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Inhibitory control and math abilities in autism spectrum disorder and typical development

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Inhibitory control and Math Abilities in autism spectrum disorder

Summary

1 Introduction

1.1 Autism spectrum disorder

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by deficits in social communication and interaction, restricted or repetitive patterns of behavior, interests, or activities, and functional impairments (American Psychiatric Association, 2013), irrespective of culture, race, ethnicity, or socioeconomic group. Although individuals with ASD are very different from one another, these core symptoms could impact functioning across personal, social, and occupational contexts and typically persist across the lifespan (Bieleninik et al., 2017; Marriage et al., 2009). Approximately 1 in 100 children are diagnosed with ASD around the world, with prevalence estimates increasing over time and varying greatly within and across sociodemographic groups; the median male-to-female ratio was around 4.2 (see Zeidan et al., 2022 for a review). The median male-to-female ratio was 4.2. In Italy, a study conducted by Narzisi and co-authors (2020) reveals that one child out of 87 residing within the Province of Pisa (Italy) in 2016 had a DSM-5 diagnosis of ASD.

1.1.1 Etiological factors

ASD is a complex disorder characterized by a significant heterogeneity in etiology and its phenotypic expression. The etiology of ASD is likely to be multifaceted, involving a combination of genetic and environmental factors (Lord et al., 2018). Genetic predisposition plays a significant role in ASD, supported by twin studies that show a high concordance rate of 70-90% among identical twins and a much lower rate of 0-10% among fraternal twins (Wells et al., 2000). In families with a history of ASD, there is a tendency for the disorder to cluster within the family, and younger siblings, especially males, have an increased risk of developing ASD (Higgins et al., 2003). Recent research suggests that genetic factors may explain 35% to 40% of autism cases. In around 20-25% of children or adults with ASD, specific genetic causes can be identified, including de novo mutations, common and rare genetic variations, and common genetic polymorphisms associated with ASD (Halmayer et al., 2011). However, the remaining 60-65% of cases are believed to result from various non-genetic factors, such as prenatal, perinatal, and postnatal environmental influences (Gardener et al., 2011; Tchaconas & Adesman, 2013). These environmental factors could encompass parental age, the nutritional and metabolic status of the mother, infections during pregnancy, prenatal stress, and exposure to specific toxins, heavy metals, or drugs (Wang et al., 2017). While many researchers accept this neurobiological understanding of ASD, there is a growing trend towards a biopsychosocial model that places greater emphasis on how social factors influence an individual's functioning and overall well-being. In this approach, core features of ASD are seen as a manifestation of neurodiversity and the challenges faced by individuals with ASD are not solely attributed to their individual deficits but are considered a result of a mismatch between their unique characteristics and the demands imposed on them by their environment (Greaves-Lord et al., 2022).

1.1.2 Core features

ASD is also characterized by significant heterogeneity in its phenotypic expression and developmental trajectories, as well as varying levels of overall functioning. The term "spectrum" is used precisely to indicate the marked variability in the presentation and severity of symptoms, which can manifest in a wide range of combinations, from mild to severe. This heterogeneity is significantly influenced by the presence of co-occurring medical, developmental, psychiatric, or behavioral conditions. In the developmental age, 95% of children with ASD exhibit at least one co-occurring condition or symptom (Soke et al., 2018). Among these, intellectual disability (ID) is frequent (estimated in up to approximately 45% of cases), sleep disturbances (with a reported prevalence between 50% and 80%), epilepsy or epileptiform abnormalities (5-38%), attention deficit/hyperactivity disorder (28-44%), gastrointestinal disorders (about 47%), atypical motor development (about 30%), and anxiety disorders (11-84%; Failla et al., 2021). Taking into account the high heterogeneity of ASD, the Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) proposed a dimensional approach to this diagnosis, with symptoms that can vary along a continuum, from very mild to severe impairments. In addition, DSM-5 mentions only the single category of ASD, which incorporates the previous subtypes of autistic disorder (AD), pervasive developmental disorders (PDD), Asperger's syndrome (AS), whereas Rett's disorder is no longer included (American Psychiatric Association, 2013). In the DSM-5, the triad of symptoms of the DSM-IV-TR has been merged into two areas of deficit: impairments in social interaction and communication are subsumed into the first area of social communication, whereas the second domain consists of restricted and repetitive behaviors and interests. Specifically, the first domain concerns persistent impairment in social communication and social interaction across multiple contexts. It includes deficit in socioemotional reciprocity (e.g., abnormal social approach or difficulties in back-and-forth conversation; reduced sharing of interests, emotions, or affect), impairment in non-verbal communicative behaviors (e.g., poorly integrated verbal and non-verbal communication, atypical eye contact and body language, or deficits in understanding and use of gestures) and deficits in developing, maintaining, and understanding relationships (e.g., difficulties adjusting behaviors to suit various social contexts or difficulties in sharing imaginative play or making friends) (Lord et al., 2018). The second area involved restricted and repetitive behaviors (RRBs) that can be divided into low-order and high-order behaviors: the first behaviors include stereotyped and repetitive movements and sensory preoccupation (e.g., simple motor stereotypies, lining up toys, or flipping objects), whereas the second ones include preoccupation, circumscribed interests, compulsive behaviors and adherence to routines (Faja & Darling 2019; Mosconi et al., 2009). Importantly, DSM-5 also highlighted the atypical sensorial processing in individuals with ASD, which could include hyper-reactivity or hypo-reactivity to sensory input or unusual interests in sensory aspects of the environment (e.g., apparent indifference to pain or temperature, or adverse responses to specific sounds or textures) (Lord et al., 2018).

The two areas of criticality related to social communication and restricted and repetitive behaviors are also highlighted in the International Classification of Diseases, 11th Revision (ICD-11), with some significant differences compared to the diagnostic manual DSM-5. In ICD-11, it is acknowledged that some individuals with ASD may not show evident social challenges and distress in childhood, as their ability to adapt to various contexts requires exceptional effort. The core features of ASD may only become fully apparent in adolescence or adulthood when social demands surpass their capacities. As a result, ASD can be clinically evident at any age (Greaves-Lord et al., 2022).

ICD-11 has aimed to address the perceived insensitivity of the DSM-5 criteria towards adolescents and adults without intellectual disability. It achieves this by broadening the diagnostic criteria and introducing concepts like 'Lack of adaptability to new experiences and circumstances,' while reducing the emphasis on criteria associated with Intellectual Developmental Disorders (such as repetitive object-related behaviors, strong attachment to unusual objects, excessive smelling or touching of objects, echolalia, and stimming). ICD-11 further distinguishes between ASD with and without intellectual disability and impairment of functional language as distinct sub-diagnoses with different diagnostic codes (Silleresi et al., 2020). In addition, the DSM-5 includes a section on differential diagnosis, implying the possibility of confusing ASD with other conditions like selective mutism or ADHD; instead, ICD-11 takes a different approach by recognizing that these conditions can often co-occur, and it places them in a section labeled 'Boundaries with Other Disorders and Conditions.' The guidelines in ICD-11 provide more detailed information than DSM-5 regarding the differentiation of conditions that may present with ASD-like characteristics. The new approach proposed by ICD-11 highlights the importance of better understanding the features associated with autism, even in children, adolescents, and adults who do not have cognitive disabilities, but whose difficulties imply a significant effort to adapt to social contexts (Greaves-Lord et al., 2022).

1.1.3 Cognitive accounts

Since the 1980s, the identification of deficits associated with ASD is becoming increasingly important to implement effective interventions aimed at improving quality of life. It has been proposed that multiple cognitive difficulties are relevant to ASD and that they may have distinct interactions with different core symptoms (Happè & Ronald, 2008; Happè & Frith, 2006). The three cognitive accounts of ASD that have received the most attention are Theory of Mind (ToM; e.g., Baron Cohen et al., 1985), weak central coherence (Frith, 1989), and executive function (EF; e.g., Ozonoff et al., 1991; Pennington et al., 1997). In the following paragraphs, the theory of mind and the theory of weak central coherence will be briefly described. Subsequently, the focus will shift to executive function, which will be one of the main topics of this dissertation. The decision to focus on executive function arises from specific reasons. In recent years, there has been a shift in the perspective on executive function in atypical development (Demetriou et al., 2019). Impairments in these processes are no longer viewed as core deficits of a specific clinical condition but are seen to play a transdiagnostic role, i.e., transversal to various neurodevelopmental disorders, thus leading to new studies also in the field of autism (Zelazo, 2020; Demetriou et al., 2019). However, the data are still heterogeneous, especially regarding the dimension of inhibitory control and need further investigation (Geurts et al., 2014). Furthermore, it has been decided to investigate more deeply executive function because it plays a significant role in mathematics learning (Cragg et al., 2017; Spiegel et al., 2021), which is another topic of focus in the current dissertation.

1.1.3.1 Theory of Mind

The Theory of Mind (ToM) represents the ability to infer the mental states of other people and to utilize this information for predicting their behaviors (Baron Cohen et al., 1985). Over the years, scholars argued that ToM deficits were prevalent in autism, with substantial empirical evidence supporting these ToM impairments in individuals with ASD, as they generally performed lower on assessment tasks compared to their neurotypical peers (Kimhi, 2014). However, performance on ToM assessments varied, and a crucial factor influencing this variability was the specific ToM component evaluated and the type of task employed (Rosello et al., 2020). Current research has supported the division of ToM into implicit and explicit components, capturing distinct aspects of social stimulus processing (Frith and Frith, 2012). Explicit ToM skills involved conceptual, logical, and controlled knowledge of ToM, characterized by sequential and conscious processing (Satpute & Liberman, 2006; Frith & Frith, 2012). Tasks with clear instructions, like classic first- and second-order false beliefs, exemplified procedures for assessing this explicit component. On the other hand, the implicit

ToM component operated spontaneously and unconsciously, enabling accurate anticipation of behavior without deliberate reflection on the other person's mental state. Interestingly, individuals with ASD and strong verbal skills may have succeeded in false belief tasks or more advanced explicit ToM tasks (Boucher, 2012; Rosello et al., 2020). However, they often struggled with comprehending other mental processes in daily life, where social interactions were rapid, requiring an intuitive understanding and, thus, an implicit ToM (Senju et al., 2009).

1.1.3.2 Weak central coherence

People with ASD may also display weak central coherence, with a detail-focused processing style and a relative failure to extract global information (Frith & Happé, 1994). The weak central coherence theory is based on two fundamental ideas. First, the individuals with ASD tend to naturally focus on the specific details of information rather than the overall picture; second, they struggle to integrate these detailed elements into meaningful representations (Frith, 1989). Various studies have supported this theory, encompassing visuospatial and linguistic tasks in children with ASD. For instance, in visuospatial tasks like the Children's Embedded Figures Test (CEFT), children with ASD have generally outperformed typically developing children, demonstrating superior performance in tasks such as identifying a hidden figure within a global meaningful picture (Jarrold et al., 2005; Keehn et al., 2009). In linguistic tasks, children with ASD have encountered difficulties in global processing and have exhibited a preference for local processing. They have also demonstrated a higher incidence of errors in tasks that require the use of context in sentence completion (Booth & Happé, 2010; Burnette et al., 2005). Despite these findings, recent research has indicated that not all tasks demonstrate context insensitivity or weak global processing in individuals with ASD (López & Leekam, 2003). Factors such as language skills and task instructions have been identified as significant influencers of global or contextual processing (Vanegas & Davidson, 2015). Furthermore, there exists variability in central coherence profiles across different tasks and domains. Some individuals with ASD exhibit stronger local processing and weaker global processing in both visuospatial and linguistic domains, while others display this pattern in only one of the domains (Loth et al., 2008).

1.2 Executive function

Executive Function (EF) encompasses a set of high-order cognitive processes necessary for planning, performing, and monitoring goal-directed actions in novel and complex situations where automatized strategies may be insufficient or inappropriate (Diamond, 2013; Friedman & Miyake, 2017). The preschool and school periods are considered critical for EF acquisition and improvement, with sensitivity to early experiences (Müller et al., 2013). The organization of EF has been a major theoretical issue. Initial models conceptualized EF as a unitary higher-order cognitive construct, where it functions as a central entity regulating lower-level cognitive processes, adhering to a hierarchical organizational structure of the cognitive system (Goldberg & Bilder, 1987). In this framework, Norman and Shallice (1986) introduced the idea of a Supervisory Attentional System (SAS), strategically allocating attention to oversee cognitive processes. Similarly, Baddeley (1996) proposed the concept of a central executive, coordinating underlying cognitive processes. However, the consensus in the literature has leaned towards a multidimensional model of EF, seen as a set of highly correlated but distinct dimensions (Miyake & Friedman, 2012; Zelazo et al., 2016). In this regard, the most recognized model is that of Miyake and colleagues (2000), identifying three correlated but separable EF components: updating, inhibition or inhibitory control (IC), and cognitive flexibility. These components support higher-order cognitive processes such as planning and problem-solving (Collins & Koechlin, 2012).

It is crucial to note that the organization of EF changes during the course of development. In young children, EF is a relatively undifferentiated and unitary construct (Wiebe et al., 2011), with early signs of differentiation emerging from 5 to 7 years of age (Lonigan et al., 2016; Miller et al., 2012; Usai et al., 2014). Longitudinal studies, such as Usai et al. (2014), suggest that a two-factor structure is more suitable for 5- and 6-year-old children, with IC distinguished from working memory

(WM) and shifting emerging as a unitary component. Finally, literature suggests that the adult three-factor model could be reached from 8 to 13 years, attaining a degree of stability by the age of 15 (e.g., Lee et al., 2013).

