Université de Montréal

Sensorimotor skills in autism spectrum disorders: a meta-analysis

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Mémoire présenté à la Faculté des études supérieures et postdoctorales
en vue de l'obtention du grade de Maître ès Sciences (M.Sc.)
En psychologie

Avril 2019

Université de Montréal
Faculté des études supérieures et postdoctorales

Ce mémoire intitulé:

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Résumé

Les habiletés sensori-motrices sont souvent rapportées comme déficitaires chez les personnes atteintes d'un trouble du spectre de l'autisme (TSA), mais peu de consensus règne sur la façon dont ces habiletés varient en fonction du développement. L'objectif de ce mémoire est de mener une méta-analyse visant à montrer une différence sur le plan des habiletés motrices fines et globales chez les TSA en comparaison avec un groupe neurotypique. Au total, 139 études ont été incluses. Les résultats montrent la présence de déficits importants des habiletés sensori-motrices chez une population TSA (k=127, g=1,25, SE=0,08; p<0,001), à la fois pour la motricité fine (k=81, g=1.11, SE = 0.09; p < 0.001) et globale (k=65, g=1.27, SE= 0.10; p< 0.001). Le but ultime est d'établir les bases théoriques pour de futures interventions cliniques, telles qu'avec la musique et la danse, chez une population autiste.

Mots-clés: autisme, sensori-moteur, coordination motrice, déficits moteurs, habiletés motrices

Abstract

Sensorimotor skills are often reported as atypical in people with autism spectrum disorder (ASD), but little is known about how these skills vary with development. The main objective of this thesis was to conduct a comprehensive quantitative meta-analysis of sensorimotor skills in ASD. The specific aim was to assess the consistency of atypical gross and fine sensorimotor behaviours in ASD. A total of 139 studies were included. Results strongly support the presence of deficits in overall sensorimotor abilities in ASD (k=127, g=1.25, SE=0.08, p <0.001), extended to both fine (k=81 , g=1.11, SE = 0.09, p <0.001) and gross sensorimotor skills (k=65, g=1.27, SE=0.10, p <0.001). The ultimate mission of this research is to support a theoretical groundwork for future sensorimotor-based interventions (e.g., music and dance) in ASD.

Keywords: autism spectrum disorder, sensorimotor, motor coordination, motor impairments, motor skills

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ADOS-G	Autism Diagnostic Observation Schedule – Generic
ADOS	Autism Diagnostic Observation Schedule
ADOS-2	Autism Diagnostic Observation Scale, Second version
ADI-R	Autism Diagnostic Interview – Revised
ASD	Autism spectrum disorder
ATEC	Autism Treatment Evaluation Checklist
Beery-VMI	Beery-Buktenica Developmental Test of Visual-Motor Integration
BOTMP/BOT	Bruininks-Oseretsky Test of Motor Proficiency
CARS	Childhood Autism Rating Scale
HFASD	High functioning Autism Spectrum Disorder
MABC-2	Movement Assessment Battery for Children-2
PDMS	Peabody Developmental Motor Scale
PANESS	Physical and Neurological Examination for Soft Signs
SCQ	Social and Communication Questionnaire
SRS-2	Social Responsiveness Scale, Second version

TD	Typical development
TGMD-3	Test of Gross Motor Development-Third Edition
VABS	Vineland adaptive Behavior Scales
ZNA	Zurich neuromotor assessment

Acknowledgments

I would like to thank my supervisor Krista Hyde for providing an excellent project, and my co-supervisor Simona Brambati for providing excellent guidance in completing this thesis, not only through her pertinent comments, but also the insightful, critical and tactful manner. I would also like to show gratitude to Nick Foster for his careful mentoring and all his investment during my master's degree. I also acknowledge the contribution of my colleague Alexa Meilleur for her sharp and scientific mind and also her great support. I would also like to thank my colleagues Emeline Wyckaert, Nathalie Roth and Kevin Jamey at the ABCD lab for their kindness and the respect they have shown me throughout my time in the laboratory. Finally, I would like to thank all my friends and family for all the support they gave me during my studies.

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Introduction

Autism spectrum disorder (ASD) is a complex neurodevelopmental condition that is characterized by difficulties in social and communication skills, restricted patterns of behaviour, and often atypical sensory and motor skills. Daily sensorimotor behaviours such as buttoning up a coat require the integration of sensory information and motor output. Intact sensorimotor integration is crucial to accomplish routine tasks, but it is not yet clear how consistently sensorimotor abilities are impaired in ASD. Additionally, very little is known about how atypical sensorimotor skills in ASD may vary across development and in relation to clinical symptom severity. The main objective of this thesis was to expand our understanding of sensorimotor skills in ASD by conducting several complementary meta-analyses on data from the current literature. In order to guide understanding and reading, the introduction of this thesis is divided into several sections. The first part gives an overview of ASD, while the second part provides a synthesis of the literature on sensorimotor differences in ASD in comparison with the neurotypical population. This section also provides further background on the effect of age on sensorimotor skills and relationship between sensorimotor skills and ASD symptom severity. The third part focuses on current clinical interventions and the potential to improve sensorimotor skills in ASD. The final part details the objectives and hypotheses of this study.

Overview of autism spectrum disorder

The earliest description of symptoms of autism emerged in 1943, in a report describing several children that shared common characteristics. These descriptions included withdrawal from the outside world, sensitivity to sounds, motions, and direct physical

contact, as well as delayed or lack of acquired language (Kanner, 1943). Although there is marked variability in the symptomatology and presentation of this disorder, these characteristics remain components of the modern clinical definition of autism spectrum disorder. The current DSM-V defines ASD as a heterogeneous neurodevelopmental disorder characterized by social and communication impairments, and restricted and repetitive patterns of behaviour (American Psychiatric Association, 2013). For example, an infant with ASD might not respond to his name by 12 months of age, has delayed speech and language skills, repeats words or phrases over and over (echolalia), lines up toys or other objects, and plays with toys the same way every time (Johnson, 2004).

ASD prevalence is one in 59 children as of 2014 (U.S. Centers for Disease Control and Prevention, 2014), with a 3:1 incidence in males compared to females (Loomes, Hull & Mandy, 2017). This represents a 15 percent increase in ASD diagnosis rate compared to 2012. Evidence suggests that prevalence changes in ASD are mostly attributable to a combination of greater public awareness, lower age at diagnosis, and changes in the diagnostic constructs and corresponding diagnostic criteria (Smith, Reichow & Volkmar, 2015). In the *Diagnostic and Statistical Manual for Mental Disorders*, 5th Edition (DSM-V) released in May 2013, changes include major alterations in criteria for developmental disorders, in particular, for ASD. Under the DSM-V, previous diagnostic subcategories of ASD were eliminated, unifying the three previously distinct diagnoses of *autistic disorder*, *Asperger's disorder*, and *pervasive developmental disorder, not otherwise specified*. The diagnosis of ASD puts particular emphasis on atypical behaviours that emerge very early in development (American Psychiatric Association, 2013). However, while behavioural symptoms of ASD are generally distinct in the second year of age, conventional markers of

ASD such as atypical social behaviour are less reliable during the first year of age (Zwaigenbaum, Bryson & Garon, 2013). For example, infants below the age of one show the same amount of shared smiles (Ozonoff et al., 2010) and affective responsivity in face-to-face interaction with their parent (Young, Merin, Rogers, & Ozonoff, 2009). However, some sensorimotor behaviours have shown clear atypicalities in ASD during infancy (Brisson, Warreyn, Serres, Foussier & Adrien-Louis, 2012), as well as underlying sensory and motor abilities (Thomas et al., 2016; Elsabbagh & Johnson, 2016). These findings led to the idea that ASD may first emerge not in the social and communicative domains but potentially in sensory, motor, and sensorimotor integrative processes (Wozniak, Leezenbaum, Northrup, West & Iverson, 2017). Thus, outside the core atypicalities that are used to diagnose ASD, motor skills and especially sensorimotor skills also appear to be affected and could be considered as a symptom in ASD (Sutera et al., 2007).

Sensorimotor differences in ASD vs typical development (TD)

Sensorimotor integration is defined as the ability of the central nervous system to integrate different sources of stimuli, and in parallel, to transform such inputs into motor actions (Machado et al., 2010). For example, postural control requires the integration of information from visual, somatosensory and vestibular systems to control motor output. Likewise, motor behaviours as diverse as grasping an object or regulating walking gait requires the integration of sensory information (Jasmin et al., 2009). Intact sensorimotor integration is crucial to accomplish routine tasks, but it is not yet clear how broadly or consistently sensorimotor skills are impaired in ASD. Interest in sensorimotor abilities in ASD has also grown due to evidence that sensorimotor impairments could play a causal role in the development and maintenance of core communication and social symptoms (Bhat,

Landa & Galloway 2011; Page & Boucher 1998). If this hypothesis is confirmed, it provides an empirical foundation to optimize therapeutic interventions. A first necessary step to address this issue is to better characterize sensorimotor symptoms in ASD as well as their relationship with development and core measures of symptom severity. A global and exhaustive portrait of sensorimotor deficits in ASD cannot be based on the results of a single study, but rather needs a quantitative synthesis of the available results across studies. In fact, although sensorimotor skills are recognized to be impaired in ASD versus TD, this domain is vastly understudied and our knowledge is based on sporadic findings on studies with small samples. Due to considerable individual differences and the large spectrum of this condition, the extent and circumstances of sensorimotor impairments are not clear. For example, some research has shown decreased motor skills in ASD particularly in terms of clumsiness, motor coordination, postural instability, and motor functioning (Bauman, 1992; Ghaziuddin & Butler, 1998; Jones & Prior, 1985; Kohen-Raz et al., 1992; Molloy et al., 2003; Rapin, 1997 ; Rogers et al., 1996; Vilensky et al., 1981). However, other work has shown no or minimal differences in motor skills in ASD relative to TD (Provost et al. 2007). In a recent literature review, Hannant, Tavassoli & Cassidy (2016) reported that children with ASD have difficulties coordinating sensory input into planning and executing movement effectively. Still, this review is limited in that it did not provide a quantitative meta-analysis of these studies (Hannant et al., 2016). To date only one previous meta-analysis has investigated sensorimotor skills in ASD versus TD (Fournier et al., 2010). Fournier and colleagues (2010) found important deficits in motor coordination, arm movement, gait, and postural stability in ASD overall. The meta-analysis by Fournier is important but presents some important limitations. Firstly, it was published 10 years ago. Consequently, it omits

more recent studies, and the field of research will benefit from an updated quantitative meta-analysis of empirical results. Secondly, the Fournier analysis did not address how the severity of impairment may depend on the type of sensorimotor behaviour (e.g., gross and fine sensorimotor skills) in individuals with ASD. This is crucial, because it has an impact on different behaviors. For instance, gross sensorimotor skills are the fundamental skills that children learn and use to explore and navigate their environment like walking up stairs, running, kicking a ball, etc. Fine sensorimotor skills consist of movements of small muscles (eg, those of the hands, feet, tongue, lips, and face) and are the basis of coordination (Lloyd, MacDonald & Lord, 2013). To these aims, the present thesis provides up-to-date quantitative meta-analyses to determine whether sensorimotor differences are impaired in ASD, and if so, which sensorimotor systems or behaviours, such as fine and gross sensorimotor skills, are the most relevant.

Effect of age on sensorimotor skills in ASD versus TD

Sensorimotor impairments in ASD can impact daily life across different stages of development. For example, as children with neurotypical development arrive at school, they are usually able to dress and undress themselves. On the other hand, some adolescents and adults with ASD cannot perform these tasks without constant assistance (Wozniak et al., 2017). Adults with ASD may also have difficulty in reaching and grasping objects, as well as controlling their strength relative to the object while it is held (Hardan, Kilpatrick, Keshavan & Minshew, 2003). As a neurodevelopmental disorder, differences in both genetic and environmental factors may lead to variations in the timing of development in behaviour for individuals with ASD (Wozniak et al., 2017), and an early critical period for sensorimotor deficits may exist below the age of two (Hannant et al., 2016). Accordingly, a number of

studies suggest that between infancy and adulthood, sensorimotor skills undergo a different developmental trajectory in ASD than TD. In a retrospective study of case records of 21 children with ASD during the first two years of life, Malhi & Singhi (2014) reported that two thirds of the children presented lack of speech, inability to follow verbal commands, lack of pretend play, no index finger pointing, difficulty in playing with toys in a constructive manner, lack of joint attention, and motor stereotypies. Cheng, Chan, Hsu & Liu (2017) reported that children and adolescents with ASD, but not adults, exhibit reduced sensorimotor gating function compared to TD controls. In addition, a review by Mosconi & Sweeney (2015) notes that individuals with autism show limited improvement in a range of sensorimotor abilities during childhood and early adolescence while no improvement is observed from adolescence to adulthood. Finally, Weiss, Moran, Parker & Foley (2013) found that older teens and young adults with ASD differ widely in their gait compared to TD and that these differences found are far more pronounced compared with younger individuals diagnosed with ASD vs TD.

However, there are other examples where sensorimotor abilities were found to undergo equivalent developmental changes in ASD as compared to TD, despite overall impairment. Siaperas and colleagues (2011) reported that children with ASD showed significant impairment of movement performance as well as proprioceptive and vestibular processing, but without presenting any interaction effects of age and clinical group on the level of performance deficit. Moreover, Young and colleagues (2011) found that 12-24 months old children who were diagnosed with ASD by 3 years old exhibited delayed imitation development compared to a low-risk typical outcome group, but were indistinguishable from other high-risk infants who showed other cognitive delays not related

to ASD. Fournier and colleagues (2010) have reported that motor impairments in ASD are consistent regardless of age groupings and seem to be pervasive in time.

Overall, due to the heterogeneity of the results in the literature and in order to better understand these developmental differences, there is a considerable need to study the effect of age on individuals with a diagnosis of ASD compared to TD controls.

Clinical symptom severity and sensorimotor skills in ASD

The core symptoms in ASD are social and communication impairments, and restricted, repetitive patterns of behaviour (American Psychiatric Association, 2013). Severity in ASD is typically assessed with diagnostic instruments such as the Autism Diagnostic Observation Schedule (ADOS) and Autism Diagnostic Interview-Revised (ADI-R), as well as social and communication focused measures like the Social Responsiveness Scale (SRS). Evidence for a link between motor impairments and severity in ASD was first documented by Hilton and colleagues (2007). However there is a need for greater insight and study into the role that sensorimotor impairments play in overall ASD severity.

Some recent studies have suggested that sensorimotor difficulties in ASD can account for reduced social attention early in development, with a subsequent effect on later social, communicative and emotional development (Hannant et al., 2016; MacDonald, Lord & Ulrich, 2013; Matsushima & Kato, 2013). Dziuk and colleagues (2007) found that the level of dyspraxia in children with ASD was associated with their overall level of impairment in social, communication and repetitive behaviour domains. More specifically, Hannant and colleagues (2016) propose that sensorimotor difficulties not only contribute to non-social difficulties, but also affect the development of social behaviours such as coordinating eye contact with speech and gesture, interpreting others' behaviour, and

responding appropriately. For example, the significant impairments shown by children with ASD include skilled motor gestures, imitations (Mostofsky et al., 2006) and development of speech sound production (Page & Boucher, 1998). Children with ASD are also less competent at recognizing emotions in others (Cummins, Piek & Dick, 2005) and are more likely to have increased anxiety on the playground due reduced social interaction (Bhat, Land & Galloway, 2011).

Although the current DSM-5 criteria (American Psychiatric Association, 2013) evaluate ASD severity based on social communication impairments and restricted/repetitive behaviours, these studies demonstrate that sensorimotor impairments may also have a considerable importance in the development of ASD. Thus, it is important to study the relationship between clinical symptom severity and sensorimotor skills in ASD in order to define this link quantitatively and facilitate future targeted interventions with this population. As Hannant and colleagues (2016) have pointed out, no studies have explored the impact of sensorimotor difficulties on the development or the maintenance of core ASD symptoms in any detailed way. However, there are a number of studies that have examined this question in a more basic manner, by calculating correlations between symptom severity measures and sensorimotor ability, and these studies are analyzed in the current meta-analyses.

Clinical interventions to improve sensorimotor skills

As awareness for ASD has increased in recent years, there are still few interventions targeting sensorimotor skills (Hannant et al., 2016). A review by Baranek (2002) notes that sensory or motor treatments are commonly used as a complement to a more holistic intervention plan, but the goals of the sensory or motor treatment are framed within the overall intervention plan (e.g., school functional skills, or self-care) rather than broadly

addressing an individual's sensorimotor impairments. Some interventions directed at sensorimotor deficits also require the child to tolerate various sensory or physical manipulations by a therapist (Baranek, 2002). In contrast, interventions based on creative movement and dance offer a practical and feasible option for children with ASD, regardless of physical capabilities (Behrends, Müller & Dziobek, 2012). A recent review showed benefits of dance-movement therapy (DMT) on sensorimotor integration in ASD (Srinivasan & Bhat, 2013). DMT is a holistic form of therapy aimed at providing physical, social, and cognitive benefits to participants. More specifically, the physical benefits of dance include increased balance, flexibility, muscular tone and strength, endurance and spatial awareness (Scharoun, Reinders, Bryden & Fletcher, 2014). While children with ASD typically have poor sensorimotor integration, DMT contributes to increase their movement repertoire (Erfer, 1995). From another perspective, movement and dancing are innate means of communication (Boris, 2001; Koff, 2000), thus provide a nonverbal means of expression for children who have difficulties communicating (Freundlich, Pike, & Schwartz, 1989), such as individuals with ASD. While the study reports are promising, the existing literature in the area of DMT and ASD is largely qualitative with few empirically based studies (Devereaux, 2012). Thus, there is a considerable need to study quantitatively individual differences in the extent and dimensions of sensorimotor deficits in ASD in order to optimize possible clinical interventions in DMT.

