intellectual disorders excluded using WRCAEDS, M-ABC balance subtest ≤15	18
King et al. (2011) Case control USA	DCD: 7 6 boys, 1 girl TD: 13 10 boys, 3 girls	DCD: 9-11 years (10.04±0.58) TD: 9-11 years (10.17±0.76)	MABC1 <5th %tile, an independent diagnosis from a paediatrician, neurodevelopmental disorders excluded using PANESS, intellectual disorders excluded using WPEBR	18
Sartori et al. (2020) Case control Brazil	DCD: 63 39 boys, 24 girls TD: 63 39 boys, 24 girls	DCD: 8-9 years (8.70±0.64) TD: 8-9 years (8.74±0.63)	DSM-V: crit. (A) M-ABC2 ≤5th %tile, crit. (B) M-ABC2 checklist, crit. (C) parental questionnaire, crit. (D) neurodevelopmental and intellectual disorders excluded using WASI and medical history	17
Tseng et al. (2019a) Experimental Taiwan	DCD: 20 11 boys, 9 girls TD: 20 11 boys, 9 girls	DCD: 9-11 years (10.55±0.72) TD:10-11 years (10.65±0.45)	DSM-V (*methods NR*), M-ABC2 ≤5th %tile, neurodevelopmental and intellectual disorders excluded by medical history and teacher reports, IQ>85	21
Wade et al. (2016) Case control Taiwan	DCD: 24 12 boys, 12 girls TD: 24 12 boys, 12 girls	DCD: 11-12 years (11.35± 0.40) TD: 11-12 years (11.32± 0.46)	M-ABC2 ≤5th %tile, rt handed	20

Zoia et al. (2002) Case control Italy	DCD: 35 29 boys, 6 girls TD: 105 94 boys, 11 girls	DCD: 5-10 years TD: 5-10 years	M-ABC1 ≤5th %tile, intellectual disorders excluded using RCPM (>70) and TROG; neurodevelopmental disorders excluded by neurological examination	19

%tile, percentile; crit., criterion; IQ, intelligence quotient; NR, not reported; PANESS, Physical and Neurological Examination for Soft Signs; RCPM, The Raven's Coloured Progressive Matrices test; rt; right; TROG, Test of Reception of Grammar; WASI, Wechsler Abbreviated Scale of Intelligence; WPEBR, Woodcock–Johnson Psycho-Educational Battery-Revised; WRCAEDS, Woodcock-Johnson Revised Cognitive Ability Early Development Scale

Apparatus and methodological procedure

Multisensory integration or cross-modal skills were measured in the studies of Bair et al. (2012) and Zoia et al. (2002) by manipulating multisensory stimuli (visual and haptic) and measuring children's behavioural responses accordingly. In Bair et al. (2012), children were asked to maintain static balance while visual (Vdrive) and haptic (Tdrive) inputs were provided through a screen and touching bar, respectively. The inputs were presented simultaneously but oscillated with different frequencies and amplitudes in the mediolateral direction (moving from left to right and vice versa). Children's reliance on (i.e., weighting) and adaptation to (i.e., up-weighting or down-weighting) each sensory input in response to changes in oscillations were explored by measuring the displacement of the head and centre of mass (body sway).

The results of Bair et al. (2012) were analysed according to the sub-groups of ages of the recruited children with the younger age group being 6.6 years of age and the older age group being 10.8 years of age. With similar input modalities, Zoia et al. (2002) investigated 17 transitive gesture skills performed using various objects such as a toothbrush or comb. The conditions of the tasks included imitation (performing the gesture as the researcher does it), visual only (performing the gesture while seeing the objects but not touching them), visual and tactile (performing the gesture while seeing and touching the objects), and verbal (performing the gesture after listening to the researcher describing it without seeing the objects). However, the number trials for each condition was not reported by Zoia et al. Correct performance was given a score of 1, whereas incorrect or incomplete performance was given a score of 0.

Tseng et al. (2019a) and Wade et al. (2016), on the other hand, removed visual inputs (objects were not visible to the participants) and measured children's performance when combining haptic and proprioception inputs. In both studies, children were asked to indicate the physical properties (size, length, curvature, etc.,) of different objects given with various sizes, however, they were only allowed to touch and move the objects to determine their physical features, but not see them.

Tseng et al. were interested in measuring children's discrimination threshold (haptic acuity) and detection threshold (haptic sensitivity). The former was measured by asking the children to use their index finger to decide which of two blocks has a higher curvature, whilst the latter required the children to use their index finger to indicate whether a block has a flat or curved surface. In addition, to measure the effect of sensory perception on movement in children with DCD in Tseng et al., children's performance on haptic acuity and sensitivity were compared with their M-ABC2 scores. Similarly, Wade et al. (2016) asked children to touch and estimate the length of an unseen rod placed on the side of the dominant hand (covered with curtains) and then move a seen rod placed on the side of the non-dominant hand to a similar length as the unseen rod. Their estimation of rod length was measured along with the percentage of errors.

Auditory and visual inputs were provided in the studies by King et al. (2011) and Sartori et al. (2020) and the participants were asked to reach or touch either stimuli on a screen. Sensory inputs were presented in different directions by King et al. (2011) and children were asked to reach for the stimuli using a digital pen and online feedback of their hand movements was provided. The feedback was then distorted for 18 trials and, after that, accurate feedback was again provided to measure the 'after exposure effect'.

The dependent variables in the study by King et al. (2011) were IDE, the variability of the IDE (Var IDE), and RMSE. Using the same sensory inputs, Sartori et al. (2020) were interested in measuring inhibitory control by which children were asked to touch or say any of 60 recorded numbers presented auditorily or visually, with number 6 being the 'no-go' stimulus to which children should show no response. Only accuracy (number of errors) was calculated by Sartori et al.

Table 3.10: Paradigm and outcome measures of the included studies - perceptual processing (cross-modal perception) category

Reference	Paradigm	Conditions and Procedure	Outcome measures
Bair et al. (2012)	Maintain static balance while looking at a screen for visual inputs and touching a bar for haptic inputs	**Conditions** $\underline{T_8V_2}$,$\underline{T_4V_2}$, and $\underline{T_2V_2}$: Vdrive amplitude kept the same and Tdrive amplitude changed systematically $\underline{T_2V_2}$,$\underline{T_2V_4}$ and $\underline{T_2V_8}$: Tdrive amplitude kept the same and Vdrive amplitude changed systematically **Procedure** 5 conditions x 3 test x 100 sec. (15 trials) Stood in modified semi-tandem position Elbow kept at 135° flexion to maintain touching the bar Randomly presented Touching the bar was monitored Fixed examination position	Movement sensors sampled at 60 Hz used for medio-lateral kinematic measurements **Gain for CoM and Head (NU)** **Phase for CoM and Head (°)** **Inter-reweighting:** change of gain to a modality in response to change in the amplitude of the other modality **Intra-reweighting:** change of gain to a modality in response to change in its amplitude **Total reweighting:** sum of intra- and inter-modal reweighting
King et al. (2011)	Reach to visual and auditory targets with visuomotor adaptation	**Conditions** Visual condition-baseline (24 trials): visual targets presented at 25°, 90°, or 155° away from the start position, with accurate online feedback presented Auditory condition-baseline (24 trials): (with eyes covered) auditory targets presented at 45° or 135° away from the start position Visual condition-exposure phase: similar target stimuli to baseline, but with distorted (60° rotation) feedback of pen movement Post-exposure: repetitions of visual and auditory baseline conditions (9 trials of each) after the exposure phase **Procedure** 192 trials	**IDE (°)** **Var IDE (°)** **RMSE (cm)**

		Dominant (right) hand Randomly presented Participants instructed to move as fast and accurately as possible	
Sartori et al. (2020)	Touch a screen when a visual or auditory input is presented	**Condition** Auditory and visual: children touch or say any of 60 numbers (go-stimuli) presented visually or auditorily, except number 6 (no-go stimulus)	**Sum of errors** (touch or say the 'no go' stimulus)
Tseng et al. (2019a)	Touch blocks with different curvatures with no visual inputs provided to indicate their physical properties	**Condition** *(with no visual information provided)* Haptic detection (sensitivity): identify curvature of a single block (flat or curved) Haptic discrimination (acuity): differentiate between curvatures between two blocks **Procedure** 20 trials x 2 conditions Index finger of dominant hand Adjustable equipment	**Detection threshold** (haptic sensitivity) (mm): indicate whether a block is curved or flat **Discrimination threshold** (haptic acuity) (mm): identify the difference of curvature between two blocks **Correlation between haptic perception and M-ABC scores**
Wade et al. (2016)	Estimate the size of a hidden rod	**Condition** Five sizes of rods: 30, 45, 60, 75, 90 cm **Procedure** 6 trials x 5 sizes Dominant hand to estimate length of hidden rod, non-dominant hand to set the length of the moveable rod Randomly presented No feedback of correct responses given	**Percentage error (%):** difference between the estimated rod length and actual rod length, divided by the actual rod length **Judged rod length (cm)**

Zoia et al. (2002)	Perform gestures with either visual or haptic or both inputs provided	**Condition** Imitation: perform gesture as carried out by the researcher Visual plus Tactile modality (V+T): perform gestures with touching real objects related to the gesture (e.g. toothbrush) Visual modality: perform gestures and mime the use of a seen object (not touched) Verbal modality: perform gestures after commands are given **Procedure** Tasks were carried out in 4 days 3 examiners carried out assessment	**Number (NU) and percentage (%)** of correct performance

%, percentage; °, degrees; cm, centimeter; CoM, centre of mass; Hz, hertz; NU, no unit; sec., seconds; Tdrive, touch drive; Vdrive, vision drive

Results

Inconsistent results were found by the six studies reporting on multisensory integration or cross-modal perception among children with DCD. In the study by Bair et al. (2012), children with DCD were unable to reweight or adapt their reliance (head and CoM gain) to visual inputs in response to changes in the oscillations of sensory inputs, thereby resulting in a significant increase in their body sway. This was evidenced as the DCD group not decreasing their vision gain when visual frequency was increased or kept constant while haptic stimuli were decreased (see Table 3.11).

However, in Bair et al.'s (2012) research, the DCD group was able to reweight (head and CoM gain) to touch stimuli (i.e., increased their touch gain when touch stimuli were decreased or kept constant while visual stimuli were increased) (see Table 3.11). In addition, the children with DCD in Bair et al.'s (2012) study demonstrated a larger phase lag between postural response and the presentation of the sensory modality across all of the recruited age groups. However, several numerical data of the results to show the differences between the groups were not reported by Bair et al.

Furthermore, the children with DCD in Bair et al.'s (2012) research were able to demonstrate improvement in total reweight which is the sum of the intra-model and inter-model reweighting, similarly to TD, at the older age group of 10.8 years but this improvement was primarily evident in the conditions that had the greatest difference between the amplitudes of the sensory inputs (e.g., lowest oscillations of touch inputs with largest oscillations of visual inputs).

In accordance with Bair et al. (2012), the study by Zoia et al. (2002) also added that children with DCD had significantly more errors when performing gesture skills across all conditions ($p<0.05$), despite their improvement in multisensory conditions (combined visual and tactile) compared to uni-sensory conditions (visual or tactile only) which was similar to their age-matched controls. Moreover, like Bair et al. (2012), the difference in performance between the groups in Zoia et al.'s research was less evident in older age children (9-10 years), however, several numerical values to show the differences between the groups were not reported (see Table 3.11).

Similarly, Tseng et al. (2019a) and Wade et al. (2016) found that children with DCD were significantly less accurate (higher sensitivity thresholds and more errors) than TD children when estimating an object's physical properties (block surface contour and rod length, respectively) when visual stimuli were occluded and only haptic and proprioceptive inputs were available (see Table 3.11). However, in Wade et al.'s study, the difference between DCD and TD was only evident in the conditions with long rods and not the short rods (see Table 3.11). Nevertheless, similar to other studies, some numerical data were not reported by Wade et al. (2016) (see Table 3.11). In addition, there was no statistically significant difference between the TD and DCD groups in Tseng et al.'s (2019a) research in terms of haptic sensitivity (detection threshold) ($p>.05$), unlike other previously mentioned studies that investigated haptic threshold (Tseng et al. 2018).

Furthermore, Sartori et al. (2020) reported that children with DCD had significantly lower scores (more errors) in both sensory conditions (visual and auditory) ($p\leq.001$). In contrast, King et al. (2011) found that the DCD groups performed with comparable skills in terms of sensorimotor integration, resulting in similar after-exposure effects between the groups (see Table 3.11). However, in the same way as several other studies, variability in the performance of DCD, specifically at the baseline measurements, was observed by King et al. (2011).

Table 3.11: Results of the included studies - perceptual processing (cross-modal perception) category

Reference	Outcome	Condition	Results Mean (±SD), effect size (ES), p-value
Bair et al. (2012)	Gain- CoM (NU)	Vdrive	**DCD** (older group: 10.8 yo) sig. more than **TD** in total reweighting, ***p*<.01,** and intra-reweighting, ***p*<0.01,** *mean values NR* **DCD** (younger group: 6.6 yo) sig. more than **TD** for total reweighting, ***p*<.05,** and intra-reweighting, ***p*<.05,** *mean values NR*
		Tdrive	Of both age groups, **DCD** not sig. different from **TD,** *NOVR* **DCD (**younger group: 6.6 yo): atypical pattern in conditions from T2V2 to T2V8 (constant touch inputs and increase in visual inputs), *NOVR*
	Gain-head (NU)	Vdrive	Group differences were the same as the CoM, *NOVR*
		Tdrive	Of both age groups, **DCD** not sig. different from **TD**, *NOVR*
	Phase (°)	Vdrive	Of both age groups**, DCD** sig. larger than **TD**, **p<0.0001,** for both CoM and Head phase, *mean value NR*
		Tdrive	Of both age groups, **DCD** sig. larger than **TD, *p*<0.0001,** for both CoM and Head phase, *mean values NR*
	Additional measures	**DCD:** Total reweighting was evidenced in older group (10.8 yo) in conditions in which stimulus amplitudes are most different (i.e. T8V2 and T2V8)	
King et al. (2011)	IDE (°)	Baseline/ visual condition:	**DCD** not sig. different from **TD, *p*=.85,** 95% CI [-1.11, 0.09], *mean values NR*
	Var IDE (°)	Baseline/ visual condition:	**DCD** sig. larger than **TD**, ***p*=.019**, 95% CI [-2.03, -0.13], *mean values NR*

	RMSE (cm)		**DCD** sig. larger than **TD**, ***p*=.019**, 95% CI [-2.37, -0.13], *mean values NR*
	All variables	Baseline/ auditory condition	**DCD** not sig. different from **TD, *p*>0.1** for all variables, *mean values NR*
	IDE (°)	Post exposure/ visual condition	**DCD** not sig. different from **TD**, ***p*=.72**, 95% CI [-1.25, 0.87], *mean values NR*
	RMSE (cm)		**DCD** not sig. different from **DCD, *p*=.09**, 95% CI [-2.25, 0.41], *mean values NR*
	IDE (°)	Post exposure/ auditory condition	**DCD** not sig. different from **TD** in location (45°), ***p*=.52**, 95% CI [-1.32, 0.77], and (135°), ***p*=0.45**, 95% CI [-1.44, 0.78], *mean values NR*
Sartori et al. (2020)	Task score (response errors; NU)	Auditory-Motor	**DCD**: 7.27(±3.12) sig. larger than **TD** 4.25(±2.23), ES(η_p^2)=.20, ***p*≤.001**
		Visual-Motor	**DCD**: 6.09(±3.65) sig. larger than TD 3.48(±2.19), ES(η_p^2)=.13, ***p*≤.001**
Tseng et al. (2019a)	Haptic sensitivity (detection thresholds) (mm)		**DCD** 4.68 mm (±1.75) not sig. different from **TD** 4.53 mm (±1.82), ***p*>.05**
	Haptic acuity (discrimination thresholds) (mm)		**DCD** 4.12 mm (±1.63) sig. higher than **TD** 2.03 mm (±0.80), ES(d')=.85, ***p*<.0001**
	Correlation between haptic perception and motor skills		No sig. correlation between the M-ABC2 sub-tests and haptic perception outcome for either group, ***p*>.05**
Wade et al. (2016)	Judged rod length (cm)		*(general)* **DCD** 47.93 cm (±26.42) sig. under-estimation than **TD** 55.47 cm (±20.19), ES(η^2)=.20, ***p*<.05**
			Sig. Group x Rod length interaction, ES(η^2)= 18, ***p*<.05; DCD** sig. underestimate rod length as rod length increases, sig. difference between **DCD** and **TD** only in long rods (60cm, 75cm, and 90 cm), *NOVR*
	Percentage errors (%)		*(general)* **DCD** sig. more errors than **TD,** ES(η^2)=.30, ***p*<.05**, *mean values NR*

				Sig. Group x Rod length interaction, ES(η^2)= 08, ***p<.05*****; DCD** sig. increased percentage error as rod length increases, sig. difference between groups in long rods only (60cm, 75cm, and 90 cm), *NOVR*
Zoia et al. (2002)	Mean number (NU) & percentage (%) of correct gestures	Imitation	5-6 years	**DCD** 2.7 (54%) not sig. different from **TD** 3.3 (67%), ***p*****=0.054**
			7-8 years	**DCD** 2.9 (57%) sig. less than **TD** 3.9 (79%), *p-value NR*
			9-10 years	**DCD** 3.3 (66%) sig. less than **TD** 4.8 (97%), *p-value NR*
			Combined age groups	**DCD** sig. less score than **TD**, 95% CI [0.1–0.4], ***p*****<.001**
		V+T	5-6 years	**DCD** 6.2 (36%) sig. less than **TD** 10.5 (62%), *p-value NR*
			7-8 years	**DCD** 9.6 (56%) sig. less than **TD** 12.4 (73%), *p-value NR*
			9-10 years	**DCD** 12.1 (72%) sig. less than **TD** 15.2 (90%), *p-value NR*
			Combined age groups	**DCD** sig. less score than **TD**, 95% CI [0.2–0.4], ***p*****<.001**
		Visual	5-6 years	**DCD** 4.2 (30%) sig. less than **TD** 5.6 (40%), *p-value NR*
			7-8 years	**DCD** 6.4 (46%) sig. less than **TD** 9.5 (68%), *p-value NR*
			9-10 years	**DCD** 9.3 (66%) not sig. different from **TD** 10.5 (75%), ***p*****=.259**

			Combined age groups	**DCD** sig. less score than **TD**, 95% CI [0.3–0.6], ***p*<.001**
		Verbal	5-6 years	**DCD** 3 (21%) sig. less than **TD** 5.1 (37%), *p-value NR*
			7-8 years	**DCD** 4.8 (34%) sig. less than **TD** 8 (57%), *p-value NR*
			9-10 years	**DCD** 5 (36%) sig. less than **TD** 11.5 (82%), *p-value NR*
			Combined age groups	**DCD** sig. less score than **TD**, 95% CI [0.1–0.3], ***p*<.001**
	Additional measures	Difference between **DCD** and **TD** was less marked in older groups; sig. difference between males and females in imitation condition only, 95%CI [0.2–0.8], ***p*<.019,** *mean values NR*		

%, percentage; °, degree; IDE, initial directional error; NR, not reported; NU, no unit; RMSE, root mean squared error; sig., significant; V+T, visual & tactile; VarID, variability of IDE; yo, years old

Conclusion

The studies that have explored cross-modal skills in children with DCD had different levels of methodological quality which might explain the different hypotheses that were arrived at by the authors. From the studies that presented haptic and visual inputs simultaneously, a deficit was reported in children with DCD's ability in terms of integrating the sensory inputs to enhance their motoric performance compared to the control group. Other studies suggested that children with DCD may benefit from multisensory information (e.g., visual and auditory) in a similar way to TD children to improve their performance. In addition, these studies agreed that better performance is observable in older children with DCD; the difference in motoric performance between DCD and TD children in older age groups is less noticeable compared to younger age groups.

With regard to the studies that occluded visual inputs and in which participants had to perform a task while integrating other sensory information such as haptic and proprioceptive sensory inputs, one study concluded that deficits in multisensory integration may be associated with task difficulty. In addition, it was indicated that sensory sensitivity may be intact among children with DCD but sensory acuity is likely to be compromised. Other studies which provided different sensory inputs independently (e.g., visual or auditory) found that a deficit in sensorimotor integration may result in significantly more errors in the DCD group compared to the TD group. However, some of these studies indicated that children with DCD may be able to show multisensory adaptation, albeit with heterogeneity in their performance.

3.3.6 Motor control

3.3.6.1 Chronometrics

Three studies sought to measure movement chronometrics (e.g., movement time (MT) and reaction time (RT)) to examine executive functioning and motor programming among children with DCD. Tsai and Wu (2008) measured the RT of both lower limbs in a task involving a pedal step and release in response to auditory or visual stimuli, whereas Debrabant et al. (2013) and Van Waelvelde et al. (2006) assessed the RT and other kinematic measurements of the upper limbs in response to auditory or visual pacing stimuli. The three studies had a 'high' methodological quality level (see Table 3.12).

Study sample

- Sample characteristics

None of the three studies performed *a priori* sample size calculation. However, two studies had a relatively sufficient sample size in the DCD group (*n*=36-60) (Tsai and Wu, 2008; Van Waelvelde et al., 2006), whereas Debrabant et al. (2013) only recruited 17 participants with mostly male participants. However, all of the studies recruited participants from a broad range of clinical and education settings (see Table 3.12).

- DCD eligibility criteria

The use of the DSM criteria was not noted in any of the three studies. However, the three studies fulfilled criterion A of the DSM-V by only involving children with a total score equal to or below the 5th percentile on the M-ABC1 and M-ABC2 motor assessment test, whereas criteria B and C were not confirmed with in any of the studies. Criterion D was addressed by the three studies by which the IQ of the participants was considered and only those with a score of >70 or ≥85 were included (see Table 3.12). Additionally, with regard to criterion D, Debrabant et al. (2013) and Van Waelvelde et al. (2006) excluded children with neurodevelopmental disorder or other medical conditions that may interfere with their physical activity. This was confirmed by an examination of the participants and their medical history.

- Confounding factors

Debrabant et al. (2013) and Tsai and Wu (2008) excluded children with a diagnosis of ADHD to further control for confounding factors (criterion D). Conversely, the study by Van Waelvelde et al. (2006) sought to reach children through rehabilitation centres and special education schools and, therefore, most of the participants in the DCD group had probably been diagnosed with comorbid learning difficulties and/or ADHD, as indicated by the authors.

Given that the study by Tsai and Wu (2008) was interested in measuring motor performance that involved the lower limbs, and because physical growth and motor development might vary at the chronological stage of the target population (Nazario and Vieira, 2013), the authors ensured that there was no significant difference between the DCD and TD groups in terms of foot size and body height.

Similarly, the study by Debrabant et al. (2013) reported that there was no significant difference in the handedness between the DCD and controls because hand preference may affect performance (Tsai et al. 2009c). Moreover, because the literature suggests that DCD is highly heterogenous (Sugden, 2007), Debrabant et al. reported that there was no significant difference in the IQ level among children with DCD. Additionally, all of the studies considered recruiting controls with similar age groups (<1 month difference) to the DCD to be able to arrive at a more meaningful comparison between their performances (see Table 3.12).

Table 3.12: Characteristics and settings of the included studies – motor control (chronometrics) category

Reference, study design & country	**Sample size & gender**	**Age range (mean±SD)**	**DCD eligibility criteria**	**Quality score**
Debrabant et al. (2013) Case control Belgium	DCD: 17 14 boys, 3 girls TD: 17 14 boys, 3 girls	DCD: 7-10 years (9.4±0.6) TD: 7-10 years (9.2±0.9)	M-ABC2 ≤5th %tile, IQ≥85 assessed using WISC-III, excluded ADHD, autism, and other medical condition using DSM-IV-TR	22
Tsai and Wu (2008) Case control Taiwan	DCD: 60 29 boys, 31 girls TD: 60 29 boys, 31 girls	DCD: 9-10 years (10.1±0.4) TD: 9-10 years (10.1±0.5)	MABC1 ≤5th %tile, IQ>70, ADHD excluded by a paediatrician assessment	22
Van Waelvelde et al. (2006) Case control Belgium	DCD: 36 22 boys, 14 girls TD: 36 22 boys, 14 girls	DCD: 9-10 years (10.0) TD: 9-10 years (10.1)	M-ABC1 ≤5th %tile, IQ>70, neurodevelopmental disorders excluded using participant's medical history	21

%tile, percentile; DSM-IV-TR, DSM-fourth edition-text revision; IQ, intelligence quotient; NR, not reported; WISC-III, Wechsler Intelligence Scale for Children- third edition

Apparatus and methodological procedures

Chronometrics of hand movements were assessed in the studies by Debrabant et al. (2013) and Van Waelvelde et al. (2006), with the former considering only visual stimuli, while the latter included both visual and auditory stimuli (see Table 3.13). A visuomotor task was employed in the study by Debrabant et al. in which children were required to press a button in response to visual signals presented systematically with fixed (predictive) or random (unpredictive) SOAs (see Table 3.13). Subsequently, children in Debrabant et al. were asked to press the button at a rate that is similar to the predictive condition (fixed SOA) without the presentation of the visual signals. The RT and percentage anticipatory responses were assessed to examine predictive motor timing among children. Additionally, brain activity was measured in Debrabant et al. using fMRI while the participants undertook the task (see Section 5.3.8).

Van Waelvelde et al. (2006) assessed motor control and programming in children using Rhythmic Movement Test (RMT) which required children to move a block sideways simultaneously with rhythmic auditory or visual stimuli. The former were pacing tones and the latter were visual targets presented on a screen. In addition, online visual feedback of the movement path was also shown on the screen. Similar to the approach applied by Debrabant et al. (2013), sensory information was then removed in the task employed by Van Waelvelde et al. and the children were asked to maintain the rhythmic movement of the block to measure their predictive motor timing. The authors of the study were interested in measuring spatial and temporal errors (see Table 3.13) including fluency profile, which is the percentage of movement deviation from a perfect sinusoidal pattern, and systematic time error, which is the measure of systematic early or late movement deviations. The authors of Van Waelvelde et al. also correlated the results of the RMT with Beery VMI (Beery, 1997) scores and their performance in KTK-jump (Kiphard and Schilling, 1974).

Tsai and Wu (2008) measured movement chronometrics using a task that involved a step release of a pedal in response to auditory or visual stimuli presented independently. Both the dominant and non-dominant legs were assessed and the RT of their response was measured. The authors also correlated the results of the RT task with the outcome of the Test of Visual-Perceptual Skills-Revised (Brown et al., 2003) and with a static balance test, through which children's sway area and path were measured in two conditions: eyes-closed and eyes-open (see Table 3.13).

Table 3.13: Paradigm and outcome measures of included studies - motor control (chronometrics) category

Reference	Paradigm	Procedure	Outcome measures
Debrabant et al. (2013)	Press a button in synchrony with visual signals/ behavioural performance correlated with brain activity	**Conditions** Predictive: regular presentation of visual signals with a fixed SOA 1200ms Unpredictive: irregular presentation of visual signals with random SOAs 900-1050-1200-1350-1500ms Self-paced: repeatedly press the button in a rate similar to the predictive condition **Procedure** 6runs x3conditions x20 trials for each of the predictive and unpredictive conditions Right index finger only Children were asked to respond as soon as possible	**RT (ms)** **Percentage anticipatory responses (%):** average of motor responses with <100ms of RT in the predictive and unpredictive conditions
Tsai and Wu (2008)	**Task one:** maintain static balance **Task two:** release a pedal step in response to sensory signals **Task three:** Test of Visual-Perceptual Skills-Revised	**Task one:** 30 sec. duration x 6 conditions (one vs two legs; dominant vs non-dominant; eyes closed vs open) **Task two:** 4 conditions (dominant vs non-dominant; auditory signals- (high tone with eyes closed) vs visual signals- light bulb) **Task three:** a motor-free test that involves the child to say or point to the right item. It includes 7 subtests: Visual Discrimination, Visual Memory, Visual-Spatial Relationships, Visual Form Constancy, Visual Sequential Memory, Visual Figure-Ground, and Visual Closure **Procedure** Randomly presented	A Balance Performer Monitor (sampled at 100 Hz) was used to measure balance performance **Task one:** sway area (mm^2) – sway path (mm) **Task two:** RT (ms) **Task three**: score of correct responses (NU)

		Equipment adjusted for each participant Same researcher took all measurements	
Van Waelvelde et al. (2006)	Rhythmic Movement Test (RMT) - move block in rhythm with visual and/ or auditory signals	**Conditions** Conditions 1 & 5 auditory and visual signals available Condition 2 visual signals removed after 4½ cycles Condition 3 auditory signals removed after 4½ cycles Condition 4 auditory and visual signals removed after 4½ cycles **Procedure** 5 conditions x 25 trials (12½ cycles) Fixed order of task performance across participants Dominant hand only Adjustable equipment	**Task one: absolute time error (sec.)** (between change of movement direction and auditory signal); **systematic time error (sec.)** (between late or early change of movement direction and auditory signal); **absolute distance error (cm)** (between movement return and the middle of target zone); **systematic distance error (cm)** (between systematic too small or too big movement return and the middle of target zone); **fluency profile (%)** (percentage of movement deviation) **Task two (Beery VMI): number of figures (NU)** **Task three (KTK-jump): number of jumps (NU)**

%, percentage; Beery VMI, Beery visual-motor integration; KTK-jump, Ko¨rper Koo¨rdination Test fu¨r Kinder jump; mm, millimetre; mm2, millimetre squared; ms, milliseconds; NU, no unit; sec. seconds; SOA, stimulus-onset asynchrony

Results

The results of Debrabant et al. (2013) show that children with DCD had a statistically significantly longer RT and less anticipatory responses ($ps<.0001$) in the predictive conditions but not in the unpredictive condition ($ps>.070$), when compared to TD children (see Table 3.14). In addition, the performance of the DCD group did not differ between the predictive and unpredictive conditions ($p>.10$), unlike the TD group that performed with significant differences between the two conditions ($p<.0001$). Results of brain activity of Debrabant et al. are illustrated in Section 5.3.8

Failing to synchronise with task time regulations in DCD was also evidenced in Van Waelvelde et al. (2006), in which the DCD group had significantly more time and distance errors in the rhythmic movement task compared to the TD (see Table 3.14). The authors also reported that variability in performance was found to be greater among DCD compared to TD children. However, the difference between the two groups was most prominent when visual information was removed ($p<.03$). In addition, the results of the fluency profile and systematic time error in Van Waelvelde et al. showed similar performance between the groups across all conditions (see Table 3.14), thereby indicating no difference between the groups in systematic movement deviations in their performance. Moreover, significantly lower scores were recorded in the Beery VMI and KTK-jump tests by the DCD group relative to the TD.

Tsai and Wu (2008) also explored the interference of motor programming on movement skills (static balance) with and without visual inputs. The findings show that children with DCD had significantly larger postural sways and longer RT across all conditions in both the static balance and RT tasks (see Table 3.14). In addition, the DCD group had significantly lower scores in all of the subtests of the Test of Visual-Perceptual Skills-Revised. Moreover, a correlational analysis was conducted by Tsai and Wu (2008) to examine the relationship between the three dependent variables for the DCD group in both conditions: eyes-closed and eyes-open. The results show no significant correlation between the variables in the eyes-closed condition. However, a significant negative correlation was found between the Test of Visual-Perceptual Skills-Revised and the RT task in the eyes-opened condition, specifically in some tasks involving timed responses, and a significant negative correlation was found between some sub-tests of the M-ABC (manual dexterity, ball skill, and balance task) and the outcomes of the Test of Visual-Perceptual Skills-Revised (see Table 3.14).