Regarding atypical development, Zelazo (2020) highlighted that difficulties in EF serve as transdiagnostic indicators of a wide range of conditions with childhood or youth onset, including learning difficulties and learning disorders (e.g., Toll et al., 2011), and other neurodevelopmental disorders such as attention deficit hyperactivity disorder and autism (e.g., Petrovic & Castellanos, 2016). In the field of autism, the wealth of empirical findings linking EF with the broader ASD phenotype supports its potential as an endophenotype (Demetriou et al., 2019). Endophenotypes, or intermediate phenotypes, are characteristics that present vulnerabilities in a particular population, linking genes, brain processes, and observed behavior (Nyden et al., 2011; Rommelse et al., 2011). Endophenotypes may encompass neurocognitive functions, making EF a likely candidate (Demetriou et al., 2019). Since 1980s executive function has long been a topic of interest, given its proposed role in contributing to specific impairments in ASD in the area of social cognition, restricted and repetitive behavior patterns, academic achievement as well as broader impacts on quality of life (Demetriou et al., 2018). EF impairment typically manifests perseverative responses, inflexibility in applying social rules or adapting behavior according to social demands (Geurts et al., 2009); moreover, a lack of generativity could limit one’s ability to generate ideas relevant to the context in conversation with others, resulting in communication impairment (Bishop & Norbury, 2005). There is accumulating evidence of the important contribution of early individual differences in EF in shaping autistic children’s developmental trajectories. Variation in children’s EF correlates with their ASD features, suggesting that EF can be considered a source of the heterogeneity in functional outcomes of autism (Pellicano, 2012), including repetitive behaviors (Mosconi et al., 2009, Pellicano, 2013, Turner, 1997) and social competence (Berger et al., 2003; Munson et al., 2008; Pellicano, 2013). Longitudinal studies have reported evidence for associations between individuals’ early EF and their adaptive functions measured over ten years later (Kenny et al., 2019; Pellicano et al., 2017), suggesting that people with ASD with strong EF abilities may be better able to use compensatory strategy across development (Johnson, 2012).

EF impairment in autism was confirmed by several meta-analyses, some of which focused on all EF dimensions (Demetriou et al., 2018; Lai et al., 2017) while others focused on a specific EF dimension (Wang et al., 2017 for working memory; Leung & Zakzanis, 2014 for cognitive flexibility; Geurts et al., 2014 for IC). However, some studies presented mixed results about the relationship between EF and ASD (Adams & Jarrold, 2012; Gardiner et al., 2017), particularly in the field of inhibitory control (Geurts et al., 2014).

1.3 Inhibitory control

Inhibitory control (IC) is an early component of executive function that allows controlling one's mental processes and responses, ignoring an internal or external prompt, and stopping or performing an alternative action (Diamond, 2013). The term inhibitory control can be considered a synonymous with the general term "inhibition" frequently used in the literature and is adopted in a broader perspective to refer to a complex and multidimensional construct that encompasses various types of inhibition (e.g., Best & Miller, 2010; Diamond, 2013). In fact, a key point in the research on IC concerns the idea that it may be better conceptualized as a set of correlated dimensions than as a unitary construct (Dempster, 1992; Nigg, 2000). Specifically, authors hypothesized the existence of diverse types of inhibition (Diamond, 2013; Harnishfeger, 1995; Nigg, 2000; Nigg, 2017), and recent studies confirmed this idea empirically (Rey-Mermet et al., 2018; Stahl et al., 2014). A review by Nigg (2000) suggested that executive or effortful inhibition can be differentiated from motivational inhibition (i.e., inhibition of behavior as a result of fear/anxiety related to the presence of punishment-related cues in the environment) and automatic inhibition (i.e., unintentional inhibition of select attentional processes that occurs as a result of the execution of a prior cognitive process or behavioral responses). Effortful inhibition included four different types of inhibition: interference control (i.e., the ability to filter our competing information), cognitive inhibition (i.e., the ability to suppress irrelevant thoughts to preserve other cognitive processes, such as working memory), behavioral inhibition (i.e., the ability to suppress a prepotent but socially inappropriate response) and oculomotor inhibition (i.e., the ability to suppress a reflexive saccade). Friedman and Miyake (2004) postulated and tested a factorial model distinguishing three forms of inhibition, namely the inhibition of prepotent responses (i.e., the ability to suppress dominant responses), the resistance to distracter interference (i.e., the ability to ignore distracting information), and the resistance to proactive interference (i.e., the ability to resist memory intrusions from information that was previously relevant to the task but has since become irrelevant). Using a structural equation modeling (SEM) approach, they found that inhibition of prepotent responses and resistance to distracter interference were very closely correlated. In contrast, Stahl and coauthors (2014) found empirical support for the separability of the three forms of inhibition (i.e., inhibition of prepotent response, resistance to distracter interference, and resistance to proactive interference). Using a different battery of tasks chosen to reduce the correlation between prepotent response inhibition and distracter interference factors, Rey-Mermet and coauthors (2018) identified a two-factor model for response inhibition and interference control as the best-fitting model to explain the observed data in young and old adults; the same bi-factorial structure was also found in preschool children aged 36–48 months (Gandolfi et al., 2014).

Response inhibition tasks (e.g., Go/No-go, Day-Night Stroop, Luria's Hand Game, Opposite Words, etc.) are intended to create a conflict between the habitual and the less prepotent dominant response. For example, they could be univalent tasks that require solving the conflict at response-level, choosing between two response options to the same stimulus (e.g., in the Day-Night Stroop, participants are presented with a picture of a moon and they are instructed to give the less prepotent verbal response saying "day" and not "night"). Response inhibition is also necessary for those tasks that require the participants to slow down their response (e.g., in the Circle Drawing task, in which the child is asked to trace a circle as slowly as possible). Instead, interference control tasks (e.g., Flanker task, Dots or Simon task) require the ability to prevent interference due to stimulus competition; these tasks generally involve stimuli with both relevant and irrelevant features and require solving the conflict at the stimulus level, filtering out the interfering but irrelevant information (e.g., in the Flanker task, participants have to identify the direction of a target stimulus ignoring distractors) (Bunge et al., 2002; Gandolfi et al., 2014).

Both response inhibition and interference control are essential for efficient functioning in everyday life and play an important role in a wide range of domains, such as self-regulation (Oeri et al., 2018) or school achievement (Clark et al., 2010). For example, in a school setting, children have to adapt their behavior to school demands: they are required to perform alternative behaviors, select and implement the correct strategies, ignoring sources of distraction (Ursache et al., 2011).

IC is also related to other important cognitive processes, in particular, working memory (WM) which is a limited capacity system that can hold in mind, manipulate and update relevant information; in fact, IC contributes to restrict access into WM to relevant information deleting input that is no longer appropriate and stopping dominant but inappropriate responses (Traverso et al., 2020). IC was also associated with verbal abilities such as vocabulary (Petersen et al., 2015) or sentence production (Cozzani et al., 2013). Thus, in the assessment of IC, it is also important to take into account other cognitive processes, such as WM or children's verbal ability (Whedon et al., 2020).

IC is crucial not only for investigating individual differences in typical development but also for advancing our knowledge of inhibitory processes in atypical development. Inhibitory impairments have been observed in several clinical populations, such as obsessive-compulsive disorders (Mancini et al., 2018), substance use disorders (Smith et al., 2014), genetic syndromes, such as Down Syndrome (Fontana et al., 2021; Traverso et al., 2018), and other neurodevelopmental disorders, including attention deficit hyperactivity disorder (Bonham et al., 2021), and autism spectrum disorder (Demetriou et al., 2018; Geurts et al., 2014).

1.4 Inhibitory control in autism spectrum disorder

Recent evidence suggested that IC difficulties contributed to different ASD features, in both the domain of social communication (Carlson & Moses, 2001; Shiri et al., 2018) and repetitive behaviors (Faja & Darling, 2019; Mosconi et al., 2009; Schmitt et al., 2017). This highlights the need for a deeper understanding of inhibitory processes in autism, and other variables that may play a moderating role in the differences between participants with ASD and those with typical development (TD). A recent meta-analysis, conducted by Demetriou et al. (2018), compared groups with ASD and TD on different direct measures of EF and found that individuals with ASD showed lower performance, with a moderate effect size, on EF tasks and inhibitory measures. It is also worth mentioning that, in the aforementioned meta-analysis, the authors considered IC as a unitary dimension, while Geurts and colleagues (2014) conducted two separate meta-analyses subdividing response inhibition and interference control within IC. Specifically, these authors reviewed 41 articles including ASD and TD groups that were published before June 2013, confirming an impaired performance in individuals with ASD, with a small effect in interference control, and with a medium effect in response inhibition; however, when directly compared, these two effects were not statistically different from each other. On the other hand, inconsistent findings on this issue have been repeatedly observed, with some studies showing no evidence of an inhibitory deficit in ASD (e.g., Boland et al., 2019; Boxhoorn et al., 2018; Sivaratnam et al., 2018), while others show the opposite (e.g., Brady et al., 2017; Golshan et al., 2019; Hopkins et al., 2017; Leno et al., 2018).

1.4.1 Inhibitory control dimensions in autism spectrum disorder

The discrepancies in the results could be, at least in part, due to the specificities of IC. A key aspect concerns the multi-componential structure of IC (Gandolfi et al., 2014; Rey-Mermet et al., 2017), which has not always been considered in the extant literature. Inhibitory difficulties in ASD might vary depending on the IC dimension considered, with important differences between response inhibition and interference control tasks. However, this aspect is still under debate, with some studies suggesting a selective inhibitory deficit in participants with ASD (Adams & Jarrold, 2012; Christ et al., 2007; Faja et al., 2016), and others indicating a similar impairment on both the IC dimensions (e.g., Agam et al., 2010; Geurts et al., 2014; Weismer et al., 2018). Adopting a multi-componential approach could also be helpful to better understand the role of potential moderators related to the characteristics of the participants, such as age or IQ, which might differentially affect response inhibition and interference control.

1.4.2 Sample-related characteristics

Inconsistent findings in the literature on inhibitory processes in ASD could probably be attributed to several sources of heterogeneity across studies. Sample-related characteristics represent relevant sources of variability. Specifically, the heterogeneity in intellectual functioning between people with ASD may result in either ceiling or floor effects and lead to misleading findings (Garon et al., 2018). Geurts and co-authors (2014) found that the IQ score of participants with ASD moderated the differences between ASD and TD for interference control, but not for response inhibition, with a higher IQ corresponding to a decrease in interference control differences between groups. Concerning age effects, a poorer performance of participants with ASD was found in studies with both children and adults (Agam et al., 2010; Mosconi et al., 2009; Solomon et al., 2014). However, the role of age-related changes in ASD is still far from clear, also because of the lack of longitudinal data (Demetriou et al., 2018). Some studies suggested a stronger deficit in ASD during adolescence and adulthood relative to childhood (Adams & Jarrold, 2012). Conversely, a cross sectional study conducted by Christ (2007) and the meta-analysis by Geurts and co-authors (2014) found a decrease in the difference of performance between people with ASD versus TD as age increased (i.e., older ASD participants performed better as compared to younger children). It is also worth mentioning that, although recent literature has highlighted the importance of IC in pre-schoolers with ASD (Garon et al., 2018), previous meta-analyses did not consider this age group. It is therefore worth evaluating these effects in this particular group.

Another relevant aspect concerns the comorbidity of ASD and ADHD (Corbett & Constantine, 2006; Yerys et al., 2009). Between 28% to 44% of children with ASD also present with a diagnosis of ADHD in comorbidity (Failla et al., 2021). Based on the observation that ADHD is a neurodevelopmental disorder characterized by impairments in EF, and, in particular, in IC, it is possible to hypothesize that in some studies reporting significant differences in IC, a subsample of these children also presented with ADHD symptoms, and this could explain, at least in part, current impairments in IC (Wallace et al., 2016). Previous meta-analyses did not investigate the possible moderating effect of ADHD (Demetriou et al., 2018; Geurts et al., 2014), which therefore needs to be further explored.

1.4.3 Measures-related characteristics

Results could also vary depending on task characteristics, such as the format of presentation (non-computerized vs. computerized tasks), abilities required by the task (verbal vs. motor abilities) or indices considered (accuracy vs. reaction time). Previous meta-analyses selected one index for each task, considering RT or accuracy scores together in the same analysis (Geurts et al., 2014) or included only accuracy, neglecting other indices (Demetriou et al., 2018). It is worth noting, however, that in tasks such as Flanker or Stroop, the interference scores for both accuracy and reaction time (RT) are not necessarily equivalent and could provide a different set of information (Magnus et al., 2019).

Sources of variability could also be found in the adopted measures: previous meta-analyses (i.e., Demetriou et al., 2018; Geurts et al., 2014) have mainly focused on direct measures, while IC has also been assessed by indirect measures, such as parental reports (e.g., Faja & Dawson, 2015; Filipe et al., 2020; Gardiner & Iarrocci, 2018). Direct measures generally involve neuropsychological or experimental tasks, while indirect measures typically include questionnaires, usually completed by different informants such as parents or teachers or the participant himself (Toplak et al., 2013). Several studies (Biederman et al., 2008; Gomez-Perez et al., 2016; Toplak, 2013) revealed significant discrepancies between direct and indirect measures of assessment. They are different in terms of method of administration. Compared to neuropsychological task, in fact, questionnaires are easier to administer and offer a cost-effective approach to identify difficulties (Toplak et al., 2013). In addition, they may also differ in terms of what specific aspects of EF they evaluate (Biederman et al., 2008; Gomez-Perez et al., 2016). Indirect measures are intended to provide an ecological measure of IC, assessed in complex and everyday situations (Toplak et a., 2013). IC difficulties in ASD could be clearer in real-life and less structured situations, in which interpersonal and problem-solving skills are also required (Gomez-Perez et al., 2016). Instead, direct assessment is generally conducted in standardized conditions, that may facilitate the performance of ASD participants.