Study objectives

A deeper understanding of sensorimotor abilities in ASD is key to better refine the ASD phenotype and to guide sensorimotor-based interventions such as dance-movement

therapy. To these aims, the present research undertook a quantitative behavioural meta-analysis of systematically reviewed work on sensorimotor skills in ASD versus TD.

Unlike literature reviews, meta-analyses offer the advantage of providing both a systematic and quantitative (statistical) analysis of previous data (Lipsey & Wilson, 2001). Systematic reviews involve a detailed research strategy decided a priori to reduce bias by identifying and synthesizing all relevant studies on a particular topic. In addition, meta-analyzes use statistical techniques to synthesize data from multiple studies into a single quantitative estimate or summary effect size. It is capable of finding effects that are obscured in other approaches and provides an organized way of handling information from a large number of study findings (Uman, 2011; Lipsey & Wilson, 2001).

Aims and hypotheses

The main objective of this thesis was to provide a quantitative and exhaustive synthesis of the available literature on sensorimotor skills in ASD through several complementary meta-analyses. The specific aims were as follows:

Aim 1 was to determine whether sensorimotor differences are a major feature in ASD, and if so which ones (gross vs fine sensorimotor skills). Significant sensorimotor differences were expected in ASD compared to TD group and in particular for motor coordination, arm movement, gait and postural stability (Fournier et al., 2010).

Aim 2 was to examine the effect of age on sensorimotor skills in ASD. Performance improvements were expected with age in ASD (Hannant et al., 2016).

Aim 3 was to examine the relationship between sensorimotor skills and the clinical symptom severity of ASD, particularly with social and communication skills. Sensorimotor

skills were expected to be more impaired as a function of greater clinical severity of ASD symptoms (Hannant et al., 2016).

Abstract

Background : Sensorimotor skills are often reported as atypical in individuals with autism spectrum disorder (ASD). Little is known about how sensorimotor skills in ASD may vary across development and with symptom severity. The main objective of this study was to conduct a comprehensive quantitative meta-analysis of sensorimotor skills in ASD. The specific aims were: to assess the consistency of atypical gross and fine sensorimotor skills in ASD, to examine the effect of age on sensorimotor skills in ASD and to examine the relationship between sensorimotor skills and ASD symptom severity.

Method : An exhaustive search was conducted in Psycnet, PubMed, Web of Science and Cochrane Database to identify studies in ASD from 1980 to 2018 that involved quantitative evaluations of motor coordination, motor impairments, arm movement, gait, postural stability, visuomotor or auditory motor integration. A total of 139 studies were included and this represent 3436 individuals with ASD.

Results : Results strongly support the presence of deficits in overall sensorimotor abilities in ASD (Hedges' $g = 1.22$, $p < 0.001$) and these atypicalities extended to fine and gross sensorimotor abilities. Sensorimotor abilities increased with age, but did not appear to covary with symptom severity.

Conclusions : These results highlight the importance to target these deficits in future interventions and consider the impact of sensorimotor impairments across research, therapy, and educational settings.

Keywords: autism spectrum disorder, sensorimotor skills, motor coordination, motor impairments

Sensorimotor skills in autism spectrum disorder: a meta-analysis

Introduction

Autism spectrum disorder (ASD) is a complex and heterogeneous neurodevelopmental disorder characterized by social and communication impairments and restricted, repetitive patterns of behaviour (American Psychiatric Association, 2013). In addition to these core features, sensory and motor skills are often affected in ASD. Sensorimotor integration is defined as the ability of the central nervous system to integrate different sources of stimuli, and in parallel, to transform such inputs into motor actions (Machado et al., 2010). For example, postural control requires the integration of information from visual, somatosensory and vestibular systems to control motor output. Likewise, motor behaviours as diverse as grasping an object or regulating walking gait require the integration of sensory information. While intact sensorimotor integration is essential to navigate our everyday world, little is known about sensorimotor skills in ASD and in particular how these abilities change across development and with clinical symptom severity. A better understanding of these dimensions will provide a foundation to optimize therapeutic interventions.

Sensorimotor differences in ASD vs typical development (TD)

A number of studies have reported impaired sensorimotor skills in ASD versus TD. However, due to considerable individual differences within ASD, the extent and circumstances of these differences are not clear. For example, some research has shown impaired motor skills in ASD particularly in terms of clumsiness, motor coordination, postural instability, and motor functioning (Bauman, 1992; Ghaziuddin & Butler, 1998;

Jones & Prior, 1985; Kohen-Raz et al., 1992; Molloy et al., 2003; Rapin, 1997 ; Rogers et al., 1996; Vilensky et al., 1981). However, other work has shown no or minimal differences in motor skills in ASD relative to TD (Provost et al., 2007). In a recent literature review, Hannant, Tavassoli & Cassidy (2016) reported that children with ASD have difficulties coordinating sensory input into planning and executing movement. Still, the Hannant and colleagues (2016) review is limited in that it did not provide a quantitative meta-analysis of these previous results.

Effect of age on sensorimotor skills in ASD versus TD

There is some evidence to suggest that sensorimotor skills develop differently in ASD than TD. In a retrospective study of case records of 21 children with ASD during the first two years of life, Malhi & Singhi (2014) reported that two thirds of the children presented lack of speech, inability to follow verbal commands, lack of pretend play, no index finger pointing, difficulty in playing with toys in a constructive manner, lack of joint attention, and motor stereotypies. Hannant and colleagues (2016) have proposed a critical period for the impact of sensorimotor deficits on cognitive and social development below the age of two, so these early atypicalities may have prolonged consequences. Later in development, Cheng, Chan, Hsu & Liu (2017) reported that children and adolescents with ASD, but not adults, exhibit reduced sensorimotor gating function compared to TD controls. In addition, a review by Mosconi & Sweeney (2015) notes that individuals with autism show limited improvement in a range of sensorimotor abilities during childhood and early adolescence while no improvement is observed from adolescence to adulthood. Finally, Weiss, Moran, Parker & Foley (2013) found that older teens and young adults with ASD

differed widely in their gait compared to TD and that differences at this stage of development were far more pronounced compared with younger individuals.

In contrast, Siaperas and colleagues (2011) reported that children with ASD showed significant impairment of movement performance as well as proprioceptive and vestibular processing, but no interaction effect between age and clinical group was found. Moreover, Young and colleagues (2011) found that 12-24 months old children who were diagnosed with ASD by 3 years old exhibited delayed imitation development compared to a low-risk typical outcome group, but were indistinguishable from other high-risk infants who showed other cognitive delays not related to ASD. Overall, the heterogeneity of these results highlights the considerable need to study the effect of age on sensorimotor abilities in individuals with ASD.

Clinical symptom severity and sensorimotor skills in ASD

In addition to examining the effect of age on sensorimotor skills, there is also a critical need to examine how these skills are related to clinical symptom severity. Some recent studies have shown that the degree of sensorimotor impairment can account for reduced social attention early in development in ASD, with a subsequent effect on later social, communicative and emotional development (Hannant et al., 2016; MacDonald, Lord & Ulrich, 2013; Matsushima & Kato, 2013). Dziuk and colleagues (2007) found that the level of dyspraxia in children with ASD was associated with their overall level of impairment in social, communication, and repetitive behaviour domains. More specifically, Hannant and colleagues (2016) suggest that sensorimotor difficulties not only contribute to non-social difficulties, but also affect the development of social behaviours such as coordinating eye contact with speech and gesture, interpreting others' behaviour, and

responding appropriately. For example, the significant impairments shown by children with ASD have included skilled motor gestures, imitations (Mostofsky et al., 2006), and development of speech sounds production (Page & Boucher, 1998). Children with ASD are also less competent at recognizing emotions in others (Cummins, Piek & Dick, 2005) and are more likely to have increased anxiety on the playground due reduced social interaction (Bhat, Land & Galloway, 2011).

Although the current DSM-5 criteria (American Psychiatric Association, 2013) evaluate ASD severity based on social communication impairments and restricted/repetitive behaviours, these studies demonstrate that sensorimotor impairments may also have a considerable importance in the development of ASD.

Previous meta-analysis of sensorimotor skills in ASD

To date only one previous meta-analysis has investigated sensorimotor skills in ASD compared with TD (Fournier et al., 2010). Fournier and colleagues found important deficits in motor coordination, arm movement, gait, and postural stability in ASD overall. They also reported that sensorimotor impairments in ASD were consistent regardless of age groupings and appeared to remain present across the lifetime. However, as the Fournier analysis was conducted almost 10 years ago it does not include more recent studies, and the field of research will benefit from an updated quantitative meta-analysis of empirical results. Although the Fournier analysis did consider age and type of diagnosis as potential moderators of sensorimotor differences between ASD and TD, they adopted a categorical approach that did not directly evaluate whether ability measures are correlated with age or with variation in clinical severity within ASD. In addition, that meta-analysis did not address potential differences in the degree of impairment between gross and fine sensorimotor skills

in individuals with ASD. Gross sensorimotor skills are the fundamental skills that children learn and use to explore and navigate their environment like walking up stairs, running, kicking a ball, etc. In contrast, fine sensorimotor skills consist of movements of small muscles (e.g., those of the hands, feet, tongue, lips, and face) and are the basis of coordination (Lloyd, MacDonald & Lord, 2013). By better understanding individual differences in the extent and dimensions of sensorimotor deficits in ASD, it is expected that interventions can be better designed to target these deficits. Thus, it is important to determine which types of sensorimotor skills are the most impaired and also to define which movements are the most difficult for individuals with ASD.

In summary, the present research will provide an up-to-date quantitative meta-analysis to determine whether sensorimotor impairment is a major feature in ASD, and if so, which sensorimotor systems or behaviours are most relevant. As reflected in the current literature, there is a considerable need to study quantitatively the effect of age on individuals with ASD and to study the relationship between clinical symptom severity and sensorimotor skills in ASD. The ultimate mission of this research is to set a theoretical groundwork for future sensorimotor-based interventions (such as music and dance) in ASD.

Aims and hypotheses

The main objective of this study was to conduct a quantitative meta-analysis of sensorimotor skills in ASD. The first aim was to determine whether sensorimotor differences are a major deficit in ASD, and if so which types of abilities are impaired (e.g., gross, fine sensorimotor skills). Significant sensorimotor differences were expected in ASD and in particular for motor coordination, arm movement, gait and postural stability (Fournier et al., 2010). The second aim was to examine the effect of age on sensorimotor skills in ASD.

Performance improvements were expected with age in ASD (Hannant et al., 2016). The third aim was to examine the relationship between sensorimotor skills and the clinical symptom severity of ASD, particularly with social and communication skills. Sensorimotor skills were expected to be more impaired as a function of greater clinical severity of ASD symptoms (Hannant et al., 2016).

Methods

Keywords

An exhaustive search for ASD studies published between 1980 and November 2018 was conducted in four online databases: (a) Psycnet (b) PubMed (c) Web of Science and (d) Cochrane Database of Systematic Reviews. Twelve keywords and phrases dictated the search: autism, asperger, autistic, motor coordination, motor impairment, gait, arm movement, postural stability, motor skill, motor control, visu* motor, or auditor* motor. The use of broad selection criteria without excluding any quantitative study at this point of the literature search was consistent with recommendations (Rosenthal, 1995). Additional searches included works cited by relevant articles, as well as unpublished theses indexed in databases including ProQuest and Papyrus. In total, these searches identified 3236 database records that matched the keywords. After removing 928 duplicates, a total of 2308 studies were then evaluated for the following inclusion/exclusion criteria. A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Liberati et al., 2009) diagram summarizing the number of studies meeting the search criteria is shown in Figure 1.

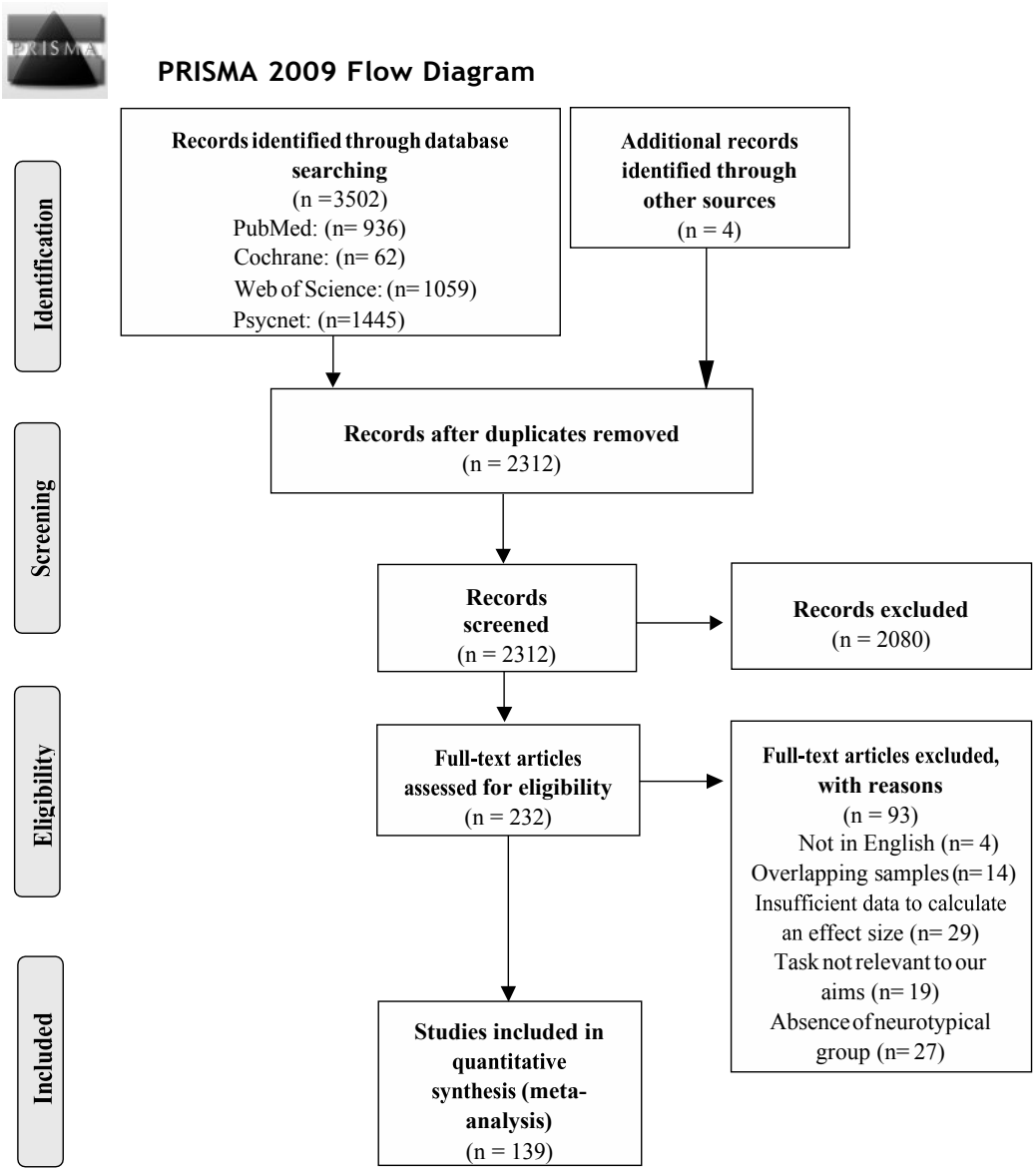

Figure 1. PRISMA flow chart explaining article inclusion/exclusion process.

Study inclusion and exclusion criteria

For inclusion, studies were required to present quantitative experimental results and be written in English or in French. If work presented in a thesis was also published as a peer-reviewed scientific article, the scientific article took precedence for inclusion because of the peer-review. Adding to the above criteria, six global pre-determined inclusion criteria were used in this meta-analysis:

- The first criterion required studies to report data from a sample of individuals with a diagnosis of ASD. 1402 studies were discarded based on this criterion.
- A second criterion required that studies report data from tasks within the scope of this meta-analysis' aims, i.e. evaluations of motor coordination, motor impairments, arm movement, gait, postural stability, visuomotor or auditory motor integration. 654 studies were excluded based on this criterion.
- A third inclusion criteria required the studies to have a cross-sectional, longitudinal or retrospective study design. This criterion resulted in the exclusion of one qualitative study, 2 commentary studies, 16 literature reviews, 4 meta-analyses and one book section.
- A fourth criterion was that studies must involve a human sample. One study was discarded because it only presented empirical results from animals.
- A fifth criterion was the presence of a comparison group of TD controls. ASD studies without a TD control group, and without any data relevant to our within-ASD aims on age or clinical severity, were not analyzed further. A total of 27 studies did not report TD control data and were excluded.

- The sixth criterion concerned data extraction problems. Studies that did not report values required to calculate effect size statistics for the present analyses were excluded. Based on this criterion, 70 studies were discarded.

Study selection and data collection process

After the first screening based on titles and abstracts, 232 studies remained and were coded. Each of the included studies was coded by the first author (SMC) and quantitative data for the meta-analysis was extracted. In addition, a second researcher (AM) completed coding of a randomly selected subset comprising 45 studies, which represented 32% of the total studies. Inter-rater agreement on this subset was 91%. The coding system compiled information from each article across seven categories: (a) quantitative data for calculation of effect sizes from measures relevant for the present meta-analyses (motor coordination, motor impairment, arm movement, gait, postural stability, motor skill, motor control, visuomotor and auditory motor integration) (b) experimental design, (c) group diagnostic definitions (e.g. ASD, Asperger syndrome) (d) group demographic characteristics (age, gender, country) (e) sample sizes for each included group (f) ASD severity scores, and (g) research quality. Research quality was evaluated with an adaptation of the Cochrane's quality assessment tool for quantitative studies (National Collaborating Centre for Methods and Tools 2008). Four sections were evaluated: selection of participants, differences between groups (age and gender), data collection methods (validity and reliability) and withdrawals or drop-outs. A score of one was given if no weak rating was present in the section, a two was given if there was one weak rating and a three was given if two or more weak ratings were present. Since the judgement was based on objective evaluation criteria, no inter-rater agreement was

applied for this tool. Authors were contacted to request any missing data as necessary. Once the coding was completed, 86 studies were discarded based on the following criteria: overlapping samples with another study (n=14), insufficient data to calculate effect size (n=29), no comparable TD group (n=27), studies in a language other than English or French (n=4), and studies without a motor component task (n=12) or a gait velocity measure (n=7). Characteristics of the 139 studies that proceeded to further analyses are listed in Table 1.