Table 3.14: Results of the included studies - motor control (chronometrics) category

Reference	Outcome	Condition		Results Mean (±SD), effect size (ES), p-value
Debrabant et al. (2013)	RT (ms)	Predictive		**DCD** 412 ms sig. longer than **TD** 284 ms, ***p*<.0001**
	Anticipatory responses (%)			**DCD** 9.50% sig. less than **TD** 17.88%, ***p*<.0001**
	RT (ms)	Unpredictive		**DCD** 439 ms not sig. different from **TD** 385 ms, ***p*>.070**
	Anticipatory responses (%)			**DCD** 7.90% not sig. different from **TD** 7.49% (ms), ***p*>.070**
	Additional outcomes	*No behavioural data reported on the self-paced condition* **DCD** no sig. difference in RT and % anticipatory responses between predictive and nonpredictive conditions, ***p*>.10** **TD** sig. shorter RT and larger % anticipatory responses in predictive than non-predictive conditions, ***p*<.0001** Brain recordings are in section 5.3.8		
Tsai and Wu (2008)	Task one: sway path (mm)	Eyes open	Two legs	**DCD** 24.98 mm (±10.27) sig. larger sway **TD** 21.78 mm (±5.19), ***p*=.03**, ES=0.39
			Dominant leg	**DCD** 33.17 mm (±12.35) sig. larger than **TD** 28.03 mm (±13.66), ***p*=.03**, ES=.39

			Non-dominant leg	**DCD** 38.93 mm (±14.54) sig. larger than **TD** 29.99 mm (±10.36), ***p*<.001**, ES=.67
			Total	**DCD** 97.08 mm (±29.45) sig. larger than **TD** 79.80 mm (±23.40), ***p*=.001**, ES=0.62
		Eyes closed	Two legs	**DCD** 32.00 mm (±95.7) sig. larger than **TD** 27.08 mm (±6.97), ***p*=.002**, ES(d')=.57
			Dominant leg	**DCD** 60.44 mm (±24.65) sig. larger than **TD** 45.19 mm (±19.56), ***p*<.001,** ES=.65
			Nondominant leg	**DCD** 63.09 mm (±25.54) sig. larger than **TD** 50.28 mm (±16.99), ***p*=.002**, ES=.59
			Total	**DCD** 155.54 mm (±48.59) sig. larger than **TD** 122.56 mm (±33.77), ***p*<.001**, ES=.74
	Task two: RT (sec.)	Eyes open	Dominant leg	**DCD** 0.45 sec. (±0.05) sig. longer than **TD** 0.40 sec. (±0.06), ***p*<.001**, ES=.83
			Nondominant leg	**DCD** 0.47 sec. (±0.07) sig. longer than **TD** 0.40 sec. (±0.06), ***p*<.001**, ES=1.00
			Total	**DCD** 0.91 sec. (±0.11) sig. longer than **TD** 0.80 sec. (±0.11), ***p*<.001**, ES=.92

		Eyes closed	Dominant leg	**DCD** 0.38 sec. (±0.09) sig. longer than **TD** 0.31 sec. (±0.06), ***p*<.001**, ES=.78
			Nondominant leg	**DCD** 0.38 sec. (±0.09) sig. longer than **TD** 0.31 sec. (±0.05), ***p*<.001**, ES=.88
			Total	**DCD** 0.77 sec. (±0.16) sig. longer than **TD** 0.62 sec. (±0.11), ***p*<.001**, ES=.94
	Task three: Total scores of Test of Visual-Perceptual Skills-Revised (NU)	**DCD** 85.77(±15.51) sig. lower than **TD** 106.92(±11.28), ***p*<.001**, ES=1.23		
	Additional measures	**<u>Pearson correlation coefficients (DCD group only)</u>** **Between task two (RT) and task three (Test of Visual-Perceptual Skills-Revised)** **Eyes open:** Sig. -ve correlation between non-dominant and visual discrimination (-.37), ***p*<.05**, 95% CI [-.57, -.13] Sig. -ve correlation between total outcome of RT and visual discrimination, (-.32), ***p*<.05,** 95% CI, [-.53, -.07] *No sig. correlation found between the eyes-closed condition and any other variable* **<u>Between M-ABC and task three (Test of Visual-Perceptual Skills-Revised)</u>** Sig. -ve correlation between manual dexterity and each of visual memory, (-.33), ***p*<.01**, 95% CI, [-.54, -.09], visual sequential memory, (-.36), ***p*<.01,** 95 % CI, [-.57, -. 12], visual figure-ground, (-.27), ***p*<.05,** 95 % CI, [-.49, -.01]), and total scores of the Test of Visual-Perceptual Skills-Revised, (-.37), ***p*<.01,** 95% CI, [-.57, -.13] Sig. -ve correlation between ball skill and visual memory (-.27), ***p*<.05,** 95 % CI, [-.02, -.49] Sig. -ve correlation between balance task and visuospatial relationships, (-.27), ***p*<.05,** 95% CI, [-.49, -.01] *All other relationships were not significant* *The outcome of the TD was not analysed for correlation*		
	Absolute time error (sec.)		Condition 1	**DCD** 0.59 sec. (±0.37) sig. longer than **TD** 0.34 sec. (±0.22), ***p*=.001**, ES=.145

Van Waelvelde et al. (2006)		Condition 2	**DCD** 0.70 sec. (±0.80) sig. longer than **TD** 0.38 sec. (±0.36), ***p*=.039**, ES=.060
		Condition 3	**DCD** 0.75 sec. (±0.75) sig. longer than **TD** 0.44 sec. (±0.32), ***p*=.027**, ES=.068
		Condition 4	**DCD** 1.19 sec. (±1.43) sig. longer than **TD** 0.48 sec. (±0.38), ***p*=.005**, ES=.106
		Condition 5	**DCD** 0.69 sec. (±0.71) sig. longer than **TD** 0.31 sec. (±0.24), ***p*=.001**, ES=.136
		Total	**DCD** 0.78 sec. (±0.60) sig. longer than **TD** 0.39 sec. (±0.17), ***p*=<.001**, ES=.19
	Systematic time error (sec.)	Condition 1	**DCD** 0.23 sec. (±0.63) not sig. different from **TD** 0.11 sec. (±0.35), ***p*=.35**, ES=.012
		Condition 2	**DCD** 0.082 sec. (±1.06) not sig, different from **TD** 0.025 sec. (±0.53), ***p*=.59**, ES=.004
		Condition 3	**DCD** 0.019 sec. (±0.98) not sig. different from **TD** 0.21 sec. (±0.50), ***p*=.22**, ES=.022
		Condition 4	**DCD** 0.61 sec. (±1.69) not sig. different from **TD** 0.18 sec. (±0.56), ***p*=.15**, ES=.030

		Condition 5	**DCD** 0.24 sec. (±0.95) not sig. different form **TD** 0.028 sec. (±0.33), ***p*=.21**, ES=.022
	Absolute distance error (cm)	Condition 1	**DCD** 1.03 cm (±0.88) sig. larger than **TD** 0.49 cm (±0.10), ***p*<.001**, ES=.163
		Condition 2	**DCD** 4.57 cm (±2.13) sig. larger than **TD** 3.10 cm (±1.24), ***p*<.001**, ES=.155
		Condition 3	**DCD** 1.17 cm (±0.95) sig. larger than **TD** 0.56 cm (±0.16), ***p*<.001**, ES=.171
		Condition 4	**DCD** 4.09 cm (±2.12) sig. larger than **TD** 2.88 cm (±1.05), ***p*=.003**, ES=.119
		Condition 5	**DCD** 1.08 cm (±0.92) sig. larger than **TD** 0.57 cm (±0.14), ***p*<.001**, ES=.136
		Total	**DCD** 2.39 cm (±1.08) sig. larger than **TD** 1.52 cm (±0.43), ***p*<.001,** ES=.20
	Systematic distance error (cm)	Condition 1	**DCD** 0.80 cm (±0.90) sig. larger than **TD** 0.41 cm (±0.15), ***p*=.007**, ES=.098
		Condition 2	**DCD** 3.86 cm (±2.66) sig. larger than **TD** 2.02 cm (±1.79), ***p*=.001**, ES=.144
		Condition 3	**DCD** 0.95 cm (±1.00) sig. larger than **TD** 0.50 cm (±0.19), ***p*=.011**, ES=.090

		Condition 4	**DCD** 3.36 cm (±2.52) sig. larger than **TD** 1.96 cm (±1.61), ***p*=.006**, ES=.102
		Condition 5	**DCD** 0.88 cm (±0.89) sig. larger than **TD** 0.49 cm (±0.15), ***p*=.013**, ES=.085
	Fluency profile (%)	Condition 1	**DCD** 13.98%(±3.77) not sig. different from **TD** 14.29%(±6.15), ***p*=.794**, ES=.001
		Condition 2	**DCD** 11.25%(±4.27) not sig. different from **TD** 9.83%(±2.70), ***p*=.096**, ES=.039
		Condition 3	**DCD** 11.34%(±4.24) not sig. different from **TD** 9.83%(±2.70), ***p*=.075**, ES=.045
		Condition 4	**DCD** 9.56%(±2.88) not sig. different from **TD** 9.39%(±1.98), ***p*=.779**, ES=.001
		Condition 5	**DCD** 12.74%(±4.43) not sig. different from **TD** 12.40%(±4.00), ***p*=.730**, ES=.002
		Total	**DCD** 11.78%(±2.98) not sig. different from **TD** 11.15%(±2.88), ***p*=.236**, ES=.02
	Task two-Beery VMI (number of figures; NU)		**DCD** 19.6(±3.6) sig. less than **TD** 24.9(±3.1), ***p*=.003**, ES=.13

	Task three-KTK jump (number of jumps; NU)	**DCD** 35.8(±12.7) sig. less than **TD** 60.5(±7.3), ***p*<.001**, ES=.58
	Additional measures	**RMT total time error:** no sig. gender difference in both groups, ***p*=.416,** ES=.010, no sig. gender x group interaction, ***p*=.111** **RMT total distance error:** no sig. gender difference in both groups**,** ***p*=.078,** ES=.045, no sig. gender x group interaction, ***p*=.086** **RMT total fluency profile**: sig. gender difference in both groups (boys had greater distortion percentage), ***p*=.007**, ES=.102, yet no sig. gender x group interaction, ***p*=.231** **Task two (number of figures):** sig. gender difference in both groups (boys had less score)**,** ***p*=.001,** ES=.156 yet no sig. gender x group interaction**,** ***p*=.973** **Task three (number of jumps):** no sig. gender difference in both groups, ***p*=.375**, ES=.012, no sig. gender group interaction, ***p*=.866** **Comparison of conditions** Condition x group interaction was not sig. in all comparisons of conditions except for **absolute distance error:** comparison between conditions 1,2,3,4, &5, ***p*=.03** and between 1&2, ***p*=.03** **Pearson correlation coefficients** **DCD:** Sig. +ve correlation between RMT time error and KTK-jump, (.43), *p*<.01; sig. +ve correlation between time error and tracing test, (.35), *p*<.05; sig. -ve correlation between Fluency profile and tracing test, (-.40), *p*<.05; sig. +ve correlation between KTK-jump and tracing test, (.40), *p*<.05 *All other variables were not significantly correlated* **TD:** sig. -ve correlation between time error and tracing test, (-.36), *p*<.05 *All other variables were not significantly correlated*

%, percentage; +ve, positive; Beery VMI, Beery visual-motor integration; cm, centimetre; KTK jump, Ko¨rper Koo¨rdination Test fu¨r Kinder jump; mm, millimetre; NU, no unit; RMT, Rhythmic Movement Test; sec., seconds; sig., significant; -ve, negative

Conclusion

The studies exploring movement chronometrics revealed that children with DCD execute a motoric response with a significantly longer RT and more spatial and temporal errors. Some studies found the difference to be most noticeable when visual information was removed or in harder tasks, such as tasks involving timing regulations. In addition, a significant correlation was found between perceptuomotor skills and motor performance. All the studies in this category had a high level of methodological quality.

3.3.6.2 Kinematics

Five studies aimed to measure the features of movements executed by children with DCD (Bo et al., 2008; Elders et al., 2009; Biancotto et al., 2011; Ferguson et al., 2015; Roche et al., 2016). Hand movement kinematics were assessed in all of the studies with the only exception being the study by Elders et al. which assessed head movement kinematics and movement coordination. All of the studies employed goal-directed tasks that were performed with the manipulation of different sensory information such as visual or auditory stimuli. Four studies had a 'high' level of methodological quality and one had a 'moderate' level (see Table 3.15).

Study sample

- Sample characteristics

None of the studies performed *a priori* sample calculations and all used relatively small samples in the DCD group (*n*=8-19), except for Ferguson et al. (2015) in which (n=40) participants were recruited. Moreover, most of the studies included in this category comprised predominantly male participants (see Table 3.15). Despite this, all of the studies included a control group of age-matched participants, with less than 4 months difference between the groups. Additionally, three of the studies included participants from broad settings (different schools and clinics) (Bo et al., 2008; Ferguson et al., 2015; Roche et al., 2016), while the other two recruited participants from just one place (Biancotto et al., 2011; Eleders et al., 2009).

- DCD eligibility criteria

Only Ferguson et al. (2015) explicitly reported that they had followed the DSM criteria to recruit participants with DCD, whereby the DSM-IV was followed. Nevertheless, criterion A of the DSM-V criteria was followed by all of the studies by only including children with a total score of $\leq 5^{th}$ percentile in the M-ABC1 or M-ABC2 motor assessment test. With regard to criteria B and C of the DSM-V, these were not considered in all of the studies, with only Ferguson et al. fulfilling criterion B by which a parental questionnaire and examination of the participants' academic history in school were used to confirm motor difficulties' interference with ADLs and academic performance. Criterion D, on the other hand, was fulfilled by all except Elders et al. (2009), by using various methods to exclude neurodevelopmental and intellectual disorders (see Table 3.15).

- Confounding factors

The exclusion of participants with ADHD was not reported in any of the studies. Moreover, with regard to the heterogeneity of DCD (Sugden, 2007), controlling for differences in individuals was overlooked in the study of Biancotto et al. (2011) in which the DCD group included children with various learning difficulties, as assessed by several neuropsychological tests (see Table 3.15). On the other hand, Elders et al. (2009) and Ferguson et al. (2015) ensured that there was no difference in the handedness of children, given that their experiments depended largely on arm movement, although the body side used for the experiment was not mentioned by Elders et al.

Table 3.15: Characteristics and settings of the included studies - motor control (kinematics) category

Reference, study design & country	Sample size & gender	age range (mean±SD)	DCD eligibility criteria	Quality score
Biancotto et al. (2011) Case control Italy	DCD: 9 8 boys, 1 girl TD: 27 8 boys, 19 girls	DCD: 7-9 years TD: 7-9 years	M-ABC1 ≤5th %tile, neurodevelopmental disorders excluded using NESS	17
Bo et al. (2008) Case control USA	DCD: 10 *Gender NR* TD: 10 *Gender NR*	DCD: *age range NR* (9.03±1.4) TD: 5-11 years (8.62±1.5)	MABC1 ≤5th %tile, typical cognitive abilities assessed using W-JRCAEDS, independent DCD diagnosis from a paediatrician	19
Elders et al. (2009) Case control UK	DCD: 8 6 boys, 2 girls TD: 10 7 boys, 3 girls	DCD: 7-9 years (8±0.8) TD: 7-9 years (8±0.7)	M-ABC1 <5th %tile	19
Ferguson et al. (2015) case control South Africa	DCD: 40 23 boys, 17 girls TD: 40 24 boys, 16 girls	DCD: 6-10 years (8.03±1.25) TD: 6-10 years (8.20±1.36)	DSM-IV: crit. (A) MABC2 ≤5th %tile, crit. (B) questionnaire developed by the authors for parents and teachers, crit. (C) other medical conditions excluded using clinical or parents' reports, crit. (D) academic performance confirmed by ensuring participants did not fail a grade level at school more than once	20
Roche et al. (2016) USA	DCD: 19 13 boys, 6 girls TD: 17 13 boys, 4 girls	DCD: 6-11 years (9.29±1.75) TD: 6-11 years (9.22±1.79)	M-ABC1 ≤5th %tile, neurological disorders excluded using PANESS and paediatrician examination, independent DCD diagnosis by a paediatrician, typical cognitive abilities assessed by WJ-III	21

NESS, Revised Neurological Examination for Subtle Signs; W-JRCAEDS, Woodcock–Johnson Revised Cognitive Ability Early Development Scale; PANESS, Physical and Neurological Examination of Subtle Signs; WJ-III, Woodcock-Johnson Psycho-Educational Battery; NR, not reported

Apparatus and methodological procedures

Movement kinematics were measured by Biancotto et al. (2011), Elders et al. (2009) and Ferguson et al. (2015) in response to spatial manipulations of visual signals. Biancotto et al. and Ferguson et al. measured hand kinematics, whereas Elders et al. measured head movement kinematics and head-torso-hand coordination by measuring the temporal and magnitude of onset and offset asynchronies for head–chair, head–finger, and chair–finger.

In the study by Biancotto et al. (2011), children were asked to reach and grasp an object that varied in size and placement (see Table 3.16) and under vision and no-vision conditions. In the no-vision condition, the object was presented for 400ms and subsequently vision was blocked. Thereafter, the children were asked to grasp the object as soon as the vision was occluded. Hand MT, trajectory length, and deceleration time were measured in addition to examining two components of MT independently, which were reaching and grasping durations. The authors were also interested in measuring the maximum grip aperture and the time taken to achieve it.

The child participants in Ferguson et al.'s (2015) study were asked to virtually track a moving target along a circular path which was visible for some conditions and occluded in others, with different speeds of moving targets (see Table 3.16). In comparison, the participants in Elders et al. (2009) were asked to point to or look at visual targets presented in different locations on the wall while sitting on a swivel chair that allowed them to move (rotate) towards the direction of the target in order to measure their head-torso-hand coordination.

Children's virtual tracking performance and within-target hand kinematics were explored by Ferguson et al. (2015). The former included three dependent variables which were the time they spent on keeping the curser on the visually moving target, the number of times they were unable to keep the curser on the target, and the time they spent reacquiring the target. The within-target kinematics included hand velocity and maximum velocity inside the target, tracking variability (TV) of the distance between the curser and the middle of the target, and gain, which is the ratio of cursor velocity to target velocity. Meanwhile, Elders et al. (2009) were interested in examining feedforward and feedback control. The feedforward control was investigated by measuring the MT, speed, and time to peak speed and the feedback control was explored by measuring the movement deceleration time.

Hand movement kinematics were also measured by Bo et al. (2008) and Roche et al. (2016), however, with manipulating auditory stimuli. Bo et al. employed a task that involved predictive motor timing in which children were required to draw circles or lines with their index finger in synchrony with auditory beats. The drawings (finger movements) were either performed continuously or intermittently, according to the rhythm of the auditory stimuli and with systematic pauses (see Table 3.16). Auditory signals were only presented at the beginning of the trials and, after they were removed, children were still asked to continue with the rhythmic movements. In the task employed by Roche et al. (2016), children were required to tap the index finger of the dominant or non-dominant hand immediately after the presentation of auditory stimuli which were presented on either side (right or left). Auditory signals were either presented gradually (with slow and regular increases) or abruptly (with rapid increases) (see Table 3.16).

Temporal and spatial variability of movement were assessed by Bo et al. (2008) by measuring the MT, total distance, coefficient of variation of MT and total distance, and RMSE. Alternatively, in Roche et al.'s (2016) study, the variability of coupling of the index finger movement between the dominant and non-dominant hand was assessed by measuring the relative phase and its standard deviation (see Table 3.16). In addition, children's ability to detect the phasing difference between the auditory stimuli was measured by Roche et al. to examine their auditory perceptual threshold.

Table 3.16: Paradigm and outcome measures of the included studies - motor control (kinematics) category

Reference	**Paradigm**	**Conditions and Procedure**	**Outcome measures**
Biancotto et al. (2011)	Reach and grasp a wooden cylinder that varied in size and placed at different distances under two sensory conditions	**Conditions** A combination of 2sensory settings (vision vs no vision) x3object sizes (1.5 cm vs 3 cm vs 5 cm) x2distances (15 cm vs 30 cm) x36 trials **Procedure** Randomly presented	Motion analysis system (sampled at 200 Hz) used for kinematic measurements **MT (ms):** time between reaching initiation and grasping completion Reaching components: **Trajectory length (TL; UNR):** distance between starting and end position of wrist **Deceleration time (DT) (ms and %):** time from peak velocity to end of movement **Reaching duration (RD) (ms):** total time between reaching initiation and completion Grasping components: **Maximum grip aperture (MGA) (mm):** distance between thumb and index finger **Time taken to achieve maximum grip (TtoMGA) (ms and %)** **Grasping duration (GD) (ms):** time between grasping initiation and completion)
Bo et al. (2008)	Move finger in rhythmic way in synchrony with auditory signals	**Conditions** 2ways of movement (circle vs line) x 2forms (continuous vs discontinuous) Continuous: movements of 550 ms duration Discontinuous: movements of 550 ms with pauses of 550 ms **Procedures**	A digitising tablet and pen were used for kinematic measurements **Movement time (MT) (ms):** time to complete one circle or one back-and-forth line **Movement time coefficient of variation (CVMT) (NU):** temporal variability of movements

		Auditory signals removed after 10-15 beeps, and for 20 seconds, while children continued with rhythmic movements	**Total distance (TD) (mm):** total movement length, i.e., one circle or one back-and-forth line **Total distance coefficient of variation (CVTD) (NU):** spatial variability of movements **Root mean square error (RMSE) (cm):** average deviation between real movement trajectory and ideal trajectory
Elders et al. (2009)	Point to or look at visual signals presented in different locations	**Conditions** <u>6visual target locations</u> (0°, 30°, 60°, 120°, 150°, 180°) x8trials **Procedure** Randomly presented Adjustable equipment	Motion analysis system (sampled at 100 Hz) was used for kinematic measurements Head kinematics: **Movement time (MT) (sec.)** **Peak speed (°/ sec.)** **Time to peak speed (TPS) (sec.)** **Deceleration time (sec.)** Coordination data (at three levels: head-chair, head-finger, chair-finger) *signed* (temporal ordering of movements) and *unsigned* (magnitude of temporal asynchrony between movements): **Onset asynchronies** **Offset asynchronies**
Ferguson et al. (2015)	Track a virtual moving target along a circular path under different visual conditions and speeds	**Conditions** A combination of 2visibility conditions x 2speeds x 2trials each (8 trials): <u>Fast condition (60°/s)</u> vs <u>slow condition (30°/s)</u> <u>Occluded target</u> vs <u>visible target</u> **Procedures** Randomly presented	Digitizing tablet and electronic pen (sampled at a frequency of 206 Hz and with an accuracy of 0.1 mm) used for kinematic measurements Tracking performance: **Time in target (sec.)** **Number of times out of target boundaries (NU)** **Time to reacquire target (sec.)**

		Dominant hand Attention monitored Feedback given after every trial	Within-target kinematics: **Velocity in target (cm/s)** **Maximum velocity (cm/s)** **TV (cm)** **Gain (ratio of cursor velocity to target velocity; NU)**
Roche et al. (2016)	Tap the index finger of both hands immediately after systematic auditory stimuli	**Conditions** Gradual: out-of-phase slow and regular increases of 11° of auditory signals from 180° to 225° Abrupt: out-of-phase rapid increases of 45° of auditory signals from 180° to 225° **Procedure** 2conditions x12trials Both dominant and non-dominant hand Excessive arm movements were reduced by stabilisers Experiment was videotaped to verify participants' performance	Motion analysis system (sampled at 100 Hz) was used for kinematics measurements **Auditory perceptual threshold (PT)**: the lowest phasing difference a child can perceive between two auditory signals **Relative phase (RP):** the ratio of the time between the non-dominant index finger tap and the dominant tap to the total time between the first and second index finger tap of the left hand **Standard deviation of relative phasing (SDrp)**

%, percentage; °, degree; cm, centimetre; Hz, hertz; mm, millimetre; ms, millisecond; MT, movement time; NU, no unit; sec. second; UNR, unit not reported

Results

The results of the studies that measured movement kinematics in response to the manipulation of visual signals arrived at similar outcomes with regard to significant differences in the performance between the DCD and TD groups (Biancotto et al., 2011; Elders et al., 2009; Ferguson et al., 2015). The studies by Biancotto et al. and Elders et al. found that the DCD group exhibited a significantly longer MT and lower speed. In a different way, the study by Ferguson et al. reported that the DCD group performed the task with significantly higher velocity and maximum velocity, thus, compared to the control group, this resulted in significantly shorter time of the virtual curser being on the target and significantly larger number of times when the curser was outside the target (see Table 3.17). Moreover, a significantly larger variability in the performance of the DCD group was evidenced in all the variables in the study by Biancotto et al. and in TV and onset asynchrony in the studies by Ferguson et al. and Elders et al., respectively (see Table 3.17).

Furthermore, the three studies reported that differences found between the DCD and TD groups were most notably in more complex tasks, such as when vision was occluded (Biancotto et al.'s ,2011; Ferguson et al.'s, 2015), movement were made to far compared to near targets, or when pointing was compared to looking (Elders et al. (2009), and fast- compared to slow-moving targets (Ferguson et al., 2015). However, there was no significant difference in the deceleration time between groups in the research by Elders et al. (2009), which is suggested to reflect feedback abilities. On the other hand, Biancotto et al. (2011) found that children with DCD perform with significantly longer deceleration time. Ferguson et al. (2015), noted that children with DCD had a higher mean and maximum velocity than TD children (see Table 3.17). Nevertheless, numerical data for several dependent variables were not reported in the three studies (see Table 3.17).

In the studies that employed tasks involving auditory stimuli manipulation, Bo et al. (2008) also found that children with DCD had a significantly longer MT ($p=.012$), with significantly higher variability (i.e., larger coefficient of variation) (see Table 3.17), regardless of task condition. However, movement distance and movement deviation were found to be similar between the groups. Conversely, in Roche et al.'s (2016) study, children of both groups were able to adapt similarly to the abrupt and gradual increase of the information available (auditory stimuli); no significant difference in the relative phase and both groups had similar auditory thresholds which is the ability to detect the phasing difference between two auditory stimuli presented with different intensities (see Table 3.17). However, similar to all of the studies in this category, the variability in performance was found to be significantly greater in the DCD group across the trials in both conditions, which was measured as the standard deviation of the relative phase between the index fingers of both hands (coupling in tapping) (see Table 3.17). However, the studies by Bo et al. and Roche et al. did not report some numerical data for the dependent variables (see Table 3.17).

Table 3.17: Results of the included studies - motor control (kinematics) category

Reference	Outcome		Condition	Results Mean (±SD), p-value, effect size (ES)
Biancotto et al. (2011)	MT (ms)		Overall	**DCD** sig. slower than **TD, *p*<.001,** sig. larger variability (SD) than **TD**, ***p*<.001**
	Reaching components	RD (ms)	Overall	**DCD** sig. longer than **TD**, ***p*<.001,** sig. larger variability (SD) than **TD, *p*<.001**
			Distance	**DCD** sig. longer than **TD** in both far and near conditions, ***ps*<.001**
		DT (ms)	Overall	**DCD** sig. longer than **TD**, ***p*=.002,** sig. larger variability (SD), ***p*<.001**
			Distance	**DCD** sig. longer than **TD** in near, ***p*=.004,** and far conditions, ***p*=.002**
		TL (cm)	Overall	**DCD** sig. greater than **TD**, ***p*=.013,** sig. larger variability (SD), ***p*=.001**
			Visibility	**DCD** sig. larger than **TD** in vision, ***p*=.008,** and no vision conditions, ***p*=.001**
			Distance	**DCD** sig. larger than **TD** when reaching medium, ***p*=.025** and large targets, ***p*=.001** in far conditions; **DCD** sig. larger than **TD** when reaching small, ***p*=0.005** and large targets, ***p*=.015** in near conditions, *NOVR*

	Grasping components	MGA (mm)	Overall	**DCD** sig. wider than **TD**, ***p*=.039**, especially wider in no vision condition, ***p*=.02** and when reaching for small targets ***p*=.001** and medium targets ***p*=.004,** *NOVR*
		MGA (mm) variability (SD)	Distance	**DCD** sig. more variable than **TD** when grasping the medium target at the near condition, ***p*=0.002,** and when grasping the large target in the far condition, ***p*=0.034,** *NOVR*
		TtoMGA (ms)	Overall	**DCD** sig. longer than **TD**, ***p*<.001**, sig. larger variability (SD), ***p*<.001**
		GD (ms)	Overall	**DCD** sig. longer than **TD**, ***p*<.001**, sig. larger variability (SD), ***p*<.001**
		TtoMGA in %	No vision	**DCD** sig. larger for the medium target than **TD**, ***p*=.012,** sig. larger variability (SD) ***p*=.016,** *NOVR*
Bo et al. (2008)	MT (ms)			**DCD** sig. longer than **TD, *p*=.012** Mean MT for TD 540 ms, DCD moved 150 ms slower on average, *NOVR*
	RMSE (cm)			No sig. difference between groups, *p-value NR*
	CVTD (NU)			**DCD** sig. higher spatial variability than **TD, *p*=.023**
	CVMT (NU)			**DCD** sig. higher temporal variability than **TD** across all conditions**, *p*=.003**

	TD (mm)	No sig. difference between groups, *NOVR*
	Additional measures	**<u>MT (ms) within-subject:</u>** Sig. longer MT in the discontinuous circling than continuous circling, ***p*=.045** Sig. shorter MT in the continuous line drawing than discontinuous line drawing, ***p*<.001** **<u>CVMT (NU) within-subject:</u>** Sig. higher variability in discontinuous circling than continuous circling, ***p*<.001** Sig. higher variability in discontinuous line drawing than continuous line drawing, ***p*<.001** Sig. higher variability in discontinuous circling than in discontinuous line drawing, ***p*=.015** **<u>RMSE (cm) within-subjects:</u>** Sig. higher variability in discontinuous circling 0.57(±0.29) than continuous circling 0.79(±0.36), ***p*< .001** Sig. higher in discontinuous line drawing 0.30(±0.12) than continuous line 0.32(±0.14), ***p*<.001** **<u>CVTD (NU) within-subjects:</u>** Sig. higher variability in discontinuous circling than discontinuous line drawing**, *p*=.013**
Elders et al. (2009)	Head MT (sec.)	**DCD** sig. longer than **TD**, ***p*<.01**
	Peak speed (sec.)	**DCD** sig. lower than **TD** (in further away targets), and higher speed than **TD** (in middle targets) *Target x group interaction* ***p<.01****, NOVR*
	TPS (sec.)	**DCD** sig. longer than **TD,** (especially in the pointing condition), ***p*<.01,** *NOVR*
	Deceleration time (sec.)	No significant main effect or interaction, *NOVR*
	Additional Measures	**<u>Deceleration as a proportion of total MT:</u> DCD** sig. smaller than **TD** (especially in pointing task), ***p*<0.05**

		Coordination data (of pointing task): __**Onset asynchronies**__ **Signed onset data:** no sig. difference between groups; all started the movement at a similar time **Unsigned onset data: DCD** sig. more variability than **TD, *p*<0.05** __**Offset asynchronies**__ **Signed offset data:** no sig. difference between groups; all groups stopped moving the chair similarly before their finger or head were moved **Unsigned offset data: DCD** sig. less coordination than **TD** (between the finger and the head or chair), ***p*<0.01;** close conjunction in movements between head and chair (relying more on chair to move head)	
Ferguson et al. (2015)	Tracking performance/ Time in target (sec.)	Overall	**DCD** 39.10 sec. (± 12.17) sig. shorter than **TD** 49.85 sec. (±8.33), ***p*<0.001**
		Speed	**DCD** 33.90 sec. (±11.93) shorter than **TD** 46.13 sec. (± 8.89) in fast condition **DCD** 44.30 sec. (±10.01) shorter than **TD** 53.57 sec. (±5.70) in slow condition Group x Speed interaction, ***p*=.02,** *NOVR*
		Visibility	**DCD** 36.36 sec. (±11.87) shorter than **TD** 48.43 sec. (±7.83) in occluded condition **DCD** 41.85 sec. (±11.87) shorter than **TD** 51.27 sec. (±8.60) in visible condition Group x Visibility interaction, ***p*=.01,** *NOVR*
	Number of times out of target (NU)	Overall	**DCD** 27.19(±11.99) sig. more than **TD** 16.47(±11.96)**, *p*<.001**
		Speed	Both groups: sig. more in fast condition (mean of both groups:28.55±12.32) than slow condition (mean of both groups:15.11±10.11), within-subjects p<.001, *mean for each group NR*
		Visibility	Both groups: no sig. effect of visibility (visible/mean of both groups: 22.40±15.27) vs (occluded/mean for both groups: 21.25±10.51), within-subjects p=.12, *mean for each group NR*

	Time to reacquire target (sec.)	Overall	**DCD** 0.79 sec. (±0.51) not sig. different from **TD** 0.69 sec. (±0.40), ***p*=.06**
		Speed	**DCD** 0.80 sec. (±0.46) slower than **TD** 0.61 sec. (±0.25) in fast condition Group x Speed interaction, ***p*=.03,** *NOVR*
		Visibility	**DCD** 0.90 sec. (±0.38) slower than **TD** 0.69 sec. (±0.25) in occluded condition Group x Visibility interaction, ***p*=.02,** *NOVR*
	Within-target kinematics Velocity in target (cm/s)	Overall	**DCD** 4.87 cm/s (±1.91) sig. higher velocity than **TD** 4.24 cm/s (±1.45), ***p*<.0001**
		Speed	Both groups: sig. increased in fast (mean of both groups:5.84 cm/s ±0.88) than slow condition (mean of both groups:3.28 cm/s ±1.38), within-subjects p<.001, *mean for each group NR*
		Visibility	**DCD** 3.93 cm/s (± 2.27) sig. faster in occluded than **TD** 2.85 cm/s (±0.36), Group x Visibility interaction, ***p*=.03,** *NOVR*
	Maximum velocity (cm/s)	Overall	**DCD** 13.54 cm/s (±13.21) sig. higher than **TD** 7.07 cm/s (±5.21), ***p*<.001**
		Visibility	Both groups: sig. slower in visible (mean of both groups: 9.70 cm/s ±10.53) than occluded (mean of both groups: 10.90 cm/s ±10.54), within-subjects p=.013, *mean for each group NR*
		Speed	Both groups: sig. slower in slow (mean of both groups: 7.93 cm/s ±11.94) than fast condition (mean of both groups: 12.68 cm/s ± 8.30), within-subjects p<.001, *mean for each group NR*
	TV (cm)	Overall	**DCD** 0.39 cm (±0.62) sig. more variability than **TD** 0.25 cm (±0.09), ***p*=.02**

		Fast	**DCD** 0.36 cm (±0.48) sig. more than **TD** 0.26 cm (±0.10), *between-group p-value NR*
		Slow	**DCD** 0.43 cm (±0.74) sig. more than **TD** 0.23 cm (±0.06), *between-group p-value NR*
		Visibility	No sig. effect found in both groups, (mean of both groups in visible:2.36 cm ±2.40, mean of both groups in occluded:1.62 cm ± 1.67), within-subjects p=.11, *mean for each group NR*
	Gain (NU)	Overall	**DCD** 1.28(±0.52) sig. higher than **TD** 1.09(±0.17), **p<.001**
		Speed	Both groups: less in fast (mean of both groups:1.12 ± 0.17) than slow condition (mean of both groups: 1.25 ± 0.53), within-subjects p<0.001, significant difference between groups p=.004, *mean for each group NR*
		Visibility	Both groups: less in visibility (mean of both groups: 1.15±0.28) than occluded (mean of both groups: 1.22±0.49), within-subjects p=.11, significant difference between groups p=.017, *mean for each group NR* *Group difference in gain was greater in the occluded condition than in the visible condition Significant interaction between visibility, group and speed was found, p=.016*
Roche et al. (2016)	RP (%)	Perceptible condition (abrupt)	No sig. main group or interaction effects, *NOVR*
		Subliminal condition (gradual)	No sig. main group or interaction effects, *NOVR*
	SDrp (%)	Perceptible condition (abrupt)	**DCD** sig. more variable than **TD,** ***p*=0.02,** *no trial or interaction effects, NOVR*

		Subliminal condition (gradual)	**DCD** sig. more variable than **TD, *p*<0.001**, *no interaction effect, NOVR*
	PT (°)	**DCD** younger group (6–8 years) 33.33°(±10.89) sig. larger than **DCD** older group (9–11 years) 25.33°(±3.89), ***p*=0.02** *PT decreased as age increased in both DCD and TD groups* *No Group effect between DCD and TD*	

%, percentage; cm, centimetre; cm/s, centimetres per second; CVMT, Movement time coefficient of variation; CVTD, Total distance coefficient of variation; DT, deceleration time; GD, grasping duration; MGA, maximum grip aperture; mm, millisecond; ms, millisecond; MT, movement time; NOVR, no other values reported; NR, not reported; NU, no unit; PT, perceptual threshod; RD, reaching duration; RMSE, root-mean-square error; RP, relative phase; SDrp, standard deviation of relative phase; sig., significantly; TD, total distance; TL, trajectory length; TPS, time to peak speed; TtoMGA, time taken to achieve maximum grip aperture; TV, tracking variability

Conclusion

In all of the studies included in this category, the MT was found to be significantly longer in children with DCD compared to TD children. In addition, the five studies agreed that greater diversity in performance in the DCD groups compared to the TD was found. Furthermore, some studies indicated that motor deterioration was most noticeable in the harder conditions of tasks, such as the tasks involving the removal of visual stimuli. In addition, studies involving the manipulation of auditory inputs found that children with DCD have similarly adapted to changes in sensory inputs when compared to TD children. However, despite that the majority of the studies had a high methodological quality level, except one that had a moderate level, the results of the studies included in this category remain questionable due the several pieces of data missing in the reporting of the findings.

3.3.7 Motor skills

Thirteen studies sought to measure the effect of manipulating sensory stimuli on motor skills using standardised motor tests including static or dynamic balance tests, with the exception being Diz et al. (2018) which aimed to explore the effect of sensory processing on fine motor dexterity and grip strength. Some studies explored the effect of manipulating spatial parameters of visual stimuli (Bonney et al., 2017; Chen et al., 2015; Chen et al., 2011; Diz et al., 2018; Przysucha and Taylor, 2004; Smits-Engelsman et al., 2015; Speedtsberg et al., 2017; Tsai et al., 2009b; Tsai et al., 2008), whilst other studies were interested in manipulating haptic information (Chen et al., 2019; Chen and Tsai, 2016) and others explored the effect of employing visual and auditory inputs (Fong et al., 2016) or proprioception (Przysucha et al., 2008). Ten of the included studies had a 'high' methodological quality and three were of a 'moderate' level (see Table 3.18).