Concerning psychometrics properties, most direct measures tend to have lower test-retest reliability (coefficients below .8 or even lower) (Friedman & Myake, 2004; Wöstmann et al., 2013) while the reliability of indirect measures tends to be higher (e.g., the Behavior Rating Inventory of Executive Function-Second Edition parent forms revealed coefficients ranging from .76 to .97, with index and composite scores ranging from .90 to .97) (Hendrickson & McCrimmon, 2019). Direct measures could possibly reflect additional error variance or variance influenced by state factors, rather than indexing trait factors. On the other hand, the use questionnaires might present with some problems (e.g., personal judgements of parents or teachers could somehow affect the results) (e.g., Sachse & Von Suchodoletz, 2008) and direct assessment provides more precisely estimate inhibitory process efficiency (Toplak, 2013) with computerized tasks that also offer a precise reaction time estimation. All these aspects suggest that direct and indirect measures, despite being correlated, should not be considered equivalent.

1.4.4 Stimuli processing and working memory demands in inhibitory measures

In addition to the variables described in the previous paragraphs, inhibitory difficulties in autism may be, at least in part, a consequence of impairment in other cognitive processes. Specifically, it is possible that impairment in EF tasks could be related to difficulties in stimuli processing (Gordon et al., 2018; Simpson & Riggs, 2006), defined as the efficiency of cognitive mechanisms in processing and responding to stimuli within a specific task environment (Shanahan et al., 2006). However, the literature on a stimuli processing deficit in autism is still controversial (Zapparrata et al., 2022). Some studies supported the generalized slowing hypothesis, according to which individuals with ASD exhibit longer mean reaction times across a range of tasks as compared to age-matched TD group (Haigh et al., 2018; Roberts et al., 2011), as well as less automaticity in processing information (Hogan-Brown et al., 2014). In this regard, a recent meta-analysis conducted by Zapparrata and coauthors (2022) found ASD groups exhibited significantly longer mean reaction times than the comparison group; this difference was found in very basic tasks requiring the participants to respond to a stimulus by pressing a button (simple reaction times tasks) or execute a forced-choice response to a specified target stimulus, choosing from two or more relatively simple alternatives (choice reaction times tasks). Stimulus type and age did not moderate the results of their meta-analysis. Starting from these findings, the authors suggested that a generalized slowing may be a domain-general characteristic of ASD. Another view was proposed by Minshew and coauthors (Minshew & Goldstein, 1998; Minshew et al., 1997) who proposed a neurobehavioral model, according to which ASD is seen as a disorder of complex information processing systems. According to this view, autism is characterized with difficulties in higher-order skills that required the integration of different cognitive processes (Minshew & Goldstein, 1998). Thus, a slowing in stimuli processing may be evident only in complex tasks (Damarla et al., 2010). In a similar vein, it is possible that inhibitory difficulties may be due to the level of complexity of the task; in fact, there are some IC tasks that required the integration of multiple cognitive processes and, in particular, place high demands on WM. In fact, performance on inhibitory tasks may be influenced by working memory capacity, that is especially required to hold the rules in mind (e.g., Luria's Hand Game) or keep in mind the target stimulus while exploring the alternatives (e.g., Matching Familiar Figures Task). It was suggested that the hardest inhibitory tasks were those that involve a combination of IC and working memory (Carlson et al., 2005) and this can be even more true for individuals with ASD, who can show WM deficit (Wang et al., 2017).

In summary, to date it is not clear if ASD is characterized by an inhibitory impairment and which sources of heterogeneity can significantly impact the performance on IC tasks. Probably due to these inconsistencies, the association between IC and other important outcomes, such as school achievement, are poorly investigated in the ASD population, although it is well-recognized that EF is crucial for academic skills.

1.5 Inhibitory control and math abilities

Research has established that EF plays a fundamental role in the acquisition of academic skills (Blair, 2002), especially for math learning (Blair et al., 2008). Previous studies have repeatedly shown that EF is linked to math skills, such as basic number knowledge, calculation, spatial skills, and mathematical reasoning, across various age groups (see e.g., Best et al., 2011; Cragg et al., 2017; Emslander & Scherer, 2022; Friso-van den Bos et al., 2013; Peng et al., 2016).

Concerning inhibitory control, most studies have adopted correlational methods to investigate the association between performance on IC measures and concurrent mathematics achievement. For example, children's performance on experimental IC tasks is related to their preschool (see Allan et al., 2014 for a review) and school mathematics grades (Brock et al. 2009; Visu-Petra et al. 2011) as well as performance on standardized mathematics tests (Nayfield et al. 2013; St Clair-Thompson & Gathercole, 2006). A relatively smaller number of studies have found that IC predicted future success in mathematics (Blair & Razza, 2007; Swanson, 2011); for example, Clark, Pritchard, and Woodward (2010) found that individual differences in IC at age 4 were predictive of individual differences in mathematics achievement at age 6. Converging evidence for this association comes also from studies that have compared the inhibitory skills in children with and without learning differences (Szucs et al., 2013; Winegar, 2013) finding that children with identified mathematical learning difficulties performed more poorly on inhibition tasks than children with average performance in mathematics.

In examining the relationship between inhibitory control and mathematics, it is of fundamental importance to also take into account the role of other dimensions related to executive function, especially working memory (Cragg et al., 2017; Spiegel et al., 2021; Traverso et al., 2021). As previously mentioned (paragraph 1.2), developmental studies on executive functions show that starting from the age of five, it is possible to distinguish the dimension of inhibitory control from that of working memory, although they are closely correlated (e.g., Usai et al., 2014); this allows for the analysis of the contribution of a specific dimension of executive function, controlling for the effect of the others. This is particularly important, especially in light of the fact that, overall, working memory is more strongly related to math achievement than inhibitory control or shifting (Cortès Pascual et al., 2019; Cragg et al., 2017; Spiegel et al., 2021). In this regard, the meta-analytic path analyses conducted by Spiegel and coauthors (2021) indicated that, after accounting for the effects of the other EF components, weaker relations between EF and math abilities were found than those obtained considering only the bivariate association between a single EF and math abilities. Importantly, the authors showed that, although the size of the relationships between specific EF components and math skills were reduced when controlling for the others EF, all components of EF remained uniquely predictive of all math abilities in a large sample of children in kindergarten through sixth grade (Spiegel et al., 2021). Their results showed that both inhibitory control and working memory were uniquely related to word problems, math fluency, and calculation, whereas shifting was not uniquely related to math fluency. The results of the chi-square difference tests indicated that in the overall sample WM was more strongly related to word problem solving and calculation than was inhibitory control, suggesting the importance of considering inhibitory control and working memory simultaneously when studying their contribution to math abilities.

In line with this perspective, in the following paragraph, a multi-componential model proposed by Cragg and coauthors (2017) was described as an integrative framework to consider specific association between EF dimension and distinct math abilities.

1.6 Integrative framework: specific math abilities, inhibitory control and working memory

In their multi-componential framework, Cragg and co-authors (2017) demonstrated that in school-aged students the contribution of each EF component varied according to the kind of knowledge required in the math tasks. The authors distinguished three types of math knowledge: factual knowledge, procedural knowledge and conceptual knowledge. Both working memory and IC were associated with factual knowledge, that is the ability to retrieve arithmetic facts from long-term memory; in fact, WM activates information in long-term memory (Unsworth & Engle, 2007) and IC may be necessary to suppress competing responses in arithmetic fact retrieval (for example, while retrieving the answer 6 in response to 3 x 2, children had to suppress 5 as the solution to 3 + 2) (Usai et al., 2018).

Procedural skills (i.e., the ability to both know which procedure to follow and complete the appropriate steps to arrive at the correct answer, for example in resolving arithmetic word problems or mental calculations) were also predicted by both IC and WM. This result was in line with the evidence that executive control is necessary to select and apply the correct procedure in different contexts and identify multiple strategies to solve the same problem or calculation (Rittle-Johnson, 2017). For example, IC and WM could assist children in using a problem model strategy, based on a mental representation of the problem, instead of a direct translation strategy, mainly focused on data and key terms reported in the text of the problem (Hegarty et al., 1995). Also, WM seems to play a key role in using arithmetic procedures, as suggested by experimental dual-task studies which have found that procedural strategies are impaired by a concurrent high cognitive load (Hubber et al., 2014).

Relatively little empirical work has investigated the role of EF in conceptual understanding (i.e., the understanding of conceptual principles underlying arithmetic). Robinson and Dubé (2013) found that 8-10-year-old children with poorer inhibitory control were less likely to use a conceptually-based shortcut than children with good inhibitory control when presented with problems where such a strategy was possible. They suggested that this may be because the children found it difficult to inhibit well-learned procedural algorithms. However, Cragg and co-authors (2017) found only an association between verbal working memory and conceptual knowledge, while the predicted relationship between IC and conceptual understanding was not found. This may be because the study used a task that required participants to apply conceptual knowledge that they already have. It may be that suppressing procedural strategies and rearranging problems into different formats to identify conceptual relationships are more important when conceptual information is being learned rather than once it has been acquired (Cragg et al., 2017).

In summary, these findings begin to help us to understand the mechanisms by which EF supports math achievement in typical development. However, these mechanisms in atypical development, and in particular in children with ASD, remained unexplored.

1.7 Math abilities in autism spectrum disorder

A significant group of students with ASD do not have concurrent ID but often face difficulties in reaching their full potential without adequate support in educational settings (Dowker, 2020). Understanding the academic strengths and weaknesses of individuals with ASD is crucial in education. However, this area of research is still not fully developed, and particularly research on math achievement in individuals with ASD is limited, resulting in a gap in evidence-based mathematics interventions for these students (Fleury et al., 2014). This is a critical issue because math and STEM disciplines in general have significant impacts on academic and career opportunities (Jordan et al., 2009). This research gap may be due to the idea that individuals with ASD have exceptional mathematical abilities, which is also supported by the "male brain theory", that suggests a preference for rule-based fields such as mathematics (Baron-Cohen et al., 2002). However, greater mathematical proficiency in autism seems to be mostly anecdotal and descriptive (Baron-Cohen et al., 2007). Only a limited number of people with ASD exhibit superior mathematical abilities (Chiang & Lin, 2007; Heavey, 2003; Hermelin & O’Connor, 1991) and mathematical difficulties seem to be commoner in individuals with ASD. Mayes and Calhoun (2006) found that 23 % of autistic children had a mathematical learning disability, which is about four times the rate found in typical developing children. Chiang and Lin (2007) reviewed 18 studies of mathematical performance in 837 individuals between 3 and 51 years, diagnosed with average or above average intellectual functioning (participants with high-functioning autism or Asperger syndrome). The majority performed at an average level on general mathematics tests but show difficulties in math abilities that require complex skills and abstract reasoning.

1.7.1 Potential moderators of math achievement in autism

Studies on math achievement in autism are limited and often provide inconsistent results (Chiang & Lin, 2007; Dowker, 2020). Titeca and coauthors (2014) have found a similar math performance of the ASD group with the comparison group; some studies have suggested better mathematical abilities in students with ASD (Iuculano et al., 2014, 2020), while other studies have shown the opposite results (Bae et al., 2015; Bullen et al., 2020).

Several factors may have contributed to these findings. First, the math domain that is measured may affect the results. Children with ASD may excel in rote arithmetic facts and procedural knowledge, but they may face challenges in more complex abilities, such as solving word problems or equations (Kim & Cameron, 2016). Reviews of the literature (Dowker, 2020; Whitby & Mancil, 2009) and recent studies (e.g., Bullen et al., 2020; Wei et al., 2015) show that students with ASD perform worse on problem-solving tasks than on computation tasks. Although following logical procedures is often considered a strength for students with ASD, understanding the content and selecting the appropriate strategy to solve mathematical word problems may be considerably more challenging (Cox & Root, 2020; Root et al., 2017).

Other measures-related characteristics may influence performance. For instance, math tasks can be presented in oral or written formats. Given that students with ASD may struggle with oral comprehension and fine motor skills (Fuentes et al. 2009; Mody et al., 2013), their math performance may vary according to the type of stimuli used (i.e., written or oral). However, this issue remains underexplored and only a limited number of studies suggested that difficulties in graphomotor skills negatively influenced the performance on written math tasks in students with ASD (Mayes & Calhoun, 2007; Assouline et al., 2012).

Characteristics of participants may account for inconsistent findings on math achievement in students with ASD. Regarding the role of age, math difficulties in individuals with ASD may not become apparent until abstract and conceptual learning tasks are introduced (Kim & Cameron, 2016). Students with ASD may progress adequately in primary school but often fall behind their peers in middle and high school, when mathematical reasoning and problem-solving skills are emphasized. However, there is limited longitudinal research on this topic (Titeca et al., 2014; Wei et al., 2015).

Among the typically developing, intellectual functioning has repeatedly been shown to be both a concurrent and predictive correlate of mathematics achievement in samples of different ages (e.g., Nogues & Vargas Dorneles, 2021). Instead, the relationship between intelligence and mathematics achievement in students with ASD is less clear. Previous research has identified full-scale IQ as a predictor of calculation and problem solving abilities in individuals with ASD without intellectual disability (Mayes & Calhoun, 2008; Oswald et al., 2016). Specifically, perceptual reasoning is found to be a unique predictor of math achievement in TD populations (Taub et al., 2008), and similar results have been found in a study with students with ASD in which perceptual reasoning was the strongest predictor of math achievement (Mayes & Calhoun, 2008). Verbal ability is also critical for math achievement, especially for solving arithmetic word problems that require reading or oral comprehension (Bullen et al., 2020; Oswald et al., 2016).

1.8 Math abilities, inhibitory control and working memory in autism spectrum disorder

In addition to intellectual functioning, recent studies and reviews (Dowker, 2020; Wang et al., 2022) suggested that impairments in EF may affect mathematics achievement in autism. However, the literature is very limited.