Selection of data for each aim

Within the range of sensorimotor abilities listed in the previous section, several types of outcome measure were identified: (a) standard motor scales (e.g. BOTMP, MABC-2, PDMS, PANESS, Vineland Motor Standard Score, Beery-VMI, Grooved Pegboard test, Zurich neuromotor assessment, TGMD-3) (b) stability of balance (e.g. center of pressure, sway area) (c) movement/reaction time (d) handwriting size of letters (e) rhythmic tapping to an external stimulus (e.g. phase, latency) and (f) gait velocity. Outcomes were categorized as a fine or gross sensorimotor measure based on the definition of Lloyd, MacDonald & Lord (2013). Two authors (SMC & NF) confirmed the final list of studies to be included in the current meta-analyses, and these authors (SMC & NF) were involved in interpreting the meta-analytic results. Consistent with conventional meta-analysis techniques and in order to maintain independence of values entered into the analyses (Borenstein et al., 2009), only one outcome measure per study was selected for each analysis. In the overall comparison between ASD and TD, comprehensive measures and batteries (e.g., Movement Assessment Battery for Children) were favoured when available. In the analyses of fine and gross sensorimotor categories in ASD and TD, measures that best fit the category of interest were

selected, and comprehensive measures were excluded unless an appropriately specific fine or gross subscore was available. In addition, 11 studies reported data from multiple ASD groups that were collectively of interest for the present analyses (e.g., groups labelled as "high" and "low-functioning"). In these cases, data were aggregated across the groups so that a single effect size was entered into analyses from each study (Lipsey & Wilson, 2001). A total of 139 studies was included for the first aim. Detailed summaries of studies included in the comparisons of sensorimotor ability between ASD and TD are presented in Appendix 1.

Comparison of gait measures was performed in a separate analysis. Kindregan, Gallagher & Gormley (2015) report in a meta-analysis that preferred walking velocity is a commonly used general measure to evaluate gait, but it is not clear that either a faster pace or slower pace in ASD would be considered an advantage. Rather than impose an assumption about the direction of the effect (e.g., that a greater preferred walking velocity is better, compared to TD, and a slower velocity represent impairment), the meta-analysis of gait was performed separately to determine whether individuals with ASD exhibit a faster or slower walking velocity compared to TD. A total of 10 studies was included. These outcome measures are presented in Table 1 and further details are presented in Appendix 1.

For the aim regarding effects of age on sensorimotor skills in ASD, only studies reporting a Pearson correlation between age (as a continuous variable) and a sensorimotor measure within an ASD group were included. A TD group was not required for this aim. A total of 5 studies was included. A summary of studies included for this aim is presented in Table 1 and more details are presented in Appendix 2.

For the aim concerning the influence of clinical severity on sensorimotor skills in ASD, only studies reporting a Pearson correlation between a measure of ASD severity and a sensorimotor measure within an ASD group were selected. Included severity measures were the *Autism Diagnostic Observation Schedule* (ADOS; Lord et al., 1989), *Social Responsiveness Scale* (SRS ; Constantino & Gruber, 2005), Autism Diagnostic Interview - Revised (ADI-R; Lord, 1994), *Childhood Autism Rating Scale* (CARS; Schopler et al., 1980), *Social and Communication Questionnaire* (SCQ; Rutter et al., 2003), and the *Autism Treatment Evaluation Checklist* (ATEC; Edelson & Rimland, 2000). A TD group was not required for this aim. A total of 18 studies was included. A summary of studies included for this aim is presented in Table 1 and more details are presented in Appendix 3.

Table 1

List of all the studies included in this current meta-analysis

Author, Year	Diagnostic groups	ASD group			TD group			Usage in analyses					
		Mean age (years)	SD	N	Mean age (years)	SD	N	*1*	*2*	*3*	*4*	*5*	*6*
Abu-Dahab, 2013	HFASD; TD	11.99	0.20	73	12.11	0.17	75	*X*	*X*				
Ament, 2015	HFASD; TD	10.27	1.28	48	10.31	1.18	69	*X*	*X*	*X*			
Beversdorf, 2001	HFASD; TD	30.80	9.30	10	30.60	12.80	13	*X*					
Biscaldi, 2014	ASD; TD	13.58	0.53	36	14.28	0.50	34	*X*	*X*	*X*			
Brandes-Aitkens, 2018	ASD; TD	10.30	1.70	14	10.40	1.30	28	*X*					
Brisson, 2012	ASD; TD	0.25-0.50	-	13	0.33-0.50	-	14	*X*					
Calhoun, 2011	Asperger; TD	6.30	-	12	6.20	-	22				*X*		
Campione, 2016	ASD ; TD	5.10	0.60	9	4.70	0.60	11	*X*	*X*				
Chang, 2010	ASD ; TD	8.75	1.34	16	8.93	1.39	22	*X*		*X*			
Chen, 2016	ASD ; TD	11.04	1.28	16	10.97	1.17	16	*X*		*X*			
Classen, 2013	ASD ; TD	15.14	1.22	7	14.32	0.72	22	*X*	*X*	*X*			
Cook, 2013	ASD ; TD	3.80	0.32	14	3.13	0.32	15	*X*		*X*			
Cox, 2016	ASD ; TD	18.28	2.29	13	16.59	0.55	26	*X*		*X*			*X*
Craig, 2018	ASD ; TD	4.60	1.10	46	4.60	1.50	43	*X*	*X*	*X*			*X*
Crippa, 2013	HFASD ; TD	6.20	2.10	14	6.30	2.30	14	*X*	*X*				
David, 2009	HFASD ; TD	11.20	3.40	13	10.80	3.10	13	*X*	*X*				
David, 2013	ASD ; TD	4.50	1.08	24	3.94	1.57	30	*X*	*X*				
Dewey, 2007	ASD ; TD	10.20	3.40	49	11.30	2.40	78	*X*					
Dowd, 2012	HFASD ; TD	6.20	1.40	11	6.60	1.50	12	*X*	*X*				
Dowell, 2009	ASD ; TD	10.26	1.70	87	10.55	1.30	50	*X*	*X*				*X*
Duffield,2013	ASD ; TD	15.61	7.48	59	15.29	6.48	30	*X*	*X*				

Author, Year	Diagnostic groups	ASD group			TD group			Usage in analyses					
		Mean age (years)	SD	N	Mean age (years)	SD	N	*1*	*2*	*3*	*4*	*5*	*6*
Dyck, 2010	ASD ; TD	8.47	2.63	30	8.72	2.30	449	*X*	*X*				
Dziuk,2007	HFASD ; TD	10.70	1.10	47	10.60	1.50	47	*X*					*X*
Fitzpatrick, 2017	ASD ; TD	8.65	1.34	45	8.31	1.44	53	*X*	*X*	*X*			
Forti, 2011	ASD ; TD	3.50	0.75	12	-	-	12	*X*	*X*				
Fournier, 2010	ASD ; TD	11.10	2.30	13	13.10	2.20	12	*X*	*X*	*X*			
Fournier, 2011	ASD ; TD	5.50	1.10	13	6.20	1.20	13	*X*	*X*	*X*			
Fournier, 2014	ASD ; TD	11.10	2.30	16	12.90	2.10	17	*X*	*X*	*X*			
Freitag, 2007	ASD ; TD	17.50	3.50	16	18.60	1.20	16	*X*	*X*	*X*			
Freitag, 2008	HFASD ; TD	16.40	2.40	12	17.90	1.60	12	*X*	*X*				
Fuentes, 2009	ASD ; TD	10.20	1.90	14	11.10	1.30	14	*X*	*X*				
Fuentes, 2010	ASD ; TD	14.40	1.40	12	13.80	1.20	12	*X*	*X*				
Fukui, 2018	ASD ; TD	18.30	2.10	12	19.10	2.20	12	*X*	*X*				
Fulceri, 2015	ASD	4.04	0.73	35	-	-	-						*X*
Fulceri, 2018	ASD ; TD	7.82	1.32	11	7.57	0.71	11	*X*	*X*				
Fulkerson, 1980	ASD ; TD	10.10	-	15	7.50	-	15	*X*	*X*				
Funahashi, 2014	ASD ; TD	8.10	0.80	16	8.20	0.70	16	*X*	*X*				
Gepner, 2002	ASD ; TD	6.00	1.20	6	5.60	0.80	9	*X*	*X*	*X*			
Gepner,1995	ASD ; TD	8.50	0.84	6	8.20	2.90	12	*X*	*X*	*X*			
Gernsbacher, 2008	ASD ; TD	7.92	3.74	172	8.17	3.81	44	*X*	*X*				
Gidley, 2008	HFASD ; TD	11.10	1.60	15	11.70	1.50	10	*X*	*X*				
Gidley, 2008a	HFASD ; TD	10.60	1.70	38	10.50	1.50	37	*X*	*X*				
Glazebrook, 2006	ASD ; TD	26.90	6.80	9	25.10	5.10	9	*X*	*X*				
Glazebrook, 2008	ASD ; TD	23.70	7.90	18	20.60	4.50	18	*X*	*X*				
Glazebrook, 2009	ASD ; TD	23.40	4.50	9	23.40	3.16	13	*X*	*X*				

Author, Year	Diagnostic groups	ASD group			TD group			Usage in analyses					
		Mean age (years)	SD	N	Mean age (years)	SD	N	*1*	*2*	*3*	*4*	*5*	*6*
Godde, 2018	ASD ; TD	26.30	4.60	21	26.60	4.60	21	*X*	*X*			*X*	
Goh, 2018	ASD ; TD	24.60	2.78	13	25.50	2.50	13	*X*	*X*	*X*			
Goulème, 2017	HFASD ; TD	12.10	2.90	30	11.05	0.80	30	*X*	*X*	*X*			
Gowen, 2005	Asperger ; TD	27.42	11.08	12	28.17	11.70	12	*X*	*X*	*X*			
Gowen, 2008	ASD ; TD	33.90	13.20	12	32.00	11.80	12	*X*	*X*	*X*			
Grace, 2017	ASD ; TD	10.58	1.37	22	10.85	1.01	20	*X*	*X*				
Graham, 2014	ASD ; TD	13.00	3.20	26	13.40	1.90	18	*X*	*X*				*X*
Green, 2016	ASD ; TD	10.57	4.76	56	11.90	5.10	36	*X*	*X*				*X*
Hallett, 1993	ASD ; TD	25-38	-	5	25-36	-	5				*X*		
Hanaie, 2013	ASD ; TD	9.82	2.80	13	10.67	1.91	11	*X*	*X*	*X*			
Hanaie, 2014	ASD ; TD	9.50	2.60	18	10.80	2.10	12	*X*	*X*	*X*			
Hannant, 2016	HFASD ; TD	9.93	2.71	18	9.16	1.89	18	*X*	*X*	*X*			*X*
Hardan, 2003	ASD ; TD	19.30	9.90	40	18.60	8.60	41	*X*	*X*				
Holloway, 2018	ASD	4.67	0.54	21	-	-	-						*X*
Hughes, 1996	ASD ; TD	13.42	0.57	36	3.65	0.25	28	*X*	*X*				
Isenhower, 2012	ASD ; TD	3.94	1.50	7	3.55	11.70	7	*X*	*X*	*X*			
Jansiewicz, 2006	ASD ; TD	11.35	2.47	40	11.60	2.72	55	*X*	*X*	*X*			
Johnson, 2013	ASD ; TD	12.35	0.64	23	11.60	1.58	12	*X*	*X*	*X*			
Johnson, 2015	ASD ; TD	11.40	1.64	26	10.48	1.52	17	*X*	*X*	*X*			
Kaur, 2018	ASD ; TD	8.09	0.58	24	7.75	0.55	12	*X*	*X*				*X*
Kohen-Raz, 1992	ASD ; TD	6-20	-	92	5-11	-	166	*X*	*X*	*X*			
Kostrubiec, 2018	HFASD ; TD	10.47	1.78	20	11.14	1.82	21	*X*	*X*	*X*			
Lee, 2018	ASD ; TD	10.60	1.40	18	10.00	2.00	18	*X*	*X*	*X*			*X*

Author, Year	Diagnostic groups	ASD group			TD group			Usage in analyses					
		Mean age (years)	SD	N	Mean age (years)	SD	N	*1*	*2*	*3*	*4*	*5*	*6*
Lim, 2016	ASD ; TD	11.20	2.80	15	11.10	2.90	15				*X*		
Liu, 2013	ASD ; TD	7.96	-	30	7.44	-	30	*X*	*X*	*X*			
Mache, 2016	ASD ; TD	9.46	2.50	11	9.35	2.41	11	*X*	*X*				
MacNeil, 2012	ASD ; TD	9.69	1.59	24	10.33	1.40	24	*X*	*X*	*X*			
Mandelbaum, 2006	ASD ; TD	9.00	1.92	74	8.80	0.91	37	*X*	*X*	*X*			
Mari, 2003	ASD ; TD	10.52	1.51	20	10.44	1.38	20	*X*	*X*				
Markoulakis, 2012	HFASD ; TD	7.00	-	12	7.00	-	12	*X*	*X*				
McDonald, 2018	ASD ; TD	9.48	2.13	33	9.45	2.05	33	*X*	*X*				
McPhillips, 2014	ASD ; TD	9.91	0.65	28	10.03	0.68	28	*X*					
Memari, 2013	ASD ; TD	11.50	1.60	21	11.60	1.90	30	*X*	*X*	*X*			*x*
Memari, 2014	ASD ; TD	11.90	1.60	19	11.80	1.70	28	*X*	*X*	*X*			
Miller, 2014	ASD ; TD	12.60	2.20	20	11.53	2.50	20	*X*	*X*				
Minshew, 2004	HFASD ; TD	17.00	10.40	79	16.70	10.50	61	*X*	*X*	*X*			
Morris, 2015	ASD ; TD	23.60	7.90	12	23.40	5.10	20	*X*	*X*	*X*			
Morrison, 2018	ASD ; TD	21.20	4.40	20	24.30	2.80	20				*X*		
Mosconi, 2015	ASD ; TD	15.00	8.00	28	15.00	7.00	29	*X*	*X*				*X*
Mostofsky, 2006	HFASD ; TD	10.30	1.70	20	10.50	1.30	36	*X*	*X*	*X*		*X*	
Mostofsky, 2007	HFASD ; TD	10.60	1.98	21	10.68	1.61	24	*X*					
Mostofsky, 2009	HFASD ; TD	10.90	1.50	12	10.50	1.40	13	*X*	*X*				
Nazarali, 2009	ASD ; TD	26.20	4.80	12	22.80	3.30	12	*X*	*X*				
Nobile, 2011	ASD ; TD	10.56	2.50	16	9.99	2.28	16				*X*		
Noterdaeme, 2002	ASD ; TD	9.83	2.33	11	8.08	0.58	11	*X*	*X*	*X*			
Nyden, 2004	ASD ; TD	12.42	0.45	30	12.51	0.58	32	*X*					

Author, Year	Diagnostic groups	ASD group			TD group			Usage in analyses					
		Mean age (years)	SD	N	Mean age (years)	SD	N	*1*	*2*	*3*	*4*	*5*	*6*
Oliver, 2014	ASD ; TD	10.33	1.75	23	11.42	0.48	22	*X*	*X*				
Ozonoff, 2008	ASD ; TD	1.00	0.08	54	0.83	2.00	24	*X*	*X*				
Pan, 2014	HFASD ; TD	14.58	1.55	31	14.70	0.59	31	*X*	*X*	*X*			
Papadopoulos, 2012	ASD ; TD	9.35	0.32	53	9.10	1.63	20	*X*	*X*	*X*			
Pasini, 2012	ASD ; TD	10.00	0.40	12	9.60	1.60	12	*X*	*X*	*X*			
Pauk, 2017	ASD ; TD	7.69	2.01	28	8.30	2.10	30				*X*		
Pierno, 2008	HFASD ; TD	11.10	1.22	12	11.20	1.22	12	*X*	*X*	*X*			
Price, 2012	Asperger ; TD	14.14	4.80	14	14.08	4.61	16	*X*	*X*				
Provost, 2007	ASD ; TD	2.53	0.38	19	2.52	0.45	18	*X*	*X*				
Pusponegoro, 2016	ASD ; TD	2.80	-	24	2.90	-	24	*X*	*X*				
Radonovich, 2013	ASD ; TD	8.18	3.40	18	8.31	4.00	28	*X*	*X*	*X*			
Ravizza, 2013	ASD ; TD	14.38	-	22	14.55	-	17	*X*	*X*			*X*	
Reinert, 2015	ASD ; TD	9.20	0.45	4	7.40	2.06	5	*X*					
Rinehart, 2006a	ASD ; TD	10.05	3.20	24	10.05	-	12	*X*	*X*				
Rinehart, 2006b	ASD ; TD	12.93	4.15	30	13.10	3.11	21	*X*	*X*				
Rinehart, 2006c	ASD ; TD	10.67	0.90	20	10.73	3.37	10				*X*		
Rinehart, 2006d	ASD ; TD	5.10	3.23	11	5.90	3.60	11				*X*		
Riquelme, 2016	HFASD ; TD	6.30	3.23	27	6.50	-	30	*X*	*X*				
Sachse, 2013	ASD ; TD	19.20	5.10	30	19.90	1.00	28	*X*	*X*				
Sahlander, 2008	Asperger ; TD	28.50	5.20	14	19.00	-	28	*X*	*X*	*X*			
Schmitz, 2003	ASD ; TD	7.90	1.30	8	6.00	2.21	16	*X*	*X*	*X*			
Sharer, 2016	ASD ; TD	38.72	18.36	18	36.36	0.08	11	*X*	*X*				
Siaperas, 2012	Asperger ; TD	10.72	2.55	50	10.84	-	50	*X*	*X*	*X*			