Study sample

- Sample characteristics

A *priori* sample size calculation was only conducted by Chen et al. (2019) with a power of 0.84. The sample size of the DCD groups of the other studies greatly varied from a minimum of *n*=9 in Speedtsberg et al.'s (2017) study to a maximum of *n*=64 in Tsai et al.'s (2008) work. Eight studies recruited participants from a broad distribution including various clinical and educational settings (Przysucha and Taylor, 2004;

Przysucha et al., 2008; Tsai et al., 2008; Tsai et al., 2009b; Chen et al., 2016; Fong et al., 2016; Speedtsberg et al., 2017; Chen et al., 2019). The studies by Bonney et al. (2017), Chen et al. (2015), Diz et al. (2018), and Smits-Engelsman et al. (2015), on the other hand, recruited participants from one setting. Meanwhile, Chen et al. (2011) did not mention the source of recruitment. Moreover, several studies had a ratio of boys to girls that ranged from 3:1 to 5:1 (see Table 3.18), while the studies by Przysucha et al. recruited predominantly male participants.

- DCD eligibility criteria

The DSM criteria were explicitly reported to be followed by Bonney et al. (2017) and Smits-Engelsman et al. (2015) who followed the DSM-V and reported the methods to conform each criterion, while Fong et al. (2016) followed the DSM-IV but did not mention the methods employed. Of the DSM-V, criterion A was fulfilled by all of the studies in which the M-ABC1 or MABC2 motor assessment tests were used. The study by Speedtsberg et al. (2017) specified in their inclusion criteria that only children in the ≤15th percentile of the M-ABC2 could participate but all of the participants were in the ≤5th percentile.

Criterion B was fulfilled by six studies by which parents' and/or teachers' report, the M-ABC2 checklist, the DCD questionnaire (DCD-Q) or the motor behaviour checklist (MBC) was used to confirm the impact of motor difficulties on ADLs and academic performance (Bonney et al., 2017; Chen and Tsai, 2016; Fong et al., 2016; Smits-Engelsman et al., 2015; Przysucha and Taylor, 2004; Przysucha et al., 2008) (see Table 3.18).

In addition, criterion C was only fulfilled by Bonney et al. (2017) using a parental questionnaire and Smits-Engelsman et al. (2015) by indicating that the age range of the recruited participants was from as young as 6 years old, which presumably suggests that DCD symptoms appear at an early developmental stage. However, the onset of DCD symptoms in the older age group of the recruited children was not referred to.

The majority of the included studies satisfied criterion D using various methods (see Table 3.18) to screen participants against any neurological (Speedtsberg et al., 2017), intellectual (Chen et al., 2019; Chen et al., 2015) or both problems (Bonney et al., 2017; Chen and Tsai, 2016; Diz et al., 2018; Fong et al., 2016; Przysucha and Taylor, 2004; Przysucha et al., 2008; Smits-Engelsman et al., 2015; Tsai et al., 2009b; Tsai et al., 2008). The exception was the study by Chen et al. (2011) in which the assessment of such problems was not reported.

- Confounding factors

Given the heterogeneity of DCD and to reach a meaningful comparison between the performance of DCD and TD, most of the studies ensured that children in both groups do not exhibit significant differences in their demographic and morphologic characteristics such as their intelligence level, activity level, postural control skills, BMI, and foot size (Bonney et al., 2017; Chen et al., 2019; Chen and Tsai, 2016; Chen et al., 2015; Chen et al., 2011; Fong et al., 2016; Przysucha and Taylor, 2004; Przysucha et al. 2008; Smits-Engelsman et al., 2015; Speedtsberg et al., 2017; Tsai et al. 2009b; Tsai et al., 2008) (see Table 3.18).

In addition, excluding children with ADHD to better understand the mechanisms behind the motor difficulties of DCD was achieved in half of the studies (Chen et al., 2019; Chen and Tsai, 2016; Diz et al., 2018; Fong et al., 2016; Tsai et al., 2009b; Tsai et al., 2008). Moreover, Chen et al. (2019), Chen and Tsai (2016), Chen et al. (2015), and Diz et al. (2018) considered handedness and only recruited right-handed participants which might help to better arrive at valid results because their experiments concerned upper limb function.

On the other hand, Przysucha and Taylor (2004), Przysucha et al. (2008), Tsai et al. (2009b), and Tsai et al. (2008) only included participants with a $\leq 5^{th}$ percentile score of the balance subtest of the M-ABC which may not be applicable to the general population of DCD and, therefore, could limit the generalisability of their results. Similarly, Przysucha and Taylor (2004) and Przysucha et al. (2008) only included male participants. However, all of the studies included in this category recruited children with similar chronological age range (<3 months difference) for both DCD and TD.

Table 3.18: Characteristics and settings of the included studies - motor skills category

Reference, study design & country	Sample size & gender	age range (mean±SD)	DCD eligibility criteria	Quality score
Bonney et al. (2017) Randomised controlled trial South Africa	DCD: 57 29 boys, 28 girls TD: 54 28 boys, 26 girls	DCD: 6-10 years (8.0±1.0) TD: 6-10 years (8.0±1.0)	DSM-V: crit. (A) M-ABC2 ≤5^{th} %tile, crit. (B) teacher or parent report, crit. (C) parental questionnaire, crit. (D) teacher report of level of intellectual and cognitive abilities	16
Chen et al. (2019) Case control Taiwan	DCD: 26 12 boys, 14 girls TD: 26 11 boys, 15 girls	DCD: 11-12 years (11.82±0.46) TD: 11-12 years (11.71±0.50)	M-ABC2 ≤5^{th} %tile, intellectual impairments excluded by KBITt (>80), ADHD excluded by Conner's Teacher Rating Scale (<70), musculoskeletal conditions that might affect posture were excluded by parental report, right-handed	22
Chen and Tsai (2016) Case control Taiwan	DCD: 30 18 boys, 12 girls TD: 30 14 boys, 16 girls	DCD: 11-12 years (11.87±0.48) TD: 11-12 years (11.73±0.52)	M-ABC2 ≤5^{th} %tile, M-ABC2 checklist ≥95^{th} %tile, intellectual difficulties excluded by KBIT-2(>80), ADHD excluded by CADS (<70), other medical conditions excluded by participant's medical history	22
Chen et al. (2015) Case control Taiwan	DCD: 24 14 boys, 10 girls TD: 24 11 boys, 13 girls	DCD: 11-12 years (11.97±0.63) TD: 11-12 years (11.94±0.61)	M-ABC2 ≤5^{th} %tile, IQ>80	19
Chen et al. (2011) Case control USA	DCD: 32 17 boys, 15 girls TD: 32 17 boys, 15 girls	DCD: 9-10 years (9.40±0.50) TD: 9-10 years (9.21±0.42)	M-ABC1 ≤5^{th} %tile, excluded ADHD using ADHD-RS	19
Diz et al. (2018) Experimental Brazil	DCD: 12 10 boys, 2 girls TD: 12 10 boys, 2 girls	DCD: 9-10 years (10.12±0.49) TD: 9-10 years (10.04±0.55)	M-ABC1 ≤5^{th} %tile, ADHD and other neurological conditions were excluded by the school team	20

Fong et al. (2016) Case control Hong Kong	DCD: 30 23 boys, 7 girls TD: 20 11 boys, 9 girls	DCD: 6-10 years (7.7±1.5) TD: 6-10 years (7.9±1.6)	M-ABC1 ≤5th %tile, independent DCD diagnosis based on the DSM-IV, DCD-Q, ADHD and other neurological, intellectual, and medical conditions were excluded	22
Przysucha and Taylor (2004) Case control Canada	DCD: 20 boys TD: 20 boys	DCD: 6-10 years (8.7±2.1) TD: 6-10 years (8.6±2)	M-ABC1 ≤5th %tile, M-ABC1 ≤5th tile on TBS, MBC (score NR)	17
Przysucha et al. (2008) Case control Canada	DCD: 17 boys TD: 19 boys	DCD: 6-11 years/ younger group (*n*=9) (7.0±0.86)/ older group (*n*=8) (10.50±1.50) TD: 6-11 years/ younger group (*n*=10) (6.9±0.7)/ older group (*n*=9) (10.65±1.20)	M-ABC1 ≤5th %tile, M-ABC1 ≤5th tile on TBS, MBC (score NR)	16
Smits-Engelsman et al. (2015) Experimental South Africa	DCD: 17 9 boys, 8 girls TD: 17 9 boys, 8 girls	DCD: 6-10 years (7.94±1.2) TD: 6-10 years (7.65±1.1)	DSM-V: crit. (A) M-ABC2 ≤5th %tile, crit. (B) teacher report, crit. (C) only included children aged 6-10 years, crit. (D) parent and teacher report	22
Speedtsberg et al. (2017) Case control Denmark	DCD: 9 7 boys, 2 girls TD: 10 7 boys, 3 girls	DCD: *age range NR* (9.0±0.5) TD: *age range NR* (9.1±0.4)	DSM-IV, M-ABC2 ≤15th %tile, independent DCD diagnosis by a qualified health professional, neurodevelopmental disorders excluded by	20
Tsai et al. (2009b) Case control Taiwan	DCD: 39 23 boys, 16 girls TD: 39 21 boys, 18 girls	DCD: 9-10 years (116.26±4.45 mo.) TD: 9-10 years (114.82±2.99 mo.)	M-ABC1 ≤5th %tile, ≤5th tile on TBS, ≤10th tile on static balance score, ADHD excluded by ADHD Rating Scale, neurodevelopmental and intellectual disorders were excluded by a peadiatrician,	21

Tsai et al. (2008) Case control Taiwan	DCD: 64 30 boys, 34 girls TD: 71 33 boys, 38 girls	DCD: 9-10 years (10.1±0.3) TD: 9-10 years (10.3±0.2)	M-ABC1 ≤5th %tile, ≤5th tile on TBS, >1 %tile on static balance score, excluded <70 of IQ, other neurodevelopmental and intellectual disorders were excluded, ADHD excluded by peadiatrician	21

%tile, percentile; ADHD, attention deficit hyperactivity disorder; CADS, Conner's ADHD DSM-IV Scales; crit., criterion; DCD-Q, DCD-questionnaire; IQ, intelligence quotient; KBIT, Kaufmann Brief Intelligence Test; MBC, motor behaviour checklist; mo., months; NR, not reported; TBS, total balance score

Apparatus and methodological procedures

Of the studies that employed the manipulation of visual stimuli and assessed visuomotor integration, Bonney et al. (2017) and Smits-Engelsman et al. (2015) used a videogame (WiiFit) through which visual stimuli were presented in different directions and participants were asked to sway their body accordingly. In both studies, children's scores were calculated based on their speed and accuracy of performance, as determined by participants' CoP displacement while leaning towards the visual inputs (see Table 3.19). In addition, another task was employed in both studies (the yoga test) that consisted of one-leg stance with which online visual feedback of participants' performance was presented. A score was calculated by counting the time taken to reach the required position and the errors made through movement deviations.

Similarly, Diz et al. (2018) measured children's grip strength (isometric finger force/torque) with and without visual feedback of the force and control exerted to measure the effect of providing extra visual cues (visual feedback) on motor control. The task of Diz et al. involved the maximum voluntary finger force/torque (MVT) and a constant isometric finger force/torque (CONST) at 25% of MVT. The MVT, RMSE and coefficient of variation were calculated in Diz et al**.**

Balance skills in response to visuospatial changes of visual stimuli were also measured by Chen and Tsai (2016) and Chen et al. (2011; 2015). In Chen and Tsai (2016) and Chen et al.'s (2011) research, the participants were asked to maintain static balance while performing a signal detection task that involved the presentation of paired vertical flashing lines as visual inputs. The task employed two levels of perceptual difficulties according the sizes and colours of the visual stimuli, which resulted in two conditions: high difficulty (HD) and low difficulty (LD) (see Table 3.19). The task of both studies required children to press a button using a device held in their dominant hand if the presented vertical lines were unequal in size. Nevertheless, Chen and Tsai (2016) provided haptic cues as a light touch condition (LT) using a touch plate placed next to the participants while they perform the task. The authors compared the outcomes of the LT to the no touch (NT) condition to measure the effect of providing extra haptic stimuli on maintaining balance and motor control (see Table 3.19).

In a similar way, a precision aiming task was employed in Chen et al. (2015) in which children had to keep a laser beam held in their hands on visual stimuli presented in different locations and of different sizes while maintaining their static balance (see Table 19). The errors of the signal detection and precision aiming tasks were calculated in Chen et al. (2015). On the other hand, similar to Chen and Tsai (2016), Chen et al. (2019) investigated the effect of providing additional haptic stimuli on postural control (static balance) in children using a touch plate while being blindfolded. The authors employed three conditions: LT, NT, and light fingertip touch after hand soaking in water (LTAS). Additionally, haptic sensitivity threshold which is the ability to detect the minimum haptic stimulus using filaments of different sizes was measured in Chen et al. (2019). Moreover, body displacement in different axes was measured in all of the abovementioned studies by Chen and colleagues (see Table 3.19).

Przysucha and Taylor (2004) and Speedtsberg et al. (2017), on the other hand, measured static balance skills with and without visual inputs (eyes open vs eyes closed). Speedtsberg et al. further employed an ‘unreliable’ visual condition by manipulating the visual inputs and disturbing spatial information using a visual conflict dome placed over the participants’ heads. In addition, to measure the effect of vestibular and proprioceptive information processing on balance skills, different surfaces (firm vs compliant) were provided for children to maintain static balance on in Speedtsberg et al.

The CoP displacements in the AP and ML axes and sway length were measured by both Przysucha and Taylor (2004) and Speedtsberg et al. (2017). In addition, the sway area was measured by Przysucha and Taylor, whereas the root mean square (RMS) was considered by Speedtsberg et al. However, because the empirical literature suggests that rambling and trembling control mechanisms contribute to postural sway (Speedtsberg et al., 2017), the dependent variables in Speedtsberg et al.’s study were separately quantified for those two components. Moreover, Romberg’s quotient (RQ), which is measured to examine the degree of reliance on visual stimuli, was explored by Przysucha and Taylor (see Table 3.19).

Balance skills with and without visual inputs (eyes open vs eyes closed) were also examined by Tsai et al. (2008; 2009b). However, similar to Chen and Tsai (2016) and Chen et al. (2011), in the eyes open condition in Tsai et al.’s (2009b) study, children had to maintain static balance while performing several cognitive tasks to measure the effect of dual-tasks and cognitive demands on maintaining balance. These cognitive tasks involved attention and memory tasks that varied in complexity, including some that required participants to hold a device and use it to indicate the correct answer while performing the static balance test (see Table 3.19).

Meanwhile, Tsai et al. (2008) adopted a different approach whereby children were asked to maintain static balance on one or two legs with their eyes closed or open. Sway area and RQ were explored in the two studies by Tsai et al. (2008; 2009b), in addition to measuring the sway path in Tsai et al. (2008). Moreover, Tsai et al. (2009b) also measured the variation index (Vi) which quantifies the magnitude of balance modification in response to cognitive demands.

Przysucha et al. (2008) and Fong et al. (2016) explored children's skills in processing multisensory information which included vestibular, proprioceptive, auditory and visual to maintain dynamic balance. In order to explore children's limits of stability (LOS), visual and auditory stimuli were presented simultaneously at various locations by Fong et al. (2016) to which children had to lean. Alternatively, Przysucha et al. (2008) asked children to lean their bodies in different directions to determine their ability to combine visual, vestibular, and proprioceptive information to maintain their balance. Several chronometric and kinematic measurements were taken in the two studies by Przysucha et al. (2008) and Fong et al. (2016). Fong et al. measured the RT, movement excursion, movement velocity, and directional control, whereas Przysucha et al. explored CoP displacement, path length, MT, mean and maximum area of sway (Aomean and Aomax), time to reach peak velocity (TTPV), relative time spent in the corrective phase (RTCP), and peak frequency of CoP profiles (*ƒ*peak) (see Table 3.19).

Table 3.19: Paradigm and outcome measures of the included studies - motor skills category

Reference	**Paradigm**	**Procedure**	**Outcome measures**
Bonney et al. (2017)	Maintain balance while leaning towards visual stimuli presented in different locations through (WiiFit) videogames	**Conditions** Ski slalom game (criterion test): lean towards different directions (to enter visual gates) with online visual feedback of performance Yoga game: static balance with one leg for both legs with online visual feedback of performance **Procedure** 10 trials x criterion test 30 sec. x each one-leg test Dominant and non-dominant legs tested Assessor blinded to group allocation of participants Instructed to move as fast as possible	Wii Fit balance board was used for balance measurement **Criterion test score (NU):** a measure of performance speed and errors (missing the visual target), with visual feedback **Yoga test score (NU):** a measure of performance speed (sec.) and posture steadiness
	Additional measures	(WiiFit) videogame was used as an intervention under repetitive and variable training programmes; measurements repeated training and a comparison between programmes was conducted	
Chen et al. (2019)	Maintain static balance with and without fingertip touch, and after finger soaking in water-solution	**Conditions** No fingertip touch (NT) Light fingertip touch (LT) Light fingertip touch after immersion in surfactant-water solution for 5 min. (LTAS) **Procedures** 3conditions x60 sec. Dominant hand only	Motion tracking system sampled at (30 Hz) used for balance measurement **Sensitivity to light touch (mean log of force):** minimum detectable touch stimulus for each participant Test 1 (baseline) Test 2 (after LT or NT condition) Test 3 (after finger soaking)

		Pseuodo-random presentation of conditions with the LTAS always the last condition Assessor blinded to group allocation of participants Fixed position of heel and toe using markers on the platform Arm posture was identical across all trials (with and without fingertip touch), arm kinematics were measured to ensure posture was fixed Force of fingertip touch was maintained for <1 N Trials were recorded to ensure the fingertip touch was maintained	**CoP displacement (cm):** AP and ML axes
Chen and Tsai (2016)	Maintain static balance with and without fingertip touch and while performing a signal detection task	**Conditions** Fingertip light touch (LT) No fingertip light touch (NT) Signal detection tasks: Target signals: lines different in length Non-target signals: lines identical in length **Procedure** 3 trials x2 conditions x2 signal detection tasks (30 target signals/ 60 non-target signals) Force of fingertip touch was maintained for <1 N Fingertip touch was monitored Instructed to respond as fast as possible Adjustable equipment	Force platform (sampled at 100 Hz) was used for balance measurements **CoP displacements (cm):** AP and ML axes **Signal detection performance (d'):** perceptual discriminability between the two tasks

Chen et al. (2015)	Maintain static balance while performing precision aiming task	**Conditions** Target locations: in front vs at the sides Target sizes: large circle (4 cm) vs small circle (2 cm) **Procedures** 3trials x2target locations x2target sizes Randomly presented Arms at the sides Arm position monitored Position of participants was fixed by markers	Motion tracking system (sampled at 120 Hz; placed at seventh cervical vertebrae) was used for balance measurements **Body displacement (cm):** AP and ML axes **Aiming task performance (NU):** Number of times the laser beam moved outside the target circle
Chen et al. (2011)	Maintain postural control while performing a signal detection task	**Conditions** Neutral: vertical lines equal in size, but dark in the LD and grey in the HD Critical: vertical lines different in size; left line with a vertical extension of 1.95° in both LD and HD, and right line with a vertical extension of 2.35° in the LD and 2.12° in the HD condition **Procedure** 6 blocks of 30 critical and 60 neutral conditions Randomly presented Dominant hand Children's attention to task was monitored, data of the participants who indicated that they were not fully attentive to the signal detection task were removed from the analysis. Kept both hands on the sides Adjustable equipment	Magnetic sensors attached to a helmet and at the seventh cervical vertebrae **Postural activity (cm):** AP and ML head and torso positional variability **Perceptual sensitivity (d'):** difference of the correct and incorrect responses of signal detection task

	Additional measures	Subjective measurement of workload was compared between the conditions and group to ensure task difficulty is similar between the groups using NASA-TLX; (Hart, 1988 #2057)	
Diz et al. (2018)	Pinch a knob with the index and thumb fingers with and without visual feedback	**Conditions** MVT (baseline) 2 trials With visual feedback (15 sec.) Without visual feedback (5 sec.) **Procedure** 20 trials Right hand only Arm position maintained with constraints	Load cell sensors sampled at (100 Hz) to measure finger force **Maximum voluntary finger force/torque (MVT, Nm)** **root mean square error (RMSE; Nm):** performance accuracy **coefficient of variation (CV; %):** performance variability
	Additional measures	Measurements repeated after five consecutive days of practicing force exertion at a constant isometric force/torque output for a target force/torque level corresponding to 25% of the MVT with visual feedback	
Fong et al. (2016)	Maintain dynamic balance while reaching for targets (auditory and visual stmuli) presented in different locations with a visual feedback on screen	**Conditions** 4 x diagonal locations 4 x cardinal locations **Procedure** Instructed to move as fast as accurately as possible	**Reaction time (sec.):** between the onset of stimuli presentation (visual-auditory) and onset of voluntary shifting **Movement velocity (°/sec.):** Average velocity of CoP movement **Maximum excursion (% LOS):** maximum distance traveled by the CoP **Endpoint excursion (% LOS):** distance of the CoP movement at first attempt toward the target **Directional control (% accuracy):** smoothness of the displacement of the CoP; percentage of the total on-target movement

	Additional measures	They also measured the incidents of fall and percentage of falls and correlated them with the body sway outcomes	
Przysucha and Taylor (2004)	Maintain static balance with and without vision	**Conditions** Eyes-open Eyes-closed **Procedure** 2 trials of each condition x20 sec. Foot position fixed with markers Arms crossed at chest Adjustable equipment	Force platform (sampled at 100 Hz) was used for balance measurements **CoP displacements (cm):** AP sway, Lateral sway (Lat), Path length (L) **Area of sway (Ao; cm2)** **Romberg's quotient (RQ; %)**: calculated as the coefficient of variance in eyes closed/ coefficient of variance in eyes open x 100
Przysucha et al. (2008)	Maintain dynamic balance in different directions	**Conditions** AP and Lateral **Procedure** 3x trials Foot position was fixed with markers	Force platform (sampled at 100 Hz) was used for balance measurements **CoP displacements (cm):** AP sway, Lateral sway (Lat), Path length (L) **Mean area of sway (Aomean; cm²)** **Maximum area of sway (Aomax; cm²)** **Movement time (MT; sec)** **Time to peak velocity (TTPV; sec)** **Relative time spent in the corrective phase (RTCP; %):** 100 – [time to peak velocity/movement time x 100] **Peak frequency of CoP profiles (*f*peak; Hz)**

Smits-Engelsman et al. (2015)	Maintain balance while reaching for visual stimuli presented in different locations through a (WiiFit) videogame	**Conditions** Ski slalom game: maintain balance while reaching visual inputs presented in different directions with online visual feedback of performance: hard (27 visual stimuli) vs easy games (19 visual stimuli) Yoga game: static balance with one leg for both legs with online visual feedback of performance Single-leg stance (BOT2): one-leg (dominant) standing on the balance beam **Procedure** 1 game session of 20 min.	Wii Fit balance board was used for balance measurement **Wii scores (NU):** a measure of performance speed and errors (missing the visual target), with visual feedback **Yoga test score (NU):** a measure of performance speed (sec.) and posture steadiness
	Additional measures	Measurements repeated after 100 trials of WiiFit games The authors tested how children improved their performance using any of three strategies: A) deacrease time to improve accuracy (speed accuracy trade-off); B) decrease accuracy without changing time (accuracy strategy); C) decrease accuracy and increase time (master strategy)	
Speedtsberg et al. (2017)	Maintain static balance on a firm or compliant surface with and without vision	**Conditions** A combination of: open vs closed eyes, firm vs compliant surface, reliable vs unreliable vision EOFS: eyes open firm surface, ECFS: eyes closed firm surface, EOCS: eyes open compliant surface, ECCS: eyes closed compliant surface, UVFS: unreliable vision firm surface, UVCS: unreliable vision compliant surface **Procedure** 3 trials x 6 conditions	A force plate (sampled at 100Hz) was used for balance measurement **CoP displacement (mm):** rambling and trembling in AP and ML **Sway length (m)**: total displacement of CoP **Root mean square/ rambling and trembling (RMS; mm):** in AP and ML **Rambling ratio:** rambling contribution to total sway length
Tsai et al. (2009b)	Maintain static balance while performing cognitive tasks	**Conditions** Single-task balancing test: no cognitive task	Force platforms (sampled at 100 Hz) was used for balance measurements

		Oral counting task (OC): count backwards Auditory–verbal reaction task (AV): indicate the level of the tone (high or low) by verbal responses Auditory–choice reaction task (AC): indicate the level of the tone (high or low) by motoric responses (press a button) Auditory–memory task (AM): recall food names Articulation alone (AA): say 'yes' for 30 s (control task) Balance test with eyes closed (EC) **Procedure** Tasks were randomly presented	**Variation index (Vi; NU):** a measure of single-task of balance (without cognitive task)/ /(each dual task) ratio values **Sway area (mm^2)** **Romberg's quotient (RQ; mm^2)**: calculated as the sway area in eyes closed/ sway area in eyes open x 100
Tsai et al. (2008)	Maintain static balance with one and two legs, and with and without vision	**Conditions** A combination of: open vs closed eyes, one vs two legs, dominant vs non-dominant **Procedure** 3 trial x each condition conditions Both dominant and non-dominant Children's eyes were monitored	Force platform (sampled at 100 Hz) for balance measurement **CoP displacement (cm):** AP and ML axes **Sway area (cm^2)** **Sway path (cm)** **Romberg's quotient (RQ; %)**: CoP in the eyes closed condition/ CoP in the eyes open condition x 100

%, percentage; °, degree; °/sec., degree per second; AP, anteroposterior; cm, centimetre; cm^2, centimetre squared; CoP, centre-of-pressure; d', an index of perceptual sensitivity; HD, high difficulty; Hz, Hertz; LD, low difficulty; LOS, limit of stability; max., maximum; ML, mediolateral; mm, millimetre; mm^2, millimetre squared; NASA-TLX, National Aeronautics and Space Administration Task Load Index; Nm, newton-metre; NU, no unit; sec., seconds

Results

Bonney et al. (2017) and Smits-Engelsman et al. (2015) found that the DCD group had significantly higher scores (i.e., more errors and slower responses) in the WiiFit balance test and significantly lower scores in the yoga test (i.e., less accurate in maintaining the position) across conditions compared to the TD group (see Table 3.20). Moreover, children with DCD performed the CONST task in Diz et al. (2018) with significantly more errors than TD children in the visual feedback condition ($p<.05$) but not in the no feedback condition. However, the p-value for the latter was not reported. The authors illustrated that the performance of the DCD group did not differ between the conditions (feedback vs no feedback), therefore the difference in performance between the groups is probably due to the improvement exhibited by the TD in the feedback condition. In addition, Diz et al. (2018) found that variation in performance was significantly greater in the DCD group both with and without visual feedback, respectively ($p<.05$ and $p<.01$) (see Table 3.20). However, similar performance in the maximum voluntary force/torque between the DCD and TD groups was evidenced by Diz et al. (2018) ($p=.50$).

Chen et al. (2019) and Chen and Tsai (2016) arrived at similar findings. Both studies found that AP body sway was significantly greater in children with DCD in the NT and LT conditions (see Table 3.20) compared to TD children. However, Chen et al. (2019) did not find a significant difference in AP sway in the LTAS condition between DCD and TD ($p=.10$) (see Table 3.20). In addition, the outcomes of Chen et al. (2019) confirm that children with DCD have a significantly lower sensitivity (i.e., higher threshold) to LT compared to TD children ($p<.05$) in all conditions. Moreover, Chen et al. (2019) and Chen and Tsai (2016) found that both DCD and TD significantly decreased body sway from the NT to LT condition (see Table 3.20). However, Chen and Tsai (2016) indicated that the reduction was significantly greater in the TD group than in the DCD group ($p=.014$). On the other hand, Chen et al. (2019) reported that the DCD group had significantly greater body sway in LT than LTAS ($p<.05$), whereas the TD group did not exhibit a significant difference ($p=.14$). Meanwhile, no significant difference was found in terms of ML body sway in either of these studies (see Table 3.20).

Similarly, Chen et al. (2011) and Chen et al. (2015) found that significantly larger body displacement was evidenced in the DCD group compared to the TD group (see Table

3.20). However, with regard to the signal discrimination task in the studies of Chen and Tsai (2016) and Chen et al. (2011), the DCD group was found to have significantly lower d' values (i.e., more errors) ($p<0.001$) in Chen and Tsai's (2016) research but not in Chen et al.'s (2011) study which found no significant difference between the groups, albeit they did not report the p-value.

Nevertheless, Chen and Tsai (2016) indicated that the d' value of the DCD group underwent a significantly greater increase from NT to LT ($p=.004$), indicating a better performance. However, the TD group did not exhibit a significant increase, which could be due to the ceiling effect of the task. Chen et al. (2011), on the other hand, found that the difference between the groups in terms of d' value was greater in the high difficulty (HD) compared to the low difficulty (LD) task.

Similar to Chen et al. (2011), Chen et al. (2015) found that a significant difference in terms of the performance of the aiming task was only evident between the DCD and TD groups in the side target conditions (i.e., harder tasks) and not in the front target conditions. In addition, Chen et al. (2015) reported that body displacement was greater in the DCD group in the side target condition (see Table 3.20). However, in both studies, several numerical data to show the statistical difference between the groups were not reported (see Table 3.20).

Similar to the studies of Chen and colleagues, Przysucha and Taylor (2004) found significantly larger body displacements among the DCD group than the TD group in the AP axes ($p<.01$) but not in the ML ($p<.19$) (see Table 3.20). In addition, the sway area was significantly larger in the DCD group compared to TD ($p<.03$). Furthermore, as measured by the RQ, Przysucha and Taylor found that children with DCD do not overly rely on visual inputs and act similarly to TD children when visual information is removed (eyes closed) to maintain postural control ($p<.51$).

Speedtsberg et al. (2017) found that children with DCD exhibit significantly greater sway (rambling and trembling) in both the AP and ML directions compared to the TD (see Table 3.20) but with large variations in their performance. However, Speedtsberg et al. found no significant difference between the groups in the conditions that involved compliant surfaces and/or occluded or unreliable vision (see Table 3.20).

The results for the cognitive tasks in the study of Tsai et al. (2009b) indicated that children with DCD were able to perform similarly to TD children (see Table 3.20). This supports the findings of Chen et al. (2011) who reported no significant difference in the performance of the cognitive task. In addition, in the study of Tsai et al., the DCD group performed similarly to the TD group in terms of the balance single-task ($p=.393$). However, regarding the outcome of the dual-tasks in Tsai et al., the authors indicated that children with DCD had a significantly larger sway area than in the single-task, yet similar to the TD group. Moreover, the dual-tasks were performed with significant large variations among the DCD group, unlike the TD group. In addition, the DCD group in Tsai et al.'s (2009b) study were able to maintain their sway area similar to the TD group in some conditions that involved a cognitive task (see Table 3.20). However, Tsai et al. only reported the within-subject p-values and did not consider between-group statistical comparisons.

Tsai et al. (2008), on the other hand, found that children with DCD performed all the balance tasks with significantly larger body sway and sway area (see Table 3.20), except when two legs and dominant leg stance were measured while the participants kept their eyes open. Moreover, in accordance with the findings of Przysucha and Taylor (2004), both Tsai et al. (2009b) and (2008) reported that the RQ, which is a measure of reliance on visual stimuli, is similar between the DCD and TD groups, thereby indicating an equivalent level of dependence on visual inputs between the groups.

The results of Fong et al. (2016) revealed no significant difference between the DCD and TD groups (see Table 3.20), except in terms of the maximum excursion in the backward direction in which the DCD group exhibited a significantly smaller CoP displacement (i.e., smaller limits of stability) ($p<.003$). Likewise, children with DCD had a significantly smaller CoP displacement in Przysucha et al.'s (2008) study in the AP axis ($p<.01$) but not in the ML (lateral sway), similar to several other studies, albeit that the p-value for the latter was not reported. Furthermore, a significantly smaller sway area and path length (ps<.01) were shown in the DCD group compared to the TD group. In addition, children with DCD took longer TTPV ($p<.05$) with larger modifications of movement, as evidenced in the significantly smaller RTCP ($p<.002$) and higher $f$peak ($p<.009$) in comparison with TD children.