Despite the extensive literature on WM and math skills in TD children (Cragg et al., 2017; Caviola et al., 2020; Hubber et al., 2014), relatively little is known about this relationship in autism (Bullen et al., 2020; Hiniker et al., 2016; Iuculano et al., 2020; Oswald et al., 2016; St. John et al., 2018). Previous meta-analyses have shown that, in general, people with ASD can display deficits in working memory (Habib et al., 2019; Wang et al., 2017). Some studies have suggested that WM impairments, especially in the verbal and central components, plays a fundamental role in predicting mathematics performance in ASD, both in computation and problem-solving tasks (Bullen et al., 2020; Chen et al., 2019). Interestingly, Wang and coauthors (2022) suggested that WM impairment in preschool may represent the main cause of later math difficulties in autism, suggesting that strong early WM may help children with ASD catch up with their peers in math. Differently, a measure of response inhibition (i.e., Day/Night Stroop) was not a significant predictor of early math abilities in this sample of pre-schoolers. Also, in a study conducted by Polo-Blanco and co-authors (2022) with older children, inhibition was not a significant predictor of math problem solving when the entire sample of participants with ASD was considered. However, poorer performers (i.e., children who obtained ≤ 25% correct answers) showed lower scores in inhibition, theory of mind and verbal comprehension. Interestingly, the authors also found a connection between the degree of abstraction employed in their strategies during the resolution of math problem and three cognitive factors: inhibition, cognitive flexibility, and theory of mind. Surprisingly, this correlation was found only in the sample of children with ASD and absent among the non-ASD group. Notably, both studies used a response inhibition measure, while to our knowledge, no previous study investigated the effect of interference control on math abilities in participants with ASD, although previous research have suggested that the ability to filter out distractors may be more related to mathematical learning (Passolunghi & Siegel, 2001; Traverso et al., 2019). In conclusion, a detailed investigation of the contribution of specific cognitive processes to different math knowledge in students with ASD is needed.

1.9 Aims of the present dissertation

The general aim of the present dissertation is to investigate inhibitory processes and math abilities in people with ASD, as compared to TD participants. Understanding the cognitive and academic strengths and weaknesses of students with ASD is crucial for education, quality of life and future outcomes. However, these areas of research are still not fully developed, particularly in the field of executive function. Research on inhibitory control in autism has reported conflicting results, and the sources of this heterogeneity are not yet understood.

Therefore, the aim of the first study of this dissertation was to conduct a meta-analysis including previous studies that have investigated inhibitory processes in autism spectrum disorder, as compared to TD participants. Specifically, this meta-analysis aimed to estimate potential differences between the two groups in inhibitory processes and better understand the significant moderating roles of various sources of heterogeneity. Both measures and participant characteristics were analyzed as possible moderators (see Chapter 2 for more details).

Recently, attention on academic outcomes has also been increasing, but many questions remain open. In particular, research on math achievement in students with ASD is limited and has reported inconsistent results, leading to a gap in evidence-based mathematics interventions. Therefore, the second study of this dissertation focused on previous literature about math abilities in participants with ASD, adopting a meta-analytic approach to estimate potential differences and identify moderating variables (Chapter 3).

In the third study of this dissertation, both inhibitory processes and math abilities were investigated in a sample of participants with ASD and a comparison TD group. The first part of the study examined inhibitory processes in detail, considering both response inhibition and interference control measures. Additionally, the study explored the role of possible mediators in explaining differences between groups, such as basic cognitive processes and working memory. The second part of the study compared the two groups on different math tasks, assessing specific types of math knowledge. Furthermore, the study investigated the unique contribution of cognitive predictors (vocabulary, response inhibition, interference control, verbal and visuospatial working memory) to specific math abilities and explored whether the association between cognitive predictors and specific math abilities varied between the group with ASD and the TD group (Chapter 4). Each study will be described in detail in the following chapters.

2 Inhibitory Control in Autism spectrum disorder: Meta-Analyses on Indirect and Direct Measures [1]

Abstract

This chapter aimed to advance our understanding of inhibitory control in autism spectrum disorder (ASD), adopting a meta-analytic multilevel approach. The first meta-analysis, on 164 studies adopting direct measures, indicated a significant small-to-medium (g=0.484) deficit in the group with ASD (n=5,140) compared with controls (n=6,075). Similar effect sizes between response inhibition and interference control were found, but they were differentially affected by intellectual functioning and age. The second meta-analysis, on 24 studies using indirect measures, revealed a large deficit (g=1.334) in the group with ASD (n=985) compared with controls (n=1,300). Presentation format, intellectual functioning, and age were significant moderators. The effect of comorbidity with ADHD was not statistically significant. Implications are discussed for IC research and practice in autism.

2.1 Research aims

Our meta-analysis aimed to advance our understanding on inhibitory processes in individuals with ASD, considering different sources of variability (by including different types of measure, multiple tasks in a single study, and both accuracy and reaction time indices). As evidenced in the introduction, different studies on IC in autism included different subsamples of participants, and frequently used different measures of IC (e.g., utilizing direct or indirect measures or recording accuracy and/or reaction times) (Demetriou et al., 2017; Christ et al., 2011; Geurts et al., 2014). Due to this complexity, a comprehensive understanding of inhibitory processes in ASD is extremely difficult to achieve. For all these reasons, and also to increase the statistical power of the analyses and to produce better estimates of the variability of the effects, in this paper we decided to implement a

[1] Tonizzi, I., Giofrè, D., & Usai, M. C. (2021). Inhibitory control in autism spectrum disorder: meta-analyses on indirect and direct measures. *Journal of Autism and Developmental Disorders.* https://doi.org/10.1007/s10803-021-05353-6

multilevel approach, which takes into account all of the effects in a single model (Borenstein et al., 2017). To obtain more precise and reliable estimates of the effect and of the heterogeneity across studies, we also decided to take a more rigorous statistical approach.

For a start, we conducted a meta-analysis investigating whether participants with ASD showed impairments in IC, assessed with direct measures. Consistent with previous reports (Geurts et al., 2014), we hypothesized a significant positive effect size, indicating significant inhibitory difficulties in ASD, as compared to controls. Given the multi-dimensional structure of IC, we also analysed whether the type of IC dimension (response inhibition vs. interference control) moderated the effect size. It is possible to hypothesize that response inhibition and interference control are similarly impaired in ASD, as found in Geurts et al. (2014), and the inclusion of a large number of studies would probably help to obtain a more precise estimation of this effect. Specifically, following Geurts et al. (2014) we conducted two separate analyses for the type of IC dimension, considering the Stroop task as an indicator of response inhibition or of interference control. In particular, a body of literature, following Friedman & Miyake's taxonomy (2004), considers the Stroop to be a measure of response inhibition (see Gandolfi et al., 2014; Mead et al., 2002; Traverso et al., 2020; Usai et al., 2020), while another, following Nigg's taxonomy (2000), considers this task to be a measure of interference control.

We aimed to conduct a systematic analysis of moderators related to sample characteristics: linear effects of age and IQ, matching for IQ or age, comorbidity with ADHD. We also aimed to investigate the role of potential moderators, related to the characteristics of the measures. Several task-related moderators were explored: format of presentation (computerized vs. non-computerized tasks), type of response (verbal vs. motor), and type of index (accuracy vs. RTs). We expected that format presentation (computerized vs. non-computerized tasks) could moderate the differences between people with ASD and controls (Dichter & Belger, 2007; Nakahachi et al., 2006; Ozonoff, 1995). Regarding the type of index, it is possible to hypothesize that the group with ASD would have similar impairments in both accuracy and RT, or alternatively that the effect size for RT would be significantly higher in response inhibition measures, as compared to RT (Geurts et al., 2014). In our moderator analyses, we also investigated resulting differences between unstandardized (experimental tasks) and standardized measures, as this aspect had not been previously investigated. Thus, in the first meta-analysis, focused on inhibitory processes assessed with direct measures, we tried to answer to the following questions:

2a. Considering studies included in the meta-analysis, is there a difference between the group with ASD and a TD comparison group in inhibitory processes assessed with direct measures?

2b. Does the type of IC dimension (response inhibition vs. interference control) moderated the difference between the two groups in direct inhibitory measures?

2c. Are there characteristics of the participants that moderated the difference between the two groups in direct inhibitory measures?

2d. Are there characteristics of the tasks that moderated the difference between the two groups in direct inhibitory measures?

Moreover, as IC is commonly assessed with indirect and direct measures and previous literature has suggested discrepancies between them (Biederman et al., 2008; Gomez-Perez et al., 2016; Gonzalez-Barrero & Nadig, 2019), we decided to conduct a second meta-analysis on indirect measures. We hypothesized that the method of assessment would be a significant moderator, and that the heterogeneity between studies would decrease after distinguishing among direct and indirect measures. In particular, given the difficulties faced by people with ASD in everyday life, we expected higher differences in indirect measures as compared to the direct ones (Gomez-Perez et al., 2016; Frith & Frith, 2012; Senju, 2012). Sample-related moderators were also investigated in indirect measures because, to the best of our knowledge, these have hardly been evaluated in the current literature. Thus, in the second meta-analysis, focused on inhibitory processes assessed with indirect measures, we tried to answer to the following questions:

2e. Is there a difference in the performance of the group with ASD, compared with a TD group, in inhibitory processes assessed with indirect measures? Is this eventual difference larger than the difference found considering direct measures?

2f. Are there characteristics of the participants that moderated the difference between the two groups in indirect inhibitory measures?

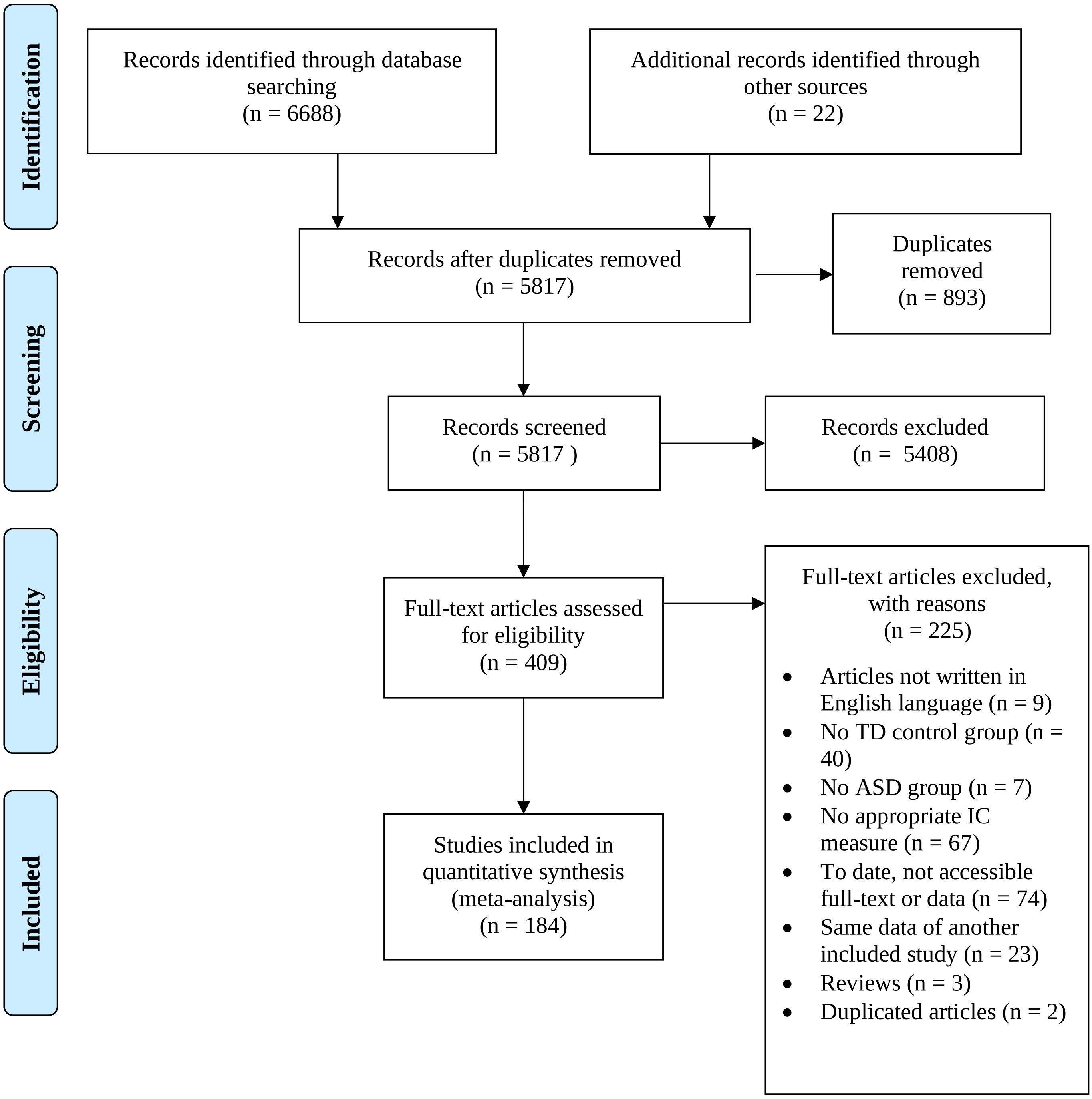
2.2 Method

In accordance with the PRISMA statement (Moher et al., 2009), we used a systematic search strategy to identify the relevant studies. Specifically, studies were selected in three phases. A flow chart illustrating the search process and the identification of included studies is shown in Figure 2.1.

2.2.1 First phase: literature search

In the first phase, relevant studies were identified through searches of the databases PsycINFO, PubMed and ProQuest, using keywords for IC and autism. We included not only published journal articles, but also book chapters and unpublished dissertations (the so-called grey literature), to cope with the effects of publication bias. Our search required that studies reported at least one of the following IC keywords: inhibition, inhibitory control, interference, response inhibition, executive function, executive functions, executive attention, executive control, cognitive control, effortful control. Studies also had to encompass one of the following keywords regarding the condition of autism: autism, autistic, ASD, autism spectrum disorder, Asperger, pervasive disorder. We limited our results by publication year, considering only studies published between January 1990 and January 2020. Next, we hand-searched citations in previous relevant reviews (see Figure 2.1 for further details).