Author, Year	Diagnostic groups	ASD group			TD group			Usage in analyses					
		Mean age (years)	SD	N	Mean age (years)	SD	N	*1*	*2*	*3*	*4*	*5*	*6*
Sigman, 1981	ASD ; TD	51.70	0.89	16	24.40	2.91	16	*X*	*X*	*X*			
Somogyi, 2016	ASD ; TD	7.83	-	18	8.08	-	12	*X*	*X*	*X*			
Soorya, 2004	ASD ; TD	6.48	2.67	12	6.30	1.20	12	*X*	*X*	*X*			
Stevenson, 2017	ASD ; TD	7.98	4.11	13	7.97	2.21	13	*X*	*X*				
Stins, 2015	ASD ; TD	10.80	1.20	9	10.80	0.95	9	*X*	*X*	*X*			
Stoit, 2013	ASD ; TD	11.55	2.88	31	10.52	5.98	29	*X*	*X*				
Sumner, 2016	ASD ; TD	8.65	1.18	30	9.11	0.95	35	*X*	*X*				
Takarae, 2008	HFASD ; TD	15.25	5.42	36	16.54	5.98	46	*X*	*X*				
Thompson, 2017	ASD ; TD	26.00	7.00	60	29.00	7.00	60	*X*	*X*				
Travers, 2010	ASD ; TD	15.10	6.96	67	15.99	2.10	42	*X*	*X*				*X*
Travers, 2013	ASD ; TD	19.00	2.11	15	19.00	3.80	14	*X*	*X*				
Travers, 2015	HFASD ; TD	9.63	2.09	21	9.64	6.46	16	*X*	*X*	*X*			
Travers, 2018	ASD ; TD	21.80	3.20	25	21.30	2.78	26	*X*	*X*	*X*			*X*
Turner, 2006	ASD ; TD	28.10	8.30	8	28.60	0.19	8	*X*	*X*				
Vanvuchelen, 2007	HFASD ; TD	8.75	0.92	17	8.74	0.97	17	*X*					
Vernazza-Martin, 2005	ASD ; TD	4-6	-	9	4-6	-	6				*X*		
Vlachos, 2007	ASD ; TD	10.35	0.23	14	10.42	0.19	14	*X*	*X*	*X*			
Wadsworth, 2017	HFASD ; TD	12.00	2.94	14	12.00	1.63	15	*X*	*X*				
Wang, 2015	ASD ; TD	12.72	3.64	22	11.67	4.53	21	*X*	*X*	*X*		*X*	
Wang, 2016	ASD ; TD	8.77	2.64	34	8.76	3.11	25	*X*	*X*			*X*	*X*
Weimer, 2001	Asperger ; TD	15.70	3.60	10	15.90	3.80	10	*X*	*X*	*X*			
Weiss, 2013	ASD ; TD	19.00	16-22	9	19.50	0.50	10				*X*		
Whyatt, 2012	ASD ; TD	10.03	1.20	18	10.99	3.30	19	*X*	*X*	*X*			

Author, Year	Diagnostic groups	ASD group			TD group			Usage in analyses					
		Mean age (years)	SD	N	Mean age (years)	SD	N	*1*	*2*	*3*	*4*	*5*	*6*
Yang, 2014	ASD ; TD	7.80	1.40	20	7.90	1.50	20	*X*	*X*				
Zachor, 2010	ASD	3.33	0.48	25	-	-	-						*X*

Notes. Studies are listed in alphabetical order. HFASD = high functioning Autism Spectrum Disorder. Age range is indicated for studies that did not report mean age or standard deviation. SD = Standard deviation of age

X indicates that a study was included in this specific analysis. 1= Sensorimotor differences between ASD and TD; 2= Fine and Gross sensorimotor skills in ASD vs TD; 3= Gross sensorimotor categories in ASD vs TD; 4= Gait in ASD vs TD; 5= Effect of age in ASD; 6= Clinical severity

Data analyses

Following meta-analytic guidelines (Lipsey & Wilson, 2001), a rigorous synthesis and analysis of the set of ASD studies were performed. This procedure involved the following steps: describing relevant characteristics of the ASD and TD groups, calculating standardized mean difference effect sizes (as Hedges' g; Hedges, 1981) for each study, and estimating overall effect sizes and their confidence intervals using random effects meta-analyses (Rosenthal 1995; Rosenthal & DiMatteo, 2001). Individual effect sizes were calculated using the Comprehensive Meta-Analysis (CMA) software, version 2.0 (Borenstein, Hedges, Higgins & Rothstein, 2005).

To ensure consistency of effect size direction across different measures, the following approaches were followed. For effect sizes representing comparisons between ASD and TD, a greater ability (or lesser impairment) in the ASD group was given a negative sign, and lesser ability (or greater impairment) in the ASD group was given a positive sign. For the analysis of gait measures, effects representing slower walking velocity in the ASD group were given a positive sign, and faster walking velocity was given a negative sign. For the effect of age in ASD, a positive correlation represented a greater ability (or decreased impairment) with increased age, and the expected effect direction was positive. Finally, for the effect of clinical severity in ASD, a positive correlation represented greater ability (or decreased impairment) with increased clinical severity, and the expected effect direction was negative.

Random-effects meta-analyses were then performed in R version 3.5.0 using the *metafor* package version 2.0 (Viechtbauer, 2017). The random-effects approach accounts for

variation across studies and is recommended when studies vary in their samples or methodology (Borenstein et al., 2009). Moreover, random effects provide for greater control for differences in sample size when estimating effect sizes (Borenstein et al., 2009). Following the recommendations of Veroniki and colleagues, (2015), between-study heterogeneity was estimated using the restricted maximum likelihood (REML) method, and confidence intervals were estimated using the Q-profile method. For ease of description, effect sizes are labelled in the text as "small" ($g \sim 0.2$; $r \sim 0.1$), "medium/moderate" ($g \sim 0.5$; $r \sim 0.3$) or "large" ($g \sim 0.8$; $r \sim 0.5$) following Cohen (1988); it is understood that these labels are approximate and their values may vary by research domain. Statistical significance is reported at the $p < 0.05$ level.

Heterogeneity measure

Heterogeneity across studies was assessed using the I^2 measure (Higgins & Green, 2006). This measure is sensitive to whether differences in results across studies are due to measuring different effects or attributable to chance, and is recommended by Cochrane Reviews (Higgins et al., 2003). I^2 values of 25% indicate a low percentage of heterogeneity, 50% indicates moderate heterogeneity and 75% indicates a high percentage of heterogeneity. Forest plots were created to display all the effect estimates and confidence intervals for both individual studies and meta-analyses (Lewis, 2001). These plots also provide an indication of heterogeneity between studies (Phan et al., 2015).

Publication bias

Publication bias refers to the increasing probability of a study being published as the effect size of its findings increases. Two techniques were used to assess the presence of

publication bias. First, as a visual diagnostic, funnel plots were generated to present the effect size of individual studies against the standard error associated with each study. Asymmetry around the triangular funnel may indicate the presence publication bias (Rothstein et al., 2005). Second, as a quantitative diagnostic, Duval and Tweedie's L0 trim and fill procedure was used to impute additional effect values as necessary to correct asymmetry (Duval & Tweedie, 2000), closely approximating an unbiased distribution (Borenstein et al., 2009).

Results

Aim 1: Sensorimotor differences between ASD and TD

A random effects meta-analysis of 127 studies indicated a significant overall effect size of $g = 1.22$ (SE = 0.08; CI = 1.08-1.37; $p < 0.001$). This large effect indicates substantial overall deficits across motor skills, motor coordination, motor control, postural stability and visuomotor integration in ASD compared to TD. Individual effect sizes for studies in this analysis are shown in Figure 2 and Appendix 1.

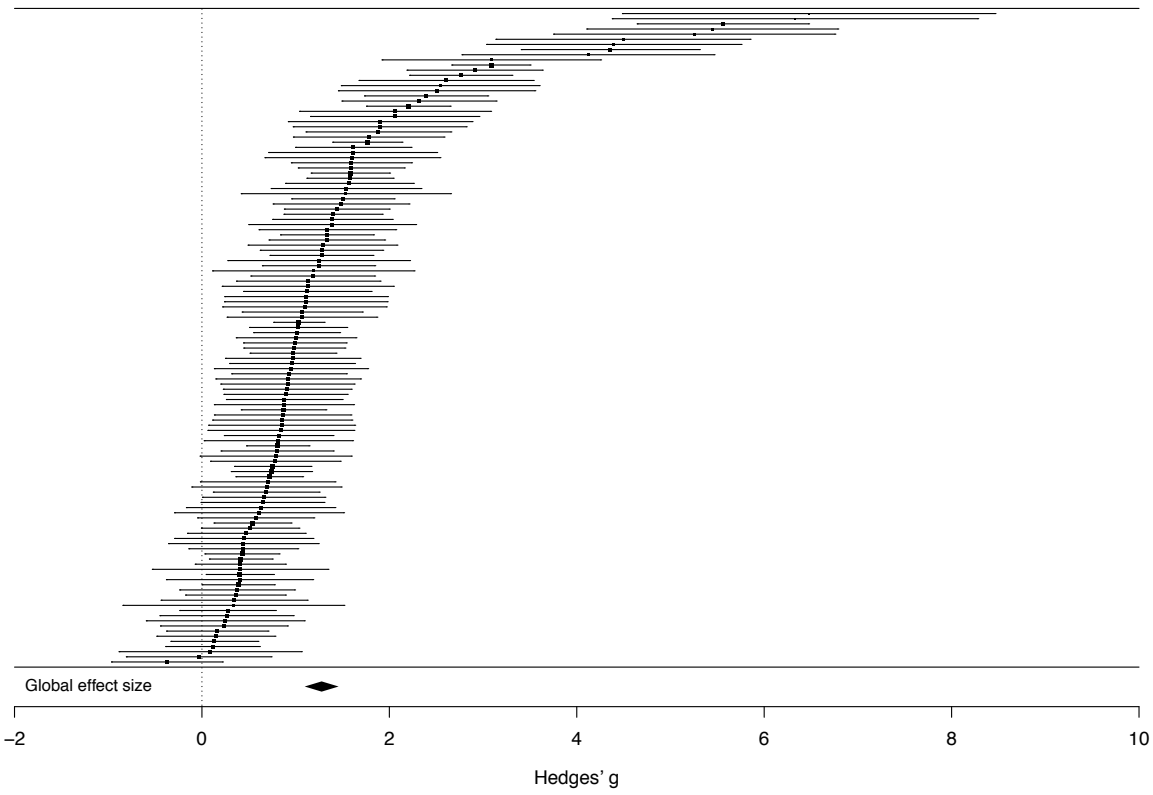

Figure 2. Forest plot of effect sizes (Hedges' g) in the comparison of overall sensorimotor abilities between ASD and TD. Positive values, to the right of the dotted line, indicate lower sensorimotor ability in the ASD group.

In order to examine these deficits in more detail, separate meta-analyses were performed for fine (k = 81) and gross sensorimotor abilities (k = 65), confirming large effect sizes for both fine sensorimotor abilities (g = 1.11, SE = 0.09; CI = 0.93 - 1.30; $p < 0.001$) and gross sensorimotor abilities (g = 1.27, SE = 0.10; CI = 1.07 - 1.48; $p < 0.001$). These effects show that individuals with ASD present major impairments in both fine and gross sensorimotor skills (see Appendix 1 for more details). An additional analysis tested whether effect size differed between these categories of fine and gross sensorimotor skills, and found

no difference ($p = 0.472$), further underlining the strong effect magnitude across both categories.

Given that gross sensorimotor skills represent a more heterogeneous category, the gross sensorimotor measures were subsequently grouped into three subcategories for further analysis: arm movements, balance and coordination. Separate meta-analyses for each of these subcategories confirmed large effect sizes representing impairments in arm movements ($k = 11$) ($g = 1.54$, SE = 0.38; $p < 0.001$, CI = 0.81-2.28), balance ($k = 43$) ($g = 1.31$, SE = 0.27; $p < 0.001$, CI = 0.78-1.84) and coordination ($k = 2$) ($g = 1.32$, SE = 0.31, $p < 0.001$; CI = 0.72-1.91). More details are included in Appendix 1. An additional analysis tested whether effect size differed between these subcategories, and found no difference ($p = 0.875$), underlining the strong effect magnitude across all subcategories.

Gait differences in ASD vs TD

As mentioned in the methods, gait measures were analyzed separately. A random effects meta-analysis of 10 studies revealed a medium to large effect size indicating slower walking velocity in ASD compared to TD ($g = 0.70$, SE = 0.31; $p < 0.05$, CI = 0.09 - 1.32) . Individual effect sizes for studies in this analysis are shown in Figure 3 and Appendix 1.

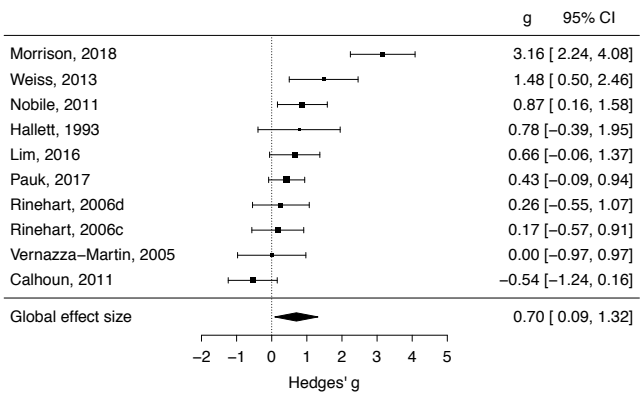

Figure 3. Forest plot of effect sizes (Hedges' g) in the gait analysis of ASD compared to TD. Positive values, to the right of the dotted line, indicate slower walking velocity in the ASD group.

Aim 2: Effect of age on sensorimotor skills in ASD

A meta-analysis of 5 studies revealed a positive overall age correlation effect of r = 0.38 ($p < 0.001$; CI = 0.19 - 0.58). This moderate effect indicates that greater age in individuals with ASD was associated with improved sensorimotor abilities. The 5 studies included in this analysis used sensorimotor measures related to motor skills, motor and postural control, and the Pearson correlation values between age and sensorimotor ability ranged from 0.19 to 0.58. Individual effect sizes for studies in this analysis are shown in Figure 4 and Appendix 2.

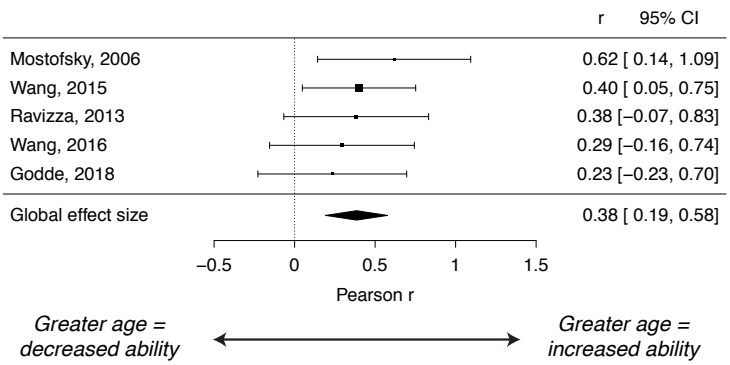

Figure 4. Forest plot of effect sizes (Pearson r) in the age analysis in ASD. Positive values, to the right of the dotted line, indicate increased sensorimotor ability with greater age.

Aim 3: Effect of clinical severity on sensorimotor skills in ASD

A meta-analysis of 18 studies indicated a small, non-significant correlation with clinical severity measures of r = -0.19 (p = 0.12; CI = -0.43 - 0.05). This result does not support the hypothesis that greater clinical severity in individuals with ASD correlates with decreased sensorimotor ability. Individual effect sizes for studies in this analysis are shown in Figure 5 and Appendix 3.

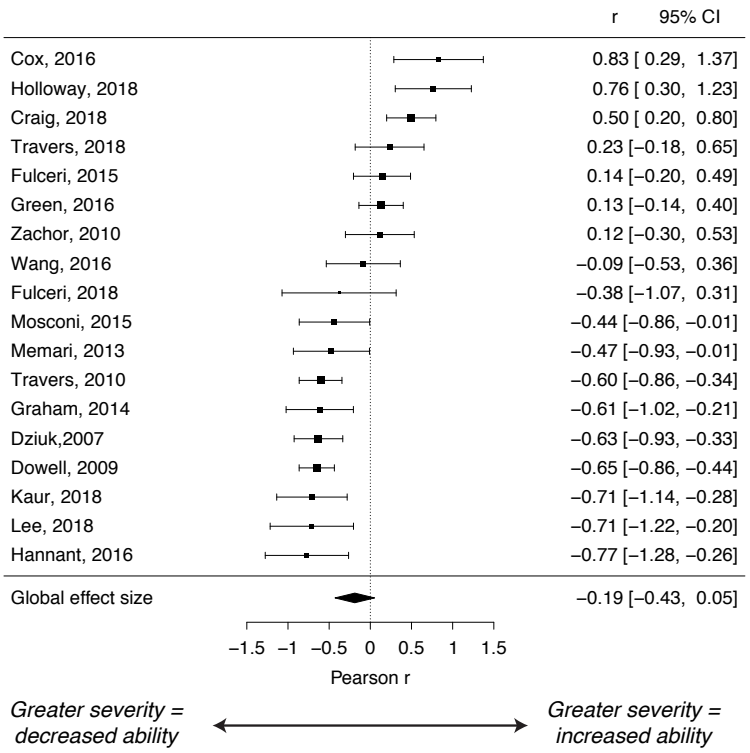

Figure 5. Forest plot of effect sizes (Pearson r) in the clinical severity analysis in ASD. Negative values, to the left of the dotted line, indicate lower sensorimotor ability in association with higher symptom severity measures.