Table 3.20: Results of the included studies - motor skills category

Reference	Outcome	Condition	Results Mean (±SD), effect size (ES), p-value
Bonney et al. (2017)	Criterion test score (NU)	Criterion test	**DCD** 175.57(±37.29) sig. larger than **TD** 155.83(±39.03), ES(η^2)=.11, ***p*<.001**
	Yoga test score (NU)	Yoga test	**DCD** sig. lower than **TD** for the left leg, ES(η^2)=.08, ***p*=.002,** and right leg, ES(η^2)=.11, ***p*<.0001,** *Mean values NR*
	Additional measures	Criterion test: no sig. difference between the variable and repetitive practice groups in both **DCD** and **TD, *p*=.34;** All groups had sig. higher scores after training period**, *p*<.0001**, no sig. practice type (variable vs repetitive) x group (**TD** vs **DCD**) interaction ***p*=0.18**	
		Yoga test: sig. large effect of training on yoga test on the left leg ***p*<.0001** and right leg ***p*<.0001** for both groups	
Chen et al. (2019)	Sensitivity to light touch (mean log of force; NU)	Test 1 (baseline)	**DCD** 2.77(±0.29) sig. higher threshold than **TD** 2.46(±0.28), ***p*<.05**
		Test 2 (post LT or NT)	**DCD** 2.71(±0.29) sig. higher threshold than **TD** 2.43(±0.29), ***p*<.05**
		Test 3 (post LTAS)	**DCD** 2.38(±0.33) sig. higher threshold than **TD** 2.13(±0.35), ***p*<.05**
		Test 1 vs test 2	Sensitivity did not sig. differ between the two tests similarly for both groups ***p*=.39**
		Test 2 vs test 3	Sensitivity sig. differed between the two tests similarly for both groups ***p*<.05**
		AP (NT)	**DCD** 0.81 cm (±0.07) sig. larger than **TD** 0.75 cm (±0.10), ES($\eta_p 2$)=.69, ***p*<.05**

	CoP displacement (cm)		
		AP (LT)	**DCD** 0.63 cm (±0.06) sig. larger than **TD** 0.54 cm (±0.04), ***p*<.05**
		AP (LTAS)	**DCD** 0.54 cm (±0.04) not sig. different from **TD** 0.53 cm (±0.03), ***p*=.10**
		AP (condition effect)	Both groups: sig. greater body sway in the NT than LT, ***p*<.05** **DCD** sig. greater body sway in LT than LTAS, ***p*<.05** vs **TD** no sig. difference in body sway between LT and LTAS, ***p*=.14**
		ML	No significant effects found for ML body sway, *NOVR*
	Additional measures	Finger touch force (of touch plate)	No sig. difference between DCD and TD across all conditions
Chen and Tsai (2016)	CoP displacement (cm)	AP	**DCD** 0.746 cm (±0.068) sig. greater than **TD** 0.645 cm (±0.101), ES(η_p2)=.310, ***p*<.001**
		AP (condition effect)	**DCD** and **TD** body sway sig. decreased from NT 0.779 cm (±0.108) to LT 0.612 cm (±0.092), ES(η_p2)=.436, ***p*<.001** **DCD** 0.141 cm (±0.062) body sway sig. less reduced than **TD** 0.194 cm (±0.096) from NT to LT, ***p*=.014,**
		ML	No significant effects found
	Signal detection task (d’)	Perceptual discrimination (d’)	**DCD** 2.931 d’ (±0.369) sig. lower than **TD** 3.441 d’ (±0.398), ES(η_p2)= 0.394, ***p*<0.001** d’ sig. increased from NT to LT for **DCD**, **p=<.001** and **TD,** ***p*=.012** **DCD** 0.559 d’ (±0.189) sig. greater increase in d’ than **TD** 0.219 d’ (±0.153) from NT to LT, ***p*=.004**

Chen et al. (2015)	Body displacement (cm)	AP	**DCD** 0.84 cm (±0.36) sig. greater than **TD** 0.67 cm (±0.22), ES(η_p2)=.16, ***p*<.01**
		Target effect	Both groups: sig. greater body sway in large targets 0.76 cm (±0.32) than small target 0.73 cm (±0.25), ES(η_p2)=.08, ***p*=.04** Sig. group × target size × target location × direction interaction, ES(η_p2)=.10, ***p*=.03** Front target (both groups): decreased ML sway and increased AP sway from large to small target, *NOVR* Side target: DCD: increased AP and ML sway from large to small target size vs TD: decreased AP sway and increased ML sway from large to small target size, *NOVR*
	Precision aiming task (NU)	Times laser beam out of target	Sig. group × target size × target location interaction, ES(η_p2)=.11, ***p*=.02** Front target (both groups): similar performance in large and small targets, *NOVR* Side target: **DCD** greater than **TD** in number of times of laser beam out of target from large to small target, *NOVR*
	Additional measures	Body sway (cm)	Both groups: body sway sig. greater in the AP 0.88 cm (±0.30) than ML 0.63 cm (±0.28), ES(η_p2)=.09, ***p*=.04**
		Target effect	Both groups: decreased body sway in large target 4.38 cm (±1.23) than small size target 6.46 cm (±2.07), ES(η_p2)=0.26, ***p*<.01**
Chen et al. (2011)	Perceptual sensitivity (d’)	Overall	**DCD** 3.20 d’ not sig. different from **TD** 3.80 d’, *NOVR*
		Task difficulty (HD vs LD)	Group x Task Difficulty interaction, ***p*<.05** Difference between the groups is larger in the HD than LD, *NOVR*
		AP (Head)	**DCD** sig. greater than **TD, *p*<0.05**

	Postural activity (cm)	ML (Head)	**DCD** sig. greater than **TD,** p**<0.05**
		AP (Torso)	**DCD** sig. greater than **TD,** p**<0.05**
		ML (Torso)	**DCD** sig. greater than **TD,** p**<0.05**
	Additional measures	Postural activity (qualitative measure)	DCD group increased their postural activity in the HD compared to the LD vs. TD decreases postural activity in the HD compared to the LD
		Mental workload (NASA-TLX)	**DCD** 68.27(±16.33) vs **TD** 63.28(±13.30), no sig. difference, *p-value NR*
Diz et al. (2018)	MVT (Nm)	**DCD** 0.45 Nm (±0.10) not sig. different from **TD** 0.48 Nm (±0.16)**,** p**=.50**	
	RMSE (Nm)	CONST (with visual feedback)	**DCD** sig. less accurate than **TD**, p**<.05**
		CONST (without visual feedback)	No sig. difference between groups*, NOVR*
	CV (%)	CONST (with visual feedback)	**DCD** sig. higher than **TD**, p**<.05**
		CONST (without visual feedback)	**DCD** sig. higher than **TD,** p**<.01**
	Additional measures	RMSE (Nm)	Both groups had sig. less errors after practice, p**<.05**
		CV	Both groups had sig. less variations after practice, p**<.05**
Fong et al. (2016)	Reaction time (sec.)	Forward direction	**DCD** 0.92 sec. (±0.47) not sig. different from **TD** 0.94 sec. (±0.31), ES(η_p^2)=.001, p**=0.838**
		Backward direction	**DCD** 0.61 sec. (±0.31) not sig. different from **TD** 0.71 sec. (±0.31), ES(η_p^2)=.025, p**=0.277**

		Right direction	**DCD** 0.83 sec. (±0.36) not sig. different from **TD** 0.68 sec. (±0.26), ES(η_p^2)=.051, ***p*=0.114**
		Left direction	**DCD** 0.77 sec. (±0.31) not sig. different from **TD** 0.82 sec. (±0.26**)**, ES(η_p^2)=.006**,** ***p*=0.606**
	Maximum excursion (% LOS)	Forward direction	**DCD** 97.97%(±12.89) not sig. different from **TD** 94.60%(±11.49**)**, ES(η_p^2)=0.018**,** ***p*=.350**
		Backward direction	**DCD** 67.63%(±22.81) sig. less than **TD** 87.15%(±20.63), ES(η_p^2)=.165, ***p*=.003**
		Right direction	**DCD** 100.07%(±11.60) not sig. different form **TD** 97.60%(±13.36), ES(η_p^2)=.010, ***p*=.492**
		Left direction	**DCD** 95.17%(±16.08) not sig. different from **TD** 134.65%(±179.81), ES(η_p^2)=.029, ***p*=.235**
	End point excursions (%)	Forward direction	**DCD** 67.10%(±28.67) not sig. different from **TD** 80.50%(±20.09), ES(η_p^2)=.064, ***p*=.076**
		Backward direction	**DCD** 59.63%(±25.62) sig. larger than **TD** 46.20%(±18.04**)**, ES(η_p^2)=.079, ***p*=.048**
		Right direction	**DCD** 77.53%(±29.52) not sig. different from **TD** 77.80%(±21.04**)**, ES(η_p^2)=<.001, ***p*=.972**
		Left direction	**DCD** 80.73%(±25.51) not sig. different from **TD** 78.00%(±14.08**)**, ES(η_p^2)=.004, ***p*=.665**
	Movement velocity (°/sec.)	Forward direction	**DCD** 4.92 °/sec. (±2.56) not sig. different from **TD** 4.67 °/sec. (±2.00**)**, ES(η_p^2)=.003, ***p*=.715**
		Backward direction	**DCD** 4.29 °/sec. (±2.20) not sig. different from **TD** 3.31 °/sec. (±1.85), ES(η_p^2)=.053, ***p*=.108**
		Right direction	**DCD** 6.02 °/sec. (±2.68) not sig. different from **TD** 6.61 °/sec. (±2.56**)**, ES(η_p^2)=.012, ***p*=.448**
		Left direction	**DCD** 6.35 °/sec. (±2.86) not sig. different from **TD** 6.17 °/sec. (±2.65), ES(η_p^2)=.001, ***p*=.820**

	Directional control (%)	Forward direction	**DCD** 78.97%(±16.44) not sig. different from **TD** 81.70%(±9.14), ES(η_p^2)=.009, ***p*=.503**
		Backward direction	**DCD** 49.13%(±23.95) not sig. different from **TD** 58.95%(±19.19), ES(η_p^2)=.047, ***p*=.132**
		Right direction	**DCD** 99.00%(±125.13) not sig. different from **TD** 74.85%(±8.55), ES(η_p^2)=.015, ***p*=.395**
		Left direction	**DCD** 74.83%(±13.32) not sig. different from **TD** 79.50%(±10.88), ES(η_p^2)=.034, ***p*=.199**
	Additional measures	**DCD**: sig. -ve correlation between (backward) LOS maximum excursion and the number of falls rho=-0.556, ***p*=.001** *Correlational data for the TD group NR*	
Przysucha and Taylor (2004)	AP sway (cm)	Eyes open	**DCD** 2.14 cm (±0.68) vs **TD** 1.66 cm (±0.52), *NOVR*
		Eyes closed	**DCD** 2.47 cm (±0.62) vs **TD** 2.04 cm (±0.63), *NOVR*
		Total	**DCD** 2.31 cm (±0.16) sig. larger than **TD** 1.85 cm (±0.12), ES(η2)=.15, ***p*<.01**
		Eyes open vs eyes closed	Both groups swayed significantly more in eyes closed condition compared to eyes opened, between-subjects, ES(η2)=.25, ***p*<.001**
	Lateral sway (cm)	Eyes open	**DCD** 2.12 cm (±0.74) vs **TD** 1.90 cm (±0.70), *NOVR*
		Eyes closed	**DCD** 2.20 cm (±0.81) vs **TD** 2.06 cm (±0.80), *NOVR*
		Total	**DCD** 2.16 cm (±0.19) not sig. different from **TD** 1.88 cm (±0.15), ES(η2)=.04, ***p*<.19**
		Eyes open vs eyes closed	Both groups swayed significantly more in eyes closed condition compared to eyes opened, between-subjects, ES(η2)=0.12, ***p*<.03**

	Path length (cm)	Eyes open	**DCD** 35.39 cm (±11.98) vs **TD** 30.63 cm (±6.58), *NOVR*
		Eyes closed	**DCD** 41.18 cm (±12.80) vs **TD** 37.78 cm (±7.27), *NOVR*
		Total	**DCD** 38.29 cm (±2.18) not sig. different from **TD** 2.18 cm (±34.21), ES(η2)=.04, ***p<.19***
		Eyes open vs eyes closed	Both groups swayed significantly more in eyes closed condition compared to eyes opened, between-subjects, ES(η2)=.65, ***p<.001***
	Area of sway (cm²)	Eyes open	**DCD** 0.52 cm² (±0.28) vs **TD** 0.33 cm² (±0.18), *NOVR*
		Eyes closed	**DCD** 0.63 cm² (±0.33) vs **TD** 0.47 cm² (±0.25), *NOVR*
		Total	**DCD** 0.578 cm² (±0.05) sig. larger than **TD** 0.406 cm² (±0.05), ES(η2)=.04, ***p<.03***
		Eyes open vs eyes closed	Both groups swayed significantly more in eyes closed condition compared to eyes opened, between-subjects, ES(η2)=.25, ***p<.001***
	Additional measures	No sig. difference between **DCD** and **TD** on RQ scores, ***p<.51***; both groups had >100% scores; larger body sway in no vision conditions	
Przysucha et al. (2008)	CoP (cm)	AP	**DCD** 7.56 cm (±1.37) sig. smaller than **TD** 9.09 cm (±1.57), ES(η2)=.29, ***p<.01***
		Lateral	**DCD** 8.96 cm (±1.41) not sig. different from **TD** 8.37 cm (±1.69), *NOVR*
		Path length	**DCD** sig. smaller than **TD, p<.01,** *NOVR*
	Aomean (cm²)	**DCD** 10.05 cm² (±4.95) sig. smaller than **TD** 14.89 cm² (±5.94), ES(η2)=.32, ***p<.01***	

	Aomax (cm²)		**DCD** 8.75 cm² (±4.26) sig. smaller than **TD** 12.93 cm² (±5.32), ES(η2)=.17, ***p*<.01**
	MT (sec.)		**DCD** 2.3 sec. (±0.75) not sig. different from **TD** 2.7 sec. (±0.74), *p-value NR*
	TTPV (sec.)		**DCD** 0.95 sec. (0.12) sig. longer than **TD** 0.52 sec. (0.11), ES(η2)=.12, ***p*<.05**
	RTCP (%)		**DCD** 54.09%(±18. 69) sig. smaller than **TD** 78.64%(±12.66), ES(η2)=.26, ***p*<.002**
	Ƒpeak (Hz)		**DCD** 1.40 Hz (±0.34) sig. higher than **TD** 1.00 Hz (±0.26), ES(η2)=. 26, ***p*<.009**
	Additional measures		No sig. differences between the groups in movement variability were found, except RTCP, ES(η2)=.13, ***p*<.05**
Smits-Engelsman et al. (2015)	Yoga task (NU)	Left leg	**DCD** 14.60(±18.91) sig. lower than **TD** 28.53(±17.48), ***p*=0.03**
		Right leg	**DCD** 17.82(±18.83) sig. lower than **TD** 32.12(±15.22), ***p*=0.02**
	Wii score (NU)	Easy	**DCD** 115.8(±28) sig. larger than **TD** 95.7(±21), ***p*=.024**
		Hard	**DCD** 178.0(±26) sig. larger than **TD** 150.1(±26), ***p*=.004**
	Additional measures		BOT2: no sig. between groups, ***p*=.055** Both groups improved after training in their Wii-score, ***p*=.001**, with sig. task difficulty effect, ***p*=.0001**, and run effect (between the sessions), ***p*=.001,** yoga task (after training) for both groups: lt leg, ***p*=.02**, rt leg, ***p*=.03,** no sig. difference between groups in yoga test after training No sig. effect of the different training programmes between the groups, ***p*=.12,** no sig. effect of a specific strategy, ***p*=.73**

Speedtsberg et al. (2017)	Overall sway length (m)	**Baseline** (EOFS)	**DCD** 0.62 m sig. larger sway length than **TD** 0.42 m**, *p*=.050**
	AP rambling (mm)		**DCD** 6.08 mm (±1.7) not sig. different from **TD** 5.02 mm (±2.4), ***p*=.142**
	AP trembling (mm)		**DCD** 1.4 mm (±0.34) not sig. different from **TD** 0.8 mm (±0.16), ***p*=.072**
	ML rambling (mm)		**DCD** 6.23 mm (±1.2) not sig. different from **TD** 4.96 mm (±2.3), ***p*=.065**
	ML trembling (mm)		**DCD** 1.65 mm (±0.37) sig. larger than **TD** 0.74 mm (±0.1), ***p*=.007**
	Overall sway length (m)	Across conditions	**DCD** not sig. different from **TD, *p*=.054**
	AP rambling (mm)	General (across conditions) **DCD** sig. larger than **TD, *p*=.0.031** **DCD** sig. larger than **TD** in ECFS, ***p*=.050**, EOCS, ***p*=.003**, UVCS, ***p*=0.041**, but not in the ECCS, ***p*=.086**, and UVFS, ***p*=.086**	
	AP trembling (mm)	General (across conditions): **DCD** sig. larger than **TD**, ***p*=.050** **DCD** sig. larger than **TD** in EOCS, ***p*=.011** and UVFS, ***p*=.05**, but not in ECFS, ***p*=.102**, ECCS, ***p*=.165**, and UVCS**, *p*=.072**	

	ML rambling (mm)	General (across conditions) **DCD** sig. larger than **TD,** ***p*=.025** **DCD** sig. larger than **TD** in EOCS, ***p*=.003,** ECCS, ***p*=.022**, but not in ECFS, ***p*=.142**, UVFS, ***p*=.121**, UVCS**,** ***p*=.051**	
	ML trembling (mm)	General (across conditions) **DCD** sig. larger than **TD,** ***p*=.007** **DCD** sig. larger than **TD** in ECFS, ***p*=.014**, EOCS**,** ***p*=.001**, UVFS, ***p*=.022**, UVCS, ***p*.013,** but not in ECCS, ***p*=.086**	
	rambling ratio (NU)	ML	**DCD** 0.77(±0.01) sig. larger than **TD** 0.82(±0.01), ***p*=.013**
		AP	**DCD** 0.78(±0.02) not sig. different from **TD** 0.80(±0.01), ***p*=.312**
	Additional measures	Sig. Group-Surface interaction on AP rambling**,** ***p*=.040**, ML rambling. ***p*=.034**, ML trembling, ***p*=.023** ML trembling showed a consistent significant increase in DCD than TD children	
Tsai et al. (2009b)	Cognitive tasks (NU)	**DCD** not sig. different from **TD** across all tasks: AC, ***p*=.080**; AM, ***p*=.266**; AV*,* ***p*=.097;** AA, ***p*=.254**	
	Balance (sway area - mm²)	Single task	**DCD** 201.21 mm² (±240.63) not sig. different from **TD** 164.03 mm² (±122.99), ***p*=.393**
		Dual task (OC)	Both groups: larger than single task, sig. large between-subjects ES(d)=1.02 for **DCD,** ***p*=.003**, but not for **TD**, ***p*=.069**
		Dual task (AV)	Both groups: larger than single task, sig. variation and large between-subject ES(d)=0.86 for **DCD,** ***p*=.011,** but not for **TD** ***p*=.100**
		Dual task (AC)	Both groups: smaller than single task, no sig. between-subject difference, **DCD,** ***p*=.471, TD,** ***p*=.493,** no sig. difference between groups, *NOVR*

		Dual task (AM)	Both groups: larger than single task, sig. variation and moderate-to-large between-subject ES(d)=0.69 for **DCD, *p*=.041,** but not for **TD, *p*=.075**
		Dual task (AA)	Both groups: larger than single task, no sig. within-subject differences in both groups, **DCD *p*=.067; TD, *p*=.585,** no sig. difference between the groups, *NOVR*
	RQ (mm²)	**DCD** 200.21 mm² (±391.62) not sig. different from **TD** 219.90 mm² (±283.18**), *p*=.696**	
	Additional measures	**Variation index (Vi): -**ve correlation between variation indexes of cognitive tasks (modification of balance) and the outcome of eyes-closed conditions	
Tsai et al. (2008)	Sway area (cm²)	Two-legs (eyes open)	**DCD** 1.80 cm² (±1.63) not sig. different from **TD** 1.36 cm² (±1.33), ES(d)=.3, ***p*=.08**
		Two legs (eyes closed)	**DCD** 2.53 cm² (±2.64) sig. larger than **TD** 1.65 cm² (±1.40), ES(d)=0.4**, *p*=.02**
		Dominant leg (eyes open)	**DCD** 2.23 cm² (±1.46) not sig. different from **TD** 1.78 cm² (±1.97), ES(d)=.3, ***p*=.14**
		Dominant leg (closed eyes)	**DCD** 5.55 cm² (±4.22) sig. larger than **TD** 3.50 cm² (±2.96), ES(d)=.6**, *p*<.01**
		Non-dominant (eyes open)	**DCD** 2.86 cm² (±2.01) sig. larger than **TD** 1.91 cm² (±1.34), ES(d)=.5**, *p*<.01**
		Non-dominant (eyes closed)	**DCD** 6.64 cm² (4.61) sig. larger than **TD** 4.47 cm² (2.67), ES(d)=.6**, *p*<.01**
	Sway path (cm)	Two-legs (eyes open)	**DCD** 23.67 cm (±9.55) sig. larger than **TD** 20.84 cm (±5.06), ES(d)=.4**, *p*=.03**
		Two legs (eyes closed)	**DCD** 30.47 cm (±8.78) sig. larger than **TD** 25.95 cm (±6.39), ES(d)=.6*,* ***p*=.01**
		Dominant leg (eyes open)	**DCD** 32.00 cm (±11.75) sig. larger than **TD** 26.95 cm (±12.60), ES(d)=.4**, *p*=.02**

		Dominant leg (eyes closed)	**DCD** 57.92 cm (±23.77) sig. larger than **TD** 43.96 cm (±19.07), ES(d)=.6, ***p*<.01**
		Non-dominant (eyes open)	**DCD** 37.13 cm (±13.75) sig. larger than **TD** 29.74 cm (±10.12), ES(d)=.6, ***p*<.01**
		Non-dominant (eyes closed)	**DCD** 61.07 cm (±24.64) sig. larger than **TD** 50.59 cm (±17.91), ES(d)=.5, ***p*<.01**
	RQ (%)	**DCD** not sig. different from **TD,** *NOVR*	
	Additional measures	Gender effect: **DCD** (boys) sig. larger sway area than **TD** (boys) in all conditions, except in two-leg (eyes open, ***p*=.05**, and eyes closed, ***p*=.10**) and dominant-leg (eyes open, ***p*=.08**); **DCD** (girls) sig. larger than **TD** only in two-legs (eyes closed), ***p*=.012** in sway area and ***p*=.006** in sway path, dominant-leg (eyes closed), ***p*=.036** in sway path, and non-dominant-leg (eyes closed), ***p*=.018** in sway area	

%, percentage; °, degree; °/sec., degree per second; AA, articulation alone; AC, auditory–choice reaction task; AM, auditory–memory task; Aomax, maximum of sway area; Aomean, mean of sway area; AP, anteroposterior; AV, auditory–verbal reaction task; BOT2, one-leg standing on the balance beam; cm, centimetre; cm^2, centimetre squared; CONST, constant isometric finger force/torque task; CoP, centre-of-pressure; CV, coefficient of variation; d’, an index of perceptual sensitivity; EC, eyes closed; ECCS, eyes closed compliant surface; ECFS, eyes closed firm surface; EOCS, eyes open compliant surface; EOFS, eyes open firm surface; *f*peak, peak frequency of CoP profiles; HD, high difficulty; Hz, Hertz; LD, low difficulty; LOS, limits of stability; lt, left; LT, light touch; LTAS, light touch after soaking; max., maximum; ML, mediolateral; mm, millimetre; mm^2, millimetre squared; MT, movement time; MVT, maximum voluntary torque; NASA-TLX, National Aeronautics and Space Administration Task Load Index; Nm, newton-metre; NOVR, no other values reported; NR, not reported; NT, no touch; NU, no unit; OC, oral counting task; RMSE, root mean square error; RQ, Romberg quotient; rt, right; RTCP, relative time spent in the corrective phase; sec., second; sig, significant; TTPV, time to peak velocity; UVCS, unreliable vision compliant surface; UVFS, unreliable vision firm surface

Conclusion

Some of the empirical studies in this category reported that children with DCD may inefficiently process sensory inputs and therefore perform balance skills with slower movement mechanisms to maintain balance and large errors compared to their age-matched controls. Other studies reported that the DCD group is not overly reliant upon visual inputs and act similarly to the TD group in response to changes in visual stimuli. It has also been indicated that motor difficulties in DCD may be due to central deficits in perceptuomotor processing, including multisensory integration and impaired feedback control. Additionally, the results in this category also showed that additional sensory cues may enhance motor control and balance performance and that children with DCD have a significantly lower sensory sensitivity (i.e., higher threshold) compared to TD children.

Moreover, several studies indicated that motor difficulties are related to task constraints and complexity in DCD. In addition, the majority of the studies indicate that body displacement is compromised in DCD in the AP axes and not in the ML. Furthermore, some studies reported variations and heterogeneity in the performance of the DCD group. However, the outcomes for this category may be inconclusive due to the numerous statistical values that were not reported in their results, despite that the majority of the studies had a high methodological quality level (10 out of 13 studies), whilst three had a moderate methodological level.

3.3.8 Brain recordings

Neural activity was explored in six of the included studies in this review via the EEG (Tsai et al., 2009a; Tsai et al., 2010; Tsai et al., 2012a; Tsai et al., 2012b) or fMRI (Debrabant et al., 2013; Debrabant et al., 2016) in order to investigate the neural underpinnings of children’s behavioural performance. Using EEG, Tsai and colleagues (2009a; 2010; 2012a; 2012b) measured event-related potentials (ERPs) to identify cue- and target-evoked components.

Studies that investigated cognitive attentional abilities reported that the N1 component (a major negative deflection appearing ~100ms after visual stimulus presentation) is correlated with participants’ identification of and visuospatial attention to the relevant stimulus (Tsai et al. 2009a). The results of Tsai et al. (2009a) confirm no significant difference in the latency and amplitude of cue-evoked N1 between the DCD and TD groups ($p=.106$ and $p=.571$, respectively). However, a significantly longer latency in the target-evoked N1 was found in the DCD group compared to the TD group ($p=.003$) but not in the amplitude ($p=.218$), thereby indicating a longer visual processing time of the target cues. Conversely, the results of Tsai et al. (2010) indicate that similar performance was found between the DCD and TD groups in terms of the amplitude and latency of the target-evoked N1 ($p=.216$).

The N2 component (another major negative deflection occurring ~200ms after stimulus presentation) is suggested to show the early stage of modality specific response inhibition and stimulus detection (Tsai et al. 2010; Tsai et al., 2012b; Tsai et al. 2009a). The outcomes of Tsai et al. (2009a, 2012b) reveal no significant difference between the DCD and TD groups regarding the amplitude and latency of the target-evoked N2 with a statistical difference of $p=.481$ for combined latency and amplitude in Tsai et al. (2009a) and $p=.197$ for latency and $p=.402$ for amplitude in Tsai et al. (2012b). These results suggest a similar detection time for the target cues between the two groups. However, compared to TD children, the children with DCD in Tsai et al.'s (2010) study had similar performance with regard to the amplitude of the target-evoked N2 ($p=.156$) but not in terms of latency in which the DCD group had a significantly longer latency ($p=.001$).

Furthermore, the P3 component (a positive major deflection appearing ~300ms after stimulus presentation) is indicated in the empirical literature to represent participants' stimulus detection and evaluation and late general inhibition control (Tsai et al., 2012b; Tsai et al., 2009a), alongside interhemispheric speed (Tsai et al. 2010). The latency of the cue-evoked P3 in Tsai et al. (2009a) was longer in the DCD group than the TD group ($p=.003$) yet, in the same study, the amplitude of the cue-evoked P3 did not significantly differ between the groups ($p=.602$). This may imply that children with DCD exhibit similar levels of attentional shifting to the visual cues but were slower to process these visual stimuli which might be due to a delay in the interhemispheric speed.

Comparable results were found between the DCD and TD groups with regard to the latency of the target-evoked P3 ($p=.338$) in the study of Tsai et al. (2009a). In contrast, the latency of the same component was significantly longer in the DCD group than the TD in Tsai et al.'s (2010, 2012b) research (p=.032 and p=.001, respectively), suggesting a longer processing time exhibited by the DCD group for stimulus identification and response inhibition. Nevertheless, children with DCD had significantly smaller amplitudes of the target-evoked P3 compared to TD children in the three studies by Tsai et al. (2010, 2009a, 2012b) (p=.040, p=.002, and p=.010, respectively). This could indicate less attentional effort exerted by the DCD group to identify the target cues. However, the amplitude of the target-evoked P3 in Tsai et al. (2009a) was larger between the DCD and TD groups in the invalid condition (p=.001) but not in the valid condition (p=.155).

N2-RT interval was measured by Tsai et al. (2010, 2009a) and was reported to illustrate the time for cognitive (i.e., stimulus identification) to motor transfer (motor response) (Tsai et al. 2009a). Moreover, Contingent Negative Variation (CNV), a slow negative potential occurring before the target presentation, was explored in these studies and is suggested to reflect anticipatory and executive processes to induce a response (Tsai et al. 2010). The N2-RT interval was found to be significantly longer in the DCD group when compared to the TD group in both Tsai et al. (2010, 2009a) (ps<.001). Likewise, a significantly smaller wave on the CNV areas was observed in DCD in Tsai et al. (2010) (p=.048) and Tsai et al. (2009a) (p=.030) compared to TD. These results suggest a delay in the transfer of information from sensory to motor areas among children with DCD and a deficit in their motor planning and programming.

Regarding the ERP findings of Tsai et al. (2012a), the amplitude of P3 was found to be significantly smaller in the DCD group than in the TD group during the recognition period (S2) (p<0.001) but not during the encoding phase (S1) in which no significant difference was found (p-value for the latter was not reported). However, the significant difference between the groups (smaller P3 amplitude in the DCD group) was only in the 3-second (p=0.002) and 6-second (p<0.001) delay conditions and not in the non-delay condition (p-value was not reported).

Tsai et al. (2012a) also measured the positive short wave (pSW) component, a major positive deflection appearing after the presentation of the second stimulus (S2) and is reported to reflect response selection and decision-making (Tsai et al., 2012a).

Similar to the previous results, the amplitude of the S2-evoked pSW was significantly smaller in the DCD group in the retrieval stage of the memory conditions (3- and 6-second delay) (p=0.003) but not in the non-delay condition (p-value for the latter was not reported). However, no significant difference was observed between the two groups in terms of the latency of both the P3 and pSW components but the p-values for latency were not reported.

The area under the curve (AUC) of the P3 and pSW components, which represent the duration and strength of cognitive processing (Tsai et al., 2012a), was also investigated by Tsai et al. (2012a) and was found significantly smaller in the DCD group than in the TD group (p=0.002). Furthermore, the AUC was positively correlated with participants' accuracy (p<0.001) (i.e., small AUC with low accuracy).

Global and local (nodal) efficiency of the brain network in children with DCD were investigated by Debrabant et al. (2016) using fMRI and diffusion tensor imaging (DTI). The authors measured the structural connectivity of specific sensorimotor white matter tracts by assessing fractional anisotropy (FA), radial diffusivity (RD), and axial diffusivity as they are suggested to represent the abilities in visuomotor integration and eye-hand coordination (Debrabant et al. 2016).

A significantly lower FA and higher RD of the left retrolenticular limb of the internal capsule was found in the DCD group in comparison with the TD group in the study by Debrabant et al. (2016) (p<.001 and p=.001, respectively). They also reported that the DCD group had significantly lower FA and higher RD in the right retrolenticular limb of the internal capsule (p=.009 and p=.003, respectively). The mean clustering coefficient was also calculated by Debrabant et al. (2016) to represent the local brain network connectivity and was found to be significantly lower in the DCD group compared to the TD group (p=.019). In addition, significantly lower global efficiency values were recorded in the DCD group in the white matter networks (p=.001) and there was poorer regional (nodal) efficiency, yet the p-value of the latter was not reported. Furthermore, a significant correlation between global efficiency and the Beery VMI trace scores of the DCD group (r=.559, p<.008), yet no significant correlation was found between the two variables in the TD group (p-value was not reported).

A significant and positive correlation was also observed in both the DCD and TD groups between the Beery VMI tracing scores and FA in the retrolenticular limb of the internal capsule (DCD r=.496, p=.022 and TD r=.530, p=.016). In addition, a low nodal efficiency of the left cerebellum VI was found to be significantly and positively correlated with the lower scores of the Beery VMI in children with DCD (r=.571, p<.007) but not in the TD (p-values were not reported).

Comparing the structural networks of the white matter of the DCD and TD groups with a random network in Debrabant et al. (2016) revealed that both groups displayed higher local node interconnectivity and higher 'small-world structure' but similar shortest path length between any pair of nodes. These results were similar between the groups and no significant difference was found (p>.12). The authors also investigated which DTI/network metrics could be highly predictive of the difference in visuomotor integration performance between the DCD and TD groups. The results revealed that nodal efficiency at the cerebellum lobule VI and at the right parietal superior gyrus could be two predictors of differences between the two groups with p<.0001.

The neural underpinnings of DCD's behavioural performance were investigated by Debrabant et al. (2013) using fMRI. The outcomes of the study revealed no significant differences in brain activation between the predictive and unpredictive conditions among children with DCD but the p-value was not reported. These findings of neural activity of the DCD group were correlated with their behavioural performance by which the percentage of their anticipatory responses (accuracy rate) was similar between the two conditions (predictive vs. unpredictive). In addition, children with DCD were found to have lower levels of activation than TD children in the right dorsolateral prefrontal cortex (DLPFC), the left posterior cerebellum (crus I), and the right temporo-parietal junction (TPJ) (p-values were not reported) only in the predictive conditions in the Debrabant et al. (2013) study.

3.4 Discussion

DCD is primarily characterised by motor difficulties that are not attributed to a known neurological diagnosis. Investigating the aetiology of the disorder will help clinicians with their diagnosis and treatment. Therefore, as some studies indicate that movement difficulties among children with DCD may be caused by sensory processing difficulties, the current systematic review aimed to identify and summarise the role of sensory processing on movement abilities among children with DCD.

Of the 46 studies included in the current review, 76% had a high methodological quality level, which is close to the percentage that was arrived at (64%) in a recent publication which sought to review the findings of 100 recent studies concerning behaviour and neuroimaging research in DCD from the empirical literature (Subara-Zukic et al., 2022). In addition, the same review by Subara-Zukic et al. (2022) summarised the aspects of study quality that were poorly addressed in the empirical literature and among these was sample size justification which is similar to the current review in which only one study (Chen et al., 2019) undertook priori analysis to estimate and justify the required sample size.

The proportion of males to females is slightly higher in the DCD than the TD group (57% vs 55%, respectively). In addition, eighteen studies had a ratio of males to females ranging from 2:1 to 9:1 when recruiting broadly from the general population of DCD, moreover, two studies had predominantly male participants. This might reflect the suggested prevalence rate of DCD being higher among males than females (Farmer et al., 2016; Blank et al., 2019). However, the high incidence of boys with DCD could be due to them being more likely than girls to be clinically identified and diagnosed. This may be because DCD is primarily characterised by movement difficulties and coordination problems and as males are more likely than females to participate in sport and leisure activities (Poulsen et al., 2006; Cairney et al., 2009), a limitation in the motor skills of males may be more likely to receive medical attention.

It is recommended that the DSM-V (APA, 2013) criteria be followed as a valid method to identify children with DCD (Blank et al., 2019). However, only six (13%) of the studies included in this review reported using the DSM-V to identify participants with DCD. Nevertheless, as 33 (72%) studies were published before the DSM-V and, therefore, it was not possible for them to follow the DSM-V, it is important to mention that only five studies (11%) followed the DSM-IV which was published earlier (APA, 1994). Considering these findings, strictly following the relevant DSM criteria for the study's year of publication date remains poorly addressed in the studies included in this review, which is similar to the findings of other reviews concerning research in DCD (Miyahara et al., 2020; Subara-Zukic et al., 2022). Given that, the various inclusion criteria of the participants with DCD may give rise to conflicting results in behavioural responses between studies using the same methods.

Despite this, all of the studies fulfilled criterion A of the DSM-V, whilst 11 (24%) and 28 (61%) of the included studies satisfied criteria B and D, respectively. Moreover, only five studies (11%) fulfilled criterion C of the DSM-V. However, Adams et al. (2016) emphasised that criteria A, B and D from the DSM-V are particularly recommended to identify the population of DCD. This was also supported by Blank et al. (2019) who indicated that criterion C (symptoms of DCD appear at an early age) of the DSM-V might not always be applicable as individuals may be identified with the disorder at a later age.

Variations in the methods used to investigate the different aspects of SP was evident, hence, the studies were categorised according to their primary goals which relate to their main area of interest regarding the SP domains and their outcomes were analysed by means of narrative synthesis. However, broad clusters of deficits in the performance of children with DCD were pronounced in the outcome of the studies and were common between the categories. In addition, despite the fact that these clusters of features might overlap or share similar trends, which is common when exploring SP and movement control that involves the interaction of multi-systems, they were classified into four themes: executive function, motor control parameters, task constraints, and heterogeneity. These groups of performance features form the basis of the discussion section below.

3.4.1 Executive functions

Deficits in sensory processing might affect executive functioning and, thus, movement abilities due to the known interaction between perceptual abilities, executive functions, and motor skills (Piek et al., 2004; Utley and Astill, 2008; Allen and Casey, 2017). Therefore, problems in sensory processing such as visuospatial processing might account for the reported deficits in executive functioning in DCD and, consequently, movement difficulties (Leonard et al., 2015a; Bernardi et al., 2018). Dysfunction in executive functioning in DCD is indicated to primarily include problems in working memory, inhibitory control and attention (Wilson et al., 2012). In accordance with this, several studies from the current review showed that performance difficulties in DCD are likely to be related to deficits in sensory processing, particularly visuospatial processing and problems in executive functioning.