Figure 2.1. PRISMA Flow chart illustrating the identification of included studies.



2.2.2 Second phase: title-abstract screening

In the second phase, references were imported from Endnote into Rayyan QCRI, a systematic reviews web application, for title-abstract screening. The records were included according to the following criteria:

1. studies were written in English and published from January 1990 to January 2020;
2. a group of participants with ASD was included. All participants with ASD met diagnostic criteria according to the DSM-III-R, DSM-IV, DSM-5, ICD-10 or ICD-11;
3. a typically developing (TD) control group was included;
4. at least one inhibition indirect or direct measure was used (i.e., questionnaires or behavioral tasks). In this phase, we also included abstracts in which unspecified EF measures were mentioned.

If the abstracts did not provide enough information to determine inclusion or exclusion, references were included in the third phase for full text screening.

2.2.3 Third phase: full text screening

The third phase resulted in 184 articles that met the eligibility criteria. We retrieved the full text of the included references and examined papers according to the eligibility criteria. We then included another inclusion criterion: we only included studies reporting at least one measure of IC. Regarding indirect measures, we only included questionnaires or subscale focusing on IC; for example, for the Behavior Rating Inventory of Executive Function (BRIEF, Gioia et al., 2000) only the performance on the Inhibit subscale was included. Concerning direct measures, we included IC experimental and standardized tasks, but also tasks typically used in eye tracking or brain imaging literature.

The exclusion criteria were the following:

1. studies not written in English;
2. studies without a group of participants with ASD diagnosis, excluding studies with participants having only autistic traits;

3. studies without a TD group, excluding studies with control groups composed of other disorders or siblings of ASD participants. Differently from Demetriou et al. (2018) we excluded studies with siblings as control groups due to the relative recurrence risk in autism (Hansen et al., 2019);
4. studies that only used tasks mainly assessing working memory or flexibility, such as the Wisconsin card sorting task. We excluded studies that did not report adequate indices for IC tasks (for example, studies that only reported RT for congruent or neutral condition in Stroop task). Studies whose IC measure showed a claimed ceiling or floor effect were not included;
5. in case of duplicated studies: we selected the article with the more comprehensive battery of tests;
6. studies with not accessible data or pdf: the corresponding author was contacted and the paper included if available.

2.2.4 Inclusion coding

A consensus coding dataset was created for extracting relevant information from the included studies, with the following variables: authors, publication year, demographics, sample sizes, ASD diagnostic criteria and instruments, IQ measures and mean scores, IQ and age match for the ASD and the TD groups, name of IC measure, type of IC measure (direct vs. indirect), type of index (accuracy vs. RT) and name of index, format presentation (computerized vs. non-computerized) and type of response required (computerized vs. non-computerized tasks). We also coded type of IC task according to the according to Friedman and Miyake (2004) classification, categorized task as response inhibition or interference control measure. We coded as response inhibition those measures (e.g., Go/No-go, Stop Signal, Luria's Hand Game, Opposite Words etc.) that create a conflict between the habitual and the less prepotent dominant response; they are generally univalent tasks requiring to solve the conflict at response-level, choosing between two response options to the same stimulus. Instead, we coded as interference control measure those tasks (e.g., Flanker task, Dots or Simon Task) in which complex stimuli with both relevant and irrelevant features are shown; the conflict is at stimulus-level and requires to inhibit the interfering information (for example, in the Flanker task, participants have to identify the direction of a target stimulus ignoring distractors) (Bunge et al., 2002; Gandolfi et al., 2014).

Concerning IQ measures, we coded the names and the mean scores of all standardized IQ measures used by the studies included in the meta-analysis (different editions of the Wechsler Intelligence Scale for Children (WISC), Wechsler Adult Intelligence Scale (WAIS), Wechsler Abbreviated Scale Intelligence (WASI), Leiter International Performance Scale, Raven Matrix, Differential Ability Scales (DAS) etc.). Where available, scores for both FIQ, VIQ, and PIQ have been encoded. If the IQ measures focused on only visuospatial reasoning, as the case of Raven Matrix, we coded the data as PIQ.

2.2.5 Inter-rater reliability

The inter-rater reliability was calculated for the second and the third phase. To this end, two authors independently double-screened 25% of both the abstracts (1454) and the full-texts (102). The percentage of agreement was 96.29% and 95.10% for the abstracts and the full-text, respectively. All disagreements were resolved by discussion.

2.2.6 Analytic strategy

Analyses were conducted following the guidelines provided by Borenstein et al. (2009). We performed all the analyses using the R software (version 4.0.3), with the *Metafor* package (Viechtbauer, 2010). To compare between-group performance (ASD vs. TD mean on inhibitory measure) for each inhibition measure, we calculated Hedges' *g* (using the *escalc* function in the *Metafor* package), which is similar to Cohen`s *d* but removes most of the bias contained in the estimation of the *d* (Borenstein & Hedge, 2019). A positive effect size indicated a better performance of the TD group than the ASD group, while a negative effect size indicated a poorer performance of the TD group. We adopted a random effects model to account for the expected variability between studies; in fact, this model assumes that the true effect size varies across studies, depending on some moderators concerning method and sample characteristics.

Random effect models are encouraged and suggested as they perform better under a series of circumstances, as effects are more generalizable and estimates less influenced by extreme studies (Borenstein, 2009).

As there were samples with multiple tasks, we applied several strategies to deal with the dependency of effect sizes. A multi-level model to meta-analysis was implemented. This approach is preferable as compared to traditional approaches as designs tend to have one level of nesting (Borenstein & Hedge, 2019). This statistical approach allowed us not to reduce the number of effect sizes, to preserve all relevant information and achieve the maximum statistical power by extracting information from all relevant effect sizes. To this end, we used the rma.mv function included in the *Metafor* package (Viechtbauer, 2015). Two levels of nesting were hypothesized, sample and task: this is traditionally known as the two-level design, in which tasks are nested within samples. To address the dependency of various measures within the same sample, variances for each study were calculated assuming that effects within each sample were correlated: this was performed using the "impute_covariance_matrix" command in the *clubSandwich* package (Pustejovsky, 2020; see also Borenstein et al., 2009 for the statistical rationale). We also employed the "robust.rma.mv" function of the *sandwich package,* which computes cluster-robust standard errors for multi-variate meta-analysis, even in cases in which covariance estimates are somewhat biased (Hedges, Tipton, & Johnson, 2010).

The heterogeneity across effect sizes was estimated using three statics: *Q*, tau squared (τ^2), and I^2 (Borenstein et al., 2009). *Q* is defined as the ratio of observed variation to within study error; if the *Q* statistic provides a significance test, it indicates that the observed range of effect sizes is larger than would be expected from considering only the within-study variance. As for the I^2, this is usually used to quantify the amount of dispersion (heterogeneity), with values of 25%, 50%, and 75%, traditionally interpreted as representing small, moderate, and high levels of heterogeneity (Deeks et al., 2008). However, this measure presents a series of shortcomings (e.g., tends to provide information about the proportion of the variance due to variation in real effects rather than sampling error) and other measures such as Tau (τ) or Tau squared (τ^2) tend to perform better and should be preferred (Borenstein et al., 2017). Tau-squared is used to assign weights under the random-effects model and indicates the variance of the true effect sizes (with Tau corresponding to the standard deviation), reflecting the absolute amount of variation expressed in the same metric as the effect size itself. In the multilevel case, when multiple sources of variations are available, tau and tau-square values are replaced by sigma (σ) values, a more precise estimate of each source of variability that is equivalent to the tau (Borenstein et al., 2017).

Significance of the moderators was tested using meta-regression with random effects (Borenstein, 2009). To assess for the presence of publication bias, funnel plots and the trim and fill method were used (Borenstein et al., 2009; Duval, 2005). In the funnel plots, a lower precision of the studies would be reflected in the greater dispersion of the values at the bottom of the plot. The symmetrical distribution of the studies around the mean effect size would indicate the absence of publication bias. On the contrary, the presence of publication bias could be identified if the symmetry was evident only at the top of the graph, with more studies missing toward the bottom; in addition, the direction of the effect toward the right, with a gap of studies in the left part of the graph, could indicate missing non-significant studies (Sterne, Becker, & Egger, 2005). The "trim-and-fill" method (Duval, 2005) was used to impute potentially missing studies and estimate the summary effect size, correcting for the asymmetry observed in the funnel plot. It is worth noting that this method cannot be used in the multilevel models and therefore was applied to the funnel plot using the traditional random model.

2.2.7 Preliminary checks

We carried out a qualitative check to the dataset: some observation presented with clear anomalies (e.g., standard deviations of zero, problems with the sign of the effects, and other problems). In these cases, we decided to write to the corresponding author asking to provide additional information; in the absence of any reply, we decided to prudentially exclude these data from the analyses (about 3% of the effects). Thus, 181 studies with 300 effects were included in the statistical analyses. Also, indirect and direct measures revealed extremely large and significant differences in the effect size and in the estimation of heterogeneity. Therefore, we preferred to conduct two separate meta-analyses; the first meta-analysis included only indirect measures (questionnaires) and the second meta-analysis included only direct measures (experimental tasks and psychometric tests).

2.3 Results

2.3.1 Inhibitory control effects for direct measures (research question 2a)

For the first meta-analysis, we selected studies that used direct inhibition measures. In Table A1 (in the Appendix section) we reported the main features of the included studies. Across the 164 studies, an estimated total of 11,215 participants (5,140 with ASD) were included. The group with ASD had a mean chronological age of 14.26 years (*SD* = 10.23) and a mean Full IQ of 101.59 (*SD* = 10.63).

A significant effect size was estimated, $k = 274$, $g = 0.484$ [0.419, 0.549], $p < .001$, $\sigma_1^2 = .008$, $\sigma_2^2 = .143$ suggesting that people with ASD had in general a small-to-medium inhibitory deficit. The *Q* statistic indicated significant heterogeneity among the studies, $Q(273) = 1058.897$, $p < .001$, and the I^2 index of 74.2% indicated a large heterogeneity (Higgins et al., 2003). The forest plot for these analyses is shown in Figure A1.

2.3.2 Inhibitory dimensions in Autism spectrum disorder (research question 2b)

We explored inhibition (response inhibition vs. interference control) as a moderator. Following Geurts et al. (2014), we first categorized inhibition tasks according to Friedman and Miyake (2004), considering the Stroop task as response inhibition task. Inhibition type was not a significant moderator, $k = 272$, $Q_M = 0.009$, $B = -0.011$, $p = .923$, $\sigma_1^2 = .094$, $\sigma_2^2 = .065$ suggesting that there was no significant difference between the two dimensions of inhibition, with very small effects in terms of the effect size. For both response inhibition and interference control, a significant small-to-medium effect size was estimated, with nearly identical estimates across the two IC dimensions, and intervals largely overlapping (for response inhibition, $k = 247$, $g = 0.493$ [0.423, 0.563], $p < .001$, $\sigma_1^2 = .112$, $\sigma_2^2 = .040$; while for interference control $k = 25$, $g = 0.436$ [0.128, 0.743], $p = .006$, $\sigma_1^2 = .350$, $\sigma_2^2 < .001$), suggesting that people with ASD had in general a small-to-medium inhibitory deficit both in controlling impulsive behaviours and in filtering distracting stimuli. The same analyses were conducted following Nigg's taxonomy (Nigg 2000), according to which the Stroop task was considered to be an interference control measure. The analysis led to similar results, with the moderator having a non-statistically significant effect, $k = 274$, $Q_M = 1.121$, $B = -0.061$, $p = .290$, $\sigma_1^2 = .097$, $\sigma_2^2 = .062$ and nearly identical estimates across the two IC dimensions, with intervals largely overlapping (for response inhibition, k = 166, g = 0.495 [0.410, 0.579], p <.001, σ_1^2 = .140, σ_2^2 = .035; and for interference control k = 106, g = 0.469 [0.366, 0.571], p <.001, σ_1^2 = .099, σ_2^2 = .041).

2.3.3 Moderator analysis for direct measures: sample-related characteristics (research question 3c)

Age-related differences. We investigated the moderating effect of age of participants with ASD, considered as continuous variables. For direct measures, age was a significant moderator, k = 271, Q_M = 6.900, B= -0.009, p = .008, σ_1^2 = .088, σ_2^2 = .066 and the increase of age was associated with a decrease in the effect size. We replicated the moderator analyses for direct measures excluding outliers (identified with the Box Plot Diagram, i.e., all effects outside the two whiskers): the effect of age was still significant, and the beta estimate was higher. We also considered whether the effect of age was explained by age-norming. However, the effect of age was statistically significant for both direct measures with norms based on age, k = 29, Q_M = 4.019, B= -0.017, p = .045, σ_1^2 = .076, σ_2^2 = .045, and direct measures that were not norms based on age, k = 238, Q_M = 3.933, B= -0.007, p = .047, σ_1^2 < .001, σ_2^2 = .151, indicating that the age-norming was not a relevant factor. A stratified approach (based on the mean age reported in the study) was used to divide studies with direct measures into four age categories: pre-schoolers (< 6 years), children (from 6 to 12 years), youth (from 12 to 18 years) and adults (> 18 years). We estimated the effect size for each category and we found a large deficit for pre-schoolers, a medium effect size for children, a small-to-medium effect size for youth and a small effect size for adults (for pre-schoolers, k = 27, g = 0.723 [0.526, 0.920], p <.001, σ_1^2 = .712, σ_2^2 = .024; for children, k = 127, g = 0.556 [0.454, 0.658], p <.001, σ_1^2 = .077, σ_2^2 = .103; for youth, k = 74, g = 0.419 [0.290, 0.548], p <.001, σ_1^2 = .106, σ_2^2 = .045; for adults, k = 43, g = 0.284 [0.138, 0.431], p <.001, σ_1^2 = .081, σ_2^2 = .023). This stratified approach was not used with indirect measures due to the limited number of studies for each category. When distinguishing between response inhibition and interference control tasks, a significant moderating effect of age emerged for response inhibition (k = 244, Q_M = 6.649, B = -0.009, p = .010, σ_1^2 = .105, σ_2^2 = .042), but not for interference control tasks (k = 25, Q_M = 0.355, B = -0.009, p = .552, σ_1^2 = .379, σ_2^2 < .001).