Measuring between-study heterogeneity

Heterogeneity between studies was anticipated in each analysis because of variation in sensorimotor measures available in each study, as well as differences in sample demographics such as age and cognitive profile. The I^2 estimates of inter-study heterogeneity were 90.55% for the sensorimotor differences analysis, I^2=94.20% for the fine sensorimotor analysis, I^2=96.05% for the gross sensorimotor analysis, I^2= 95.41% for the categories in gross sensorimotor skills, I^2= 83.84% for the gait analysis, I^2= 0% for the analysis of age correlations in ASD (in which only 5 studies were included), and I^2= 86.61% for the analysis of symptom severity correlations in ASD. Notwithstanding the 0% estimate in the small age correlation analysis, these values indicate a consistently large degree of variability between the studies (Higgins & Green, 2006; Higgins et al. 2003), and reinforce the necessity to conduct a random-effects meta-analyses to directly account for such variability (Borenstein et al., 2009; Higgins & Green, 2006).

Publication bias

Publication bias was assessed by visual inspection of symmetry in funnel plots, in combination with Duval and Tweedie's trim and fill technique (Duval & Tweedie, 2000). Funnel plots corresponding to the overall sensorimotor comparison between ASD and TD, gait differences in ASD compared to TD, age effects in ASD, and severity effects in ASD are shown in Figure 6. No overt departures from symmetry are noted in the funnel plots, although extreme effect sizes (> 4 standard deviations) for several studies on the right side of the funnel plot for the overall ASD-versus-TD comparison (Figure 6a) are unmatched by correspondingly extreme values in the opposite direction. The trim and fill procedure did not

impute any additional values to correct symmetry in the main analysis of ASD vs TD or the age analysis, and imputed one value on the right (positive) side in the severity analysis and three values on the right (ASD slower than TD) side in the gait analysis. These additional imputed values did not change the significance of any effect sizes reported in the present meta-analyses. The trim and fill results do not suggest any strong publication biases affecting the present analyses.

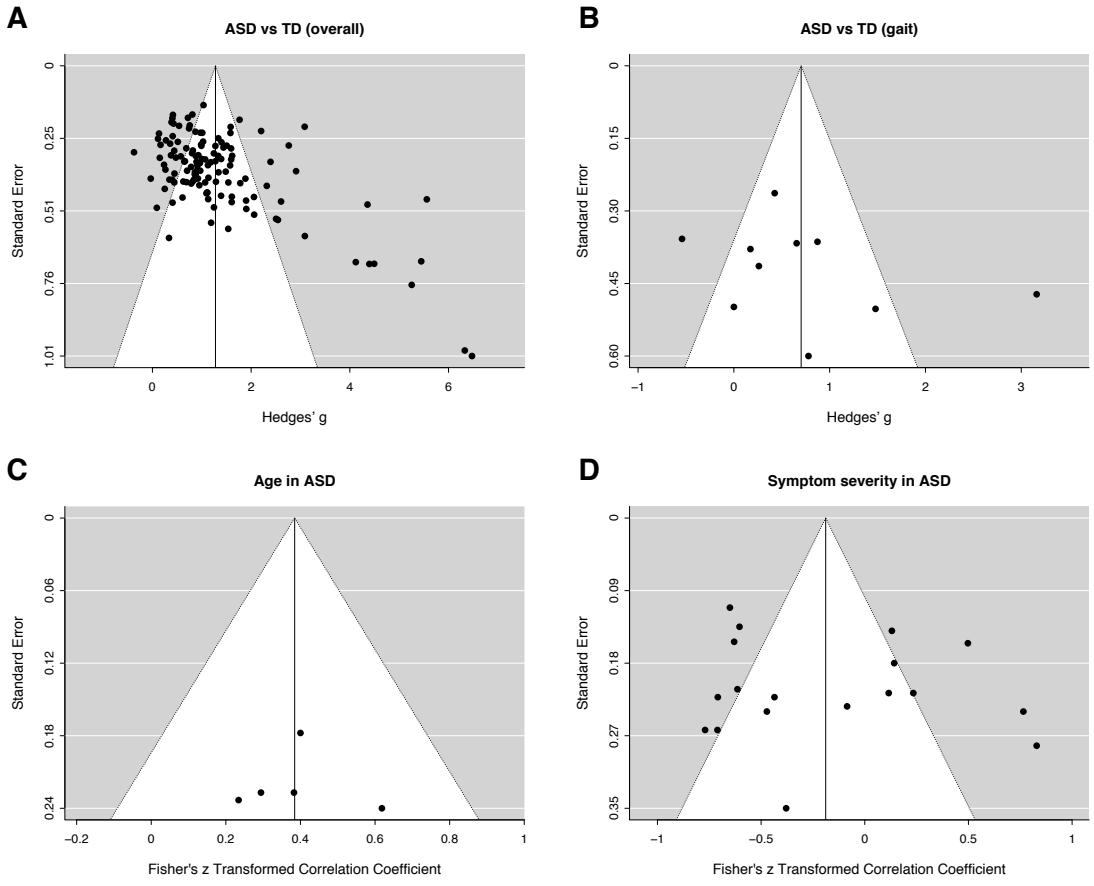

Figure 6. Funnel plots of study effect size vs standard error. (a) Overall sensorimotor differences between ASD and TD, (b) gait differences in ASD compared to TD, (c) correlation between age and sensorimotor performance in ASD, (d) correlation between symptom severity and sensorimotor performance in ASD.

Discussion

The present research provides a meta-analysis of studies between 1980 and 2018 confirming that sensorimotor abilities are strongly and consistently impaired in ASD across a broad range of skills including fine coordination (e.g. handwriting), arm movement, walking speed and balance. The results also support a progressive increase in sensorimotor performance with age in ASD, but do not confirm an association between sensorimotor ability and clinical symptom severity. The inclusion of 127 studies for the overall comparison between ASD and TD represents more than twice the studies included in the previous meta-analysis of sensorimotor skills in ASD (*c.f.* Fournier et al., 2010). These results broaden the understanding of sensorimotor atypicalities in ASD, and provide a foundation to better design interventions to target these deficits.

Fine and gross sensorimotor skills

To further our understanding of the underlying sensorimotor deficits in ASD, the present analyses examined several different categories of sensorimotor ability, spanning both fine and gross abilities, and found them all to be impaired in ASD. In the case of fine sensorimotor abilities, these impairments are important to understand because they may not only affect daily activities, but can potentially confound performance across a range of laboratory tasks that rely on fast motor responses to stimuli. Impairments in coordination, balance and gross movements may be related to the high incidence (one-third of children diagnosed with ASD) of hypotonia, an abnormally low level of muscle tone (Kindregan, Gallagher & Gormley, 2015). These results also complement a previous report that in individuals with ASD, coordinating hand/head movements and inhibiting reflexes may

constrain the ability to develop mobility and hand manipulation skills for daily living tasks (Shumway-Cook & Woollacott, 2001). For example, sensorimotor skills are required to accomplish daily activities such as reaching and grasping a cup of water, writing a text or walking while crossing a street. Impairments in both fine and gross sensorimotor abilities may also cascade to influence social interactions and communication in individuals with ASD (MacDonald, Lord & Ulrich, 2013).

The present results confirm that walking velocity is generally decreased in children with ASD compared to TD peers. Children with ASD may demonstrate multiple gait stereotypies (Goldman et al., 2009) such as idiopathic toe walking (Barrow, Jaworski & Accardo, 2011) and a reduced stride length (Kindregan, Gallagher & Gormley, 2015). These atypicalities are associated with decreased stability (Nobile et al., 2011). In combination with the broad range of impaired gross sensorimotor abilities shown in the present meta-analyses, these contributing factors may explain the decreased walking speed in individuals with ASD.

Age effect in sensorimotor skills

The analysis of age-related changes in sensorimotor ability found a significant increase in performance with age for ASD across 5 studies. The overall range of participant ages in this analysis was 5 to 35 years old. We note that effect sizes in this analysis are somewhat greater for studies whose samples extended earlier in childhood, and diminished for those extending into adulthood. However, the small size of the analysis precludes any strong generalizations and highlights the need for further research to better define the developmental trajectory of sensorimotor impairments in ASD. Nonetheless, impaired development of motor ability has been reported in ASD as early as the first 2 years of life

(Landa & Garrett-Mayer, 2006). Sensorimotor improvement with age in ASD has also been shown in the context of another type of task, visually guided saccades, where performance increased during childhood and early adolescence but no improvement was observed from adolescence to adulthood (Luna et al., 2007). This suggests an alteration in maturational processes that leads to a persistent impairment in the ability to quickly plan and initiate behavioural actions (Mosconi & Sweeney, 2015). As noted by Fournier and colleagues (2010), an improvement in sensorimotor skills with age in ASD could be explained by a natural consequence of development, of interventional programs or a combination of both factors. Importantly, as a within-ASD analysis, it is not possible to determine from the present data whether the age-related improvement ultimately results in a convergence or normalization to a similar level of ability as neurotypical adults. However, the age category meta-analysis previously performed by Fournier (2010) supports a persistent, strong impairment in sensorimotor ability in ASD compared to TD that continues into adulthood, although the impairment may be slightly more pronounced in toddlers and children. Additionally, most of the studies did not note or describe interventions being received by the ASD participants. Thus, it is difficult to gauge how much influence this might have had in these results. Overall, despite the small size of the present analysis, the age-related improvement in ASD is consistent with several other studies whose design precluded inclusion in these meta-analyses (Landa & Garrett-Mayer, 2006; Ming et al., 2007; Luna et al., 2007).

Clinical severity

Even though no statistical relationship between sensorimotor skills and clinical severity was found (Pearson *r*, 95% confidence interval -0.43 - 0.05), the direction and confidence interval of the results do not strongly exclude the possibility that sensorimotor ability may have associations with measures of core ASD symptoms. Hannant and colleagues (2016) suggest that sensorimotor difficulties can affect the development of social behaviours such as coordinating eye contact with speech and gesture, interpreting others' behaviour, and responding appropriately. For example, socially-relevant sensorimotor impairments shown by children with ASD include skilled motor gestures, imitations, and development of speech sounds production (Mostofsky et al., 2006; Page & Boucher, 1998). However, relatively few studies were available to evaluate this aim in the present meta-analysis (n=18), and there was variability across studies both in the type of sensorimotor task and in the clinical severity measure used. Additionally, because this analysis was based on within-study correlations, studies having a smaller range of severity in their ASD sample (e.g., due to the circumstances of recruitment or inclusion criteria) are limited in sensitivity to detect associations between sensorimotor ability and clinical severity. The severity measures used in the present analysis varied from overall diagnostic scores such as the ADOS, to parent reports across multiple types of behavioural outcome such as the ATEC and parent reports of social behaviour such as the SRS. ASD core symptoms include atypicalities in social, communication and repetitive/restricted behaviour (American Psychiatric Association, 2013). As more studies directly test associations between sensorimotor abilities and symptom severity, it will become more feasible to determine

whether particular dimensions of ASD severity show associations with sensorimotor abilities.

Strength and Limitations of this meta-analysis

In addition to assessing the consistency of sensorimotor impairments in ASD across a large body of literature, this work provides a novel contribution to the field by quantitatively examining the relationships between sensorimotor skills, development, and clinical symptom severity in ASD. The results further our knowledge of sensorimotor skills by confirming impairments across a broad range of motor abilities including fine coordination, arm movement, walking speed and balance. Unlike previous meta-analyses, this study included studies that directly examined correlations between sensorimotor skill and age in ASD, providing evidence for improvement in sensorimotor ability over development in ASD. The advantage of this approach over a meta-regression (i.e., a moderator analysis of mean age per study) is that the present analysis benefits from the high variability of age within each study, whereas a meta-regression does not account for within-study variation while estimating the effect of age.

Variation in ASD samples and diagnostic labels was evident across studies (see Table 1), and within the time period of the analyzed literature the classification of severity in ASD has changed from the DSM-IV to the DSM-V. For this reason, it was not possible to analyze severity-based subgroups with any degree of certainty in the present study. Instead, a meta-analysis was performed for studies that directly estimated the association between ASD severity measures and sensorimotor ability. As with the analysis of age effects, this approach

has the advantage of benefiting from (rather than being limited by) the inevitable variability of ASD severity within any study sample.

The scope of the present aims necessitated including a broad range of sensorimotor measures from different tools and batteries in order to better generalize conclusions about impaired performance in ASD. Therefore, it was not possible to use a single type of measure or a specific battery as recommended by the Cochrane Handbook for meta-analyses (Higgins & Green, 2011) and this is a weakness of this meta-analysis approach . By performing analyses across a comprehensive set of sensorimotor behaviours, as well as within more focused categories of fine and gross abilities (as availability of the literature permitted), the present results provide both an overview of general sensorimotor impairment and specific confirmation of impairments within more homogeneous types of sensorimotor ability and also at different degrees of severity in ASD.

Two additional caveats are necessary to mention regarding the study samples. The included studies were conducted mostly in North America, which may to some extent limit the generalization of results to ASD populations in other regions around the world. Furthermore, most studies in this analysis had a greater representation of males with ASD than females, following the greater rate of ASD incidence in males, and this may limit the generalization of these results to females with ASD.

Future directions

Research on sensorimotor skills in ASD is an important field of study. While the present meta-analysis provides strong support for the presence of impairments across many sensorimotor abilities in ASD, many questions remain to be answered. Do sensorimotor

impairments persist in ASD through adolescence and adult life? Is ASD severity correlated with sensorimotor skills during a specific or critical period of development? Do existing ASD therapies have an impact on any sensorimotor abilities, and might they influence results of the present meta-analyses, particularly for older children? Overall, it is suggested that future studies describe any therapy or intervention programs received by participants in their clinical sample, as this could affect individual sensorimotor performance.

A potential impact of the present research is to contribute to a theoretical groundwork for future sensorimotor-based interventions (e.g., music and dance) in ASD. Dance based therapies may promote integration between the sensory and motor systems in ASD (Scharoun et al., 2014). Children with ASD typically have poor perceptual-motor integration (i.e., the integration of motor activity with visual or auditory perceptions), as confirmed in the present analyses, and there is evidence that this results in a more limited repertoire of movement in this population (Erfer, 1995). Dance-movement therapy, through exploration and learning, can act to expand their movement repertoire (Erfer, 1995). Movement and dancing are also innate means of communication (Boris, 2001; Koff, 2000) and thus provide a nonverbal means of expression for children who have difficulties communicating (Freundlich, Pike & Schwartz, 1989), such as individuals with ASD. By better understanding differences in sensorimotor deficits in ASD, interventions can therefore be better optimized to target these deficits.

Conclusion

These meta-analyses consistently support the presence of impairments in both fine and gross sensorimotor skills in ASD. The strength and diversity of these deficits emphasize

their importance and impact across a wide range of daily behaviours in ASD. For these reasons, sensorimotor impairments should be given strong consideration in clinical assessment of individuals with ASD and more broadly across research, therapy, and educational settings. Interventions aimed at improving sensorimotor skill should be further investigated beginning at young ages, and may help to ameliorate both the direct and indirect consequences of sensorimotor impairments in ASD.

General discussion

The main objectives of this thesis were to determine if sensorimotor impairments are consistent in ASD across a range of abilities, and to examine potential relationships between sensorimotor skills and both age and clinical symptom severity. Taken together, the present research provides meta-analyses of studies between 1980 and 2018 confirming that sensorimotor abilities are strongly and consistently impaired in ASD. The results also support a progressive increase in sensorimotor performance with age in ASD, but do not confirm an association between sensorimotor ability and clinical symptom severity.
More specifically, findings revealed that:

1. Strong effect sizes confirmed substantial overall deficits across motor skills, motor coordination, motor control, postural stability and visuomotor integration in ASD compared to TD. Moreover, individuals with ASD presented major impairments in both fine and gross sensorimotor skills; in particular, in arm movements, balance, coordination and a slower walking velocity compared to TD.
2. A positive association between sensorimotor performance and age in ASD was found, in which greater age was associated with improved sensorimotor abilities across a range of measures related to sensorimotor skills and postural control.
3. No relationship was found between clinical symptom severity and sensorimotor ability in children with ASD.

Contributions of this master's thesis to research in sensorimotor skills in ASD

The present research provides up-to-date quantitative meta-analyses to determine whether sensorimotor impairment is a major feature in ASD, and if so, which sensorimotor

systems or behaviours are most relevant. Due to heterogeneity of results across the current literature, there was a considerable need to study quantitatively the effect of age on sensorimotor ability in individuals with ASD and to study the relationship between clinical symptom severity and these skills in ASD. The ultimate mission of this research was to support a theoretical groundwork for future sensorimotor-based interventions (such as music and dance) in ASD.

First, these findings strengthen and clarify our understanding of sensorimotor skills in ASD. The present research examined several different categories of sensorimotor ability, spanning both fine and gross abilities, and found them all to be impaired in ASD. In the case of fine sensorimotor abilities, impairments may not only affect daily activities, but can potentially confound performance across a range of laboratory tasks that rely on fast motor responses to stimuli. These results also complement a previous report that in individuals with ASD, coordinating hand/head movements and inhibiting reflexes may constrain the ability to develop mobility and hand manipulation skills for daily living tasks (Shumway-Cook & Woollacott, 2001). Taken together, these results better define the broad extent of sensorimotor deficits in ASD.