For instance, deficits in visuospatial processing, inhibitory control and attention in DCD were reported in some studies in which children with DCD exhibited a significantly larger RT and/or less accuracy compared to their peers in tasks requiring a shift in attention to different locations of visual stimuli and the suppression of irrelevant behavioural responses (Tsai, 2009; Tsai et al., 2009a; Tsai et al., 2009c; Tsai et al., 2010; Chen et al., 2012; Tsai et al., 2012b; Sartori et al., 2020). This is consistent with the findings of several studies that indicated compromised visuospatial processing (Wilson and McKenzie, 1998) and visuospatial attentional skills (Wilson et al., 2012; Lachambre et al., 2021) as well as inhibitory control (Lachambre et al., 2021) in DCD. It is suggested that children with DCD may not have a problem identifying visual stimuli (Wang et al., 2017; Sugden and Chambers, 2005) but inefficient processing and motor preparation are suggested to result in slow and delayed responses (e.g. RT) (Sugden and Chambers, 2005; Wilson et al., 2012; Wilson et al., 2017b).

The neurophysiological data included in this review also supports this by which no significant difference was shown between the DCD and TD groups with regard to the amplitude of ERP components reflecting stimuli detection and identification abilities (such as N1, N2, and P3) (Tsai et al., 2009a; Tsai et al., 2010; Tsai et al., 2012b). However, the same study reported significantly longer latencies of those components indicating slower information processing. In addition, it was found in the studies by Tsai et al. (2009a; 2010) that the N2-RT interval was significantly longer in the DCD group when compared to the TD group. Likewise, a significantly smaller wave on the Contingent Negative Variation (CNV) areas was observed in DCD in Tsai et al. (2010) ($p=.048$) and Tsai et al. (2009a) ($p=.030$), suggesting a delay in the transfer of information from sensory to motor areas among children with DCD and a deficit in their motor planning and programming. These findings may offer a reasonable explanation for the results of Tsai et al. (2009; 2009a; 2009c;

2010; 2012b) and the result of the hand task with no instructions given (HR-NI) of Williams et al. (2008) in which the DCD and TD groups had similar error rates yet the DCD group performed with significantly longer RTs.

Difficulties in sustaining (Saban et al., 2014) and shifting attention (Wilmut et al., 2007), in addition to problems in visuospatial working memory (Alloway and Temple, 2007; Wang et al., 2015) have been identified in the empirical literature as core deficits in DCD affecting motor learning and movement abilities (Wilson et al., 2012). Studies included in the current review also revealed that children with DCD have problems with visuospatial attention and working memory such as recalling the target location (Biancotto et al., 2011; Gheysen et al., 2011; Tsai et al., 2012a), target size (Chen and Wu, 2013), and limb joint position (Tseng et al., 2019b), resulting in significantly poorer motoric performance compared to TD children. In agreement with this, the neurophysiological data of Tsai et al. (2012a) showed that children with DCD had significantly lower amplitudes of P3 and smaller AUC of the P3 and pSW components than the control group during the response phase in which participants had to retrieve the location of the stimuli. The P3 and AUC components of the ERP data are suggested to be associated with attention and memory of stimuli allocation and the duration and strength of cognitive processing, respectively. These results possibly suggest a slow and/or inefficient neural processing of sensory information into memory among the DCD group.

3.4.2 Motor control parameters

As discussed in previous chapters, visual information and proprioception are suggested to be basic elements for motor control and movement programming. With regard to visual processing, a large proportion of the studies (35%) included in this review investigated the effect that visual processing has on movement in DCD. As mentioned in the previous section, a deficit in visuospatial processing was sought to primarily account for motor difficulties among children with DCD which is in accordance with the findings in the empirical literature (Wilson and McKenzie, 1998; Blank et al., 2019). In addition, with regard to proprioceptive and kinaesthetic abilities in DCD, these skills were investigated in a number of studies in this review, yet they arrived at different outcomes. Three studies indicated that children with DCD have comparable abilities to TD children in position sense systematic error (positional bias) (Adams et al., 2016; Tseng et al., 2018; Tseng et al., 2019b) which reflects the degree to which the sensed limb is placed in relation to the reference position. Mon-Williams et al. (1999), on the other hand, found that the DCD group performed with significantly larger position sense error, yet their performance in terms of limb position directional bias was similar to that of the TD children except when both limbs were occluded. The lack of consistency between the studies may be due to the different tools used to measure joint position sense. The studies by Adams et al. and Tseng and colleagues used goniometer and adjustable bimanual manipulanda, respectively, whereas Mon-Williams et al. used electromagnetic trackers which are suggested to be more reliable (Reddy et al., 2022).

Additionally, Tseng and colleagues (2018; 2019b) found that the DCD group have significantly larger variation than the TD group in random error which is suggested to represent precision abilities in the joint position sense. Moreover, studies measuring the effect of proprioception abilities on movement skills (using the M-ABC2) found no statistical correlation between them (Adams et al., 2016; Tseng et al., 2018), unlike other studies from the empirical literature (Chen et al., 2020) in which children with DCD had significantly greater position sense bias and less position sense precision compared to TD children, and a significant correlation was found between proprioception acuity and M-ABC2 scores. The different results reported may be due to the different methods used in the studies. The task in the studies by Tseng and colleagues and Adams et al. involved active movement of the joints, whereas participants' limbs in the study by Chen et al. (2020) were passively moved to explore their kinaesthetic abilities. Hillier et al. (2015) argue that active movement may involve more combined sources of information to produce the movement required, such as efference copy of motor command being received by the central nervous system to predict and anticipate the movement, and that examination of peripheral joint sensors presenting proprioceptive abilities is less likely to be measured using active movement-based tests. This is also supported by Li et al. (2015) who used 'passive' joint motion test and the results revealed that kinaesthetic deficits were found in children with DCD to detect joint motion. However, only very few studies were found in the empirical literature that aimed to explore kinaesthetic and proprioceptive skills in children with DCD and, therefore, a firm conclusion cannot be reached to determine their abilities.

Visual perception and proprioception are also suggested to play a major role in feedforward and feedback processes (Utley and Astill, 2008). Therefore, slow and delayed visuospatial processing and deficits in proprioception, as previously mentioned, may largely affect feedback and feedforward processing and, thus, account for movement difficulties in DCD (Sugden and Cambers, 2005; Plumb et al., 2008; Wilson et al., 2017b). The study by Biancotto et al. (2011) from the kinematic category supports this by which the deceleration time, which is measured by some studies to explore feedback processing (Elders et al., 2009; Campione et al., 2016), was evidenced to be significantly larger in the DCD group than in the TD group, thereby indicating compromised feedback processing. From the same category, Elders et al., (2009), on the other hand, found no significant difference between the groups in terms of deceleration time but with no numerical data reported, therefore, their outcome remains questionable.

In addition, some studies included in this review found that children with DCD exhibited a significantly longer movement time and lower speed compared to their age-matched controls (Bo et al., 2008; Elders et al., 2009; Biancotto et al., 2011; Ferguson et al., 2015; Roche, 2016). Hence, as these measurements are suggested to represent movement programming (Elders et al., 2009), the results may indicate a problem in children with DCD's ability in feedforward processing and motor planning. Feedforward planning deficits may also contribute to children's motor imagery abilities and internal modelling which largely affect motor prediction timing and control (Adams et al., 2014). Internal modelling allows a person to anticipate a movement outcome and consequences before feedback becomes available (Adams et al., 2014; Noten et al., 2014; Blank et al., 2019). It is indicated from the studies included in the current review that children with DCD are unable to efficiently form an internal presentation of body parts in relation to the external cues that allows them to plan and predict an accurate behavioural response (Williams et al., 2008; Adams et al., 2016; Diz et al., 2018).

Therefore, because motor planning and programming are believed to be compromised in DCD, it is suggested that children with DCD are overly reliant on feedback-based control depending on external sensory inputs such as visual, haptic, or proprioceptive stimuli (Wilson et al., 2012; Blank et al., 2019). This is also supported in studies exploring brain activation during motoric performance such as the study by Zwicker et al. (2010) which reported greater activity in brain areas associated with visual and spatial processing in DCD when compared to TD children. External feedback cues are suggested to be used by children with DCD as a compensatory strategy to control movement (Fong et al., 2012; Wilson et al., 2012; Blank et al., 2019). However, these compensatory strategies may be presented as atypical movement patterns (Deconinck et al., 2006), as seen in the study by Ferguson et al. (2015) from the kinematic category in which children were probably unable to efficiently form an internal representation of the visual target or hand movement and therefore were tracking the target with significantly higher mean and maximum velocity when compared to TD children. Similarly, the smaller movement excursion reported by Fong et al. (2016) and the smaller RTCP and higher $f$peak observed by Przysucha et al. (2008) in the motor skills category may be exhibited by the DCD group as compensatory strategies to control their balance. Other examples from the empirical literature included in this review include Chung and Stoffregen (2011) and Bair et al. (2012) in which atypical balance control strategies were used by children with DCD when the presentation of the sensory inputs changed, resulting in a different movement pattern of body sway when compared to TD children (see Tables 3.5 & 3.12).

In accordance with this, a number of studies included in this review reported that children with DCD performed significantly worse than TD children when external sensory cues, particularly visual inputs, were not available (eyes closed), suggesting an over reliance on visual inputs to compensate for motor planning deficits and maintain motor control. For instance, Van Waelvelde et al. (2006) reported that children with DCD performed with larger deterioration (more errors) relative to TD children when visual feedback was removed, compared to when it was available. Other studies indicated that children with DCD exhibited larger body sway (Wann et al., 1998), produced more errors in rod length judgement (Wade et al., 2016), and had a larger perception threshold (Tseng et al., 2019a) when visual inputs were removed. However, the study by Wann et al. also reported larger body sway among the DCD group in the eyes-open condition, albeit that the p-value was not stated. In addition, the studies by Wade et al. and Tseng et al. did not consider children’s performance when visual inputs were available (eyes open). Therefore, the mechanism behind the problems exhibited by children with DCD in motor control could not be ascertained. It could be that movement difficulties displayed in the eyes-closed conditions are due to problems in efficiently integrating different sensory inputs (cross-modal perception), such as haptic and proprioceptive inputs, to execute the required behavioural reaction. This was suggested by Coats et al. (2015) who found that children with DCD may have problems integrating multisensory stimuli to maintain motor control. (Kashiwagi et al., 2009) also confirmed this in their neuro-imaging study whereby activity in the areas associated with integrating multimodal sensory inputs relevant to motor control was found to be lower among participants with DCD than their age-matched controls.

Unlike the studies by Wann et al. (1998), Van Waelvelde et al. (2006), Wade et al. (2016), and Tseng et al. (2019a) which reported a deteriorating performance in the DCD group when visual information was removed, Bair et al. (2012) from the cross-modal category and Speedtsberg et al. (2017) from the motor skills category reported that the performance of children with DCD deteriorated in conditions that required greater reliance on visual inputs compared to conditions requiring more reliance on other sensory inputs such as haptic and proprioceptive. This is aligned with the findings from the empirical literature in which children with DCD swayed significantly more when they had to rely more on visual stimuli while other sensory inputs were distorted or removed (Fong et al., 2012). A few studies from the motor skills category also corroborate the abovementioned findings, reporting that children with DCD are not overly reliant on visual inputs to maintain motor control, as measured using Romberg's quotient (Przysucha and Taylor, 2004; Tsai et al., 2008; Tsai et al., 2009b).

The notion of children with DCD being excessively dependent on visual inputs as a compensatory strategy to maintain motor control has been extensively discussed in the empirical literature and, as indicated by Wilson et al. (2012), the evidence remains equivocal. Disagreement between the outcomes may be due to the different joints (upper limbs vs lower limbs) involved in the tasks given. For instance, all of the studies included in this review which reported that children with DCD are not overly reliant on visual inputs to improve performance tested the effect of visuomotor integration on postural and balance control which primarily involves the function of the lower limbs, unlike the majority of the opposing studies included in this review in which only the function of the upper limbs was considered (Van Waelvelde et al., 2006; Wade et al., 2016; Tseng et al., 2019a). While the empirical literature indicates that children with DCD may be characterised by deficits in both fine and gross motor function (Schott et al., 2007), some studies included in this review found different responses between the performance of the upper and lower limbs among children with DCD and indicated that motor dysfunction may be more pronounced in the lower limbs in DCD (Tsai et al., 2009c), which is similar to the findings of other studies from the empirical literature (Ferguson et al., 2014; Aertssen et al., 2016; Draghi et al., 2021). Dysfunctions in neuromuscular control in DCD (Diz et al., 2018), such as atypical muscle synergies (Fong et al., 2015) and the inefficient neuronal firing of muscles (Biancotto et al., 2011), are reported in the empirical literature. Therefore, tests involving the lower limbs, such as balance tests, are more complex and may require greater interlimb coordination, muscle load and postural control than fine motor tasks. Therefore, studies indicating that the large deterioration in balance performance shown in conditions when only visual information was available may be due to pronounced neuromuscular deficits in lower limb function (Przysucha and Taylor, 2004; Tsai et al., 2008; Tsai et al., 2009b).

Delgado-Lobete et al. (2020) and Mikami et al. (2021) indicated that children with DCD may be characterised as having a low registration pattern sensory profile and, thus, need a higher intensity of stimuli to be processed, which supports the findings of studies included in this review (Tseng et al. (2018) and Chen et al. (2019)) in which children with DCD had a significantly higher discrimination threshold compared to TD children. This was also in parallel with the study by Chung (2018) because a significant correlation was found between the sensory pattern of children with DCD (i.e., low registration) and their motor difficulties, as measured using the developmental coordination disorder questionnaire (DCDQ). The hypothesis concerning low registration of sensory stimuli may also explain the findings of the studies by Kagerer et al. (2006), Chung and Stoffregen (2011), and Bair et al. (2012) included in this review in which children with DCD were able to adapt to changes in sensory stimuli presentation when a large amount of sensory inputs was presented or a large discrepancy was displayed between sensory inputs (e.g., lowest oscillations of haptic inputs combined with highest oscillations of visual inputs). In a similar way, the studies by Chen et al. (2019), Chen and Tsai (2016), and Tsai et al. (2009b) from the motor skills category indicated that providing additional sensory stimuli (i.e., haptic inputs) enhanced balance control and cognitive performance among children with DCD. This may also support the aforementioned hypothesis stating that children with DCD use external sources of sensory information (feedback) to compensate for compromised internal modelling and the low-registration threshold (Zoia et al., 2002; Adams et al., 2016).

Deficits in executive functions, visual processing, proprioception, and motor programming, as previously mentioned, might largely affect motor learning in children with DCD and, thus, also affect their motor skills (Sugden and Chambers, 2005). In several studies included in the current review, children with DCD were found to be unable to synchronise their movement to the rhythmic presentation of the sensory stimuli in tasks involving timed and fast responses (Tsai and Wu, 2008; Van Waelvelde et al., 2006; Debrabant et al., 2013). Hence, they performed tasks with slower and less accurate responses and failed to adapt to the time regulations of the tasks. Failing to synchronise movement with sensory inputs in tasks involving temporal constraints had previously been established in research concerning DCD (Wilson and McKenzie, 1998; de Castelnau et al., 2007; Blank et al., 2019). This was also evidenced by Gheysen et al. (2011) from the visuospatial category in which children with DCD were unable to learn the sequence of the visual stimuli presentation and, hence, their performance did not change between the fixed and random sequence presentations. This was also supported in a systematic review by Wilson et al. (2017b) which reported that several studies showed that, compared to their age-matched peers, children with DCD have several under-activated brain networks that are associated with observational learning and internal modelling regions.

3.4.3 Task constraints

It has been well established in the empirical literature that movement difficulties in DCD are highly likely to be associated with task constraints and complexity such as tasks involving high physical and informational attributes (Adams et al., 2014; Adams et al., 2017; Wilson et al., 2017a; Wilson et al., 2017b; Bhoyroo et al., 2018). In addition, deficits in motor planning and internal modelling in DCD are also reported to be linked to the nature of the task (Noten et al., 2014). This is probably due to the notion that because poor cognitive functioning (e.g., inefficient sensory processing and problems in executive functioning) plays a major role in motor difficulties in DCD (Wilson et al., 2017b), tasks with considerable cognitive demand may result in apparent performance difficulties. Moreover, studies included in this review which investigated brain activity reported that significantly lower activation in attentional processing and lower exertions of cognitive processing were evidenced in DCD compared to TD children during tasks requiring higher cognitive demands such as inhibitory control conditions (i.e., invalid) (Tsai et al., 2009a), memory conditions (Tsai et al., 2012a), and conditions requiring adaptation with timed responses (Debrabant et al., 2013). Furthermore, Debrabant et al. (2016) examined the properties of some sensorimotor tracts of the white matter among children with DCD while they performed the Beery VMI task which required them to adapt to changes in visual inputs. They reported reduced myelination that probably resulted in decreased global and regional network efficiency among children with DCD compared to TD children which is highly likely to account for their slow and inaccurate behavioural responses.

Several studies included in this review supported the above-mentioned hypothesis and demonstrated that motor difficulties in DCD are related to task complexity. For instance, some studies found that the significant difference between TD and DCD groups was greater when performing tasks involving more advanced planning, behavioural adaptations, or larger inter-limb coordination. For example, the tasks that required locating targets that are further away compared to closer ones (Elders et al., 2009; Chen and Wu, 2013), pointing tasks compared to looking only (Elders et al., 2009), maintaining postural control on compliant surface compared to firm one (Speedtsberg et al., 2017), and the single leg-stance test (particularly in the non-dominant leg) compared to the balance test with both legs (Tsai et al., 2008).

In a similar way, a significant difference in performance between the TD and DCD groups was only noticed in the complex tasks of Adams et al. (2016) (i.e., critical trials of the sword task) and Wade et al. (2016) (i.e., long rods) which involved careful motor planning and internal modelling to grasp the object and/or estimate its size. The critical trials and the long rods of Adams et al. and Wade et al., respectively, are likely to involve more wrist and arm rotation to be able to achieve the end-state comfort position (ESC) in Adams et al. and maintain a grip and estimate the size of the rod in Wade et al. In addition, the long rods of Wade et al. might also be heavier than the short ones and, therefore, require greater effort and control to wield them. These might have resulted in compromised motor control and, thus, more errors were obtained in the DCD group compared to the TD group. Likewise, children with DCD had significantly more errors than TD children only in the conditions that required larger cognitive demand (i.e., memory) in the studies by Tsai et al. (2012a) and Zoia et al. (2002).

In line with this, Williams et al. (2008) showed that children with DCD exhibited greater deterioration in internal modelling (predicting the limb side), mostly when the picture was rotated away from the upright position (see Table 3.5), making more difficult predictions. In addition, weak RT-accuracy trade-off was also evident in Williams et al.'s in which children with DCD were significantly slower at the baseline task but had similar accuracy to TD children. Conversely, they made a response with a similar speed to that of TD children when performing the hand and whole-body tasks but with a significantly lower accuracy level.

Deficits in cognitive processing and limited attentional capacity in tasks involving mental workload may also explain why children with DCD experience difficulty performing dual tasks (Schott, 2019). Performing cognitive tasks while maintaining postural control was assessed by Chen and Tsai (2016) and Chen et al. (2011; 2015) and the results confirmed that children with DCD had significantly larger body sway when asked to maintain balance while performing the signal detection task, similar to what was observed in the empirical literature (Laufer et al., 2008). More importantly, their sway further increased when performing the more difficult cognitive task, which may be due to children prioritising the cognitive task.

Dual tasks also affected the performance of children with DCD in research of Bonney et al. (2017) and Smits-Engelsman et al. (2015) in which they had to maintain balance while performing a videogame. Children with DCD were unable to guide their movement using the feedback given through the videogames and were unable to adapt to the spatial and temporal changes of the visual stimuli. Therefore, they performed the tasks with significantly lower scores and larger RT compared to

TD children. In contrast, the studies by Kagerer et al. (2006) and King et al. (2011) employed simple single-tasks involving only the upper limbs to explore children's adaptation to visuospatial changes of visual stimuli and multisensory abilities, revealing comparable results between the DCD and TD groups.

3.4.4 Heterogeneity

Heterogeneity in functional ability, motor skills and cognitive profiles among individuals with DCD has been extensively discussed in the empirical literature (Sugden, 2007; Alloway and Archibald, 2008; Smits-Engelsman et al., 2017). However, Blank et al. (2019) suggest that the heterogeneity of data examining cognitive and motor abilities among children with DCD probably reflect the different experimental paradigms and assessment tools used. For instance, the differences in performance among participants with DCD may be attributed to the sample not being representative of the DCD population to reach comparative and generalisable findings (Sinani et al., 2011). Individual characteristics may act as confounding factors to breach the homogeneity of the DCD group and, hence, influence the results. Therefore, as stated in criterion D of the DSM-V, addressing the medical conditions and comorbidities associated with DCD in participants may be necessary to arrive at valid results and better understand the underlying mechanisms of DCD.

In accordance with this, several studies included in this review which reported high variability in the performance of children with DCD did not identify and exclude children with other medical conditions and/or co-morbidities such as ADHD (Wann et al., 1998; Van Waelvelde et al., 2004; Bo et al., 2008; Elders et al., 2009; Biancotto et al., 2011; Ferguson et al., 2015; Roche et al., 2016). Therefore, deficits in movement control may be attributed to impulsivity and the attentional problems associated with ADHD (Rasmussen and Gillberg, 2000; de Castelnau et al., 2007). Hence, it is necessary to consider that the internal validity of these studies might not be achieved. Moreover, it has been shown in the current review that large variations (heterogeneity) in the behavioural responses of participants with DCD are common in studies with relatively small sample sizes in the DCD group (n=7-12) (Kagerer et al., 2006; Chung and Stoffregen, 2011; King et al., 2011; Speedtsberg et al., 2017; Diz et al., 2018) which might have led to results with type I/II errors and limited generalisability.

Movement difficulties among children with DCD are suggested by some studies to be attributable to developmental delay in perceptomotor processing and motor learning rather than a deficit (Pieters et al., 2012). Therefore, it has been suggested in the empirical literature that motor control in children with DCD may improve with age (Hyde and Wilson, 2013; Ruddock et al., 2015) and, hence, the behavioural performance of older children with DCD is found to be comparable to that of TD children. The findings of Bair et al. (2012) support this notion by reporting that only the older age group of DCD (10 years of age) were able to demonstrate multisensory integration skills, which is reported in the empirical literature to start showing at the age of 8 years in children with typical development (Gori et al., 2008). In accordance with this, Zoia et al.'s (2002) study from the cross-modal category indicated that the difference in perceptomotor abilities between children with DCD and their age matched controls was shown to be significantly less pronounced in the older age groups (Zoia et al., 2002). Therefore, this might explain the reason behind the findings of some studies included in this review that predominantly included participants from the older age group and reported similar performance between the DCD and TD groups (Wann et al., 1998; Kagerer et al., 2006; King et al., 2011).

The hypothesis of developmental delay might also account for the interstudy differences in studies with similar outcomes of interest in research concerning DCD. For example, the different conclusions that were arrived at by Tseng et al. (2018; 2019b), Adams et al. (2016), and Mon-Williams et al. (1999) regarding proprioceptive abilities among children with DCD may be related to the age range of the sample. The participants in the studies by Tseng et al. (2018; 2019b) and Adams et al. (2016) were primarily from the older age group (mean ages between 8-10 years) and this might explain the finding of similar performance between the DCD and TD groups. Mon-Williams et al. (1999), on the other hand, recruited children from the younger age group (aged 5-7 years) and reported that children with DCD had significantly lower performance in proprioceptive abilities compared to TD children. It is reported that children with DCD have a similar developmental trajectory of kinaesthetic acuity to TD children, albeit with more gradual and slower improvement with age (Li et al., 2015). This was evidenced in the empirical literature where it was reported that 11 year-old children with DCD have similar kinaesthetic abilities to 7 year-old TD children but not to 11 year-olds without DCD

(Li et al., 2015). Nevertheless, because there is a paucity of longitudinal studies examining the different aspects of functional abilities in DCD (Blank et al., 2019), it is not possible to make definite conclusions about the hypothesis that developmental delay is an underlying mechanism of the disorder.

Methodological effects on the heterogeneity of the findings between studies aiming to explore the same area of interest were noticed in several studies included in this review. For instance, it was found that postural sway was only significantly compromised (i.e., increased) in the AP axis and not in the ML in DCD, compared to TD children when sensory stimuli were manipulated (Przysucha and Taylor, 2004; Przysucha et al., 2008; Chen et al., 2013; Chen et al., 2016; Fong et al., 2016; Chen et al., 2019). These results could be attributed to the biomechanics of the ankle joint which allows more movement in the AP direction rather than the ML (Chen et al., 2015; Speedtsberg et al., 2017). On the other hand, the study by Bair et al. (2012) found significantly greater body sway exhibited by participants with DCD compared to TD children in the ML axis which may be due to the direction used to spatially manipulate the sensory inputs (haptic and visual) in the study by Bair et al. (2012) whereby the sensory stimuli were moved from left to right, and vice versa, and this may have led to excessive ML body displacement.

Another example of the methodological effect on heterogeneity was noticed in the studies by Tseng et al. (2019a) and Tseng et al. (2018). There was no statistically significant difference between the TD and DCD groups in Tseng et al.'s (2019a) research in terms of haptic sensitivity (detection threshold), whereas it was significantly higher among children with DCD than TD children in Tseng et al. (2018). The conflicting results of the two studies may be attributed to the different joints (phalangeal versus wrist joints) involved in the tasks. Proprioceptive information are probably derived from different joint receptors, muscle spindles, and tactile mechanoreceptors which are reported to be more sensitive at the fingertips (Johansson and Vallbo, 1979; Williams and Okamura, 2020).

Studies investigating inhibitory control in DCD also reported several conclusions that might be due to methodological differences. Tsai et al. (2010) reported that the target-evoked N1 latency (reflecting attentional abilities) did not differ between the DCD and TD groups, whereas it was shown to be significantly longer in the DCD group in the study by Tsai et al. (2009a). The conflicting results may be due to the shorter SOA in the study of Tsai et al. (2009a) which could result in a more difficult task and, thus, require a longer time to process sensory information. In addition, the mode of attention employed (endogenous vs exogenous) may have affected the results. It is indicated that inhibitory control problems are mostly pronounced in DCD in tasks requiring voluntary shifting of attention (endogenous mode) (Tsai et al., 2009c), which was employed in the study by Tsai et al. (2009a). Moreover, the target-evoked P3 latency, which represents target detection skills, was found to be significantly longer in Tsai et al. (2010; 2012b) but similar to that of TD children in Tsai et al. (2009a). The difference between the studies may be due to the type of visual cues used. The study by Tsai et al. (2009a) employed a green circle visual cue, whereas the studies by Tsai et al. (2010; 2012b) employed an eye-gazed visual cue. It is suggested that the various cues are processed differently with diverse cortical networks of attention involved (Tsai et al., 2010).

3.5 Strengths and limitations

The current review sought to acknowledge the sensory processing effects on movement in children with DCD. Several aspects of sensory processing abilities in DCD have been established in the empirical literature. However, analyses of its effect on movement skills have not been updated or comprehensively investigated since 1998. Robust methods were employed in the current review, including registering and publishing the review protocol in the International Prospective Register of Systematic Reviews (PROSPERO) to ensure a thorough reporting of the systematic review. In addition, the review included a broad search of all dimensions of sensory processing to thoroughly review perceptuomotor abilities in DCD in the empirical literature.

To be able to answer the review question, it was necessary to specify comprehensive inclusion criteria. One of the criteria specified that only papers using the M-ABC as a diagnostic tool to identify participants with DCD were to be included in the current review. However, although this assessment tool is widely used in the empirical literature to display movement difficulties, this might be considered a limitation because it restricted the number of empirical studies that were included in the review. Including other papers that used the DSM criteria as a diagnostic method may have resulted in a wider range of studies from the empirical literature being included. However, because several outcome measures may be used to fulfil the DSM criteria, these may not be valid and reliable to arrive at a representative sample of children with DCD. In addition, due to the limited translation resources, only studies that were published in the English language were included which could also be considered a limitation of the current review.

Other limitations of the current review comprise the inclusion of predominantly case-control studies which are suggested to be less capable of identifying the relationships between causes and effects than other study designs such as cohort and experimental studies. In addition, the various sample sizes, outcome measures used to test the effect of SP on motor performance, and the different outcomes of interest (e.g., visual processing, perceptual processing, etc.) may have affected the results and led to various interpretations. Moreover, the narrative nature of the review meant that it was not possible to critically evaluate each paper and statistically combine the results. Therefore, a precise estimation of the effect size was probably not reached which might adversely affect the generalisability of the results. Finally, as only published work was included, this may have resulted in publication bias because it has been suggested that published articles are more likely to include higher values and positive findings than abstracts, dissertations or unpublished works.

3.6 Conclusion

In summary, 46 empirical studies were included in the current review and were grouped into six categories representing the paradigms and type of sensory stimulus employed in the empirical studies to explore the role of sensory processing on movement among children with DCD. The studies were divided into four main categories: visual processing, perceptual processing, motor control abilities, and motor skills. The methods used to understand SP in the studies included in this review were diverse, thus, making it difficult to draw a solid conclusion regarding the effect of SP on movement abilities in DCD, however, despite this, the majority of the studies were of a high methodological quality, as assessed by the CASP.

The empirical literature is replete with studies attributing movement difficulties in DCD to the inefficient processing of sensory information and/or deficits in internal modelling and cross-modal perception that resulted in compromised executive functioning such as problems in working memory, inhibitory control and attention. These deficits were highly likely to affect movement control parameters such as movement planning and programming in DCD. However, these deficits were reported to be largely associated with environmental and task constraints such as reduced visual inputs, unreliable support surface, dual-tasks, speeded responses, and increased movement complexity. In addition, some of the studies observed that children with DCD may no longer experience sensory processing difficulties as they grow older, thereby supporting the hypothesis of developmental delay rather than deviance from typical development.

Numerous studies in this review demonstrated variability in the motoric performance of DCD with regard to sensory processing, thereby supporting the hypothesis of heterogeneity in the disorder. However, this is highly likely to be due to variations in the methods and diagnostic criteria of DCD employed and/or the small sample size recruited. The findings of the current review may be helpful for researchers and clinicians to develop their knowledge regarding the disorder and to be able to manage treatment programmes that address the problems that lead to motor difficulties in DCD.

Implications for clinical practice suggest that the assessment of movement abilities in DCD is better to be applied in different environmental settings to specifically identify the task constraint that reveals movement difficulty and this will help clinicians to tailor treatment programmes accordingly. Moreover, addressing sensory processing abilities in intervention programmes for DCD such as including sensory feedback in practice and modifying the available sensory information (e.g., visual inputs, support surfaces, and movement complexities) are encouraged. In addition, it would be advantageous if future empirical research seeking to explore sensory processing in DCD were to employ robust methods when recruiting children with DCD and examining their perceptuomotor abilities. This includes accounting for confounding factors that may affect the results such as treatment received in the past, the co-occurrence of comorbidities, individual’s lifestyle, sample size and gender (Cairney et al., 2009; Saban and Kirby, 2018). In addition, most of the studies were only interested in measuring perceptuomotor skills of the upper limbs and failed to consider lower limb function. More research is needed to reach a wider picture of the effect of SP on movement in DCD. Moreover, longitudinal studies are warranted to better understand the mechanism behind DCD and its prognosis with regard to perceptuomotor skills.

Chapter 4 Study two: The relationship between sensory processing, movement control, preference for and levels of physical activity among children

4.1 Introduction

Sensory processing (SP) refers to the ability to receive and interpret different sensory stimuli derived from everyday experiences and thus execute behavioural responses (Parker and Robinson, 2018). According to Dunn's SP Framework, each individual exhibits a predominant SP pattern that is primarily based on their behavioural responses to sensory stimuli (Dunn, 2014). Two components are suggested to determine the SP pattern for each person: neurological threshold for sensory stimuli detection and self-regulation strategies to deal with the received sensory stimuli (Dunn, 2014). The neurological threshold ranges from high (i.e., slow to detect sensory stimuli) to low (i.e., quick to detect sensory stimuli) whilst self-regulation, on the other hand, can be categorised as passive (for individuals who do not respond to all surrounding sensory stimuli) or active (for individuals who are usually reactive to stimuli).

The above mentioned two continua overlap to form four sensory processing patterns: low registration (high threshold and passive self-regulation), sensation seeking (high threshold and active self-regulation), sensory sensitivity (low threshold and passive self-regulation), and sensation avoiding (low threshold and active self-regulation) (Dunn, 2014). This, in turn, is suggested to affect the fundamental motor skills of each person and shape the characteristics of their personality (Dunn, 2007; Dunn et al., 2016). Consequently, this could also determine a person's preferences for physical activity (PA) and the amount of PA they engage in (Engel-Yeger, 2008; Ismael et al., 2015).

Atypical development of SP is commonly evidenced in children with various neurodevelopmental disorders (Critz et al., 2015). SP difficulties are highly likely to be associated with dysfunction in performing motor skills (Ayres and Robbins, 2005) and, hence, low levels of participation in leisure and PA (Cairney et al., 2017; Roberts et al., 2018). Levels of PA are important for both the physical and mental health of children (Poitras et al., 2017). However, as movement control is a fundamental block of basic motor skills and PA, investigating how movement control is influenced by SP, and consequently affects PA participation and levels, is imperative to understand the aetiology of movement difficulties and the consequences of SP problems among children with neurodevelopmental disorders.

The aim of the current study was to explore the relationship between SP abilities, movement control, levels of and preferences for PA among TD children using four self-report questionnaires. The Short Sensory Profile2 questionnaire (SP2) (Dunn, 2014) was used to measure SP patterns among children, whilst the Developmental Coordination Disorder Questionnaire (DCDQ'07) (Wilson et al., 2009) was used to measure their movement control. Additionally, the Children Assessment of Participation and Enjoyment (CAPE) and the Preferences of Activities for Children (PAC) (King et al., 2004) was used to explore children's level and preferences of participation. Finally, the Physical Activity Questionnaire for Children (PAQ-C) (Kowalski et al., 1997) was used to investigate the PA level of children. The hypothesis of this study was that the different SP patterns may determine children's movement control and account for their preferences of PA as well as their level of engagement in PA. It was hypothesised that SP patterns anticipating high sensory inputs (i.e., sensation seeking and low registration) will be related to higher levels of motor abilities and participation, whereas SP patterns anticipating low sensory inputs (i.e., sensation avoiding and sensory sensitivity) will be related to lower levels of motor abilities and participation.

4.2 Methods

4.2.1 Study sample

Participants were recruited by contacting local primary schools using our pre-existing contacts and by emails to faculties at the University of Leeds. Children aged 8-12 years of both genders were the target population for the current study. The age range was chosen because children undergo developmental changes in SP that are suggested to continue to mature until the age of 12 years (Gori et al., 2008; Brandwein et al., 2011; Gori et al., 2012). In addition, two of the questionnaires employed in the current study are self-report questionnaires that were to be answered by children, including one that was suitable for children with a minimum age of 8 years.