Age-matching. We also tested moderator effects of sample matching (between ASD and TD) based on age. Age-matching was not a significant moderator, $k = 271$, $Q_M = 0.819$, $B = 0.092$, $p = .366$, $\sigma_1^2 = .097$, $\sigma_2^2 = .065$, with non-significantly different estimates for age-matched and non-matched samples (for age-matched $k = 240$, $g = 0.499$ [0.429, 0.569], $p <.001$, $\sigma_1^2 = .068$, $\sigma_2^2 = .077$, for non-age-matched samples, $k = 31$, $g = 0.403$ [0.180, 0.626], $p <.001$, $\sigma_1^2 = .217$, $\sigma_2^2 = .024$). A non-significant moderating effect of age-matching was found for both response inhibition ($k = 244$, $Q_M = 1.043$, $B = 0.105$, $p = .307$, $\sigma_1^2 = .115$, $\sigma_2^2 = .041$), and interference control tasks ($k = 25$, $Q_M = 1.020$, $B = -0.518$, $p = .313$, $\sigma_1^2 = .344$, $\sigma_2^2 < .001$).

IQ-related differences. The FSIQ score of participants with ASD had a significant moderating effect for direct measures, $k = 173$, $Q_M = 10.598$, $B= -0.013$, $p <.001$, $\sigma_1^2 = .056$, $\sigma_2^2 = .071$. Specifically, an increase in FSIQ score corresponded with a decrease in the ASD vs. TD standardized mean difference on IC direct measures. A stratified approach (based on the mean FSIQ reported in the study) was used to divide studies with direct measures into four FSIQ categories: FSIQ below 70, between 70 and 85, between 85 and 115, and above 115. We estimated the effect size for each category and we found a large deficit for FSIQ below 70, a medium effect size for both FSIQ 70-85 and FSIQ 85-115, and a small effect size for FSIQ above 115 (for FSIQ below 70, $k = 3$, $g = 1.334$ [0.304, 2.364], $p = .011$, $\sigma_1^2 = .097$, $\sigma_2^2 = .509$; for FSIQ between 70 and 85, $k = 8$, $g = 0.517$ [0.056, 0.979], $p = .028$, $\sigma_1^2 < .001$, $\sigma_2^2 = .207$; for FSIQ between 85 and 115, $k = 156$, $g = 0.489$ [0.405, 0.573], $p <.001$, $\sigma_1^2 = .074$, $\sigma_2^2 = .066$; for FSIQ above 115, $k = 6$, $g = 0.293$ [0.081, 0.505], $p = .007$, $\sigma_1^2 = .001$, $\sigma_2^2 = .001$). Considering response inhibition and interference control tasks, a significant moderating effect of FSIQ emerged for response inhibition ($k = 157$, $Q_M = 8.518$, $B = -0.012$, $p = .004$, $\sigma_1^2 = .084$, $\sigma_2^2 = .031$), but not for interference control tasks ($k = 14$, $Q_M = 1.848$, $B = -0.052$, $p = .174$, $\sigma_1^2 = .307$, $\sigma_2^2 = .307$).

IQ-Matching. IQ-matching had a direct moderating effect for direct measures $k = 247$, $Q_M = 13.020$, $B = -0.285$, $p <.001$, $\sigma_1^2 = .076$, $\sigma_2^2 = .056$, with a larger effect size for non-matched IQ samples (for IQ-matched $k = 181$, $g = 0.424$ [0.347, 0.500], $p <.001$, $\sigma_1^2 = .090$, $\sigma_2^2 = .035$) as compared to non-IQ-matched samples ($k = 66$, $g = 0.718$ [0.580, 0.857], $p <.001$, $\sigma_1^2 = .066$, $\sigma_2^2 = .089$). Distinguishing between response inhibition and interference control tasks, a significant moderating effect of IQ-matching emerged for response inhibition (k = 220, Q_M = 10.568, B = -0.265, p = .001, σ_1^2 = .095, σ_2^2 = .032), but not for interference control tasks (k = 25, Q_M = 1.460, B = -0.441, p = .227, σ_1^2 = .338, σ_2^2 < .001).

ADHD Comorbidity. We investigated the potential moderating effect of ADHD comorbidity. Specifically, we identified a subgroup of studies in which participants with ASD and a comorbidity of ADHD were excluded (k = 43). Additionally, we identified a subgroup of studies in which all participants with ASD also had a comorbidity with ADHD (k = 7). The presence of ADHD comorbidity did not have a significant moderating effect on direct measures, k = 50, Q_M = 0.190, B = 0.108, p = .663, σ_1^2 = .087, σ_2^2 = .155, for studies with participants with ASD and a comorbidity with ADHD k = 7, g = 0.551 [0.015, 1.088], p= .044, σ_1^2 = .336, σ_2^2 = <.001; for studies with participants with ASD without a comorbidity of ADHD, k = 43, g = 0.547 [0.350, 0.745], p <.001, σ_1^2 = <.001, σ_2^2 = .266). This analysis was performed for direct measures only, due to the paucity of studies selectively excluding or including ADHD comorbidity in indirect measures.

2.3.4 Moderator Analysis for Direct Measures: Measures-related Characteristics (research question 3d)

Presentation format (computerized vs. non-computerized tasks). In the meta-analysis on studies considering the direct measure, we found a significant moderating effect of the presentation format, computerized vs. non-computerized, k = 270, Q_M = 8.582, B = -0.185, p = .003, σ_1^2 = .073, σ_2^2 = .076. This result seems to indicate that the mean difference between ASD and TD was greater when inhibition was measured with non-computerized tasks (a small effect size for computerized tasks, k = 161, g = 0.396 [0.317, 0.475], p < .001, σ_1^2 = .054, σ_2^2 = .077; a medium effect size for non-computerized tasks, k = 109, g = 0.626 [0.520, 0.731], p < .001, σ_1^2 = .064, σ_2^2 = .113).

Type of response (motor vs. verbal). The type of response required by the task was also investigated. The moderating effect of type of response was not statistically significant k = 273, Q_M = 0.335, B = 0.038, p = .563, σ_1^2 = .088, σ_2^2 = .069, indicating non-significantly different effect sizes for tasks requiring a motor or a verbal response (for motor response, k = 195, g = 0.456 [0.377, 0.536], p < .001, σ_1^2 = .093, σ_2^2 = .085; while for verbal response, k = 78, g = 0.569 [0.460, 0.677], p < .001, σ_1^2 = .054, σ_2^2 = .064).

Type of index (accuracy scores vs. reaction times). Type of index was not a significant moderator, k = 269, Q_M = 1.724, B = -0.080, p = .189, σ_1^2 = .095, σ_2^2 = .066, suggesting that there was no significant difference in effect size between the two types of indices. In fact, for both accuracy scores and reaction times a significant small-to-medium effect size was found, with only small differences between accuracy and reaction times (for accuracy, k = 211, g = 0.491 [0.420, 0.562], p < .001, σ_1^2 = .067, σ_2^2 = .076; while for reaction times, k = 58, g = 0.406 [0.246, 0.567], p <.001, σ_1^2 = .237, σ_2^2 < .001), suggesting that in general the inhibitory deficit in people with ASD was evident in both accuracy and reaction times. Then we investigated the moderating effect of type of index separately for the two IC dimensions, and type of index was not a significant moderator for both response inhibition, k = 242, Q_M = 0.831, B = -0.063, p = .362, σ_1^2 = .114, σ_2^2 = .041, and interference control tasks, k = 25, Q_M = 0.796, B = -0.115, p = .372, σ_1^2 = .343, σ_2^2 < .001.

Unstandardized vs. standardized measures. As direct measures also involved unstandardized tasks, we included standardized vs. unstandardized tasks in a moderator analysis. The moderator was not statistically significant, k = 273, Q_M = 0.190, B = 0.0289, p = .663, σ_1^2 = .096, σ_2^2 = .065, suggesting that there was no significant difference in effect size between the two types of tasks. In fact, similar estimates for unstandardized and standardized measures were found (for unstandardized measures, k = 190, g = 0.481 [0.402, 0.561], p < .001, σ_1^2 = .089, σ_2^2 = .063; while for standardized measures, k = 83, g = 0.508 [0.387, 0.629], p <.001, σ_1^2 = .153, σ_2^2 = .021), suggesting that in general the inhibitory deficit in people with ASD was found using both unstandardized and standardized measures.

2.3.5 Inhibitory control effects for indirect measures (research question 2e)

For the second meta-analysis, we selected studies that adopted a questionnaire to measure inhibitory control. In Table A2, we reported the main characteristics of the included studies. Across the 24 studies, an estimated total of 2,285 participants (985 with ASD) were included. The group with ASD had a mean chronological age of 9.75 (SD = 2.91) and a mean Full Scale IQ (FSIQ) of 102.88 (SD = 9.29). A significant effect size was estimated, k = 27, g = 1.407 [1.186, 1.628], p < .001, σ_1^2 = .024, σ_2^2 = .227, suggesting that people with ASD had in general a large inhibitory deficit, if we consider results based on indirect measures, specifically parent reports. The confidence interval was wide, suggesting a large variability across studies, but the interval did not include the zero, meaning that the effect was statistically significant. The *Q* statistic indicated significant heterogeneity among the studies, $Q(26) = 136.363$, $p < .001$, and the I^2 index of 80.93, which indicated a large heterogeneity (Higgins et al., 2003). The forest plot for these analyses is shown in Figure A2. As it referred to the multilevel model, it provided the reader with a visual representation of all the considered effects.

2.3.5.1 Moderator analyses for indirect measures: sample-related characteristics (research question 2f)

Age-related differences. We investigated the moderating effect of age of participants with ASD, considered as continuous variables. For indirect measures, age was not a significant moderator, $k = 26$, $Q_M = 0.886$, $B = -0.036$, $p = .347$, $\sigma_1^2 = .115$, $\sigma_2^2 = .115$, suggesting that the effect size did not change according to the age of participants. As far as the age-norming is concerned, the effect of age was not statistically significant for both indirect measures with norms based on age, $k = 14$, $Q_M = 0.041$, $B = -0.013$, $p = .841$, $\sigma_1^2 = .063$, $\sigma_2^2 = .063$, and indirect measures that were not norms based on age, $k = 9$, $Q_M = 0.229$, $B = 0.033$, $p = .063$, $\sigma_1^2 = .239$, $\sigma_2^2 = .239$, indicating that the age-norming was not a relevant factor.

Age-matching. We also tested moderator effects of sample matching (between ASD and TD) based on age. Age-matching was not a significant moderator, $k = 25$, $Q_M = 0.034$, $B = 0.078$, $p = .853$, $\sigma_1^2 = .118$, $\sigma_2^2 = .118$, with non-significantly different estimates for age-matched and non-matched samples (for age-matched samples $k = 23$, $g = 1.353$ [1.118, 1.588], $p < .001$, $\sigma_1^2 = .123$, $\sigma_2^2 = .123$, for non-age-matched samples $k = 2$, $g = 1.308$ [0.899, 1.717], $p < .001$, $\sigma_1^2 < .001$, $\sigma_2^2 < .001$).

IQ-related differences. The FSIQ score of participants with ASD was not a significant moderator for indirect measures, $k = 16$, $Q_M = 0.035$, $B = 0.003$, $p = .852$, $\sigma_1^2 = .117$, $\sigma_2^2 = .117$, suggesting that the effect size did not change according to the FSIQ of participants.

IQ-Matching. IQ-matching did not have a significant moderating effect for indirect measures, $k = 21$, $Q_M = 0.151$, $B = 0.099$, $p = .698$, $\sigma_1^2 = .111$, $\sigma_2^2 = .111$, with a similar effect size for IQ matched samples and non-IQ-matched samples (for IQ-matched samples k = 14, g = 1.298 [1.094, 1.502], p <.001, σ_1^2 = .034, σ_2^2 = .034; for non-IQ-matched samples k = 7, g = 1.259 [0.691, 1.828], p <.001, σ_1^2 = .253, σ_2^2 = .253).

2.3.6 Publication Bias

To examine the effect of publication bias, we used the funnel plot and the trim-and-fill method. In Figures 2.2 and 2.3, we presented the funnel plot for direct and indirect measure respectively. For both direct and indirect measures, the trim-and-fill procedure (applied to the funnel plot of the random model) did not adjust the previous results, and no asymmetry was observed in the funnel plot, with no missing studies on the left side of the graph.

Figure 2.2 Funnel plot for direct measures.