Second, our findings shed light on the development of sensorimotor skills in individuals with ASD. Specifically, results revealed a significant relation between age and sensorimotor skills across both fine and gross sensorimotor skills in ASD. Unlike previous meta-analyses, this study included studies that directly measured correlations between sensorimotor skill and age in ASD, providing evidence for improvement in sensorimotor ability over development in ASD. The advantage of this approach over a meta-regression

(i.e., a moderator analysis of mean age per study) is that the present analysis benefits from the high variability of age within each study, whereas a meta-regression does not account for within-study variation while estimating the effect of age.

Third, our findings inform us on the relation between sensorimotor skills and ASD symptom severity. Specifically, results did not show a significant association between social and communication symptom severity and sensorimotor skills. However, the findings do not strongly exclude the possibility that sensorimotor ability may have associations with some individual measures of core ASD symptoms. It should be noted that some widely used severity measures such as the ADOS have relatively coarse scoring increments, and were designed to aid diagnosis rather than serve as a continuous quantitative measure. Both these factors may somewhat diminish the sensitivity of this analysis to variation in symptom severity. Additionally, while not significant in this meta-analysis, the effect size direction is consistent with the observation by Hannant and colleagues (2016) that sensorimotor difficulties can affect the development of social behaviours such as coordinating eye contact with speech and gesture, interpreting others' behaviour, and responding appropriately

Fourth, another potential impact of the present research is to contribute to a theoretical groundwork for future sensorimotor-based interventions in ASD. Studies have shown atypical movement preparation in participants with ASD which was characterized by a difficulty to adjust the motor preparation time in response to a movement or a signal (Rinehart et al., 2006 ; Rinehart, Bradshaw, Brereton, & Tonge, 2001). Following this evidence, a recent review suggest that participants with ASD showed a deficit in anticipatory preparation of movement in participants with ASD (Janzen & Thaut, 2018). Dance based

therapies may promote integration between the sensory and motor systems in ASD (Scharoun et al., 2014) and a recent review showed benefits of this type of therapy on sensorimotor skills in ASD (Srinivasan & Bhat, 2013). Children with ASD typically have poor perceptual-motor integration (i.e., the integration of motor activity with visual or auditory perceptions), as confirmed in the present analyses, and there is evidence that this impairment results in a more limited repertoire of movement in this population. Dance-movement therapy, through exploration and learning, can act to expand their movement repertoire (Erfer, 1995). By better understanding differences in sensorimotor deficits in ASD, interventions can therefore be better designed to target these deficits and future studies could address if these sensorimotor interventions would be more efficient for individuals who show relative spared abilities in rhythmic sensorimotor tasks.

Implications

These large impairments in both gross and fine sensorimotor skills in ASD support previous findings of difficulties in daily sensorimotor behaviours such as buttoning up a coat, which require intact integration of sensory information and motor output (Jasmin et al. 2009). The present meta-analyses find impairments across abilities including arm movements, coordination and handwriting. Deficits in accuracy, speed, coordination, and the ability to integrate visual information into motor learning may also have a cascading impact upon social learning opportunities in ASD, reinforcing the development and maintenance of social and communication difficulties characteristic of this population (Hannant et al., 2016). For example, difficulties in integrating eye movements with body movements could account for social communication and interaction difficulties in ASD such as coordinating eye contact with gestures and speech (American Psychiatric Association, 2013). Another

potential contributor is difficulty in integrating other cues, especially visual information in motor learning. This could explain the challenges faced in social imitation in ASD (Marsh, Pearson, Ropar & Hamilton, 2013). Furthermore, in the presence of sensorimotor impairments, children are less likely to engage in physical activities that can be important for social interactions and communication, such as playing at a park (Bhat, Landa & Galloway 2011). Relatively few studies have examined a correlation between sensorimotor skills and social impairments in early development; in the present meta-analyses, there were insufficient studies to evaluate this specifically. However, there is some evidence that there is an early, causative role of sensorimotor ability in the development of core communication and social impairments (Bhat, Landa & Galloway 2011; Page & Boucher 1998). In combination with the strong overall impairments found in the present analyses, this reinforces the critical need to focus on sensorimotor skills early in development in ASD.

Novelty of this master's thesis

This work provides a novel contribution to the field of ASD by quantitatively examining the relationships between sensorimotor skills and development, as well as clinical symptom severity in ASD. The present results broaden the knowledge of sensorimotor atypicalities in ASD, and provide a foundation to better design interventions to target these deficits. To support a deeper understanding of the relationship between clinical intervention and sensorimotor ability, we recommend that future studies describe any therapy or intervention programs received by participants in their clinical sample, as this could affect individual sensorimotor performance. Furthermore, the present findings show a progressive increase in sensorimotor performance with age in ASD. However, most of the studies did not

note or describe interventions being received by the ASD participants. Thus, it is difficult to gauge how much influence this might have had in these results. We suggest that future studies report what type of intervention/services (e.g. speech therapy, muscial intervention, Applied Behaviour Analysis training, etc.) was received by participants with ASD; this information could be requested from participating families in conjunction with a socio-demographic questionnaire. Moreover, given that no relationship was found between clinical symptom severity and sensorimotor skills in ASD, it is recommended that more studies directly test associations between sensorimotor abilities and symptom severity, so that it will become more feasible to determine whether particular dimensions of ASD severity show associations with sensorimotor abilities.

Future directions

Our results lead us to question and compare two principal axes: fundamental bases of sensorimotor skills and future clinical interventions.

Firstly, what the brain mechanisms are involved in sensorimotor deficits in individuals with ASD? Neurobiological research has implicated the cerebellum in atypical sensorimotor skills in ASD (Fatemi et al., 2012). The cerebellum contains pathways that connect sensory signals to the motor areas of the brain, which play an important role in controlling and coordinating movement (Glickstein, 1998; Paulin, 1993). More recent studies in ASD have also documented abnormalities in motor-related brain structure as well as reduced activation in regions including motor and lateral premotor cortex, supplementary motor area, and cerebellum during finger tapping tasks (Allen & Courchesne, 2003; Muller et al., 2001). Given that the present results strongly support the existence of sensorimotor

impairments that extend to both fine and gross categories of sensorimotor skills in ASD, further neuroimaging research may help elucidate the relation between specific brain regions and these behavioural impairments.

Secondly, to what extent might purely perceptual deficits explain the sensorimotor deficits found in ASD? Although sensory deficits could disrupt the perception-action cycle, most studies in this analysis did not assess for such deficits before the sensorimotor task. Testing both perceptual and motor tasks can help elucidate whether differences in ability are more related to perceptual, integrative or motor deficits.

Thirdly, are cognitive abilities associated with sensorimotor skills in ASD? Some studies have reported that sensorimotor functions often involve automatic responses mediated by frontostriatal systems in the brain (Goldberg et al., 2002; Thakkar et al., 2008). This compensatory use of frontostriatal systems to support sensorimotor functions may have negative effects on later developing cognitive processes (Mosconi & Sweeney, 2015) such as executive dysfunctions reported in ASD (Demetriou et al., 2016).

Lastly, do sensorimotor dysfunctions precede the emergence of core deficits in ASD? A number of studies have demonstrated the early emergence of atypical sensorimotor behaviour in the first 12 months in ASD, while core diagnostics of impaired social behaviour are less reliably observed until the second year of life (Wozniak et al., 2017). As an example, in infants between 3-6 months old who were later diagnosed with ASD, deficits were observed for the mouth opening in anticipation of a spoon's approach while feeding (Brisson et al., 2012). Moreover, another study reported that at one year old, infants later diagnosed with ASD achieved the ability to sit independently at slightly lower rates than the TD group (Ozonoff et al., 2010). Some studies also suggest that sensorimotor deficits could affect the

development of social and emotional abilities later in development (Hannant et al., 2016; MacDonald, Lord & Ulrich 2013; Matsushima & Kato, 2013). Based on these facts, more studies should be done in order to better understand the role of sensorimotor deficits in relation to core ASD symptoms.

Accounting for specific sensorimotor atypicalities early in the clinical diagnostic stage in ASD is important to properly characterize clinical phenotypes, account for heterogeneity and especially to individualize treatments. Recent evidence suggests that sensorimotor deficit is central to ASD (Mosconi & Sweeney, 2015), although additional research into the underlying brain mechanisms is clearly needed. Therefore, future studies on sensorimotor skills in ASD may complement the findings of the present thesis by examining the contributions of the above variables.

Conclusion

The meta-analyses presented in this thesis consistently support the presence of sensorimotor impairments in both fine and gross sensorimotor skills in ASD. These findings are consistent with existing literature and further expand the knowledge of sensorimotor skills across a broad range of impairments in individuals with ASD. The magnitude and diversity of these deficits emphasize their importance and impact upon a wide range of daily behaviours in ASD. For these reasons, sensorimotor impairments should be given strong consideration in clinical assessment of individuals with ASD and more broadly across research, therapy, and educational settings. Interventions aimed at improving sensorimotor skill should be further investigated beginning at young ages, and may help to ameliorate both the direct and indirect consequences of sensorimotor impairments in ASD.

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* References of studies included in this current meta-analysis

APPENDIX 1. Tables included for the sensorimotor differences analyses

Table 2

Summary of studies included in the sensorimotor motor analysis

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Abu-Dahab, 2013	HFASD; TD	11.99	0.20	73	12.11	0.17	75	Grooved Pegboard test: Motor coordination	0.80	0.17
Ament, 2015	HFASD; TD	10.27	1.28	48	10.31	1.18	69	MABC-2: Total motor performance	1.98	0.23
Beversdorf, 2001	HFASD; TD	30.80	9.30	10	30.60	12.80	13	Handwriting size: Vertical extent of each letter	1.39	0.45
Biscaldi, 2014	ASD; TD	13.58	0.53	36	14.28	0.50	34	Zurich Neuromotor Assessment: Block pure motor performance	0.89	0.25
Brandes-Aitkens, 2018	ASD; TD	10.30	1.70	14	10.40	1.30	28	Visuomotor control (composite score): visumotor tracking test	0.89	0.34
Brisson, 2012	ASD; TD	0.25-0.5	-	13	-	-	14	Number of attemps in anticipation of spoon-feeding	0.92	0.39

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Campione, 2016	ASD; TD	5.10	0.60	9	4.70	0.60	11	Reach time: 3-D optoelectronic SMART system	1.07	0.46
Chang, 2010	ASD; TD	8.75	1.34	16	8.93	1.39	22	Postural control: magnetic tracking system	0.94	0.34
Chen, 2016	ASD; TD	11.04	1.28	16	10.97	1.17	16	Kistler force platform: Magnitude of postural sway	2.52	0.47
Classen, 2013	ASD; TD	15.14	1.22	7	14.32	0.72	22	BOTMP: Motor performance	2.35	0.52
Cook, 2013	ASD; TD	3.80	0.32	14	3.13	0.32	15	Infrared-based Vicon motion tracking system: Kinematic of the arm movement	4.49	0.69
Cox, 2016	ASD; TD	18.28	2.29	13	16.59	0.55	26	Driver guidance system (DGS-78): Composite sample z-score of driving skills	0.40	0.34
Craig, 2018	ASD; TD	4.60	1.10	46	4.60	1.50	43	MABC-2: Total test score	5.56	0.47
Crippa, 2013	HFASD; TD	6.20	2.10	14	6.30	2.30	14	Eye-hand coordination	0.46	0.37

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
David, 2009	HFASD; TD	11.20	3.40	13	10.80	3.10	13	Reach and grasp task: Grip forces at onset	0.82	0.40
David, 2013	ASD; TD	4.50	1.08	24	3.94	1.57	30	Reach and grasp task: Grip forces at onset	0.36	0.27
Dewey, 2007	ASD; TD	10.20	3.40	49	11.30	2.40	78	BOTMP Short Form: Total score	2.20	0.23
Dowd, 2012	HFASD; TD	6.20	1.40	11	6.60	1.50	12	Simple movement task with visual distractor: Movement time	0.44	0.41
Dowell, 2009	ASD; TD	10.26	1.70	87	10.55	1.30	50	PANESS: Basic motor skills	0.72	0.18
Duffield,2013	ASD; TD	15.61	7.48	59	15.29	6.48	30	Motor coordination: Grooved Pegboard test	0.76	0.23
Dyck, 2010	ASD; TD	8.47	2.63	30	8.72	2.30	449	McCarron Assessment of Neuromuscular development: Motor coordination	3.08	0.21
Dziuk,2007	HFASD; TD	10.70	1.10	47	10.60	1.50	47	PANESS: Basic motor skills	1.58	0.23

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Fitzpatrick, 2017	ASD; TD	8.65	1.34	45	8.31	1.44	53	Polhemus Liberty sensors: Bimanual drumming task	0.75	0.21
Forti, 2011	ASD; TD	3.50	0.75	12	-	-	12	Infrared motion analysis: Time to reach peak velocity	0.66	0.41
Fournier, 2010	ASD; TD	11.10	2.30	13	13.10	2.20	12	Forceplate Bertec: Dynamic balance	-0.82	0.40
Fournier, 2011	ASD; TD	5.50	1.10	13	6.20	1.20	13	Forceplate Bertec: AreaCE95	0.84	0.40
Fournier, 2014	ASD ; TD	11.10	2.30	16	12.90	2.10	17	Forceplate Bertec: Center of pressure COP sway	0.71	0.35
Freitag, 2007	ASD; TD	17.50	3.50	16	18.60	1.20	16	Zurich Neuromotor Assessment: Balance score	1.95	0.42
Freitag, 2008	HFASD; TD	16.40	2.40	12	17.90	1.60	12	Block component adaptative peg board: Zurich Neuromotor Assessment	5.21	0.85
Fuentes, 2009	ASD; TD	10.20	1.90	14	11.10	1.30	14	PANESS: Total score	1.29	0.41

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Fuentes, 2010	ASD; TD	14.40	1.40	12	13.80	1.20	12	PANESS: Total score	2.54	0.54
Fukui, 2018	ASD; TD	18.30	2.10	12	19.10	2.20	12	Movement duration (blocked: 4 cm: full vision)	2.50	0.53
Fulceri, 2018	ASD; TD	7.82	1.32	11	7.57	0.71	11	Asynchrony of reaching: Unclear EP	1.11	0.44
Fulkerson, 1980	ASD; TD	10.10	-	15	7.50	-	15	Beery VMI: Visual-motor integration	0.70	0.37
Funahashi, 2014	ASD; TD	8.10	0.80	16	8.20	0.70	16	Total time needs to complete all the subtest of the STEF	0.24	0.35
Gepner, 2002	ASD; TD	6.00	1.20	6	5.60	0.80	9	Center of pressure of postural instability (eyes open) (CP shift)	-0.09	0.50
Gepner,1995	ASD; TD	8.50	0.84	6	8.20	2.90	12	Force platform: Center of pressure	1.36	0.53
Gernsbacher, 2008	ASD; TD	7.92	3.74	172	8.17	3.81	44	Manual motor skills	1.76	0.19
Gidley, 2008	HFASD; TD	11.10	1.60	15	11.70	1.50	10	Reaching adaptation task of force field	0.33	0.40

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Gidley, 2008a	HFASD; TD	10.60	1.70	38	10.50	1.50	37	Non-variable RPM block 1	1.32	0.25
Glazebrook, 2006	ASD; TD	26.90	6.80	9	25.10	5.10	9	OPTOTRAK: Reaction time	1.96	0.51
Glazebrook, 2008	ASD; TD	23.70	7.90	18	20.60	4.50	18	Movement time when the light was near the participant	0.65	0.33
Glazebrook, 2009	ASD; TD	23.40	4.50	9	23.40	3.16	13	OPTOTRAK: Spatial variability	1.18	0.49
Godde, 2018	ASD; TD	26.30	4.60	21	26.60	4.60	21	French adaptation of the Concise Evaluation Scale for Children's Handwriting: Handwriting total quality score	1.57	0.35
Goh, 2018	ASD; TD	24.60	2.78	13	25.50	2.50	13	Force platform: Center of pressure	1.03	0.41
Goulème, 2017	HFASD ; TD	12.10	2.90	30	11,05	0.80	30	Force platform: Surface of center of pressure	1.25	0.28
Gowen, 2005	Asperger; TD	27.42	11.08	12	28.17	11.70	12	Mean force of grip force task	0.40	0.40

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Gowen, 2008	ASD; TD	33.90	13.20	12	32.00	11.80	12	Difference in error plane deviation (biological - non-biological)	0.63	0.40
Grace, 2017	ASD; TD	10.58	1.37	22	10.85	1.01	20	MABC-2: Total score	2.46	0.41
Graham, 2014	ASD; TD	13.00	3.20	26	13.40	1.90	18	Balance: eyes open, double leg stance	0.86	0.31
Green, 2016	ASD; TD	10.57	4.76	56	11.90	5.10	36	Beery-VMI: Total score	0.74	0.22
Hanaie, 2013	ASD; TD	9.82	2.80	13	10.67	1.91	11	MABC-2: total test score	1.15	0.43
Hanaie, 2014	ASD; TD	9.50	2.60	18	10.80	2.10	12	MABC-2: total test score	1.35	0.40
Hannant, 2016	HFASD; TD	9.93	2.71	18	9.16	1.89	18	MABC: Total score	1.49	0.37
Hardan, 2003	ASD; TD	19.30	9.90	40	18.60	8.60	41	Grooved pegboard test: Dominant time	0.87	0.23
Hughes, 1996	ASD; TD	13.42	0.57	36	3.65	0.25	28	Rod task: Underhand score	1.03	0.26