A G*Power calculator was used based on Faul et al. (2009) to determine the sample size. As the aim of the current study was to measure the effect of SP on movement control and, hence, levels of and preferences for participation in PA, SP was treated as a predictor of the outcome (i.e., movement control, levels of and preference for participation in PA). The statistical test used for the G*Power calculation was linear multiple regression with an 85% statistical power and a standard significance alpha level of $\alpha=0.05$, as suggested by Hicks (2009) and Portney and Watkins (2009). Additionally, the effect size of SP as a predictor of movement control, PA level, and participation preferences was anticipated from similar previous studies (Chien et al., 2016; Choi and Jung, 2021), and revealed values between $f^2=0.08$-0.25 which were within the range of a medium effect size for multiple regression, as indicated by Cohen (1988). Therefore, a suggested conventional medium size effect of $f^2=0.15$ (Cohen, 1988) was inputted. Accordingly, a sample size of 56 participants was considered appropriate for the current study to achieve sufficient power to detect the change in outcomes. However, as studies indicate that the return rate of questionnaire surveys is approximately 40% (Hicks, 2009; Portney and Watkins, 2009), we planned to distribute the questionnaires to at least 140 participants (28 participants in each age group) so that the required sample size is reached.

Sixty-two participants took part in the study. However, eight participants were excluded because more than 80% of their data were missing from their questionnaires (see section 4.2.5). Hence, the data of 56 participants (24 females and 32 males) were included in the analysis. A summary of the age and body mass index (BMI) of the study sample is shown in Table 4.1 and Figure 4.1.

Table 4.10: Age and BMI of the study sample

	N	**Minimum**	**Maximum**	**Mean**	**Std. deviation**
Age (years, months)	56	8.0	12.11	10.55	1.28

BMI (kg/m²)	36 (20 missing)	13.88	29.94	18.67	3.37

BMI = body mass index; N= number of participants; Std.=standard

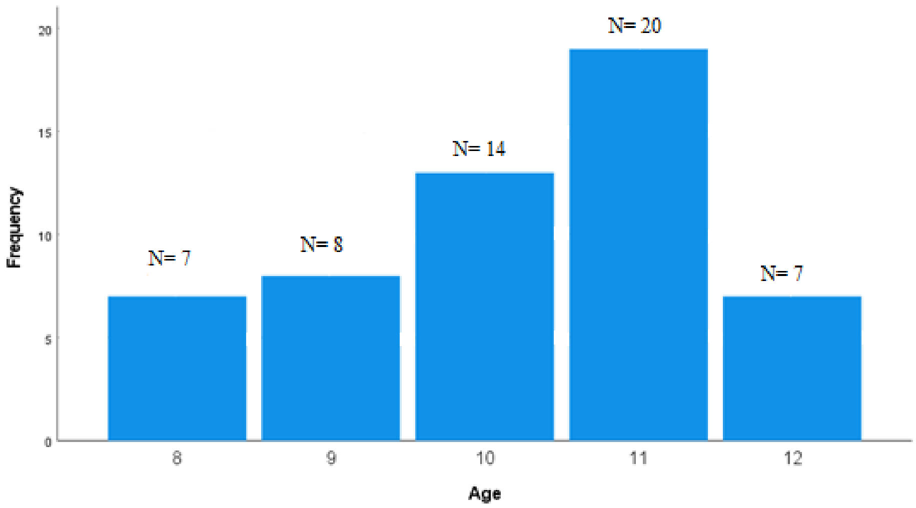


Figure 4.1 Distribution of the study sample according to their ages (years), N= number of participants in each age group.

4.2.2 Ethical considerations

Ethical approval for the study was obtained from the Faculty of Biological Sciences Research Ethics Committee at the University of Leeds (REF: BIO SCI 20-023; see Appendix I). Additionally, an information sheet was provided for the participants along with the four questionnaires, which included the aims of the study and instructions regarding how the questionnaires should be completed and returned to the researcher (see Appendix II). In addition, an information sheet that was easy to read was also provided for the children (see Appendices III). Moreover, the parent/guardian was asked to give written informed consent for their child's involvement in the study and a written assent was obtained from the child as well.

4.2.3 Questionnaires

- *Short Sensory Profile2 questionnaire*

The SP2 (Dunn, 2014) is the short, revised form of the original Sensory Profile assessments (Dunn, 1999) and is a parent-report questionnaire that is used to assess sensory processing patterns in children aged three to fourteen years. Answers to the questionnaire are primarily based on the observed habitual behavioural responses of the child to sensory events experienced in everyday contexts such as reacting to auditory and/or visual distractions in an environment, which, in turn, will help to identify the SP pattern of the child. The SP2 is a 34-item questionnaire including Likert scale questions that reflect participants' performance on each of the four SP patterns: Seeking, Avoiding, Sensitivity, and Registration. Choices of answers are provided for each question ranging from 'Almost Always' with a score of 5 to 'Almost Never' with a score of 1. The scores are then calculated to give a total sub-score for each pattern to classify participants' predominant SP pattern. Essentially, the higher the score in a specific pattern, the higher the indication of the subject's primary pattern.

In a recent review, SP2 was indicated to be one of the most used assessment tools to measure SP among children (Yeung and Thomacos, 2020). Other studies reported that the SP2 has strong psychometric properties (Dean, 2015; Licciardi and Brown, 2021). Based on 180 typically developing children, Shahbazi et al. (2021) concluded that the SP2 offers a good to excellent test–retest reliability (ICC=0.72-0.95), acceptable to good internal consistency (ICC=0.67-0.91) and good content validity >0.78. Jorquera-Cabrera et al. (2017) also added that the SP2 offers the advantage of having specialised forms using different questionnaires for each age group (e.g., infants, young children, adolescents, and adults), unlike other assessment tools. Moreover, SP2 has been reported to identify SP patterns in diagnosing clinical conditions (e.g., (Schulz and Stevenson, 2019; Delgado-Lobete et al., 2020) and in different cultural contexts (Nieto et al., 2017; Dean and Dunn, 2018; Chojnicka and Pisula, 2019).

- *Developmental Coordination Disorder Questionnaire*

The DCDQ'07 (Wilson et al., 2009) is a revised version of the original DCDQ (Wilson et al., 2000). It is a 15-item parent-report questionnaire that is used to examine general motor abilities in children aged five to fifteen years in both clinical and non-clinical populations (Cairney et al., 2008). The focus of the questions is on coordination abilities in gross and fine motor skills whereby the respondents need to compare the performance of their child to other children of the same age. Similar to the SP2, the DCDQ’07 also uses a Likert scale by which a series of answers are given to each question ranging from ‘not at all like your child’ with a score of 1, to ‘extremely like your child’ with a score of 5. A total score, ranging from 15 to 75, is then calculated to give an indication of motor coordination problems. Scores higher than 56 are reported to refer to typical motor ability performance.

Studies investigating the psychometric properties of the DCDQ’07 revealed that it has a high internal consistency ($\alpha > 0.88$) (Cairney et al., 2008; Civetta and Hillier, 2008) and excellent test-retest reliability (ICC= 0.956) (Ray-Kaeser et al., 2019). The construct validity was also measured in the study by Ray-Kaeser et al. (2019), revealing that the DCDQ’07 total scores were significantly correlated with the MABC-2 total percentile scores ($r_s = 0.802$, $p < 0.001$). Moreover, like the SP2, the DCD-Q has been translated into various languages and has been validated in various cultural contexts (Cantell et al., 2019; Caravale et al., 2019; Ferreira et al., 2020).

- *Children Assessment of Participation and Enjoyment and Preferences for Activities for Children*

The CAPE and PAC (King et al., 2004) are child-report questionnaires that aim to measure children’s level of participation and preferences in outside-school activities. Both are 55-item questionnaires that are suitable for children aged six to twenty-one years. The CAPE and PAC aim to explore different aspects of children’s participation in outside-school activities in the past four months. They measure children’s participation level and preferences in formal and informal activities grouped into five activity types: recreational, active-physical, social, skill-based, and self-improvement. The aim of the CAPE is to examine five dimensions of participation: Diversity (to indicate whether a child has done the activity within the past four months), Intensity (to indicate how often they have done it in the past four months), With Whom and Where (to identify the people and place involved when the activity took place), and Enjoyment (to indicate the level of enjoyment while taking part in the activity).

Various question formats are used in CAPE to address the five dimensions of participation. Using the Diversity dimension, a total overall score of participation is calculated with higher scores (ranging from 0-55) indicating higher levels of participation. The other four dimensions include questions comprising 5- to 7-point Likert scale answers. The mean score for each dimension is then calculated with higher sub-scores (ranging from 1 to 7) indicating higher levels of engagement and enjoyment. The PAC, on the other hand, provides the same activities given in CAPE but focuses on measuring the preferences of children for these activities by providing questions with 3-point Likert scale answers ranging from 'I would not like to do at all' with a score of 1 to 'I would really like to do' with a score of 3. Mean scores (ranging from 1 to 3) are then calculated to give an overall score for children's preferences (higher scores indicate larger variety of activities) and total sub-scores for each activity type (i.e., formal, informal, social, active-physical, etc.) to indicate children's level of interest in each activity type.

A systematic review by Cordier et al. (2016) reported that the PAC is one of the most used tools to measure occupational performance among children with the strongest psychometric properties compared to similar outcome measures. Another systematic review by Chien et al. (2014) indicated that, out of fourteen outcome measures found in the empirical literature to examine the different domains of participation in children, the CAPE and PAC are among the very few outcome measures that had sufficient evidence to demonstrate their reliability and validity. Additionally, similar to the abovementioned questionnaires, the CAPE and PAC have been validated to be used in several cultures with different languages, thereby confirming the cross-cultural validity of the questionnaires (Brown and Thyer, 2020).

- *Physical Activity Questionnaire for Children*

The PAQ-C (Kowalski et al., 1997) is a child-report recall questionnaire that is suitable for children aged eight to fourteen years. Responses regarding the level of physical activity of children are based on their habitual performance in PA before, during, and after school over the last seven days. It primarily asks about the frequency of participation in physical activities, such as bicycling or walking to and from school. This was applied through Likert-scale questions, with the answers provided ranging from 'None' with a score of 1 to '6-7 times last week' with a score of 5. Hence, higher mean scores (ranging from 1 to 5) indicate higher levels of PA. Additionally, to help achieve more reliable answers, the questionnaire also requires the children to indicate whether there were any exceptional circumstances in the previous seven days that prevented them from performing their usual activities.

Similar to other studies (Thomas and Upton, 2014; Aggio et al., 2016), several amendments were adapted to item wording and cultural adaptations and were made to the questionnaire to make it more suitable for children living in the UK. These included changing the terms of 'recess' to 'school break-time', 'in-line skating' to 'roller skating', 'aerobics' to 'group exercise', 'ice-hockey/ringette' to 'cricket', 'soccer' to 'football', 'street hockey' to 'hockey', 'cross country skiing' to 'snow/dry slope skiing', and 'floor hockey' to 'tennis'. One activity was also added to the checklist: 'rugby'. In addition, three questions were added to address all possible PA exerted within the last 7 days, making it a 13-item questionnaire. These questions asked about whether the children had done any PA before going to school and whether they actively travelled (i.e., walking, cycling, etc.) to and from school. Finally, a few specifications of the time mentioned in the questions were added for clarity. This included adding 'from the last school session until 6:30pm' to 'right after school', 'from 6:30pm until you go to bed' to 'evenings', and 'Saturday and Sunday' to 'weekend'.

In several reviews, the PAQ-C is reported to be widely used in the empirical literature and is regarded as one of the most reliable self-report questionnaire to assess PA in children (Chinapaw et al., 2010; Marasso et al., 2021). Biddle et al. (2011) reviewed 89 PA measures established in the empirical literature and indicated that the PAQ-C is one of the few self-report outcome measures that is practically and psychometrically validated to be used among children. In addition, Thomas and Upton (2014) reported that the PAQ-C has good scale reliability ($\alpha = 0.82$) and good construct validity ($\alpha = 0.88$) when compared to similar outcome measures. Moreover, the PAQ-C was also validated to be used in different languages and cultural contexts (Bervoets et al., 2014; Gobbi et al., 2016; Wang et al., 2016).

4.2.4 Data collection approach

Questionnaires were taken to participating schools and given to class teachers to be distributed to their pupils. Interested and willing participants were asked to fill in the four questionnaires and subsequently return them to the class teacher to be collected by the researcher. In addition, eligible participants from staff and students at the University of Leeds were also contacted and given the questionnaires. The researcher then collected the completed questionnaires on a later day.

4.2.5 Missing data protocol and statistical analysis

As missing data are common in questionnaire research, a protocol was set for data entry to avoid arriving at false interpretations. This included the primary investigator (SS) contacting the participants as a first step to fill in the missing data. However, if it was not possible to reach the participants, as suggested by King et al. (2004) and Dunn (2014), questionnaires with less than 80% of the answers provided should be treated with caution and, therefore, were excluded from the analysis.

Moreover, in terms of reporting the SP pattern reached for each participant when data were missing, Dunn (2014) suggested that a minimum (score of 1) and a maximum (score of 5) raw scores be added to the question with the missing answer and, thereafter, the final sub-scores are calculated for each pattern. Accordingly, if a specific pattern remains with the highest score, compared to the other patterns, when the minimum and maximum raw scores are added, the pattern with the highest score is assigned to the participant. However, if the highest score changes across the SP patterns when adding the minimum and maximum raw scores, this could be interpreted as the participant having two predominant SP patterns.

Shapiro-Wilk test was used to assess the distribution of the data. Descriptive statistics included means and standard deviation (SD) for parametric data, whilst categorical data were presented using frequencies and proportions. A Spearman rank correlation test was used to explore the relationship between the four variables of interest (SP, movement control, levels of and preferences for PA). Furthermore, to measure the association between SP patterns and movement control and, hence, PA levels and preferences, multiple linear regression was used for the analysis, in accordance with similar studies (Choi and Jung, 2021). Multiple linear regression allows us to account for all the variables of interest in one model and, thus, results in a better understanding of the independent relationship between the predictor and the outcome. SP patterns (SP2) were treated as the predictors, which are the independent variables, whereas movement control (DCDQ'07), levels of and preferences for participation (CAPE & PAC), and levels of PA (PAQ-C) were treated as the outcome which are the dependent variables. Moreover, several tests were run using the SPSS to test that the assumptions of the statistical tests used are not violated and that valid results are reached. All data were analysed using SPSS version 28 (SPSS Inc., Chicago, Illinois), with an accepted significance level set at $p<0.05$.

4.3 Results

4.3.1 Descriptive data

The descriptive statistics for the results of movement control (DCDQ'07), levels of PA (PAQ-C) and participation (CAPE), and preferences for activities (PAC) are shown in Tables 4.2 and 4.3 below. High scores (>56) for the DCDQ'07 indicate that the child is probably not experiencing motor difficulties. The mean total score for DCDQ'07 (63.80±9.52) does not show an indication of motor problems (see Table 4.3). Furthermore, high scores for PAQ-C, CAPE, and PAC refer to high levels of PA, participation, and preferences for activities, respectively. Regarding the CAPE questionnaire scores, most of the participants preferred informal activities, as indicated by the Diversity measurement (see Table 4.2). In addition, the highest level and frequency of participation were found in recreational activities, as measured by the Diversity and Intensity of the different types of activity (see Table 4.2). Moreover, as indicated by the Enjoyment score, the social activities were mostly preferred by the participants (see Table 4.2). Additionally, the average score for PA using the PAQ-C (out of a maximum of 5) was found to be 2.95 (see Table 4.3), whereas the average score for the preferences for activities using the PAC (out of a maximum of 3) was found to be 2.24 (see Table 4.3).

Table 4.2: Descriptive statistics for the CAPE scores, values presented as means ± SD

	Overall	Domain		Activity type				
		Informal	Formal	Recreational	Physical	Social	Skill-based	Self-improvement
Diversity	31.09 (±8.97) (score range=0–55)	24.69 (±6.26) (score range=0–40)	6.41 (±3.50) (score range=0–15)	8.44 (±2.18) (score range=0–12)	5.94 (±2.722) (score range=0–13)	7.04 (±1.91) (score range=0–10)	3.57 (±2.61) (score range=0–10)	6.09 (±2.040) (score range=0–10)
Intensity (score range=1–7)	4.75 (±0.58)	2.79 (±0.72)	2.06 (±1.12)	3.44 (±1.05)	2.10 (±1.03)	2.872 (±0.86)	1.60 (±1.20)	2.92 (±1.03)
Enjoyment (score range=1–5)	3.98 (±0.48)	3.98 (±0.48)	3.95 (±0.67)	4.09 (±0.52)	4.10 (±0.77)	4.23 (±0.55)	3.60 (±1.34)	3.29 (±0.77)
With Whom (score range=1–6)	2.72 (±0.50)	2.49 (±0.52)	3.74 (±0.77)	2.42 (±0.66)	3.44 (±0.74)	2.79 (±0.62)	3.26 (±1.42)	2.10 (±0.60)
Where (score range=1–5)	2.98 (±0.69)	2.76 (±0.74)	4.03 (±0.74)	2.30 (±0.95)	3.80 (±1.00)	3.01 (±0.88)	3.57 (±1.52)	2.61 (±0.81)

CAPE= Children's Assessment of Participation and Enjoyment

Table 4.11: Descriptive statistics for the DCDQ'07, PAC, and PAQ-C scores, values presented as means ± SD

Outcome measure	Mean (±SD)
Movement control (DCDQ'07) (score range=15-75)	63.80 (±9.52)
Preferences level (PAC) (score range=1-3)	2.24 (±0.29)

PA level (PAQ-C) (score range=1-5)	2.95 (±0.61)

DCDQ'07= developmental coordination disorder questionnaire (revised 2007); PAC=preferences for activities of children; PAQ-C=physical activity questionnaire for children

4.3.2 Relationship between SP, movement control, and physical activity

To confirm the association between SP (SP2), movement control (DCDQ'07), levels of PA (PAQ-C) and participation (CAPE), and preferences for activities (PAC), Spearman rank correlation test was employed. The results revealed a significant moderate positive correlation between sensation seeking and physical activities ($r_s(54)=.324$, $p<.05$) and between low registration and formal activities ($r_s(54)=.324$, $p<.05$). No other significant correlation emerged (see Table 4.4).

Table 4.12: Correlation matrix between the four sensory patterns of SP2, movement control (DCDQ'07), levels of PA (PAQ-C) and participation (CAPE), and preferences for activities (PAC)

Domains	Sensory profile patterns			
	Sensation seeking	Sensation avoiding	Sensory sensitivity	Low registration
Movement control (DCDQ'07)	-0.032	-0.108	-0.236	-0.020
Informal activities (PAC)	0.159	-0.019	-0.154	0.155
Formal activities (PAC)	0.253	0.139	0.045	**.324***
Recreational activities (PAC)	0.090	0.046	0.014	0.183
Physical activities (PAC)	**.324***	0.149	0.052	0.233
Social activities (PAC)	0.167	-0.022	-0.209	0.230
Skill-based activities (PAC)	0.059	-0.038	-0.088	0.183
Self-improvement activities (PAC)	0.162	-0.034	-0.105	0.117
Level of PA (PAQ-C)	0.187	-0.001	0.051	0.069
Level of participation (CAPE)	0.233	-0.042	-0.018	0.157

* $p < .05$

Multiple regression analysis was used to analyse whether movement control, levels of PA and participation, and preferences for activities can be predicted based on the different SP patterns. The assumptions of the multiple regression linear test were considered to ensure they are not violated and the outcome revealed that the Durbin-Watson score for the dependent variables (DCDQ'07, PAC, CAPE, PAQ-C) ranged from 1.348 to 2.205 which suggests independence of observations. Moreover, the tests of linearity and homoscedasticity using scatterplots revealed a linear relationship between the dependent and independent variables and that homoscedasticity emerged, indicating equal error variances. Moreover, collinearity did not appear in the data set as all values of Tolerance were greater than 0.1.

The results of the multiple regression revealed that sensory sensitivity significantly and negatively predicted movement control (DCDQ'07) and preferences for activities (PAC) (p=.035 and p=.030, respectively) (see Tables 4.5 and 4.8). In addition, sensation seeking significantly and positively predicted participation level and enjoyment (CAPE) (p=.021) (see Table 4.7). No other significant predictions were found. The results are summarised in the tables below.

Table 4.13: Regression analysis results for sensory processing patterns (SP2) as predictors of movement control (DCDQ'07)

	Movement control (DCDQ'07)			
	B	Std. Error	Beta	p-value
(Constant)	71.912	4.421		0.000
Sensation seeking	0.585	0.383	0.392	0.133
Sensation avoiding	-0.160	0.276	-0.119	0.565
Sensory sensitivity	-0.685	0.316	-0.468	**0.035**
Low registration	0.014	0.349	0.008	0.968

R^2 = .109, F= 1.494, p= .218, Durbin-Watson= 1.348

Table 4.14: Regression analysis results for sensory processing patterns (SP2) as predictors of level of physical activity (PAQ-C)

	Level of PA (PAQ-C)			
	B	Std. Error	Beta	p-value
(Constant)	3.166	0.292		<.001
Sensation seeking	0.036	0.025	0.382	0.157
Sensation avoiding	-0.011	0.018	-0.131	0.539
Sensory sensitivity	-0.015	0.021	-0.159	0.48
Low registration	-0.018	0.023	-0.163	0.435

R^2 = .046, F= .590, p= .671, Durbin-Watson= 2.205

Table 4.15: Regression analysis results for sensory processing patterns (SP2) as predictors of level of participation and enjoyment (CAPE)

	Level of participation (CAPE)			
	B	Std. Error	Beta	p-value
(Constant)	34.220	4.124		0.000
Sensation seeking	0.853	0.357	0.608	**0.021**

Sensation avoiding	-0.305	0.257	-0.241	0.241
Sensory sensitivity	-0.493	0.295	-0.357	0.101
Low registration	0.015	0.325	0.009	0.962

R^2 = .125, F= 1.757, p= .153, Durbin-Watson= 1.633

Table 4.16: Regression analysis results for sensory processing patterns (SP2) as predictors of preferences for activities (PAC)

	Preferences for activities (PAC)			
	B	Std. Error	Beta	p-value
(Constant)	2.306	0.130		0.000
Sensation seeking	0.021	0.011	0.462	0.067
Sensation avoiding	-0.008	0.008	-0.193	0.331
Sensory sensitivity	-0.021	0.009	-0.464	**0.030**
Low registration	0.016	0.010	0.296	0.130

R^2 = .179, F= 2.667, p= .043, Durbin-Watson= 2.157

4.4 Discussion

SP is suggested to play a significant role in movement control and, hence, affect the levels of engagement in PA and preferences for these activities. The current study aimed to establish the relationship between the differences in SP abilities, movement control, and levels of participation in PA and preferences for activities among children aged 8-12 years using four questionnaires. Dunn's SP framework, which categorises SP abilities into four patterns, was used to identify the differences in SP abilities among children. In accordance with the stated hypothesis, differences in SP abilities using the four patterns were highly likely to determine children's movement control abilities and engagement in and preferences for physical activities. This was evidenced as a significant correlation between certain SP patterns and types of activities. For example, higher sensation seeking and low registration scores were significantly correlated with an increase in physical and formal activities scores, respectively (see Table 4.4). In addition, it was shown that high scores for sensation seeking as a SP pattern significantly predicted high levels of participation in outside school activities (see Table 4.7). On the other hand, high scores in sensory sensitivity as a SP pattern significantly predicted low movement control abilities and low scores in preferences for activities (see Tables 4.5 and 4.8).

As mentioned in Chapter Two, SP refers to the ability to receive, modulate, and respond to sensory inputs (Parker and Robinson, 2018). Sensory inputs are received through various sensory receptors and individuals are reported to react differently with regards to sensory stimulation (Engel-Yeger and Dunn, 2011). Dunn's SP Framework categorises individuals' reaction to sensory stimuli into four patterns based on two continua: neurological thresholds for detecting and responding to sensory inputs and self-regulation of interacting with the received sensory inputs. Some individuals are suggested to have a high neurological threshold and require intensive sensory stimulation to detect and respond to sensory inputs, whereas others have a low neurological threshold and can be attentive and reactive to small amounts of sensory inputs (Engel-Yeger and Dunn, 2011; Dunn, 2014). The other component of Dunn's framework is self-regulation which is suggested to reflect people's strategies of dealing with the received sensory inputs, given their specific neurological threshold. Individuals categorised as having passive self-regulation strategies allow sensory stimuli to occur and do not always take action (Dunn, 2007). On the other hand, individuals characterised as having active self-regulation strategies manage to take action to control the quantity and nature of sensory inputs being received (Dunn, 2007). These patterns were validated in studies measuring brain activities which confirmed that sensory patterns assigned to children were reflected in their brain activity (Davies and Gavin, 2007).

The outcome of the current study has shown that high scores for the sensation seeking pattern were significantly related with high levels of participation in physical activities, as measured using the PAC questionnaire (see Table 4.4), which included a variety of sports activities such as bicycling, water sports, skating, etc. Additionally, higher scores for sensation seeking also predicted higher levels of general participation in outside school activities, as measured using the CAPE questionnaire. This supports previous findings in which individuals identified with a sensation seeking pattern were found to have high levels of participation in various types of activities including physical activities (Choi and Jung, 2021). In a similar way, Watts et al. (2014) reported in their systematic review that children identified as having sensation seeking patterns prefer particular play activities that entail intense sensory properties, such as creative arts and building blocks, when compared to their peers.

Conversely, Ismael et al. (2015) recruited young children and did not find a significant correlation between sensation seeking and the level of participation using the CAPE questionnaire and/or preferences for activities using the PAC questionnaire. The discrepancy between the studies may be due to the fact that Ismael et al. (2015) were interested in establishing the relationship between SP and participation among children with extreme SP patterns. Studies indicate that children with atypical SP patterns have significantly different scores in the four quadrants of Dunn's SP framework when compared to TD children (Engel-Yeger, 2008). Likewise, Chien et al. (2016) found no significant correlation between the scores of sensation seeking and play and leisure. Several possible explanations may account for the discrepancy between our results and those of Chien et al. (2016). Chien et al. utilised a sample of similar size to that of our study, however, with a wide age range (3-14 years) and with more than half (56%) of the participants having probable or definite SP problems. More importantly, the questionnaire regarding the level of participation and enjoyment was completed by the parents in Chien et al.'s research, unlike our study in which the children themselves were the respondents. It is indicated in the empirical literature that parents may not accurately predict their children's preferences and may not be aware of their experiences (Haraldstad et al., 2011). Hence, the differences between the point of views of the respondents may have influenced the results and lead to different conclusions in the studies.

Among the SP patterns, sensation seeking is characterised by having a high neurological threshold and active self-regulation (Dunn, 2014). Individuals identified with sensation seeking patterns are indicated to anticipate gaining large amounts of sensory stimulation from the environment and are suggested to be geared to detect novelty (Cross et al., 2013). This is reflected in the outcome of the current study in which participants with sensation seeking patterns were found to have higher levels of participation and preferences for physical activities that probably involve large amounts of proprioceptive and vestibular inputs such as sports. This is reported to fulfil the needs of sensory seekers (Lawson and Foster, 2016) such as enjoyment and satisfaction (Ismael et al., 2015) and to maintain their optimal level of arousal (Chien et al., 2016).

Another finding that was reached in the current study is the significant negative predictions of the sensory sensitivity pattern; higher scores for sensory sensitivity predicted lower movement control abilities and lower preferences of activities. Similarly, Choi and Jung (2021) indicated that sensory sensitivity was a predictor of low levels of enjoyment in participating in outside school activities using the CAPE questionnaire (especially in skill-based and self-improvement activities). They also reported a significant correlation between high scores for the sensory sensitivity pattern and participation preferences for activities that involve a limited number of people, as indicated using the 'With Whom' measure of the CAPE questionnaire, and activities that take place at specific and familiar places (e.g., the home), as indicated using the 'Where' measure of the CAPE questionnaire. Likewise, the study by Ismael et al. (2015) found that high scores for sensory sensitivity were linked to low scores for social and skill-based activities.

Sensory sensitivity is characterised by low sensory thresholds with passive self-regulation (Dunn, 2014). It is reported that small amounts of sensory inputs from the environment are sufficient to be noticed and detected by individuals characterised by sensory sensitivity (Serafini et al., 2016). This results in them having difficulty remaining doing one task because they are easily distracted by surrounding sensory inputs (Dunn, 1997; Brown and Dunn, 2002). In addition, large amounts of sensory inputs are indicated to be considered as invasive and may possibly trigger anxiety and discomfort among individuals with sensory sensitivity patterns (Serafini et al., 2016). Therefore, this will probably result in them not enjoying or not feeling comfortable when undertaking various activities and, thus, explain why high scores in sensory sensitivity predicted low scores in PAC in the current study. Chien et al. (2015) support this view as they found a positive correlation between routines and habits and sensory sensitivity. This might be because routines and habits involve known and familiar sources of sensory inputs and, therefore, will not cause discomfort to individuals with dominant sensory sensitivity patterns. Another consequence reported in the empirical literature of being overwhelmed with intense sensory inputs is difficulty becoming close to people (Lee and Park, 2020) which probably limits their participation in many activities such as social activities, as indicated by Choi and Jung (2021) and Ismael et al. (2015).

Movement control abilities range from learning simple limb movements that form the basic elements of developmental milestones to performing more complex movements such as juggling a ball or rope skipping (Shadmehr et al., 2010). Motor learning depends largely on sensory processing of various sensory inputs such as the information deriving from somatosensory, vestibular, and visual inputs to build a body image in relation to the world and, thus, be able to adapt and adjust movements to reach a coordinated goal-directed action (Borghuis et al., 2008; Scott, 2012). Therefore, as individuals classified with the sensory sensitivity pattern are suggested to be sensitive and overwhelmed by the amount of sensory inputs received, this may interfere with the trajectory of learning abilities of motor skills (Dunn, 1997) and may explain the negative prediction of movement control abilities, as indicated by the outcome of the current study.

A positive correlation between low registration and participating in formal activities such as community and school clubs, swimming, and gymnastics was also evidenced in the outcome of the current study. Choi and Jung (2021), on the other hand, found that a low registration pattern is negatively correlated with the overall level of enjoyment of participation, particularly in formal activities. However, this was only reported for the Enjoyment part of the CAPE by Choi and Jung, unlike the current study which only considered the Diversity which reflects the participation level regardless of the enjoyment level. Furthermore, the conflicting results are highly likely to be due to the population involved in the studies. Unlike our study, the study by Choi and Jung (2021) had a large sample (n=140) and only focused on children aged 11-12 years. Developmental changes in sensory processing are suggested to take place at the age of 8 years (Gori et al., 2008; Nardini et al., 2008) with some empirical studies indicating that it continues to mature until adolescence (Brandwein et al., 2011). In addition, skill development and motor coordination are reported to change within the period of 4-11 years and, hence, might affect the level of participation in outside school activities (Cairney et al., 2009; Giuriato et al., 2019). Finally, the reliability of score calculations in Choi and Jung’s (2021) study might be questionable as several domains included scores that were higher than the score range mentioned in the manual of CAPE. Consequently, it might be necessary to treat their findings with caution.

Low registration is characterised as having a high neurological threshold and passive self-regulation (Dunn, 2014). Individuals identified with this pattern are reported to require a large amount of sensory inputs to react and are usually passive in reaction (Dunn, 2014). Sensory inputs around them are not usually noticeable, even if they are helpful or important (Jorquera-Cabrera et al., 2017). Therefore, as formal activities (such as social clubs and team sports) are known being structured and organised with specific instructions to be followed (King et al., 2005), they may act as motivators for individuals with a low registration pattern as they need a lot of sensory inputs and guidance to remain focused. Other formal activities mentioned in CAPE include swimming, gymnastics, and playing music may have provided individuals with a low registration pattern with the sensory inputs required to fulfil their needs of support, arousal level, and satisfaction. The nature of the low registration pattern might also explain the non-significant correlation with the other informal activities mentioned in CAPE such as performing chores. This may be due to those individuals with low registration being unaware of issues around them that need to be organised and set properly and being passive in self-regulation so they do not have the motivation to take an action.

4.5 Limitations

Several limitations might have affected the results of the current study. The lack of a significant association between PA levels using the PAQ-C questionnaire and any of the SP patterns may be related to the seasonability of the period during which the data were collected. The questionnaires which focused on children's level of PA and participation sought to measure children's performance within the last 7 days to 4 months. For that reason, because most of the data were collected during the autumn and winter period, this might have limited the usual and preferred physical activities that children undertake. Other potential limitations include the relatively small sample size, compared to similar studies, and group characteristics such as BMI and age which were not evenly represented.

Another element that might have affected the results is the role of respondents in relation to the child participating (i.e., the mother or the father). Inter-parental disagreements have been indicated in the empirical literature when reporting their child's behaviour (Davé et al., 2008). Future research may consider comparing parental reports to improve the sensitivity of identifying the behavioural responses of children. In addition, the views of parents may differ from those of their children's teachers. This is due to parents generally comparing their child's behaviour to a small number of children around them, whereas teachers can compare a child's behaviour against large groups of age-matched peers. Furthermore, parents' reports may be influenced by the educational level of the parents (Lawson and Foster, 2016).

4.6 Conclusion

The results of the current study indicate that movement abilities and participation in leisure and physical activities may be influenced by sensory processing abilities. This was evidenced as participants identified with SP patterns that rely on large amounts of sensory inputs to improve arousal and satisfaction levels such as sensation seeking and low registration prefer activities that involve high sensory inputs like physical activities including sport. Others that are identified with sensory patterns which are characterised by being overwhelmed and anxious when receiving large amounts of sensory inputs such as sensory sensitivity are found to have low preferences for activities and low motor control abilities. Therefore, differences in the development of movement skills and, hence, levels of participation in leisure and physical activities among children may be explained by the diversity in sensory processing abilities.

This knowledge could help clinicians and researchers to identify the type of activities that may be linked to and affected by sensory processing abilities to better understand a child's needs when planning for an intervention programme. Learning about the role of SP on movement control and participation may also help to train a child with extreme and atypical sensory processing patterns about how to suppress and deal with irrelevant sensory inputs and selectively focus and respond to other relevant sensory inputs.

The empirical literature is replete with studies measuring the correlation between movement control and participation in activities among children, however, there is a paucity of empirical studies in the existing body of literature exploring how SP abilities may influence these correlations. It is important to look into young children's participation and PA levels and the reasons behind low and high levels of

PA as levels of participation in PA from an early age are believed to predict the activity levels of individuals during adulthood (Kjønniksen et al., 2009; Mäkelä et al., 2017). Future research may take objective measurements of movement skills and PA levels such as using the movement assessment battery for children-2 (M-ABC2) and accelerometers, respectively, and link them with SP abilities. Moreover, future research may find it useful to consider other personal characteristics that may have influenced the data such as the difference between boys and girls, BMI, ethnicity, socioeconomic status, and the educational levels of households.

Chapter 5 Study three: Multisensory decision- making in typically developing children

5.1 Introduction

Various sensory inputs need to be processed to make a relevant perceptual decision and produce behavioural responses that can be expressed via movements (Seilheimer et al., 2014). Sensorimotor abilities are largely dependent on the interplay between two intertwined cognitive processes: multisensory processing and perceptual decision-making (Gold and Shadlen, 2007) (see Chapter Two). The former process refers to the ability to process sensory information coming from different senses (Murray and Wallace, 2011), whereas the latter refers to the process of interpreting the sensory information to guide goal-directed movements (Heekeren et al., 2008).