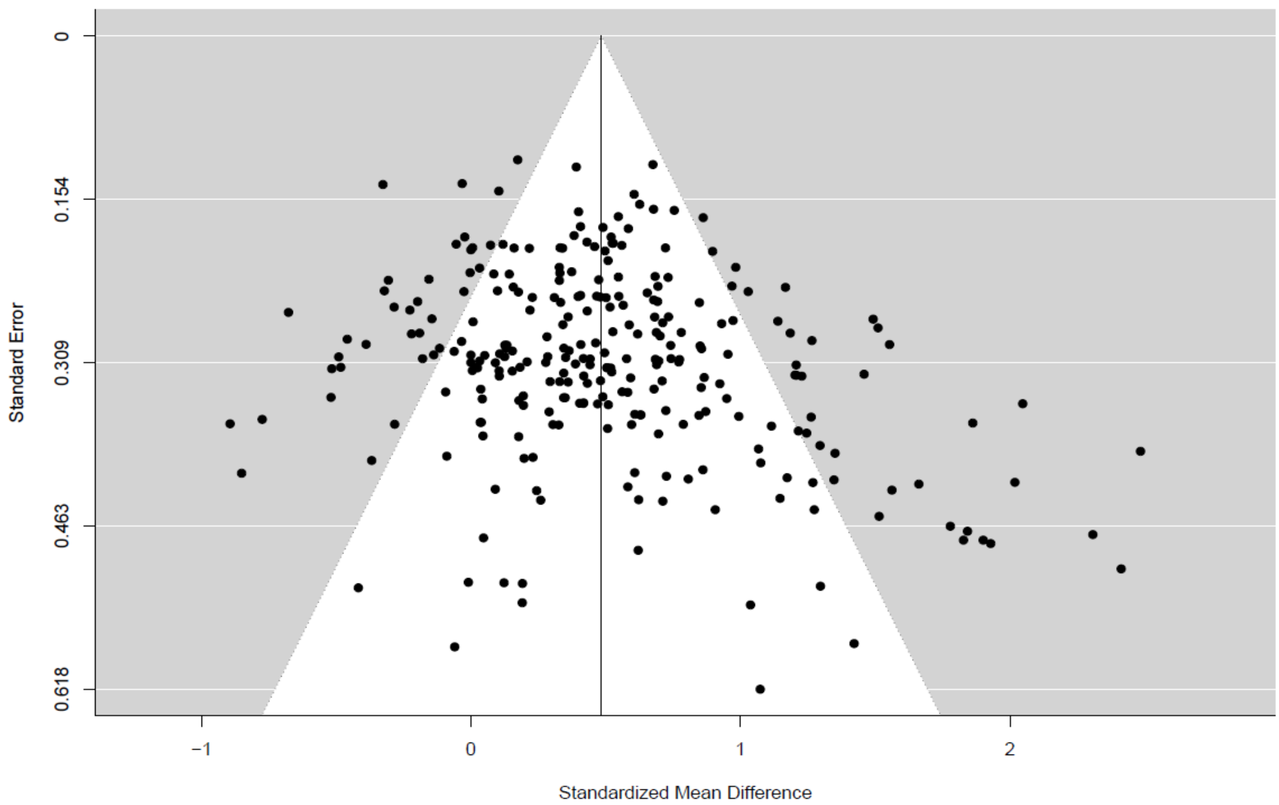
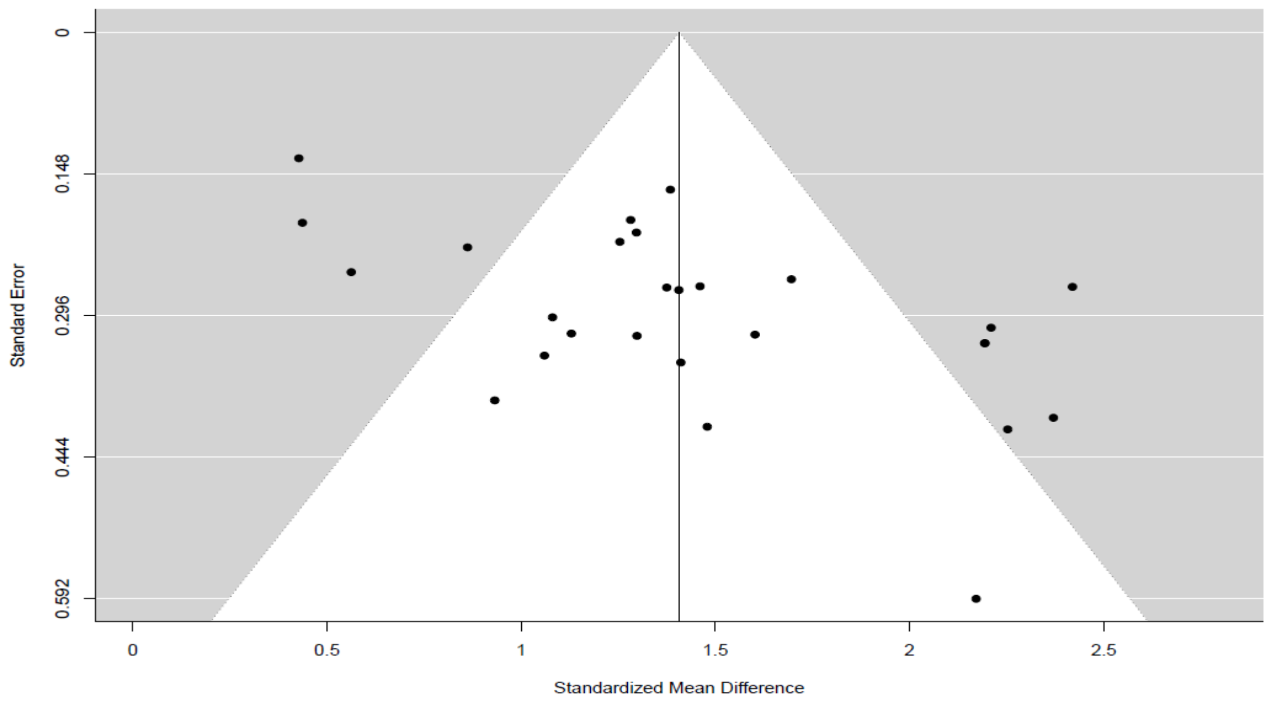


Figure 2.3. Funnel plot for indirect measures.



2.4 Discussion

2.4.1 **Inhibitory control dimensions in autism spectrum disorder** (research question 2a and 2b)

This study aimed to investigate inhibitory processes in ASD. We investigated whether participants with ASD present with impairments in different aspects of IC. Results showed that both response inhibition and interference control were similarly impaired in participants with ASD (Agam et al., 2010; Geurts et al., 2014; Goddard et al., 2013; Weismer et al., 2018). Such a finding indicates that participants with ASD present with difficulties in both retraining a prepotent response and in filtering out irrelevant, but conflictual information. Even though these two inhibitory aspects were similarly impaired, we found key differences in how response inhibition and interference control were affected by age and IQ. This latter finding corroborates the importance of differentiating these two IC dimensions, which are closely related but intrinsically different aspects (e.g., with different pathophysiological mechanisms) of IC (Bunge et al., 2002; Rey-Mermet, et al., 2018).

2.4.2 **Sample-related characteristics in direct measures** (research question 2c)

Considering IC abilities as a whole, both age and IQ were significant moderators for direct measures, with an increment in age or IQ of participants with ASD associated with a decrease in the effect size (Geurts et al., 2014; Demetriou et al., 2018). However, after distinguishing between response inhibition and interference control, interference control in participants with ASD seems not to be affected by the age of the participants or their general intellectual functioning.

Regarding the role of age, we replicated, using a larger group of studies, the finding that the IC deficit was more pronounced in children than in adults with ASD (Geurts et al., 2014; Demetriou et al., 2018). The result suggests that response inhibition specifically may have a prolonged period of development in individuals with ASD compared to individuals with TD, whereas the interference control deficit appears stable across ages. Based on this finding, it is reasonable to hypothesize the presence of potential differences in the developmental trajectories of the two aforementioned abilities, in children with ASD as compared to children with TD. For example, it is well established that response inhibition abilities develop rapidly during childhood, then begin to plateau in adolescence in children with typical development (e.g., Luna et al., 2004, 2007; Williams et al., 1999). Research on typical development also suggests that interference suppression improved over time (Richardson, Anderson, Reid, & Fox, 2018), however it shows a distinct maturational process from response inhibition (Vuillier, Bryce, Szücs, Whitebread, 2016). Previous studies suggested that the developmental trajectory of individuals with ASD differed from that of controls; however, their results were in part controversial with some studies indicating an attenuated rate of development with age in individuals with ASD (Schmitt et al., 2018) and others that showed the opposite finding (Happè, Booth, Charlton, & Hughes, 2006). The inclusion of several inhibitory tasks and a large number of participants from early childhood into adulthood allows us to better understand the development of response inhibition in autism; specifically, our results could suggest that individuals with ASD demonstrate a delayed development of response inhibition abilities and begin to catch up to TD peers when TD development plateaus. Instead, it seems that the difference between the two groups in the dimension of interference control remain relatively stable throughout the development. Thus, present findings provide support to the hypothesis that the two IC processes are also distinct in individuals with ASD being impaired differently across ages.

It is also possible that, since IC interventions generally focussed on response inhibition (Wallace et al., 2016), children with ASD could have fewer opportunities to be engaged in activities targeting interference control. This fact may explain, at least in part, the reason why the gap between ASD and TD in this specific IC dimension tends not to decrease with age. Alternatively, the relative independence of interference control impairment from intellectual functioning and age might suggest that this inhibitory dimension tends to be more stable during the development and, therefore, hardly improved through specific interventions.

The inclusion of preschoolers adds to previous knowledge since this age group had not previously been considered. The higher deficit showed by preschoolers is in line with previous results (Garon et al., 2018) and seems to be particularly pronounced in most inhibitory tasks, such as Luria's hand game (Pellicano et al., 2017), Stroop-like-tasks (Valeri et al., 2020; Hanson & Atance, 2014), or Delay Response tasks (Bonli, 2005). Therefore, it seems important to provide early interventions aimed at supporting the development of both IC abilities.

Our results indicated that IQ was a significant moderator with larger differences in participants in the normal range or with IQs below 70. Conversely, differences were smaller in the case of participants with ASD and higher intellectual functioning (i.e., an IQ above 115). This is a valuable result and highlights the importance of considering the general intellectual functioning in participants with ASD (Garon et al., 2018).

However, only a few studies were devoted to participants with higher or lower intellectual functioning. Based on this observation, we decided to refrain from performing more advanced statistical techniques (e.g., the evaluation of the region of significance, useful to provide thresholds where the moderators exert their effect), which would have been extremely interesting, but not ideal under these constraints. Thus, future research, for example investigating inhibitory processes in ASD in participants with different intellectual profiles, is needed.

It is worth noting that the large difference in the number of studies using response inhibition tasks versus interference control tasks may have had led to differences in power across the two-moderator analysis. In fact, when tasks were categorized following Friedman & Miyake's taxonomy (2004), with Stroop tasks considered as measures of response inhibition, a lower number of interference control effects was identified (k = 25). Notably, the interference control dimension, as compared to the response inhibition ones, is somewhat less investigated in children with ASD. For this reason, it would be important to further examine IC, as well as the role of a variable such as IQ or age of participants, using tasks assessing interference control.

Concerning the role of ADHD comorbidity, recent findings suggested that ADHD symptoms are associated with IC in participants with ASD; however, few studies addressed this important issue (e.g., Biscaldi et al., 2016; Ptzianti et al., 2016). Intriguingly, our results showed that including or excluding participants with a comorbidity of ADHD did not significantly affect the results; this is a very interesting finding and suggests that IC difficulties in participants with ASD are not necessarily imputable to the presence of participants with a diagnosis of ADHD in comorbidity. Nevertheless, few studies with interference control tasks provided details about the ADHD comorbidity, consequently, these findings do not allow to distinguish the effect separately for response inhibition and interference suppression dimensions.

2.4.3 **Measures-related characteristics** (research question 2d)

We found that inhibitory difficulties in individuals with ASD are reduced in computerized tasks, where the situation is highly standardized, and relational demands are minimal, in comparison with non-computerized tasks. Although this aspect has been poorly investigated in the current literature (Demetriou et al., 2018; Ozonoff et al., 1995), our result seems to be consistent with previous evidence indicating that the processing of social stimuli interferes with the functioning of brain regions involved in IC tasks (Dichter & Belger, 2007). However, for some IC tasks, such as Stop Signal or Flanker, only computerized versions are generally available. For this reason, it can be argued that differences could be, at least in part, a reflection of differences in the actual measurement selection, which could be addressing slightly different aspects of IC.

Other sources of heterogeneity, such as the type of response required by the task (verbal vs. motor) or the type of index (accuracy vs. RTs) were not statistically significant. Participants with ASD show the same level of impairment on both motor and verbal inhibition tasks; however, it is worth noting that differences might potentially emerge when considering specific subgroups of participants with ASD with a language delay, in which struggles in verbal tasks are very likely. Both accuracy and RTs are impaired in participants with ASD, in line with a part of evidence that found this effect, particularly in incongruent trials (e.g., Faja et al., 2016; Sachse et al., 2013). It is worth noting that this meta-analysis includes several well-known response inhibition tasks (e.g., Luria's Game, Hayling Test, Matching Familiar Figure Task, Opposite Worlds), which provide additional informative accuracy indices and scores that were not considered in previous meta-analyses, and this might explain why our results diverge to some extent from previous reports (e.g., Geurts et al., 2014).

2.4.4 **Inhibitory difficulties in indirect measures** (research question 2e)

While previous meta-analyses on IC have focussed on direct measures, we also aimed to use indirect measures to investigate inhibitory processes in ASD, which remained relatively unexplored so far. In line with previous studies, our results revealed significant differences between indirect and direct measures. Specifically, differences between the group with ASD and TD were significantly larger in indirect measures (i.e., questionnaires), as compared to the direct ones. Several hypotheses can be formulated to explain this very intriguing finding.

Inhibitory difficulties in people with ASD could be more prominent in ecological contexts, which are directly investigated using questionnaires. Individuals with ASD generally encounter more difficulties in real-world settings, in which social problem-solving and generalization skills are often required, in comparison with experimental or clinical contexts, in which rules are more clear and unexpected events are less frequent (Frith & Frith, 2012; Volkmar et al., 2004).

It is also possible that the two methods of assessment identify different components of IC functioning, with questionnaires being used as screening measures, and direct measures being used to provide a quantitative estimate of the extant deficits of these participants (Gross et al., 2014).