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Isenhower, 2012	ASD; TD	3.94	1.50	7	3.55	11.70	7	Motor coordination: Intra-trial standard deviation of drumming movement periods	1.10	0.54
Jansiewicz, 2006	ASD; TD	11.35	2.47	40	11.60	2.72	55	PANESS: Balance	1.10	0.22
Johnson, 2013	ASD; TD	12.35	0.64	23	11.60	1.58	12	MABC-2: Total motor performance	0.97	0.37
Johnson, 2015	ASD; TD	11.40	1.64	26	10.48	1.52	17	MABC-2: Total motor performance	1.07	0.33
Kaur, 2018	ASD; TD	8.09	0.58	24	7.75	0.55	12	SIPT-BMC: Total score	6.06	0.79
Kohen-Raz, 1992	ASD; TD	6-20	-	92	5-11	-	166	Posutral stability: Stability quotient eyes open	1.04	0.14
Kostrubiec, 2018	HFASD; TD	10.47	1.78	20	11.14	1.82	21	Motor coordination: Absolute error (AE of relative phase)	0.98	0.32
Lee, 2018	ASD; TD	10.60	1.40	18	10.00	2.00	18	MABC-2: Total performance	1.88	0.39
Liu, 2013	ASD; TD	7.96	-	30	7.44	-	30	MABC-2: Overall percentile motor score	2.66	0.35

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Mache, 2016	ASD; TD	9.46	2.50	11	9.35	2.41	11	TGMD-3: Locomotor score	1.61	0.48
MacNeil, 2012	ASD; TD	9.69	1.59	24	10.33	1.40	24	PANESS: Total score	1.60	0.33
Mandelbaum, 2006	ASD; TD	9.00	1.92	74	8.80	0.91	37	PANESS: Gross motor skills	0.04	0.20
Mari, 2003	ASD; TD	10.52	1.51	20	10.44	1.38	20	Reach and grasp: Peak velocity in near distance task	0.38	0.31
Markoulakis, 2012	HFASD; TD	7.00	-	12	7.00	-	12	Motor control: Mean tapping event	-0.03	0.39
McDonald, 2018	ASD; TD	9.48	2.13	33	9.45	2.05	33	Beery VMI: VMI-VI composite score	0.74	0.25
McPhillips, 2014	ASD; TD	9.91	0.65	28	10.03	0.68	28	MABC-2: Total score	0.99	0.28
Memari, 2013	ASD; TD	11.50	1.60	21	11.60	1.90	30	Bertec Force plate: Root mean square	1.25	0.31
Memari, 2014	ASD; TD	11.90	1.60	19	11.80	1.70	28	Bertec force plate: Sway area (difference between groups)	1.36	0.32

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Miller, 2014	ASD; TD	12.60	2.20	20	11.53	2.50	20	Beery-VMI: Total score	1.18	0.34
Minshew, 2004	HFASD; TD	17.00	10.40	79	16.70	10.50	61	PCA-derived equilibrium measure	0.47	0.17
Morris, 2015	ASD; TD	23.60	7.90	12	23.40	5.10	20	Force platform: Center of foot pressure	0.84	0.37
Morrison, 2018	ASD; TD	21.20	4.4	20	24.30	2.80	36	Pegboard Test: Assembly task	1.64	0.32
Mosconi, 2015	ASD; TD	15.00	8.00	28	15.00	7.00	29	Grip force: Accuracy for initial force pulse	0.17	0.26
Mostofsky, 2006	HFASD; TD	10.30	1.70	20	10.50	1.30	36	PANESS: Total score	0.80	0.31
Mostofsky, 2007	HFASD; TD	10.60	1.98	21	10.68	1.61	24	Rraxis examination: Total number of errors	1.62	0.31
Mostofsky, 2009	HFASD; TD	10.90	1.50	12	10.50	1.40	13	PANESS: Total score	1.90	0.47
Nazarali, 2009	ASD; TD	26.20	4.80	12	22.80	3.30	12	Movement planning: Movement time	0.91	0.42

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Noterdaeme, 2002	ASD; TD	10.56	2.50	11	8.08	0.58	11	Neurological examination procedure: Fine motor functions	1.71	0.48
Nyden, 2004	ASD; TD	9.83	2.33	30	12.51	0.58	32	Motor control: Lateral dominance test right hand	0.11	0.26
Oliver, 2014	ASD; TD	12.42	0.45	23	11.42	0.48	22	Beery VMI: Subscore of visuomotor integration	0.44	0.30
Ozonoff, 2008	ASD; TD	10.33	1.75	54	0.83	2.00	24	Mullen: Fine motor score	1.40	0.27
Pan, 2014	HFASD; TD	1.00	0.08	31	14.70	0.59	31	BOT-2: Composite total score	1.59	0.29
Papadopoulos, 2012	ASD; TD	14.58	1.55	53	9.10	1.63	20	MABC: Total score	1.44	0.29
Pasini, 2012	ASD; TD	9.35	0.32	12	9.60	1.6	12	PANESS: Total speed of timed activities	6.33	0.99
Pierno, 2008	HFASD; TD	10.00	0.40	12	11.20	1.22	12	Visuomotor: Movement duration	2.96	0.58

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Price, 2012	Asperger; TD	14.14	4.80	14	14.08	4.61	16	Dean-Woodcock neuropsychology battery: Gross motor composite score	1.54	0.41
Provost, 2007	ASD; TD	2.53	0.38	19	2.52	0.45	18	PDMS-II: Total motor quotient	2.32	0.42
Pusponegoro, 2016	ASD; TD	2.80	-	24	2.90	-	24	Vineland Adaptive Behavior Scales, 2nd edition: Mean gross motor v-scale scores	1.33	0.31
Radonovich, 2013	ASD; TD	8.18	3.40	18	8.31	4.00	28	Force plate: Center of pressure	0.93	0.31
Ravizza, 2013	ASD; TD	14.38	-	22	14.55	-	17	Rhythmic tapping task: Continuation tapping phase	0.47	0.32
Reinert, 2015	ASD; TD	9.20	0.45	4	7.40	2.06	5	BOT-2: Overall score	0.34	0.60
Rinehart, 2006a	ASD; TD	10.05	3.20	24	10.05	-	12	Kinematic movement: Preparation time of level 1: No manipulation of target-side expectancy	0.76	0.36

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Rinehart, 2006b	ASD; TD	12.93	4.15	30	13.10	3.11	21	Motor functioning: movement time duration	0.69	0.29
Riquelme, 2016	HFASD; TD	6.30	3.23	27	6.50	-	30	Purdue Pegboard test: Fine motor dexterity	4.36	0.48
Sachse, 2013	ASD; TD	19.20	5.10	30	19.90	1.00	28	Motor screening test: Latency	0.27	0.26
Sahlander, 2008	Asperger; TD	28.50	5.20	14	19.00	-	28	BOTMP: Balance score	1.02	0.34
Schmitz, 2003	ASD; TD	7.90	1.30	8	6.00	2.21	16	Motor control: Latency of biceps inhibition during voluntary unloading	1.90	0.50
Sharer, 2016	ASD; TD	38.72	18.36	18	36.36	0.08	11	Motor learning: Reaction time	0.20	0.37
Siaperas, 2012	Asperger; TD	10.72	2.55	50	10.84	-	50	MABC-2: Overall score	2.76	0.28
Sigman, 1981	ASD; TD	51.70	0.89	16	24.40	2.91	16	Poor use of object and support	0.91	0.36
Somogyi, 2016	ASD; TD	7.83	-	18	8.08	-	12	Sway area: Virtual Human Interface platform	1.13	0.39

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Soorya, 2004	ASD; TD	6.48	2.67	12	6.30	1.20	12	PANESS: Overall score	1.61	0.46
Stevenson, 2017	ASD; TD	7.98	4.11	13	7.97	2.21	13	Motor skills composite score	2.86	0.55
Stins, 2015	ASD; TD	10.80	1.20	9	10.80	0.95	9	Postural control: Sway path length	0.61	0.46
Stoit, 2013	ASD; TD	11.55	2.88	31	10.52	5.98	29	Grasping task: Movement time of the grip cue	2.91	0.37
Sumner, 2016	ASD; TD	8.65	1.18	30	9.11	0.95	35	MABC-2: Total standard score	1.30	0.27
Takarae, 2008	HFASD; TD	15.25	5.42	36	16.54	5.98	46	Grooved Pegboard test: Dominant hand	1.01	0.23
Thompson, 2017	ASD; TD	26.00	7.00	60	29.00	7.00	60	Purdue Pegboard test: Right, Left, both hands	0.37	0.18
Travers, 2010	ASD; TD	15.10	6.96	67	15.99	2.10	42	Finger tapping score	0.85	0.38
Travers, 2013	ASD; TD	19.00	2.11	15	19.00	3.80	14	Motor learning: Reaction time	0.16	0.28

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Travers, 2015	HFASD; TD	9.63	2.09	21	9.64	6.46	16	Postural control: Group total of sway area	0.39	0.20
Travers, 2018	ASD; TD	21.80	3.20	25	21.30	2.78	26	Postural waver: two feet, eyes open	0.66	0.33
Turner, 2006	ASD; TD	28.10	8.30	8	28.60	0.19	8	Visuomotor coordination: Mean reaction time in Condition B	0.41	0.48
Vanvuchelen, 2007	HFASD; TD	8.75	0.92	17	8.74	0.97	17	MABC: Total score	1.34	0.37
Vlachos, 2007	ASD; TD	10.35	0.23	14	10.42	0.19	14	Postural stability: Maintenance of posture	2.06	0.46
Wadsworth, 2017	HFASD; TD	12.00	2.94	14	12.00	1.63	15	PANESS: Total score	0.26	0.36
Wang, 2015	ASD; TD	12.72	3.64	22	11.67	4.53	21	Natural postural sway	0.99	0.28
Wang, 2016	ASD; TD	8.77	2.64	34	8.76	3.11	25	Force grip task: Force accuracy at primary pulse offset 45% MVC average	-0.37	0.30

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges' g	SE
		Mean age (years)	SD	N	Mean age (years)	SD	N			
Weimer, 2001	Asperger; TD	15.70	3.60	10	15.90	3.80	10	Grooved pegboard test: Total time	0.44	0.43
Whyatt, 2012	ASD; TD	10.03	1.20	18	10.99	3.30	19	MABC-2: Total score	1.13	0.35
Yang, 2014	ASD; TD	7.80	1.40	20	7.90	1.50	20	Beery VMI: Total score	0.57	0.32

Notes. Studies are listed in alphabetical order. HFASD = high functioning Autism Spectrum Disorder. SD = Standard deviation.

SE = Standard Error. Age range is indicated for studies that did not report mean age.

Table 3

Summary of studies included in the fine and gross sensorimotor skills analysis

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Abu-Dahab, 2013	HFASD; TD	Fine	Grooved Pegboard test: Motor coordination	0.81	0.17
Ament, 2015	ASD; TD	Fine	MABC-2: Manual dexterity	1.20	0.20
Beversdorf, 2001	HFASD; TD	Fine	Handwriting size: Vertical extent of each letter	1.39	0.45
Biscaldi, 2014	ASD; TD	Fine	ZNA: Block pegboard	1.11	0.25
Brandes-Aitkens, 2018	ASD; TD	Fine	Visuomotor control (composite score): visuomotor tracking test	0.89	0.34
Brisson, 2012	ASD; TD	Fine	Number of attemps in anticipation of spoon-feeding	0.92	0.39
Campione, 2016	ASD; TD	Fine	Reach time: 3-D optoelectronic SMART system	1.13	0.47
Classen, 2013	ASD; TD	Fine	Beery VMI: Total score	2.35	0.52
Craig, 2018	ASD; TD	Fine	MABC-2: Manual dexterity	1.39	0.23
Crippa, 2013	HFASD; TD	Fine	Eye-hand coordination	4.40	0.69
David, 2009	HFASD; TD	Fine	Reach and grasp task: Grip forces at onset	0.85	0.40
David, 2013	ASD; TD	Fine	Reach and grasp task: Grip forces at onset	0.36	0.27

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Dowd, 2012	HFASD; TD	Fine	Simple movement task with visual distractor: Movement time	0.44	0.41
Dowell, 2009	ASD; TD	Fine	PANESS: Basic motor skills	0.72	0.18
Duffield,2013	ASD; TD	Fine	Motor coordination: Grooved Pegboard test	0.97	0.23
Dyck, 2010	ASD; TD	Fine	McCarron Assessment of Neuromuscular Development: fine motor measure	2.48	0.20
Forti, 2011	ASD; TD	Fine	Infrared motion analysis: Time to reach peak velocity	0.69	0.41
Freitag, 2007	ASD; TD	Fine	Zurich Neuromotor Assessment: Balance score	1.78	0.41
Freitag, 2008	HFASD; TD	Fine	Block component adaptative peg board: Zurich Neuromotor Assessment	5.25	0.77
Fuentes, 2009	ASD; TD	Fine	PANESS: Timed movement	1.03	0.39
Fuentes, 2010	ASD; TD	Fine	PANESS: Timed movement	1.99	0.49
Fukui, 2018	ASD; TD	Fine	Movement duration (blocked: 4 cm: full vision)	2.50	0.53
Fulceri, 2018	ASD; TD	Fine	Asynchrony of reaching: Unclear EP	1.11	0.44
Fulkerson, 1980	ASD; TD	Fine	Beery VMI: Visual-motor integration	0.70	0.37
Gidley, 2008	HFASD; TD	Fine	Reaching adaptation task of force field	0.34	0.40

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Gidley, 2008a	HFASD; TD	Fine	Non-variable RPM block 1	1.34	0.25
Glazebrook, 2006	ASD; TD	Fine	OPTOTRAK: Reaction time	1.25	0.49
Glazebrook, 2008	ASD; TD	Fine	Movement time when the light was near the participant	0.65	0.33
Glazebrook, 2009	ASD; TD	Fine	OPTOTRAK: Spatial variability	2.06	0.52
Godde, 2018	ASD; TD	Fine	French adaptation of the Concise Evaluation Scale for Children's Handwriting: Handwriting total quality score	1.57	0.35
Gowen, 2005	Asperger; TD	Fine	Mean force of grip force task	0.40	0.40
Grace, 2017	ASD; TD	Fine	MABC-2: Manual dexterity	2.46	0.41
Green, 2016	ASD; TD	Fine	Beery-VMI: Total score	0.74	0.22
Hanaie, 2014	ASD; TD	Fine	MABC-2: Manual dexterity	1.15	0.43
Hanaie, 2015	ASD; TD	Fine	MABC-2: Manual dexterity	1.35	0.40
Hannant, 2016	ASD; TD	Fine	Beery VMI: Total score	0.95	0.34
Hardan, 2003	ASD; TD	Fine	Grooved pegboard test: Dominant time	0.87	0.23
Hughes, 1996	ASD; TD	Fine	Rod task: Underhand score	1.03	0.26

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Jansiewicz, 2006	ASD; TD	Fine	PANESS: Repetitive timed movement	1.10	0.22
Johnson, 2013	ASD; TD	Fine	MABC-2: Manual dexterity	0.73	0.36
Johnson, 2015	ASD; TD	Fine	MABC-2: Manual dexterity	0.72	0.32
Lee, 2018	ASD; TD	Fine	MABC-2: Manual dexterity	1.08	0.35
Liu, 2014	ASD; TD	Fine	MABC-2: Manual dexterity	2.66	0.35
MacNeil, 2012	ASD; TD	Fine	PANESS: Timed movement	1.31	0.31
Mandelbaum, 2006	LFASD; TD	Fine	PANESS: Fine motor skills	0.10	0.25
Mari, 2003	ASD; TD	Fine	Reach and grasp: Peak velocity in near distance task	0.38	0.31
McDonald, 2018	ASD; TD	Fine	Beery VMI: VMI-VI composite score:	0,41	0,25
Morrison, 2018	ASD; TD	Fine	Pegboard Test: Assembly task	5.45	0.68
Mosconi, 2015	ASD; TD	Fine	Grip force: Accuracy for initial force pulse	0.51	0.27
Mostofsky, 2009	HFASD; TD	Fine	PANESS: Timed movement	0.29	0.39
Nazarali, 2009	ASD; TD	Fine	Movement planning: Movement time	0.95	0.42
Noterdaeme, 2002	ASD; TD	Fine	Neurological examination procedure: Fine motor functions	1.11	0.44

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Oliver, 2014	ASD; TD	Fine	Beery VMI: Subscore of visuomotor integration	0.44	0.30
Ozonoff, 2008	ASD; TD	Fine	Mullen: Fine motor score	1.40	0.27
Pan, 2014	HFASD; TD	Fine	BOT-2: Fine manual control	1.66	0.29
Papadopoulos, 2012	ASD; TD	Fine	MABC: Manual dexterity	0.96	0.27
Price, 2012	Asperger; TD	Fine	Dean-Woodcock neuropsychology battery: Fine motor measure	1.15	0.39
Provost, 2007	ASD; TD	Fine	PDMS: Fine motor quotient	2.04	0.40
Ravizza, 2013	ASD; TD	Fine	Rhythmic tapping task: Continuation tapping phase	0.47	0.32
Rinehart, 2006a	ASD; TD	Fine	Kinematic movement: Preparation time of level 1: No manipulation of target-side expectancy	0.82	0.30
Rinehart, 2006b	ASD; TD	Fine	Motor functioning: movement time duration	0.69	0.29
Riquelme, 2016	HFASD; TD	Fine	Purdue Pegboard test: Fine motor dexterity	4.36	0.48
Sachse, 2013	ASD; TD	Fine	Motor screening test: Latency	0.27	0.26
Sahlander, 2008	Asperger; TD	Fine	BOTMP: Visuo-motor score	1.02	0.34
Sharer, 2016	ASD; TD	Fine	Motor learning: Reaction time	0.45	0.38