Decision-making is suggested to be primarily explored by measuring the reaction time (RT) and response accuracy of a behavioural response (Stafford et al., 2020). The empirical literature is replete with studies indicating that processing spatially and/or temporally combined multisensory inputs rather than unisensory inputs results in improvements in behavioural outcomes (Barutchu et al., 2011; Parker and Robinson, 2018) that are probably linked to enhancements in decision-making (i.e., decreased RT and increased response accuracy). As such, the interaction between multisensory integration (MSI) and decision-making significantly interfere with motoric abilities. However, the contribution of the process of MSI in relation to perceptual decision-making to produce a behavioural outcome in children is not yet understood (Mercier and Cappe, 2020).

Developmental changes with regards to MSI are suggested to take place throughout childhood. The ability to integrate multisensory inputs to enhance behavioural performance is suggested to start showing at the age of 9 years (Brandwein et al., 2011). Moreover, children aged 8-10 years are indicated to undergo transitional changes with regards to MSI that may not reachbr the optimal level before adolescence (Gori et al., 2008; Nardini et al., 2008; Brandwein et al., 2011). Thus, older children might benefit more from MSI than younger children to improve perceptual decision-making abilities (Petrini et al., 2014; Broadbent et al., 2018).

Several factors are reported in the empirical literature to contribute to MSI and, thus, they are highly likely to affect the cognitive process of decision-making. These include attention abilities that can interfere with sensory stimuli selection for further processing and interpretation (Talsma et al., 2010; Seilheimer et al., 2014; Barutchu et al., 2019). Attention can be driven to specific sensory stimuli depending on the observer's intentions and past experience or the nature of the sensory stimuli presentation (e.g., salient display of a particular stimuli) that leads to the involuntary shifting of attention between modalities (Talsma et al., 2010). Recalibrating the dependence on various sensory stimuli might also be related to modality dominance that may affect the process of MSI and guide behavioural performance (Lustig and Meck, 2011; Seilheimer et al., 2014). It has been suggested that modality dominance changes across an individual's lifespan (Zélanti and Droit-Volet, 2012), although it is indicated to largely depend on the situation and task being tested (Innes-Brown et al., 2011)

Motor difficulties and movement coordination problems are reported to be a core deficit in a range of neurodevelopmental disorders among children (Colizzi et al., 2020). It is indicated in the empirical literature that movement difficulties and coordination problems may be attributed to deficits in MSI and SP (Piek et al., 2004). Therefore, to better understand the role of multisensory processing on sensorimotor skills across childhood and identify the mechanism behind motor difficulties, the current study aims to investigate the effect of multisensory versus unisensory stimulation on two elements contributing to perceptual decision-making among children using a well-established categorisation task adapted from previous work (Philiastides and Sajda, 2005, 2006; Diaz et al., 2017). It was hypothesised that performance in multisensory contexts will result in an enhanced process of decision-making by means of shorter RTs and higher accuracy rates and, consequently, improved behavioural responses will be evidenced. Another hypothesis was that older children will benefit more than younger children from multisensory stimulation in terms of decreasing their RT and increasing their accuracy level.

5.2 Methods

5.2.1 Study sample

Recruitment of the volunteering participants entailed advertising for the study via social media, using posters distributed across different departments at the University of Leeds (see Appendix IV), and through word of mouth. The inclusion criteria were typically developing children of both genders aged 5-12 years, whereas the exclusion criterion was any known neurodevelopmental disorder or medical condition that may affect participants' ability to perform the task properly.

To better understand the development of perceptual decision-making in children, the target population were children between the ages of 5-12 years. Moreover, in accordance with prior relevant work (Gori et al., 2008; Brandwein et al., 2011; Nardini et al., 2013), we aimed to recruit 100 participants (~12 participants in each age group). However, as erroneous data had to be removed to reach valid results (see section 5.2.5), the data of 93 participants (42 females, 51 males) were included in the analysis. A summary of the ages of the study sample is presented in Table 5.1 and Figure 5.1.

Table 5.17: Age of the study sample

Descriptive statistics: Age (years, months)					
	N	Minimum	Maximum	Mean	Std. Deviation
Total	93	5.03	12.07	9.06	1.07
5-8 years	35	5.03	8.09	8.0	0.09
9-12 years	58	9.0	12.06	10.05	1.02

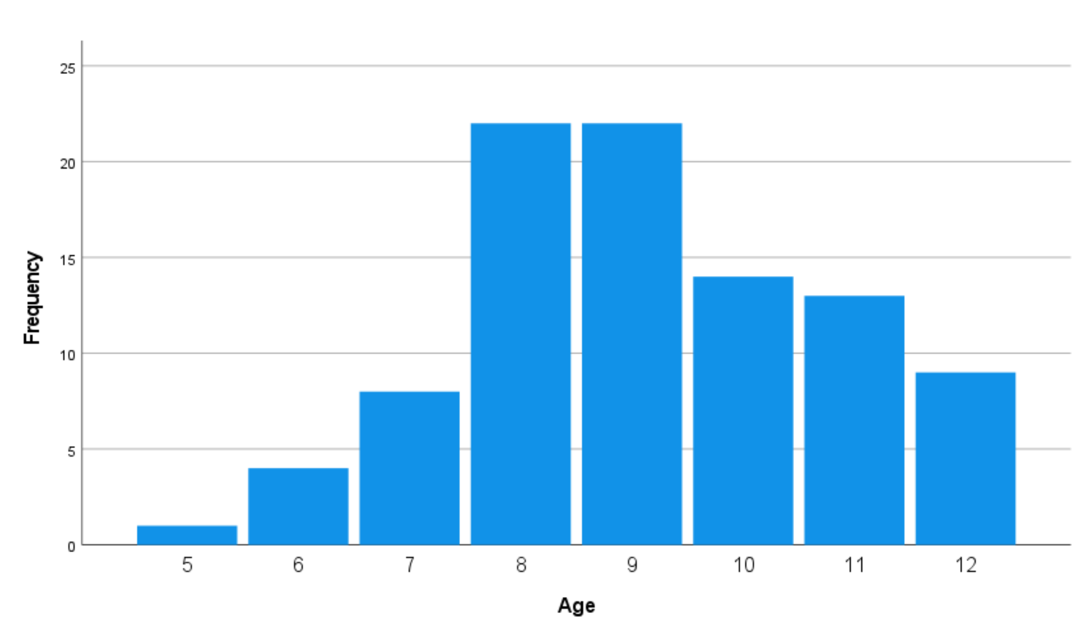


Figure 5.1 Distribution of the study sample according to their ages (years).

5.2.2 Ethical considerations

Ethical approval for the study was obtained from the Faculty of Biological Sciences Research ethics committee at the University of Leeds (REF: BIO SCI 19-021). The categorisation task included a digital information sheet for the participants' parents/guardians to read before commencing the online task. The information sheet included the aims of the study and the instructions regarding how to perform the task. All parents/guardians of the children who participated were then requested to give consent for their children to take part in the study by electronic means prior to the start of the online task. In addition, another electronic information sheet was provided to the children which was suitable for them to read, and they provided assent to participate.

5.2.3 Task procedure

Prior to undertaking the audio-visual task, and after reading the information sheet and providing consent, the parents were asked to complete a demographic page that included information about the child's age, gender and whether they suffer from any medical condition. This was followed by children's information sheet that was provided before commencing the task. The experiment consisted of a simple categorisation task that required the participants to identify whether the pictures displayed on the screen represented a face or a car, and accordingly press a specific button using the computer keyboard.

5.2.4 Audio-visual task paradigm

The paradigm was adapted from a previous study which explored multisensory effects on perceptual decision-making (Philiastides and Sajda, 2005; Philiastides et al., 2006; Diaz et al., 2017; Franzen et al., 2020). The sensory stimuli consisted of visual and auditory inputs that were presented either simultaneously or independently to test multisensory and unisensory effects, resulting in three conditions: audio-visual (AV), visual (V) and auditory (A).

Adapted from the protocol of Diaz et al. (2017), the visual stimuli consisted of 18 face and 18 car greyscale visual images (512 x 512 pixels, 8-bits per pixel) presented against a white background using PsychoPy software (Peirce, 2009; Peirce and MacAskill, 2018). All of the images were equated for spatial frequency, luminance and contrast and uploaded into Gorilla Experiment Builder (www.gorilla.sc) which was used to create the task and collect data (Anwyl-Irvine et al., 2019).

To better identify differences between the participants' performance, the amount of sensory evidence in the image was altered into two levels of phase coherence: 32.5% (low coherence) and 37.5% (high coherence) (see Figure 5.2) (Philiastides et al., 2006). This is reported to manipulate the noise and consequently the difficulty of the task (Diaz et al., 2017). The high and low levels of phase coherence were presented randomly.

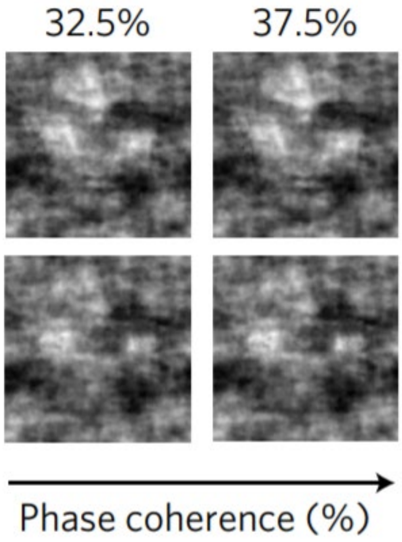


Figure 5.2 An example of a distorted face (upper row) and a car image (lower row) over two levels of phase coherence (32.5% and 37.5%).

The auditory stimuli consisted of 18 car-related (e.g., driving sounds) and 18 face-related (e.g., human speech) sounds obtained from online sources and adapted in PsychoPy software (Peirce, 2009; Peirce and MacAskill, 2018). Moreover, the auditory stimuli were sampled at a consistent Hertz (Hz) rate (60 Hz), controlling for temporal sequencing, pitch and volume. In addition, similar to the visual stimuli, they were also altered to two levels of coherence (high and low), matching the psychophysical threshold. The two different sensory stimuli (i.e., visual and auditory) were always presented with the same level of coherence (i.e., low and high).

The children were asked to categorise the distorted images and/or sounds as a human or a car by pressing an allocated key button on a standard computer keyboard; the ‘J’ button was for humans and the ‘K’ was for cars. The participants were instructed to make a response as quickly and as accurately as possible. There were 216 trials divided equally into three consecutive blocks (72 trials per block) with a one-minute break in between. Each block included 24 trials of each of the three conditions (i.e., AV, V, A). The three conditions along with the two levels of coherence of the sensory stimuli were presented randomly throughout the task.

The stimuli appeared for 300ms and after each trial, feedback was given in the form of a tick for correct responses and a cross for incorrect responses. After that, a centred fixed cross was presented for 1,000ms before the next stimulus was presented. The children were given a maximum period of 3,000ms to make a response and in cases where the participant did not make a response within the timeframe allowed, the fixation cross appeared without feedback. Figure 5.3 summarises the experimental paradigm of the task.

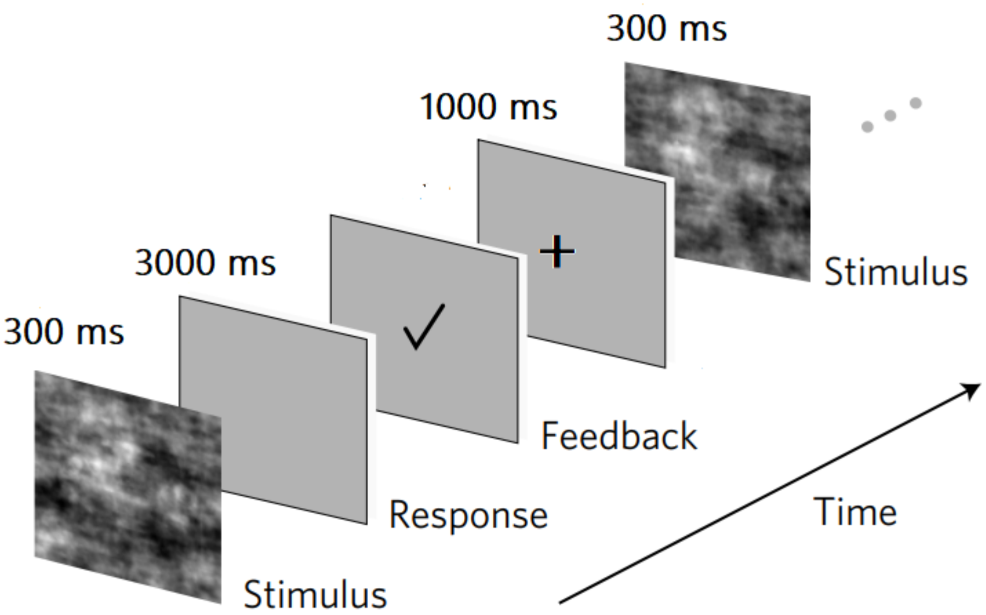


Figure 5.3 Participants were required to categorise distorted visual and auditory stimuli as a face or a car. Each stimulus was presented for 300ms, followed by a period of up to 3,000ms, during which the participants had to make a response by pressing a button. Accordingly, feedback was given for 1,000 ms as means of a cross (incorrect) or tick (correct) to indicate the accuracy of responses. After that, a fixation cross was presented for 1,000ms before the next trial.

5.2.5 Data pre-processing and statistical analyses

All data were entered into Excel and SPSS version 28 (SPSS Inc., Chicago, Illinois) was used for the purpose of analysis. Moreover, based on previous similar work (Getz and Kubovy, 2018), the data were excluded from the analysis if they were presented with less than 60% of the overall response accuracy. In addition, trials with less than 50ms of RT in either of the sensory conditions were excluded as this may indicate that responses were based on random guesses (Getz and Kubovy, 2018). In addition, the outliers were calculated and excluded if they were presented with >2.5 median absolute deviation (MAD) (Leys et al., 2013).

To find the if there was a significant effect of interaction between the participants' performance and the sensory conditions, a mixed-effects linear regression was used. This test is reported to control for individual differences when subjects are set as a random effect and, thus, better account for inter-subject variability in responses (Baayen et al., 2008). Specifically, as multiple independent variables were involved in the analysis, which were the three sensory conditions (AV, V, A) of the task and the two levels of coherence (high and low), to measure the RT, mixed-effects linear regression was used because the dependent variable (RT) is considered to be continuous. Moreover, to measure the effect of the three conditions and levels of coherence on accuracy, mixed-effects logistic regression was used because the dependent variable (accuracy) is dichotomous. Furthermore, a one-way ANOVA and paired t-tests were run to confirm the differences between the conditions among participants. The significance level is set at 0.05 in this study and a p-value of less than 0.05 is considered to show a statistically significant result.

Several tests were conducted prior to running the statistical tests to assess the violations of assumption. These included testing for outliers, checking normality and linearity, testing independence of residuals, detecting outliers, and testing for homogeneity of variances. In addition, the participants' data were categorised into two groups (5-8 years and 9-12 years). This was based on the developmental changes across these age stages in multisensory processing as evidenced from the empirical literature (Gori et al., 2008; Brandwein et al., 2011; Petrini et al., 2014; Broadbent et al., 2018b). The reported descriptive statistics included means and standard deviation (SD) for parametric data, whilst categorical data were presented using frequencies and proportions.

5.3 Results

5.3.1 Reaction time

Prior to running the mixed-effects linear regression test, several procedures were followed using SPSS to test the assumptions of the statistical test to ensure assumptions are not violated. These included testing the linearity of the dependent variable (RT) which revealed significant linearity between the dependent variable and the factors involved in the analysis (i.e., sensory conditions, coherence level, age groups) ($p<.05$). Moreover, the assumption of independence of residuals (i.e., uncorrelated observations) was tested using the Durbin-Watson test, as recommended by Field (2013), which revealed a value of 1.2. The closer the value is to 2, the more valid the test will be (Watson and Durbin, 1951), however, values <1 or >3 may lead to serious concerns regarding the ability to reach a valid conclusion from the outcome (Field, 2013). In addition, the assumption of normal distribution of the residuals of the dependent variable (RT) was tested by plotting a histogram of the residuals for every predictor value which confirmed that the residuals were normally distributed. Finally, the homogeneity of variance was assessed using a plot of studentised residuals versus unstandardised predicted values. Visual inspection of the scatterplots showed that there was a homogeneity of variance.

The outcome revealed a significant main effect of condition ($F(2,18386)=349.344$, $p<.001$), age group ($F(1,18386)=682.902$, $p<.001$), and coherence ($F(1,18386)=12.416$, $p<.001$). Combined age groups had significantly shorter RT in the audiovisual condition (950.573ms ±4.210) than in the visual (965.972ms ±4.246, $p=.009$) and auditory (1094.231ms ±4.303, $p<.001$) conditions (see Figure 5.4). In addition, children were also significantly faster in the visual condition than the auditory condition ($p<.001$) (see Figure 5.4). Furthermore, combined age groups were significantly faster in conditions with high coherence phase (995.051ms ±3.485) than with low coherence phase (1012.134ms ±3.504, $p<.001$) (see Figure 5.5). Moreover, the older children (9-12 years) had significantly shorter RT (937.834ms ±3.044) than the younger age group (5-8 years) (1069.351ms ±4.008, $p<.001$) (see Figure 5.6).

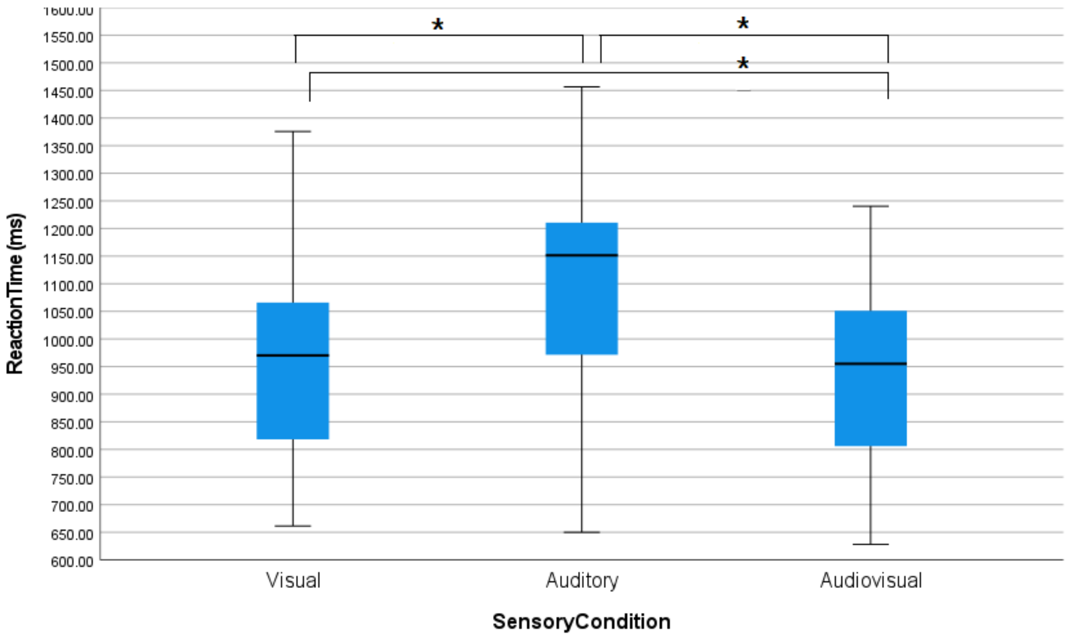


Figure 5.4 Combined age groups RT (means ± standard errors) for the three conditions: visual, auditory, and audiovisual, (*) denotes significant difference in RT between the conditions.

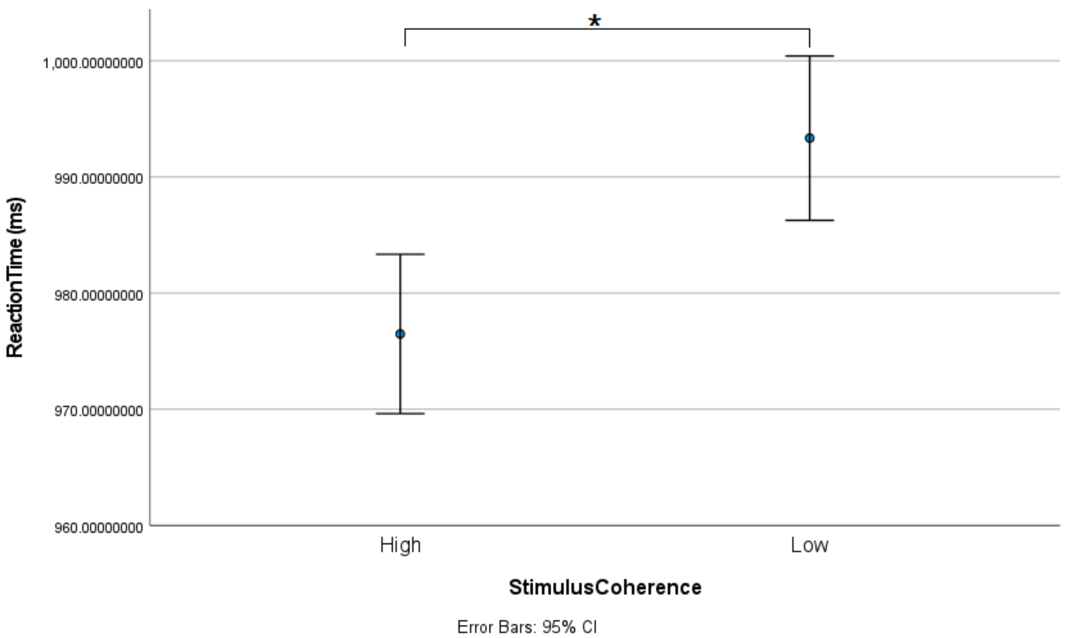


Figure 5.5 Combined groups RT (mean) for the two levels of phase coherence: high (37.5%) and low (32.5%), (*) denotes significant difference in RT between the conditions.

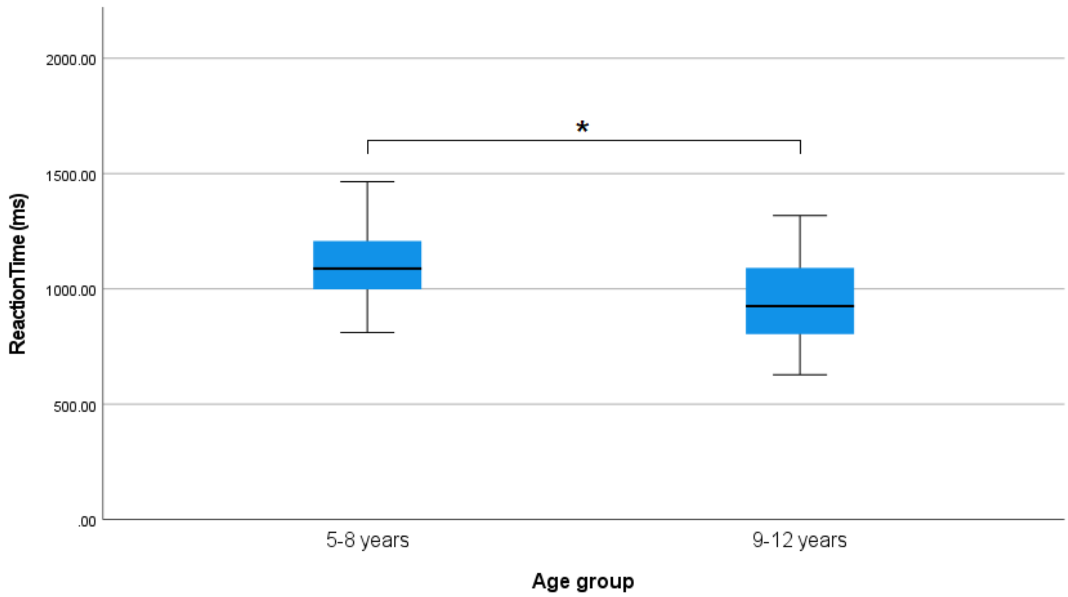


Figure 5.6 RT (means± standard error) for the younger group (5-8 years) vs the older group (9-12 years), (*) denotes significant difference in RT between the groups.

Interaction between task conditions and age groups was analysed and significant sensory condition by age group ($F(4,18383)=17.342$, $p<.001$) and stimulus coherence by age group ($F(2,18383)=6.196$, $p=.002$) interactions were found. After considering the assumptions of the one-way repeated measures ANOVA (detecting outliers, checking normality, and sphericity), the test was run to confirm the differences between the groups and the conditions. The older age group (9-12 years) were significantly faster in the audiovisual condition (875.161ms ±24.884) than in the visual (895.468ms ±25.909, $p=.006$) and auditory (1015.361ms ±28.688, $p<.001$) conditions, however, they were also significantly faster in the visual condition compared to the auditory condition ($p<.001$) (see Figure 5.7). On the other hand, the younger age group (5-8 years) were significantly faster in the audiovisual condition (1014.647ms ±35.816) compared to the auditory condition (1176.231ms ±40.990, $p<.001$) but not to the visual condition (1025.677ms ±37.014, $p=.704$) (see Figure 5.7).

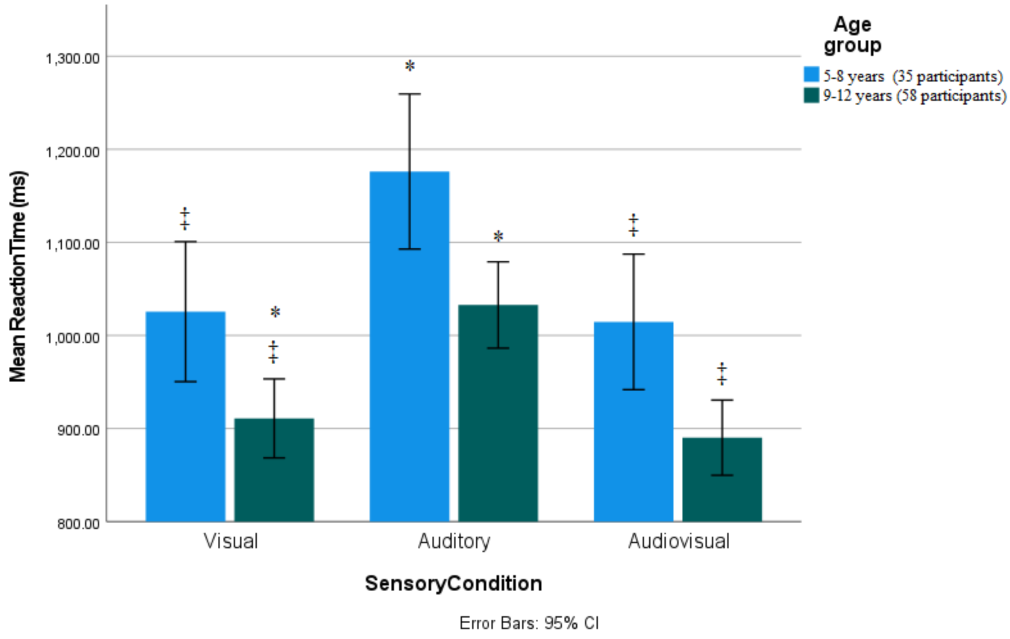


Figure 5.7 RT (means± standard error) for the younger group (5-8 years; 35 participants) vs the older group (9-12 years; 58 participants) in the three conditions, (*) denotes significant difference in RT when compared to the audiovisual condition, (‡) denotes significant difference in RT when compared to the auditory condition.

After considering the assumptions of the paired t-test (identifying outliers and checking the normality of the data), the test was run to confirm the differences between the age groups and the levels of the coherence phase. The results revealed that the older group (9-12 years) had significantly lower RT in the condition of the high level of coherence phase (934.8457ms ±20.125) than the low level (951.1455ms ±20.284, $p<.001$). Conversely, there was no significant difference in RT between the high (1060.7971ms ±36.889) and low (1077.3486ms ± 36.744) levels of coherence phase for the younger age group (5-8 years) ($p=.073$) (see Figure 5.8).

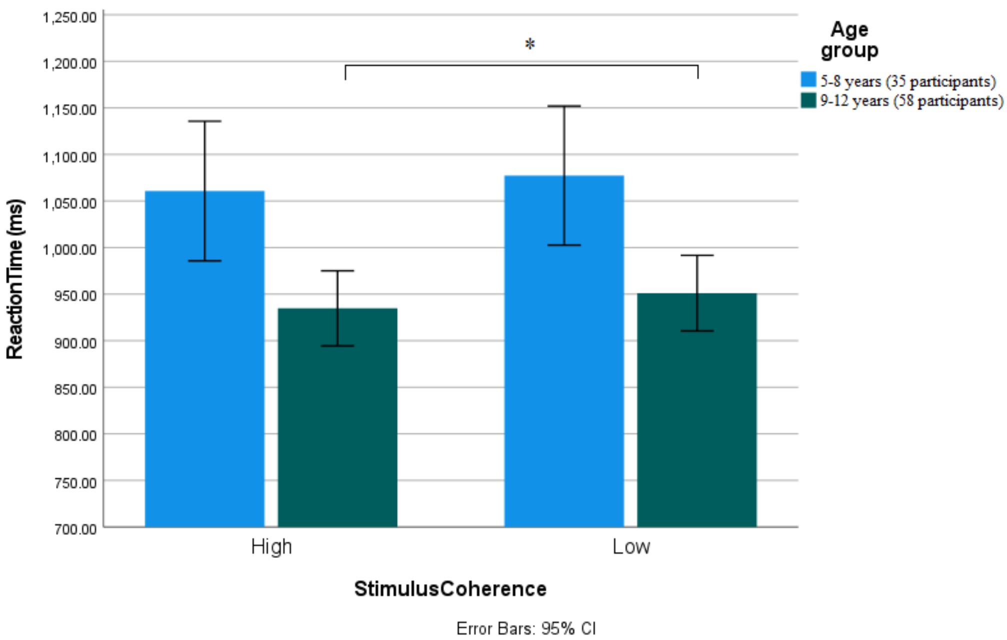
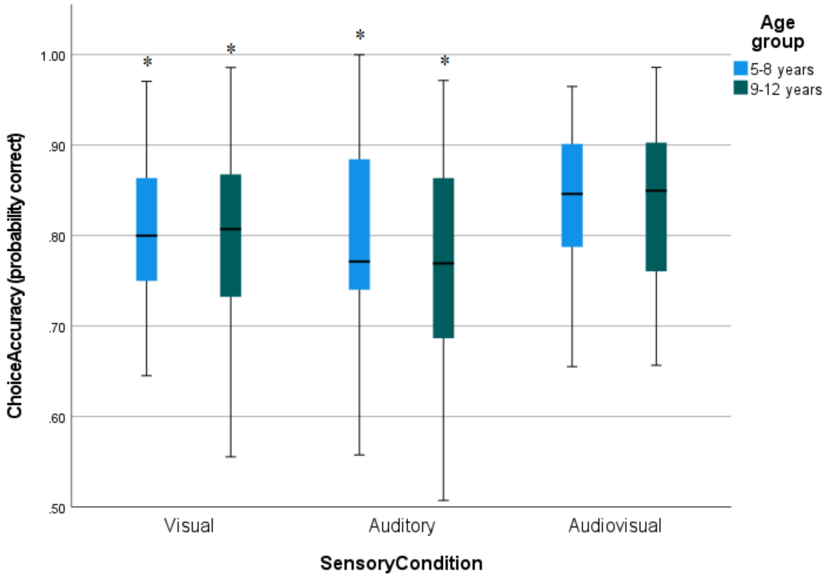


Figure 5.8 RT (means± standard error) for the younger group (5-8 years; 35 participants) vs the older group (9-12 years; 58 participants) in the two levels of coherence phase: high (37.5%) and low (32.5%), (*) denotes significant difference in RT between the two levels.

5.3.2 Accuracy

As the outcome of the mixed-effects logistic regression is categorical (accuracy) and the three independent variables involved are categorical (i.e., sensory condition, phase coherence, age group), it is not required to test the assumptions of the test. The outcome of accuracy revealed a significant main effect of condition ($F(2,7)=20.661$, $p=.001$) and level of coherence phase ($F(1,7)=46.982$, $p<.001$). However, no significant main effect of age group was found ($F(1,7)=.642$, $p=.449$). Combined age groups had a significantly larger percentage of correct responses in the audiovisual condition (83.2%) than the visual (79.6%, $p=.014$) and auditory (77.9%, $p=.006$) conditions. Nevertheless, no significant difference was found in response accuracy between the visual and auditory conditions ($p=.253$) for either group (see Figures 5.9a and 5.9b).

a



b

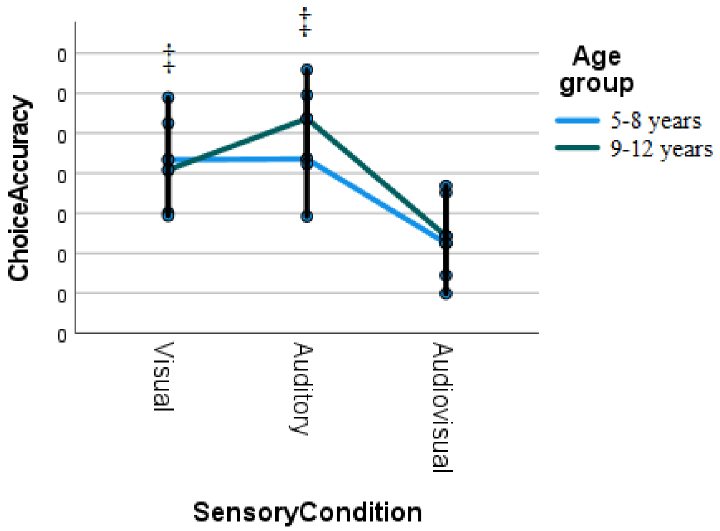


Figure 5.9 Accuracy level (proportion of correct choices) for the younger age group (5-8 years) vs the older age group (9-12 years) in each sensory condition, (a) (*) denotes significant difference in accuracy level when compared to the audiovisual condition, (b) (‡) denotes significant difference in accuracy when compared to the audiovisual condition for both groups.

In addition, combined age groups had a significantly greater percentage of correct responses in the high coherence phase (82.6%) than in the low phase (77.9%) (p=.003) (see Figure 5.10). Moreover, no significant interaction was found between task sensory conditions or stimulus coherence and age group (p=.491 and p=.580, respectively).

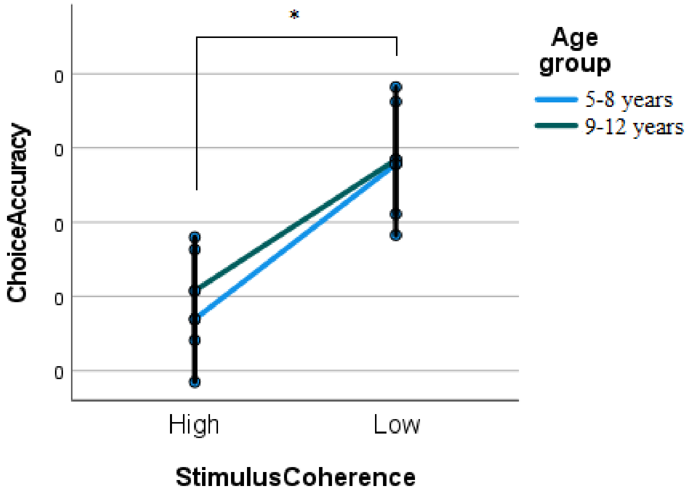


Figure 5.10 Accuracy level for the younger age group (5-8 years) vs the older age group (9-12 years) in each level of the coherence phase: high (37.5%) and low (32.5%), (*) denotes a significant difference in the accuracy level of both groups.