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Siaperas, 2012	Asperger; TD	Fine	MABC-2: Manual dexterity	10.75	0.79
Soorya, 2004	ASD; TD	Fine	BOTMP: visuomotor (copying circle)	1.25	0.43
Stevenson, 2017	ASD; TD	Fine	Motor skills composite score	4.12	0.69
Stoit, 2013	ASD; TD	Fine	Grasping task: Movement time of the grip cue	2.91	0.37
Sumner, 2016	ASD; TD	Fine	VABS: Fine Motor Raw Score	1.48	0.28
Takarae, 2008	HFASD; TD	Fine	Grooved Pegboard test: Dominant hand	1.01	0.23
Thompson, 2017	ASD; TD	Fine	Purdue Pegboard test: Right, Left, both hands	0.40	0.18
Travers, 2010	ASD; TD	Fine	Finger tapping score	0.39	0.20
Travers, 2013	ASD; TD	Fine	Motor learning: Reaction time	0.16	0.28
Turner, 2006	ASD; TD	Fine	Visuomotor coordination: Mean reaction time in Condition B	0.41	0.48
Wadsworth, 2017	HFASD; TD	Fine	Beery-VMI: Total score	0.29	0.36
Wang, 2016	ASD; TD	Fine	Force grip task: Force accuracy at primary pulse offset 45% MVC average	-0.37	0.30
Weimer, 2001	Asperger; TD	Fine	Grooved pegboard test: Total time	0.25	0.43

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Whyatt, 2012	ASD; TD	Fine	MABC-2: Manual dexterity	0.86	0.34
Yang, 2014	ASD; TD	Fine	Beery VMI: Total score	0.57	0.32
Ament, 2015	ASD; TD	Gross	MABC-2: Balance	1.58	0.21
Biscaldi, 2014	ASD; TD	Gross	ZNA: Block dynamic balance	0.89	0.25
Chang, 2010	ASD; TD	Gross	Postural control: magnetic tracking system	0.96	0.34
Chen, 2016	ASD; TD	Gross	Kistler force platform: Magnitude of postural sway:	2.61	0.47
Classen, 2013	ASD; TD	Gross	Balance: one-legged stationary hop	1.35	0.46
Cook, 2013	ASD; TD	Gross	Infrared-based Vicon motion tracking system: Kinematic of the arm movement	4.49	0.69
Cox, 2016	ASD; TD	Gross	Driver guidance system (DGS-78): Composite sample z-score of driving skills	0.91	0.35
Craig, 2018	ASD; TD	Gross	MABC-2: Balance	0.79	0.22
Fitzpatrick, 2017	ASD; TD	Gross	Polhemus Liberty sensors: Bimanual drumming task	0.76	0.21
Fournier, 2010	ASD; TD	Gross	Forceplate Bertec: Dynamic balance	0.84	0.40
Fournier, 2011	ASD ; TD	Gross	Forceplate Bertec: AreaCE95	0.78	0.35
Fournier, 2014	ASD ; TD	Gross	Forceplate Bertec: Center of pressure COP sway	0.82	0.40
Freitag, 2007	ASD; TD	Gross	ZNA: block dynamic balance	1.95	0.42

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Funahashi, 2014	ASD; TD	Gross	Total time needs to complete all the subtest of the STEF	0.24	0.35
Gepner, 2002	ASD; TD	Gross	Center of pressure of postural instability (eyes open) (CP shift)	0.09	0.50
Gepner,1995	ASD; TD	Gross	Force platform: Center of pressure	1.54	0.57
Gernsbacher, 2008	ASD; TD	Gross	Manual motor skills	1.77	0.19
Goh, 2018	ASD; TD	Gross	Force platform: Center of pressure	1.07	0.41
Goulème, 2017	HFASD; TD	Gross	Force platform: Surface of center of pressure	1.28	0.28
Gowen, 2005	ASD; TD	Gross	Balance	2.90	0.58
Gowen, 2008	ASD; TD	Gross	Difference in error plane deviation (biological - non-biological)	0.63	0.40
Grace, 2017	ASD; TD	Gross	MABC-2: Balance	1.13	0.33
Graham, 2014	ASD; TD	Gross	Balance: eyes open, double leg stance	0.88	0.32
Hanaie, 2013	ASD; TD	Gross	MABC-2: Balance	0.59	0.40
Hanaie, 2014	ASD; TD	Gross	MABC-2: Balance	0.81	0.38
Isenhower, 2012	ASD; TD	Gross	Motor coordination: Phase X group interaction (drumming movement)	1.19	0.55

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Jansiewicz, 2006	ASD; TD	Gross	PANESS: Balance	0.54	0.21
Johnson, 2013	ASD; TD	Gross	MABC-2: Balance	0.49	0.35
Johnson, 2015	ASD; TD	Gross	MABC-2: Balance	0.76	0.32
Kaur, 2018	ASD; TD	Gross	SIPT-BMC: Total score	6.48	1.01
Kohen-Raz, 1992	ASD; TD	Gross	Posutral stability: Stability quotient eyes open	1.04	0.14
Kostrubiec, 2018	HFASD; TD	Gross	Motor coordination: Absolute error (AE of relative phase)	1.01	0.33
Lee, 2018	ASD; TD	Gross	MABC-2: Balance	1.25	0.36
Liu, 2013	ASD; TD	Gross	MABC-2: Balance	1.50	0.29
Mache, 2016	ASD; TD	Gross	TGMD-3: Locomotor score	1.61	0.48
Mandelbaum, 2006	ASD; TD	Gross	PANESS: Gross motor skills	0.43	0.20
Memari, 2013	ASD; TD	Gross	Bertec Force plate: Root mean square	1.25	0.31
Memari, 2014	ASD; TD	Gross	Bertec force plate: Sway area (difference between groups)	1.39	0.33
Miller, 2014	ASD; TD	Gross	Homemade questionnaire: Gross motor total score	0.68	0.32
Minshew, 2004	HFASD; TD	Gross	PCA-derived equilibrium measure	0.42	0.17

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Morris, 2015	ASD; TD	Gross	Force platform: Center of foot pressure	0.86	0.37
Mostofsky, 2006	HFASD; TD	Gross	PANESS: Total score	1.62	0.31
Noterdaeme, 2002	ASD; TD	Gross	Standardized neurological examination: Gross motor functions	1.71	0.48
Pan, 2014	HFASD; TD	Gross	BOT-2: Body coordination (composite score)	0.54	0.26
Papadopoulos, 2012	ASD; TD	Gross	MABC: Balance	1.47	0.29
Pasini, 2012	ASD; TD	Gross	PANESS: Total speed of timed activities	6.33	0.99
Pierno, 2008	HFASD; TD	Gross	Visuomotor: Movement duration	3.09	0.60
Price, 2012	Asperger; TD	Gross	Dean-Woodcock neuropsychology battery: Gross motor composite score	1.54	0.41
Provost, 2007	ASD; TD	Gross	PDMS: Gross motor quotient	1.87	0.39
Pusponegoro, 2016	ASD; TD	Gross	Vineland Adaptive Behavior Scales, 2nd edition: Mean gross motor v-scale scores	1.33	0.31
Radonovich, 2013	ASD; TD	Gross	Force plate: Center of pressure	0.93	0.31
Sahlander, 2008	Asperger; TD	Gross	BOTMP: Balance score	0.15	0.32

Author, Year	Diagnostic groups	Sensorimotor categorization of outcome	Type of measure	Hedges' g	Standard Error
Schmitz, 2003	ASD; TD	Gross	Motor control: Latency of biceps inhibition during voluntary unloading	1.90	0.50
Siaperas, 2012	Asperger; TD	Gross	MABC-2: Balance	16.09	1.15
Sigman, 1981	ASD; TD	Gross	Poor use of object and support	0.91	0.36
Somogyi, 2016	ASD; TD	Gross	Sway area: Virtual Human Interface platform	1.13	0.39
Soorya, 2004	ASD; TD	Gross	Balance (Seconds Standing on one leg)	1.65	0.46
Stins, 2015	ASD; TD	Gross	Postural control: Sway path length	0.61	0.46
Sumner, 2016	ASD; TD	Gross	VABS: Gross Motor Raw Score	1.30	0.27
Travers, 2015	HFASD; TD	Gross	Postural control: Group total of sway area	0.88	0.38
Travers, 2018	ASD; TD	Gross	Postural waver: two feet, eyes open	0.66	0.33
Vlachos, 2007	ASD; TD	Gross	Postural stability: Maintenance of posture	2.06	0.46
Wang, 2015	ASD; TD	Gross	Natural postural sway	0.99	0.28
Weimer, 2001	Asperger; TD	Gross	Balance: Combined legs time	0.31	0.43
Whyatt, 2012	ASD; TD	Gross	MABC-2: Balance	0.27	0.32

Notes. Studies are listed in alphabetical order. HFASD = high functioning Autism Spectrum Disorder.

Table 4

Summary of studies included in the gross categories analysis

Author, Year	Sensorimotor category	Hedges' g	Standard Error
Cook, 2013	Arm movement	4.49	0.69
Cox, 2016	Arm movement	0.91	0.35
Fitzpatrick, 2017	Arm movement	0.76	0.21
Gowen, 2008	Arm movement	0.63	0.40
Isenhower, 2012	Arm movement	1.19	0.55
Nazarali, 2009	Arm movement	1.11	0.44
Pierno, 2008	Arm movement	1.54	0.41
Ravizza, 2013	Arm movement	1.02	0.34
Schmitz, 2003	Arm movement	0.45	0.38
Sharer, 2016	Arm movement	16.09	1.15
Stoit, 2013	Arm movement	1.50	0.28
Ament, 2015	Balance	1.58	0.21
Biscaldi, 2014	Balance	1.11	0.25
Chang, 2010	Balance	0.96	0.34
Chen, 2016	Balance	2.61	0.47
Classen, 2013	Balance	1.09	0.45
Craig, 2018	Balance	0.79	0.22
Fournier, 2010	Balance	0.84	0.40

Author, Year	Sensorimotor category	Hedges' g	Standard Error
Fournier, 2011	Balance	0.78	0.35
Fournier, 2014	Balance	0.82	0.40
Freitag, 2007	Balance	1.78	0.41
Gepner, 2002	Balance	0.09	0.50
Gepner,1995	Balance	1.54	0.57
Goh, 2018	Balance	1.07	0.41
Goulème, 2017	Balance	1.28	0.28
Gowen, 2005	Balance	2.90	0.58
Grace, 2017	Balance	1.13	0.33
Graham, 2014	Balance	0.88	0.32
Hanaie, 2013	Balance	0.59	0.40
Hanaie, 2014	Balance	0.81	0.38
Jansiewicz, 2006	Balance	1.10	0.22
Johnson, 2013	Balance	0.49	0.35
Johnson, 2015	Balance	0.76	0.32
Kohen-Raz, 1992	Balance	1.04	0.14
Lee, 2018	Balance	1.25	0.36
Liu, 2013	Balance	1.50	0.29
Mandelbaum, 2006	Balance	0.10	0.25
Memari, 2013	Balance	1.25	0.31

Author, Year	Sensorimotor category	Hedges' g	Standard Error
Memari, 2014	Balance	1.39	0.33
Minshew, 2004	Balance	0.42	0.17
Morris, 2015	Balance	0.86	0.37
Noterdaeme, 2002	Balance	0.54	0.26
Pan, 2014	Balance	1.47	0.29
Papadopoulos, 2012	Balance	3.09	0.60
Radonovich, 2013	Balance	0.47	0.32
Sahlander, 2008	Balance	1.90	0.50
Siaperas, 2012	Balance	1.13	0.39
Somogyi, 2016	Balance	1.65	0.46
Soorya, 2004	Balance	2.91	0.37
Travers, 2013	Balance	2.06	0.46
Vlachos, 2007	Balance	0.99	0.28
Wang, 2015	Balance	0.31	0.43
Weimer, 2001	Balance	0.27	0.32
Whyatt, 2012	Balance	1.62	0.31
Kostrubiec, 2018	Coordination	1.01	0.33
Mostofsky, 2006	Coordination	0.95	0.42

Notes. Studies are listed in alphabetical order.

Table 5

Summary of studies included in the gait analysis

Author, Year	Diagnostic groups	ASD group			TD group			Type of measure	Hedges'g	Standard Error
		Mean age (years)	Standard deviation	N	Mean age (years)	Standard deviation	N			
Calhoun, 2011	Asperger; TD	6.30	-	12	6.20	-	22	Walking speed	-0.54	0.36
Hallett, 1993	ASD; TD	25-38	-	5	25-36	-	5	Gait velocity	0.78	0.60
Lim, 2016	ASD; TD	11.20	2.80	15	11.10	2.90	15	Gait velocity	0.66	0.37
Morrison, 2018	ASD; TD	21.20	4.40	20	24.30	2.80	20	Gait velocity	3.16	0.47
Nobile, 2011	ASD; TD	10.56	2.50	16	9.99	2.28	16	Gait velocity	0.87	0.36
Pauk, 2017	ASD; TD	7.69	2.01	28	8.30	2.10	30	Preferred gait velocity	0.43	0.26
Rinehart, 2006c	ASD; TD	10.67	0.90	20	10.73	3.37	10	Gait velocity	0.17	0.38
Rinehart, 2006d	ASD; TD	5.10	3.23	11	5.90	3.60	11	Gait velocity	0.26	0.41
Vernazza-Martin, 2005	ASD; TD	4-6	-	9	4-6	-	6	Gait velocity	0.00	0.50
Weiss, 2013	ASD; TD	19.00	16-22	9	19.50	0.50	10	Gait velocity	1.48	0.50

Notes. Studies are listed in alphabetical order. Age range is indicated for studies that did not report mean age.

APPENDIX 2. Summary of studies included in the age analysis

Table 6

Summary of studies included in the age analysis

Author, Year	Type of Group	ASD group			Type of measure	Correlation (Pearson)	Confidence Interval	
		Mean Age (years)	Age Range	N				
Godde, 2018	ASD	26.30	18-35	21	Correlation between chronological age and overall visuomotor integration score	0.23	-0.22	0.02
Mostofsky, 2006	HFASD	10.30	8-12	20	Correlation between age and total error on praxis examination	0.62	0.14	1.09
Ravizza, 2013	ASD	14.38	12-17	22	Correlation between age and tapping error	0.38	-0.07	0.83
Wang, 2016	ASD	12.72	5-15	22	Correlation between standard deviation of static stance and age	0.29	-0.16	0.74
Wang, 2015	ASD	8.77	7-18	34	Correlation between age and Type 1 initial pulses used for the 2-s test at both 45% and 85% MVCs	0.40	0.05	0.75

Notes. Studies are listed in alphabetical order. HFASD = high functioning Autism Spectrum Disorder.

APPENDIX 3. Summary of studies included in the clinical severity analysis

Table 7

Summary of studies included in the clinical severity analysis

Author, Year	Diagnostic group	ASD group			Type of measure	Clinical severity tool	Correlation (Pearson)	Confidence Interval	
		Mean age (years)	Age Range	N					
Cox, 2016	ASD	18.28	15-23	16	Driving performance: braking skills reaction time	SRS-2 (total score)	0.83	0.29	1.37
Craig, 2018	ASD	4.60	3-6	46	MABC-2: Total score	SCQ (total score)	0.50	0.20	0.80
Dowell, 2009	ASD	10.26	8-13	87	Postural control	ADOS-G (total score)	-0.65	-0.86	-0.44
Dziuk,2007	HFASD	10.70	8-14	47	Praxis examination: Total errors	ADOS-G (total score)	-0.63	-0.93	-0.33
Fulceri, 2015	ASD	4.04	2.5-5	35	PDMS: Total motor quotient	ADOS-G (total score)	0.14	-0.20	0.49
Fulceri, 2018	ASD	7.82	5-10	11	Asynchrony of reaching	ADOS-G (total score)	-0.38	-1.07	0.31
Graham, 2014	ASD	13.00	7-17.8	26	Balance: eyes open, double leg stance	ADOS (subtotal social score)	-0.61	-1.02	-0.21
Green, 2016	ASD	10.57	3-26	56	Beery VMI: total score	SRS (total score)	0.13	-0.14	0.40

Author, Year	Diagnostic group	ASD group			Type of measure	Clinical severity tool	Correlation (Pearson)	Confidence Interval	
		Mean age (years)	Age Range	N					
Hannant, 2016	HFASD	9.93	7-16	18	MABC: total score	ADOS-2 (total score)	-0.77	-1.286	-0.26
Holloway, 2018	ASD	4.67	4.5-6.7	21	PDMS: Gross motor quotient	CARS (social skills)	0.76	0.30	1.23
Kaur, 2018	ASD	8.09	5-12	24	Praxis errors: total score	ADOS-2 (total score)	-0.71	-1.14	-0.28
Lee, 2018	ASD	10.60	8-12	18	MABC-2: Total score	SCQ (total score)	-0.71	-1.22	-0.20
Memari, 2013	ASD	11.50	9-14	21	Postural control: Total root mean square	ATEC (total score)	-0.47	-0.93	-0.01
Mosconi, 2015	ASD	15.00	5-35	24	Reach and Grasp: Increasing of force	ADOS (subtotal social score)	-0.44	-0.86	-0.01
Travers, 2010	ASD	15.10	5-33	60	Finger tapping score	SRS (total score)	-0.60	-0.86	0.34
Travers, 2018	ASD	21.80	16-28	25	Postural waver: standing eyes open	SRS (total score)	0.23	-0.18	-0.65
Wang, 2016	ASD	8.77	5-15	22	Postural control: Static stance	ADI-R (social score)	-0.09	-0.53	0.36
Zachor, 2010	ASD	3.33	2.67-4.25	25	PDMS: gross motor skills	ADOS (total score)	0.12	-0.30	0.53

Notes. Studies are listed in alphabetical order. HFASD = high functioning Autism Spectrum Disorder.

SRS = Social Responsiveness Scale, Second version; ADOS-G = Autism Diagnostic Observation Schedule - Generic; ADOS = Autism Diagnostic Observation Schedule; ADOS-2 = Autism Diagnostic Observation Scale, Second version; ADI-R = Autism Diagnostic Interview – Revised; CARS = Childhood Autism Rating Scale; SCQ = Social and Communication Questionnaire; ATEC = Autism Treatment Evaluation Checklist