5.4 Discussion

Children's behavioural responses are suggested to primarily depend on the development of MSI and perceptual decision-making. Therefore, the current study aimed to establish the effect of multisensory stimuli on perceptual decision-making among children aged 5-12 years using a categorisational task. In accordance with the stated hypothesis, children's performance in multisensory conditions resulted in enhanced behavioural responses by which a shorter RT and higher accuracy were evidenced. However, multisensory effects differed between the age groups involved in the study. The older age group (9-12 years) benefited from multisensory stimuli to improve both elements contributing to decision-making (RT and accuracy). On the other hand, multisensory stimuli only benefited response accuracy among the younger group (5-8 years) and their RT was significantly shorter in the conditions that primarily involved visual information.

Consistent with several studies (Barutchu et al., 2010; Brandwein et al., 2011), the outcome of the current study revealed that younger children (5-8 years) were significantly slower (i.e., had larger RT) in all the conditions of the audiovisual categorisation task than the older children (9-12 years). As behavioural RTs are indicated to represent the speed of information and cognitive processing that may develop at different rates (Scantlebury et al., 2014), the slower performance of the younger age group is highly likely to be due to immature cognitive processing. Information processing is indicated to be largely dependent on the interconnectivity between white matter tracts in the brain (Penke et al., 2012; Scantlebury et al., 2014) which are reported to undergo a gradual maturation until the age of 13 years (Scantlebury et al., 2014). Therefore, this may have accounted for the slower responses exhibited by the younger age group in the current study compared to the older age group.

Other studies suggest that improvements in behavioural responses take place in early cognitive processing of sensory inputs and late cognitive processing which primarily account for attention and decision-making (Diaz et al., 2017; Franzen et al., 2020). Therefore, the attention abilities of children can significantly affect multisensory perception and the interplay between attention and MSI may affect behavioural performances (Miller et al., 2009; Barutchu et al., 2019). Like other cognitive processes, attention abilities undergo a gradual developmental trajectory that may continue to mature until adolescence (Lustig and Meck, 2011; Abundis-Gutiérrez et al., 2014). Studies indicate that transitional changes in attentional abilities take place between the ages of 7 to 10 years (Abundis-Gutiérrez et al., 2014) and children aged 5-8 years have limited attentional capacity (Zélanti and Droit-Volet, 2012). Curtindale et al. (2007) attribute these developmental changes to the less experience exhibited by younger children in modulations of cognitive processing compared to older children. In addition, tasks involving timed responses, such as the task in the current study, place greater demands on attention and perceptual abilities and thus usually result in larger RTs (Cromer et al., 2015). Therefore, the immature cognitive processing (including attention skills) of younger children may have affected their outcome and led to a larger RT compared to the older group.

The ability of multisensory stimuli to enhance behavioural performance has been well established in the empirical literature (Matusz et al., 2017) with some suggesting that brain activity significantly increases when multisensory inputs are spontaneously displayed compared to unisensory inputs (Brett-Green et al., 2008). However, although children have been reported to be able to show cross-modal matching from infanthood (Parker and Robinson, 2018), the ability to integrate sensory inputs to enhance perceptual cognitive processes and behavioural performance is suggested to continue to develop throughout childhood and early adolescence (Barutchu et al., 2011; Brandwein et al., 2011; Broadbent et al., 2019). Moreover, studies of the neural correlates of the effect of multisensory stimuli indicate that multisensory neurons have large receptive fields at birth and these receptive fields tend to narrow with age, thus becoming more selective (Innes-Brown et al., 2011). Consequently, older children may become more attentive and responsive to multisensory inputs (Innes-Brown et al., 2011). In accordance with this, the results of the current study revealed that the ability of multisensory stimuli to enhance the RT was only pronounced among the older age group and not in the younger group. This outcome was supported by Murray and Wallace (2011) who indicated that audiovisual integration does not become mature before the age of 10-11 years and developmental changes start to be observed at the age of 7 years.

On the other hand, with regard to response accuracy, participants in both age groups were able to enhance their error rate in the audiovisual conditions compared to the auditory and visual unisensory conditions. In addition, there was no significant difference between the age groups with regard to response accuracy and no significant interaction between age and condition. Thus, the ability of multisensory stimuli to enhance accuracy was similar for the younger and older children and this finding corresponds well with previous studies investigating similar age groups (Nardini et al., 2016; Broadbent et al., 2018b; Barutchu et al., 2020). The outcome of Barutchu et al. (2020) indicated that younger children (aged 8 years) and older children (aged 11 years) had significantly fewer errors in the multisensory (audiovisual) conditions compared to the unisensory conditions and no significant difference was evidenced between the two age groups with regard to error rate. Moreover, Nardini et al. (2016) revealed that children benefit from multisensory information to enhance accuracy from the age of four years. Accordingly, response accuracy results of the current study could not be solely explained by developmental changes in multisensory perception.

One factor that may have influenced the outcome of the younger age group in the current study is the speed-accuracy trade-off which is suggested to play a significant role in multisensory integration and, hence, decision-making (Seilheimer et al., 2014). Experimental tasks involving speeded decision making may largely affect the error rate of the respondents (Liesefeld and Janczyk, 2019). For instance, in the current study, response accuracy was rewarded more than the speed of responses by means of feedback given after each trial of the task to indicate correct or incorrect choices. Therefore, as speed-accuracy trade-off is suggested to be affected by the development of cognitive processing and, hence, the skill may vary between age groups (Innes-Brown et al., 2011; Nardini et al., 2016), it may have affected the outcome of the younger age group whereby a larger RT was evidenced in the multisensory conditions when compared to the older group, however, with improved accuracy that was comparable to that of the older age group.

Nevertheless, unlike the outcome of the current study which showed that children of both age groups were able to improve their accuracy in the multisensory conditions with a similar performance, a study by Gori et al. (2012) indicated that children are unable to enhance their accuracy rate using multisensory stimuli before the age of 12 years. One possible explanation for this difference is that Gori et al. (2012) were primarily investigating audiovisual integration with regard to the spatial and temporal perception of the sensory inputs. The sensory stimuli (auditory and visual) were incongruently presented (i.e., at different locations or different timings) in some trials of Gori et al., unlike the current study. Another possibility is the factor of learning which may have contributed to the results of our study. It is indicated that learning and past experience play a significant role in the process of gaining behavioural advantage from multisensory stimuli (Miller et al., 2009; Brandwein et al., 2011; Innes-Brown et al., 2011; Seilheimer et al., 2014). The sensory stimuli in the current study were presented for 300-ms and the feedback of response accuracy was given after each trial which might have helped the participants in the learning processes of the correct choices. Gori et al. (2012), on the other hand, presented the visual and/or auditory stimuli for 74-75-ms and, more importantly, no feedback was given to the participants in the experimental trials and, thus, the learning factor might not have influenced their results. Furthermore, Gori et al. (2012) compared the performance of children to that of adults to explore MSI developmental abilities which was not considered in our study. Finally, the authors of the study by Gori et al. (2012) have not looked into the RT and only considered accuracy. Therefore, given all of these points, a direct comparison between the studies might not be possible.

Modality dominance has been extensively explored in the empirical literature and shifting the attention between sensory modalities has also been suggested to contribute to the process of multisensory integration (Miller et al., 2009; Seilheimer et al., 2014). Children are reported to be driven by modality dominance for their performance to a greater extent when compared to young adults (Lustig and Meck, 2011). A large body of research indicates that auditory modality dominates in infants and during early childhood (Parker and Robinson, 2018) which is suggested to be due to the large volume of language learning in the early years of development (Hillock-Dunn et al., 2016). However, auditory dominance tends to shift to visual dominance in children (Lustig and Meck, 2011) starting from the age of 6 to 7 years (Curtindale et al., 2007; Gori et al., 2012; Nava and Pavani, 2013; Barnhart et al., 2018; Broadbent et al., 2018). However, modality dominance is suggested to largely depend on several factors such as the reliability of the sensory inputs being displayed as well as the task requirements (Curtindale et al., 2007; Ernst, 2008; Innes-Brown et al., 2011; Murray and Wallace, 2011; Gori et al., 2012; Nava and Pavani, 2013). For instance, vision dominates in tasks involving location and auditory dominates in tasks involving time.

Consistent with the hypothesis of modality dominance, the outcome of the current study confirmed that both age groups had superior performance with regard to their RTs in the conditions that only involved visual stimuli compared to the auditory stimuli. Furthermore, the performance of the younger age group (5-8 years) in terms of their RT was predominantly guided and enhanced by the visual stimuli and probably not by the multisensory stimuli as no significant difference was found between the visual and audio-visual conditions with regard to the RT. This may be due to the limited attentional abilities exhibited by young children which is suggested to result in selecting one type of sensory stimuli to be processed whilst ignoring others (Matusz et al., 2015). Therefore, the younger age group might have experienced difficulties shifting their attention between the modalities. Moreover, it is indicated that tasks that require a higher concentration of visual inputs, such as the distorted images employed in the current study (different levels of coherence phases), may deplete the attention to auditory inputs for performance and result in attentional bias in favor of visual inputs (Nava and Pavini, 2013; Matusz et al., 2015; Barnhart et al., 2018). In addition, although auditory stimuli might be faster to detect and pay attention to (Lustig and Meck, 2011; Barnhart et al., 2018), it is indicated that visual inputs are faster encoded in the long-term memory (Lustig and Meck, 2011) and are reported to receive priority in the brain to be attended to and processed (Lukas et al., 2014).

5.5 Limitations

One potential limitation with the current study is the large variations in the number of participants in each age group which might have influenced the outcome and given an inconclusive interpretation regarding the developmental differences in MSI. However, the total sample size of the current study was found to be comparable to or larger than several similar studies (Brandwein et al., 2011; Gori et al., 2012; Nardini et al., 2016; Barutchu et al., 2020). In addition, the nature of the task employed in the current study being applied through online platforms might have helped to reach a wider representation of the population of children. Nevertheless, this might have acted as a limitation to control for individual differences and confounding factors between participants such as their academic or IQ levels.

Furthermore, due to the nature of the task, controlling for participants' attention such as monitoring their eye-fixation was not possible. However, this is likely to be controlled using the exclusion criteria of the trials which might be invalid (participants with <60% accuracy level, trials with <50-ms of response time, and outliers with >2.5 MAD) and adversely affect the outcome. Finally, involving a task that explores more than two sensory stimuli (e.g., haptic) or measuring brain activity while participants do the task would have led to a more extensive analysis of the contribution of MSI process to decision-making. However, this was not possible due to the time restrictions imposed by the PhD programme. Future research may consider incorporating these to provide a wider picture and better understand the relationship between MSI and decision-making throughout childhood.

5.6 Conclusion

Multisensory information play a significant role in enhancing decision-making and behavioural performance. However, this was evidenced to vary significantly between younger and older children. Older children were able to gain a behavioural advantage from multisensory stimuli to improve both elements contributing to decision-making (RT and accuracy). On the other hand, younger children were only able to enhance their accuracy level in multisensory conditions. The RT of the younger children was predominantly guided and improved by visual stimuli. Several reasons may attribute to the findings of the current study. These include the learning process and speed-accuracy trade-off that may have influenced the results of the younger age group. In addition, the developmental changes of cognitive and sensory processing among children, such as attentional abilities and modality dominance, are suggested to result in bias to visual inputs and, thus, superior performance in the unisensory conditions of visual stimuli compared to auditory stimuli.

Chapter 6 General discussion and conclusion

6.1 Introduction

For any movement to be produced, a dynamic interaction of SP and motor programming takes place to execute a coordinated and goal-directed movement (Woollacott and Shumway-Cook, 1990; Utley and Astill, 2008). SP consists of receiving and interpreting various sensory inputs derived from the body and the environment through several sensory systems including the visual, auditory, vestibular, and haptic (Prochazka and Ellaway, 2012). Motor programming, on the other hand, involves producing motor commands that are based on cognitive processing such as forming internal body representations and regulating sensory feedback in order to execute and control a movement (Grove and Lazarus, 2007; Summers and Anson, 2009). Therefore, SP abilities are reported to largely contribute to movement control (Nakagawa et al., 2016; Jorquera-Cabrera et al., 2017) which forms the basic element for performing physical activities (PA) (Rosenbaum, 2009). As such, it is suggested that movement difficulties and developmental delays may be attributed to deficits in SP (Sigmundsson et al., 1997).

The first study aimed to summarise the role of SP on movement abilities among children with movement difficulties, particularly with DCD. This is due to the empirical literature being replete with studies measuring the role of SP on movement among children with DCD, however, no recent systematic review to summarise the findings has been published. Moreover, the second study of this thesis aimed to explore the relationship between SP abilities, movement control, levels of and preferences for PA. This was established to build on previous research that sought to explore movement skills and levels of PA among TD children, however, rarely considered SP abilities. It is imperative to understand the attributes of movement abilities and the factors leading to low and high levels of PA among TD children as this may predict the level of PA in adulthood. In addition, given what has been discussed in previous chapters regarding the role of SP on movement abilities, it might be important to explore how SP abilities interfere with movement skills and levels of participation and PA to recognise the mechanism behind movement difficulties and low participation levels among different neurodevelopmental disorders such as DCD. Furthermore, to better understand children’s behavioural responses and identify potential advantages to maturing sensory systems, the third study aimed to investigate the effect of multisensory versus unisensory stimuli on two elements contributing to perceptual decision-making (reaction time (RT) and accuracy). This was conducted because there is limited research in the empirical literature measuring how MSI contributes to decision-making among typically developing children and the trajectory of the development of this interaction remains unclear. The three studies sought to test the following hypotheses:

1. The various dimensions of SP, such as visuospatial, kinaesthetic and proprioception processing, have a significant effect on movement abilities among children with DCD.

2. SP patterns anticipating high sensory inputs (i.e., sensation seeking and low registration) will be related to higher levels of motor abilities and participation, whereas SP patterns anticipating low sensory inputs (i.e., sensation avoiding and sensory sensitivity) will be related to lower levels of motor abilities and participation.
3. Performance in multisensory contexts will result in an enhanced process of decision-making by means of shorter RTs and higher accuracy rates and, consequently, improved behavioural responses will be evidenced.

4. Older children will benefit more than younger children from multisensory stimulation in terms of decreasing their RT and increasing their accuracy level.

6.2 Main findings and implications

In agreement with the first hypothesis, SP was indicated by the first study to significantly contribute to the movement abilities of children with DCD. Several aspects of SP were explored in relation to movement in this study. Visual perception, which has been suggested to significantly affect SP abilities and, hence, the behavioural responses (Ayres, 1996) was found in many forms, to primarily account for movement difficulties in DCD. One aspect is the inefficient processing of visual information which is in accordance with several studies (Wilson and McKenzie, 1998; Wilson et al., 2012; Wilson et al., 2017b; Blank et al., 2019). Dysfunction in visual perception has also been a diagnostic feature of several other neurodevelopmental disorders such as ASD (Chung and Son, 2020), ADHD (Jung et al., 2014), and specific learning difficulties (Aral, 2021).

Inefficient SP (including visual processing) in DCD are reported to be due to delays in sensorimotor networks (Blank et al., 2019; Rinat et al., 2020) such as low sensitivity to sensory inputs (i.e., high sensory thresholds) and slow processing of sensory feedback (Geuze, 2003; Gomez and Sirigu, 2015). These deficits are indicated to lead to problems in internal modelling (Adams et al., 2014; Ferguson et al., 2015). Deficits in internal modelling have been reported to significantly affect movement control parameters such as movement planning and programming in DCD (Adams et al., 2014; Emanuele et al., 2022). This has also been supported by studies exploring brain activity in which reduced activation in neural regions related to motor planning and attention was found among individuals with DCD (Reynolds et al., 2015; Reynolds et al., 2019). Similarly, it was evidenced in several studies included in our review that difficulties in internal modelling and predictive motor control were found among children with DCD. This was observed as disruptive internal representations of the body and inefficient online error correction which probably resulted in atypical speed and accuracy of movement (Zoia et al., 2002; Bo et al., 2008; Williams et al., 2008; Elders et al., 2009; Biancotto et al., 2011; Ferguson et al., 2016; Adams et al., 2016; Roche et al., 2016).

Despite the fact that multi-level approaches for treatment programmes are recommended for children with DCD (Blank et al., 2019), deficits in SP and, hence, internal modelling may encourage approaching intervention programmes involving mechanisms that pertain cognitive processing or adaptation. Such types of intervention include motor imagery training which had promising outcomes in the empirical literature to improve motor control in DCD (Wilson, 2005; Wilson et al., 2016; Adams et al., 2017). These may include treatment activities involving both behaviour and computational motor control training such as enhancing attention abilities and using feedback strategies to improve movement control (Wilson et al., 2012).

Executive functioning has been reported to be significantly associated with movement difficulties among children with DCD (Leonard, 2016; Wilson et al., 2020; Fogel et al., 2021). The underpinnings of problems with executive functioning such as poor working memory and attention in DCD have also been suggested to be linked to deficits in visual perception and visuospatial processing (Wilmut et al., 2007; Alloway and Archibald, 2008). This supports the findings of several studies included in our systematic review including those of Tsai and Wu (2008), Biancotto et al. (2011), Gheysen et al. (2011), and Tsai et al. (2012a). The relationship between executive functioning and movement skills may emphasise the importance of providing treatment intervention to children with DCD to improve their motor skills as this, in turn, will probably yield some benefits in terms of their visual perception and executive function, as indicated in the empirical studies (Yu et al., 2018; Hashemi et al., 2022).

Inefficient SP is suggested to result in performance deficits in DCD being more prominent with task constraints involving large cognitive demands (Wilson et al., 2017a). This was supported in the studies included in our review which explored movement abilities in tasks involving several task constraints such as unreliable support surfaces (Speedtsberg et al., 2017), dual-tasks and higher cognitive demands (Zoia et al., 2002; Williams et al., 2008; Chen et al., 2011; Tsai et al., 2012a; Chen et al., 2015; Smits-Engelsman et al., 2015; Adams et al., 2016; Chen and Tsai, 2016; Wade et al., 2016; Bonney et al., 2017), speeded responses (Debrabant et al., 2013; Debrabant et al., 2016), and increased movement complexity (Tsai et al., 2008; Elders et al., 2009; Chen and Wu, 2013). For clinical practice, this may suggest that the assessment of movement abilities in DCD is effective and accurate when applied at an individual level to specifically identify the task constraint that reveals movement difficulties and this will help clinicians to tailor treatment programmes accordingly. This may include a broad assessment of both cognitive and motor skills and in different task contexts. Furthermore, as indicated by recent reviews (Smits-Engelsman and Verbecque, 2022), identifying task constraints that make a motoric performance difficult for a child with DCD could also be used when planning intervention programmes. This could be applied by setting the level at which a treatment activity should be based on. For instance, starting with tasks involving simple movements or low cognitive load and gradually increasing the complexity of the task.

Movement skills and motor coordination are the basic elements for performing physical activities (Shadmehr et al., 2010). It is indicated that individuals differ in terms of their processing of and response to sensory stimuli and, consequently, this diversity in SP abilities may determine a person's movement abilities which, in turn, may explain their activity level and preference for activities (Dunn, 2007; Dunn et al., 2016). In accordance with this, the results of the second study indicate that movement skills and participation in leisure and physical activities are influenced by SP abilities (hypothesis two). This was evidenced as a significant association between high levels of participation in activities that involve high sensory inputs and SP patterns characterised as requiring large amounts of sensory inputs for satisfaction and arousal. Furthermore, low preferences for activities and low motor control abilities were found to be associated with SP patterns characterised as being overwhelmed and anxious when receiving large amounts of sensory inputs. This extends to empirical studies indicating that the different SP patterns may determine a person's mood and feelings (Engel-Yeger and Dunn, 2011) and children's preferences for play (Roberts et al., 2018).

This may emphasise the importance of understanding differences in SP abilities among children as this knowledge could help clinicians and researchers to better understand the attributes of low and high activity levels among children and the diversity in their behavioural responses to different situations. It could also help clinicians to identify the consequences of atypical SP and the symptoms associated with each SP pattern to identify a child's needs when designing treatment programmes. This may include setting an environment for a patient that suits their sensory needs and preferences and choosing activities in a treatment session that may result in greater benefits for patients. On the other hand, identifying the activities that alleviate discomfort to a child may help a therapist to gradually introduce those activities and progressively teach a child appropriate management strategies.

Execution of movement and motor control are suggested to be strongly linked to the SP of various inputs (Nakagawa et al., 2016). SP consists of several stages including the ability to detect sensory stimuli, regulate and interpret them, and provide a behavioural response accordingly (Jorquera-Cabrera et al., 2017; Engel-Yeger and Dunn, 2011). Behavioural responses to sensory inputs involve an interplay between multisensory integration (MSI) and perceptual decision-making (Gold and Shadlen, 2007). Therefore, enhancement of decision-making was sought in many empirical studies when sensory information are presented from different modalities compared to unisensory presentations (Drugowitsch et al., 2014) This supports the findings of the third study of this thesis by which children were able to improve their perceptual decision-making in multisensory contexts (hypothesis three). However, this was found to vary between age groups; older children were able to gain a behavioural advantage from conditions involving multisensory stimuli to improve both elements contributing to decision-making (RT and accuracy), whereas younger children were only able to enhance their accuracy level in multisensory conditions (hypothesis four).

Several factors were reported in the empirical literature to contribute to MSI and, hence, may affect perceptual decision-making abilities. These include reweighting the dependence on the different sensory modalities (e.g., modality dominance), speed-accuracy trade-off, and the incorporation of past experience (e.g., learning factor) (Seilheimer et al., 2014). These aspects may have influenced the outcome of the third study in this thesis. For instance, children of both age groups were significantly faster in visual conditions compared to auditory conditions which could be attributed to changes in modality dominance across development. It is indicated that children undergo a shift from auditory to visual dominance at the age of 6-7 years (Lustig and Meck, 2011). Another possible explanation for the bias to visual inputs is the difference in sensitivity between the two sensory modalities (auditory vs. visual) to occupy the task demands (Drugowitsch et al., 2014; Bizley et al., 2016; Dunifon et al., 2016). Visual information may be more reliable and dominant in discrimination tasks (e.g., faces and cars in our study) (Hecht and Reiner, 2009) and auditory information are suggested to be more dominant and reliable in temporal tasks (i.e., detected more quickly) (Bizley et al., 2016; Dunifon et al., 2016).

The study of Gori et al. (2012) contradicts the findings of our study by indicating that children are unable to enhance their accuracy level in conditions involving multisensory stimuli before the age of 12 years. Our study, on the other hand, found that older children (9-12 years) were able to enhance their performance and gain a larger advantage from multisensory contexts compared to younger children (5-8 years). The learning factor and the incorporation of previous experience may explain the difference in the results arrived at by the studies. The task in our study involved providing feedback of correct responses which may have resulted in children learning the correct responses and increasing their accuracy level, unlike the study by Gori et al. (2012) in which no feedback was provided. Moreover, in contrast to Gori et al. (2012) in which only the accuracy level of participants was investigated, our task explored both RT and accuracy of children's performance.

The differences between the age groups in terms of gaining behavioural improvement in multisensory conditions may be due to several developmental changes in cognitive and sensory processing such as the attentional abilities of children (Innes-Brown et al., 2011). Furthermore, speed-accuracy trade-off, which is suggested to vary between age groups (Innes-Brown et al., 2011; Nardini et al., 2016), may also have played a role in the performance of the younger age group in which they were able to enhance their accuracy level in multisensory conditions but with slower performance when compared to older children.

Understanding decision-making abilities provides a predictive picture of how children react differently to situations with various tasks involving dynamic and fast decisions. For example, faster information processing (i.e., lower RT) exhibited by the older age group in our study may indicate a better ability to encounter challenges in treatment settings. Therefore, knowledge of the distinctions between age groups may help clinicians and researchers to anticipate variations in performance when assessing and treating children of various ages in different situations.

6.3 Summary of future directions

With regard to the systematic review, as previously reported, the methods used in the studies included in our review to underpin the role of SP on movement in DCD were diverse and, hence, probably led to differences in the outcomes. This may lead to our conclusions being considered preliminary and this can be strengthened by further studies using robust methods to address SP in DCD. These can be achieved by increasing adherence to the diagnosing criteria of identifying children with DCD and addressing several confounding factors that may influence their performance such as considering comorbidity, treatment history, gender, and academic level. Furthermore, given the intertwined relationship between motor abilities and a range of domains such as cognitive, social, and academic performance, future studies may consider the role of SP on these outcomes as they could link to motor abilities. Moreover, as some of the studies support the hypothesis of developmental delay rather than deviance in DCD, further research focusing on the adult population and longitudinal studies are warranted to better understand the mechanism behind DCD and its prognosis with regard to perceptuomotor skills.

For the second study, knowledge about the association between SP, movement abilities and participation among TD children is limited in the empirical literature. Further research is warranted in this field and, importantly, it is necessary to incorporate children's reports to assess their participation level and preferences for activities. In addition, to better understand this association, including brain activity and reflecting it with behavioural performance (movement abilities and participation levels) and SP abilities could enhance the validity of the results. Furthermore, future research may take objective measurements of movement skills and PA levels such as using the movement assessment battery for children-2 (M-ABC2) and accelerometers, respectively, and link them with SP abilities. Moreover, future research may find it useful to consider other personal characteristics that may have influenced the data such as the difference between boys and girls, BMI, socioeconomic status, and the educational levels of households.

In terms of the third study, it might be worth repeating this study while involving different SOAs between the sensory inputs and compare the results as other similar studies evidenced contradicting results when different SOAs were employed. In addition, future research may consider removing the set duration of time for the presentation of sensory stimuli. This is indicated to better understand the processing time of sensory stimuli and identify how fast children of various age groups can accumulate sensory evidence (Drugowitsch et al., 2014). Moreover, as in the second study, correlating behavioural performance with brain activity may strengthen the validity of the results.

6.4 Conclusion

The association between SP and movement among children has been investigated through three studies in this thesis. The first study focused on children with movement difficulties (particularly DCD) by providing an update from the empirical literature regarding the role of SP on movement abilities among children with DCD. The second study sought to expand knowledge of the role of SP in determining individual's movement abilities as well as levels of and preferences for PA. The third study addressed how SP and particularly MSI contribute to perceptual decision-making.

The findings suggest that the various dimensions of SP may interfere with perceptual decision-making and movement abilities among children contributing to their motor planning and movement control. As such, this might determine a child's preferences for PA and determine their participation level in PA. In conclusion, the thesis confirms that SP plays a significant role in movement abilities and, thus, should be addressed in assessment and treatment programmes for various diagnoses.

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Appendices

Appendix I

Dear Shaikha

NB: All approvals/comments are subject to compliance with current University of Leeds and UK Government advice regarding the Covid-19 pandemic.

I am pleased to inform you that the above research ethics application has been reviewed by the Faculty of Biological Sciences Ethics Committee and on behalf of the Chair, I can confirm a favourable ethical opinion based on the documentation received at date of this email.

Please retain this email as evidence of approval in your study file.

Please notify the committee if you intend to make any amendments to the original research as submitted and approved to date. This includes recruitment methodology; all changes must receive ethical approval prior to implementation. Please see https://ris.leeds.ac.uk/research-ethics-and-integrity/applying-for-an-amendment/ or contact the Research Ethics Administrator for further information fbsesearchethics@leeds.ac.uk if required.

Ethics approval does not infer you have the right of access to any member of staff or student or documents and the premises of the University of Leeds. Nor does it imply any right of access to the premises of any other organisation, including clinical areas. The committee takes no responsibility for you gaining access to staff, students and/or premises prior to, during or following your research activities.

Please note: You are expected to keep a record of all your approved documentation, as well as documents such as sample consent forms, risk assessments and other documents relating to the study. This should be kept in your study file, which should be readily available for audit purposes. You will be given a two week notice period if your project is to be audited.

It is our policy to remind everyone that it is your responsibility to comply with Health and Safety, Data Protection and any other legal and/or professional guidelines there may be.

I hope the study goes well.

Best wishes
Kaye Beaumont
On behalf of David Lewis, Acting Chair, FBS

Appendix II

UNIVERSITY OF LEEDS

Information Sheet for Parents and Guardians

INVESTIGATION TITLE: *The relationship between sensory processing, movement control and physical activity in children*

Your child has been invited to take part in a research study looking at the relationship between how they react to sensory information (e.g. audio, visual), their movement capability and how active they are. This study is also being carried out in part to fulfil a research degree or PhD. The information below should explain the purpose of the study.

What is the purpose of the study?

The purpose of this study is to examine types of sensory processing in children, how this relates to their movement capability and how much physical activity they take part in.

Why has my child been chosen?

Your child has been chosen because our target population are children between the ages of 8-12 years.

What will happen if my child and I take part?

Your child will have brought home two envelopes which contain all project papers. Please read this information sheet carefully and kindly encourage your child to read their 'children information sheet'. After that, if you want to take part, please sign the 'parent/guardian consent form' and allow your child to sign the 'children assent form'. Then, answer the 'demographic questionnaire', which will be used confidentially for processing study results. Then, we would like you to answer the Sensory Profile2 (SP2) and the Developmental Coordination Disorder Questionnaire (DCDQ-'07) and let your child answer the Children's Assessment of Participation and Enjoyment (CAPE) and Physical Activity Questionnaire for Children (PAQ-C), as the format is suitable for their age. Each questionnaire will take between 5 and 20 minutes to complete. A description of how to answer the questions will be given at the beginning of each questionnaire. Finally, you are kindly asked to put the questionnaires back to the same envelope they were in, seal them to make sure the answers are kept private, and give them to your child to return them to the class teacher. To give you enough time, we would appreciate it if you return the questionnaires by next week. The researcher will pass again to collect the answered questionnaires from class teachers.

What are the possible benefits of taking part?

Your child's participation in the study is voluntary and will be greatly appreciated. However, there are no immediate benefits to taking part in the study. In the long term it could help us better understand the relationship between sensory processing in children and their performance in different daily activities.

What are the possible disadvantages and risks of taking part?

There are no risk or disadvantages associated with volunteering for the study.

Will my child's participation in the study be kept confidential?

All information collected about your child from the questionnaires will be kept strictly confidential. Personal identification information will only be asked in the demographics sheet to help us sort out the answers and just in case future project-related communication is needed. Each child will be given a participant number and this number will be used in all the paperwork associated with the research. In this way, no one other than the researcher will be able to identify who the results belong to. All data will be stored on secure storage devices, with only principal investigator, as well as a select research team at the University of Leeds, having access to the data. The safe storage of this data will be managed by the researchers in collaboration with the Faculty of Biological Sciences Information Technology Manager. We will comply with the University of Leeds' General Data Protection Regulations to protect your personal data. For further information please visit the following website: https://dataprotection.leeds.ac.uk/.

Can I ask further questions about the research project?

You may ask more questions about the study at any time – before, during, or after the study. The researchers will provide their telephone number and email addresses, so that they are available to answer your questions or concerns about the study. Please do not hesitate to ask the researcher if there are any points about the study that remain unclear to you.

Can my child withdraw from the study?

Your child's involvement in this research project is voluntary. You may withdraw from the research for any reason without explaining why and this will not affect your legal rights as a guardian. However, by submitting your answers, you consent for your data to be used and at that stage your answers/data collected cannot be withdrawn.

What will happen to the results of the study?

When the study is completed, the results will be revised and may be included in a PhD thesis. Study results may also be published in scientific journals and presented in health-related conferences. Remember that your child's results are confidential, and their name and personal details will not be associated with any information published from the study.

Who has reviewed this study?

This study has been reviewed and approved by the Faculty of Biological Sciences Ethics Committee at the University of Leeds.

Further information

If you require any further information about the study and its results, or have any questions and/or worries please contact us through any of the details below:

Project supervisor:

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Department of Sport & Exercise Sciences

5.21, Miall, University of Leeds

LS2 9JT

Email: S.L.Astill@leeds.ac.uk

Telephone Number: +44(0)113 343 7267

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Thank you for your cooperation!

Appendix III

Version 1
BIOSCI 20-023

UNIVERSITY OF LEEDS

INFORMATION SHEET FOR CHILDREN

How much I do and how much I enjoy being active

Hello ☺,

My name is Shaikha and I am a researcher at the University of Leeds.

I am trying to understand what activities children aged between 8 and 12 years like to take part in and how often. I'm also interested in how children use information such as light and sound, and how that affects how much you move and if you like to move. I will also ask your parent or guardian to tell me some more about your movement and if and how much you like light and sound. If you would like to, you could help me by answering some of these questions. I wouldn't know it was you who has answered them as you do not need to write your name on them.

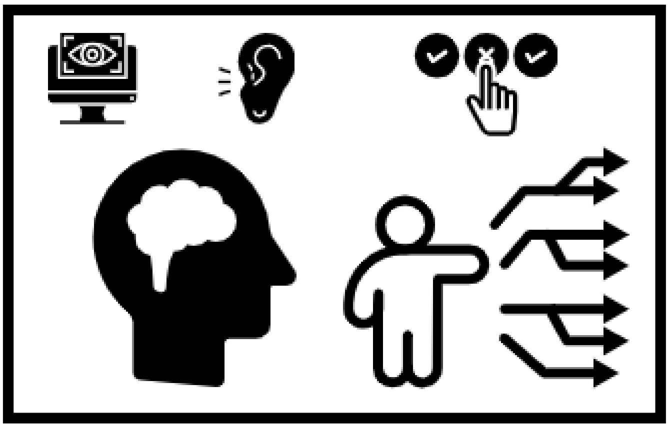
If you have any question about the project, ask your parent or guardian and they can always phone me and ask me.

Thank you!

Appendix IV

UNIVERSITY OF LEEDS

Multisensory Decision-Making Study



We are currently seeking to recruit participants for an <u>online experiment</u> investigating how we make decisions using our visual and auditory senses.

The experiment involves:

- A **simple perceptual decision-making task**, involving a computer/laptop screen that presents different images and a speaker presenting different sounds. Participants would identify the image/sound and press the correct key according to their choice.
- Following the URL below and completing the experiment, **which will last approximately 20-25 minutes**.
- For your online participation, you will receive a *****£10 Amazon Voucher***.**

Selection criteria:

- **Males/Females from 5-90 years of age** (*feel free to share with friends/family!*).
- Normal or corrected-to-normal vision (including glasses or contact lenses).
- Free from any known hearing impairments
  Free from any known musculoskeletal, motor, or neurological impairments

Experiment URL:
<ENTER WHEN READY TO GO>

If you require any further information, please feel free to contact any of the following researchers:

- Dr Ioannis Delis – University of Leeds (I.Delis@leeds.ac.uk)
- Mr Joshua Bolam – University of Leeds (bsjwb@leeds.ac.uk)

Mrs Shaikha Sultan – University of Leeds (bssamm@leeds.ac.uk)