Another possible explanation arises from the consideration that questionnaires also reflect the particular point of view of parents. Although the literature has generally pointed out the risk of social desirability (i.e., a tendency to choose positive responses) in the use of questionnaires (McCoy, 2019), it is possible that parents of children with ASD tend to generalize and overestimate the difficulties of their children (Gomez-Perez et al., 2016). On the other hand, many indices of IC in parent-report measures could also assess more general EF aspects as compared with direct measures, providing an invaluable source of additional information. Moreover, indirect measures are reported over an extended period, whereas direct measures provide a picture of performance on a specific day and time. It can also be argued that direct IC measures do not always have good psychometric properties (Friedman & Myake, 2004; Wöstmann et al., 2013). For example, the majority of standardized instruments tend to have test-retest reliability coefficients below .8 or even lower, while the reliability of indirect measures tends to be higher. Although the sources of these low reliabilities are not clear, it can be argued that direct measures reflect additional error variance or variance due to state factors, and this can explain, at least in part, the lower psychometric properties of these instruments. Thus, direct measures, as compared to the indirect ones, tend to be less stable, suggesting that performance might be influenced by state factors rather than indexing trait factors, meaning that indirect measures could potentially capture IC traits, while direct measures could potentially capture IC states.

2.4.5 **Sample-related characteristics in indirect measures** (research question 2f)

Differently from previous meta-analyses, we also investigated the moderating effect of age and IQ on indirect measures of IC. Results showed that age was not a statistically significant moderator. This result should be interpreted carefully because indirect measures tend to be used prevalently on children (e.g., Berenguer et al., 2018; Golshan et al., 2019) and young adolescents (e.g., Samyn et al., 2015; Van Eylen et al., 2015), and – for this reason – the number of studies on older participants is not particularly large. In a similar vein, IQ was not a statistically significant moderator on indirect measures. Questionnaires can in fact capture the quality of adaptation to daily conditions, and this result is in line with studies in which a significant association between IQ and level of functioning in everyday life was not found (Ventola et al., 2014; Kanne et al., 2011). However, it is worth mentioning that indirect measures are generally used in studies with participants having their IQ in the normal range; in fact, most indirect measures have not been validated for participants with IQs lower than 70. This is a problematic aspect that needs to be addressed by future research and might have somehow affected our results. It is also noteworthy that the number of studies using indirect measures was not particularly large. Also, the number of studies investigating participants with ages over 40 was extremely limited, and this should probably be addressed in future research. This would also allow the use of more advanced statistical techniques (e.g., the calculation of the region of significance). For all these reasons, we believe that this issue should be further investigated in the future as the use of indirect measures is fast becoming popular, thus making it possible to include a larger number of studies in future meta-analyses.

2.4.6 Limitations

Results from this meta-analysis should be interpreted in light of some limitations. It should be noted that the heterogeneity across studies was rather high. This can potentially reflect systematic differences in study design or potential psychometric weaknesses in the measures used to index IC. In fact, we only included some moderators, and different variables and other sources of variability that were not included in our meta-analysis should be further investigated.

For instance, there is a large heterogeneity within the ASD diagnostic group; according to DSM-5, ASD involves individuals with very different cognitive and linguistic functioning. Moreover, the severity of the ASD symptoms is expected to vary across different studies. It is also worth mentioning that ASD includes participants with very different challenges, for example, following the DSM-5 guidelines, some participants who would have previously received a diagnosis of Asperger syndrome would now receive a diagnosis of ASD. This particular aspect, in fact, makes it hard to perform finer-grained analyses on specific subgroups of participants within the ASD category.

Although the total number of studies reporting the FSIQ was reasonably high, only few studies were targeted to participants with IQs below 70 (Drayer, 2008; Han & Chan, 2017). This makes it hard to evaluate linear effects of the IQ. Additionally, due to the very limited number of studies using indirect measures, or investigating interference control and response inhibition separately and providing information about the inclusion or exclusion of ADHD comorbidity, it was not possible to estimate the moderating effect of ADHD comorbidity. Therefore, these aspects should be addressed in future studies.

Another important issue that needs to be addressed in future studies and meta-analyses is the possibility of male-female differences in inhibitory abilities in participants with ASD. This aspect was not investigated in our meta-analyses due to the paucity of studies on females with ASD (Lai et al., 2011; Lemon et al., 2011). However, it is possible that some male-female differences could contribute to a portion of the variance on the IC performance. In fact, ASD in females is often associated with different peculiarities as compared to males, for example, females with ASD are more successful in using strategies to mask their social and cognitive difficulties (Kiep & Spek, 2017). Moreover, only male participants with ASD showed an impaired performance on tasks measuring inhibition and planning, suggesting that sex may somehow modulate these aspects in individuals with ASD (Lai et al., 2011).

Several characteristics related to the measures could somehow affect the results. For example, although IC tasks are intended to evaluate the same construct, they could in vary in other aspects (Fontana et al., 2021), such as the demands imposed on working memory or the level of complexity (e.g., a Matching Familiar Figure task could be more challenging than a classic Go/No-go paradigm because it requires participants to also adopt visual-scanning strategies or to keep the target figure in mind).

In our meta-analysis, we included widely known indices for IC measures, but other informative indices are available. Considering, for instance, the Stop Signal task, we included the SSRT (Stop Signal Reaction Time), which is the most commonly used index and reflects a measure of reactive IC (i.e., the ability to stop a behaviour in response to external signals). However, recent studies (e.g., Mosconi et al., 2009; Schmitt et al., 2017) also estimated an index of proactive inhibition (i.e., the ability to slow our behavioural responses in preparation for stopping cues). This is particularly interesting, given the difficulties people with ASD have in slowing their responses during a Stop Signal task (Schmitt et al., 2017). In addition, given that people with ASD may encounter difficulties in basic cognitive processes such as processing speed (Zapparrata et al., 2022), it could be useful investigating the moderating role of such processes. However, the use of these additional indices is not widespread and future research exploring, for example, differences between proactive or reactive IC is therefore needed.

In addition, we included tasks of inhibition that fall within the category of cool executive function and did not focus on hot inhibition tasks. It's important to note that the literature distinguishes between the cool and hot aspects of executive function and inhibition (Zelazo & Muller, 2002; Zelazo & Carlson, 2012). According to this distinction, cool executive function encompasses processes that are activated in non-affective, motivationally neutral situations and are typically assessed by decontextualized tasks such as Go/No-Go and the Tower of London (Anderson et al., 2008). Instead, hot aspects of executive function are engaged in motivationally significant, affective conditions, like delay discounting and affective decision-making tasks such as the Gambling Task and Delay Discounting tasks (Kouklari et al., 2018). Although deficits in hot inhibition tasks have also been observed in autism (Kouklari et al., 2018; Yu et al., 2021; Zimmerman et al., 2016), we chose to focus on cool inhibition tasks. The inclusion of hot inhibition tasks would have required a dedicated exploration and the consideration of additional moderator variables closely related to autism characteristics. Hot inhibition is closely connected to domains of social cognition, such as emotional regulation and theory of mind (Yu et al., 2021). For example, hot inhibition tasks require the ability to make decisions based on social inferences that take into account the context, aspects that are particularly challenging for individuals with autism and would have necessitated a specific investigation (Goldenfeld et al., 2005; Mathersul et al., 2013; Perner & Wimmer, 1985). However, given the relevance of hot executive function, further research and meta-analyses may enhance our understanding of the higher-order cognitive deficits that contribute to social interaction problems in autism.

Indirect measures considered in the current report were constituted by parent reports, and there is a paucity of studies using IC questionnaires with other informants (e.g., teachers or the participants themselves). As previous studies (Johnson et al., 2009; Lerner et al., 2012) reported differences between reports of parents and children with ASD (with a tendency to an under and over-estimation of the effects, respectively) further empirical investigations are particularly warranted. As for direct measures, although we did not find statically significant differences between standardized and unstandardized tasks, the reliability was not always reported in studies using unstandardized measures. We believe that this is an important issue, as the psychometric properties of the tests considered can have important consequences, significantly affecting the results, and this information should always be provided. Also, we decided to include unpublished materials (e.g., dissertations). This decision was made in accordance with the PRISMA guidelines, which strongly recommend the inclusion of unpublished materials to reduce the risk of publication bias (Rethlefsen et al., 2021). However, it is important to stress that these materials are not peer reviewed, thus making it very hard to ascertain the quality of these reports. In any case, in our meta-analysis the number of unpublished studies was not particularly large (i.e., only 8 studies out of the 184 included in the current meta-analysis), and when excluded, our results changed very little.

2.4.7 Implications and Future Directions

Findings from our meta-analyses suggest some practical implications for both assessment and interventions. The use of different methods of assessment could be helpful for a comprehensive evaluation of inhibitory skills in people with ASD. Indirect and direct are not interchangeable and seem to convey different information. Indirect measures reflect the ability of using inhibitory processes in real life context and can be useful for the screening of IC problems, and to assess the potential negative impact on everyday life situations, whereas direct measures could be more indicative of the efficiency of inhibitory processes and the degree of IC difficulties (Toplak, 2013).

In assessment with direct measurement, it is also important to be aware of the differences between computerized and non-computerized tasks. Although computerized tasks have several advantages (e.g., standardized instructions, and a more precise estimation of RTs), the use of additional tasks administered in a traditional format by the clinician might also be important to take into account the influence of the relational dimension on inhibitory abilities.

The moderating role of computer use may be also considered in the implementation and the evaluation of interventions for improving IC in autism. It is well known that computerized trainings tend to be more attractive and engaging for people with ASD (e.g., Grynszpan et al., 2007; Moore & Calvert, 2000), and the use of a computer could represent a helpful strategy to foster a new skill, reducing additional relational demands. However, to improve generalization to real contexts, it could be helpful to incorporate training in small group settings, adopting different types of measures to evaluate the efficacy (Beaumont & Sofronoff, 2008). Another element to consider for the implementation of an intervention is that individuals with ASD encounter significant difficulties not only in ceasing impulsive behaviour, but also in filtering out irrelevant but conflictual stimuli. Though most EF interventions for ASD focus on response inhibition (Wallace et al., 2016), trainings on interference control are also promising and more research is needed.

2.4.8 Conclusions

The current meta-analysis provides an overview of inhibitory difficulties in participants with ASD. Response inhibition and interference control were similarly impaired but differently affected by age and IQ, supporting a multi-componential view of inhibitory processes. Results also suggest that impairments on inhibitory processes are independent from an ADHD comorbidity, indicating that these deficits are a distinguishing feature of participants with ASD. Finally, this meta-analysis establishes that the assessment, using direct vs. indirect measures, provides a different set of information, and that several different sources of information could be beneficial for the assessment of participants with ASD.

3 Math abilities in autism spectrum disorder: a meta-analysis[2]

Abstract

Studies focusing on math abilities in autism spectrum disorder (ASD) are limited and often provide inconsistent results. The current meta-analysis was conducted to investigate math abilities in people with autism spectrum disorder (ASD) compared to typically developing (TD) participants. According with PRISMA guidelines, a systematic search strategy was adopted. First, 4405 records were identified through database searching; then, the title-abstract screening led to the identification of 58 potentially relevant studies and, finally, after the full-text screening, 13 studies were included. Results shows that the group with ASD (n=533) performed lower than the TD group (n=525) with a small-to-medium effect (*g*=0.49). The effect size was not moderated by task-related characteristics. Instead, sample-related characteristics, specifically age, verbal intellectual functioning, and working memory, were significant moderators. This meta-analysis shows that people with ASD have poorer math skills than their TD peers, suggesting the importance of investigating math abilities in autism, taking into account the role of moderating variables.

3.1 Research aims

Research on math skills in individuals with autism spectrum disorder (ASD) is restricted and frequently yields inconclusive findings (Bullen et al., 2020; Dowker, 2020; Iuculano et al., 2020).The primary aim of this study was to explore the math abilities of students with ASD compared with a comparison TD group to establish whether their abilities are considered strengths or weaknesses for this population. A series of moderation analyses were conducted to understand which factors could significantly impact the results. First, the role of some measure-related characteristics was examined. Specifically, whether the type of math task had a moderating role was explored, considering two different math tasks: numerical operations and word problem solving. It is possible that solving math

[2] Tonizzi, I., & Usai, M. C. (2023). Math abilities in autism spectrum disorder: A meta-analysis. *Research in Developmental Disabilities*, 139, 104559. https://doi.org/10.1016/j.ridd.2023.104559

word problems is more challenging for students with ASD, as they require more complex skills, such as the ability to understand the text, connect linguistic information with mathematical factors to generate a mental representation of the problem, select and apply the adequate procedures to perform the required calculations (Root et al., 2017; Whitby & Mancil, 2009). For this reason, the difference between the two groups could be larger in the math word problems. Additionally, the format of the task (oral vs. written) was investigated. It is possible to hypothesize that the group with ASD may show verbal and/or graph-motor difficulties that could potentially impact the performance of math tasks (Assouline et al., 2012): for example, a student's math achievement on written tasks can be negatively impacted if handwriting is poor or slow, but at the same time, weak oral comprehension may affect the execution of an oral math task. However, these specific aspects have not been previously investigated.

Then, the role of three characteristics of the participants (i.e., age, intellectual functioning, and WM) were explored. It is conceivable that an increase in age is associated with increased math difficulties in participants with ASD compared with a TD group (Kim & Cameron, 2016); moreover, an increase in IQ may be associated with a decrease in the difference between the two groups (Bullen et al., 2020; Oswald et al., 2016). Concerning the role of IQ, the role of full-scale IQ (FSIQ), performance IQ (PIQ), and verbal IQ (VIQ) was explored in detail. Eventually, WM may also play an important role in explaining ASD vs. TD differences in math abilities (Bullen et al., 2020; Chen et al., 2019). In summary, the current meta-analysis tries to answer the following research questions:

3a. Considering studies included in the meta-analysis, is there a difference between the group with ASD and a TD comparison group in math abilities?

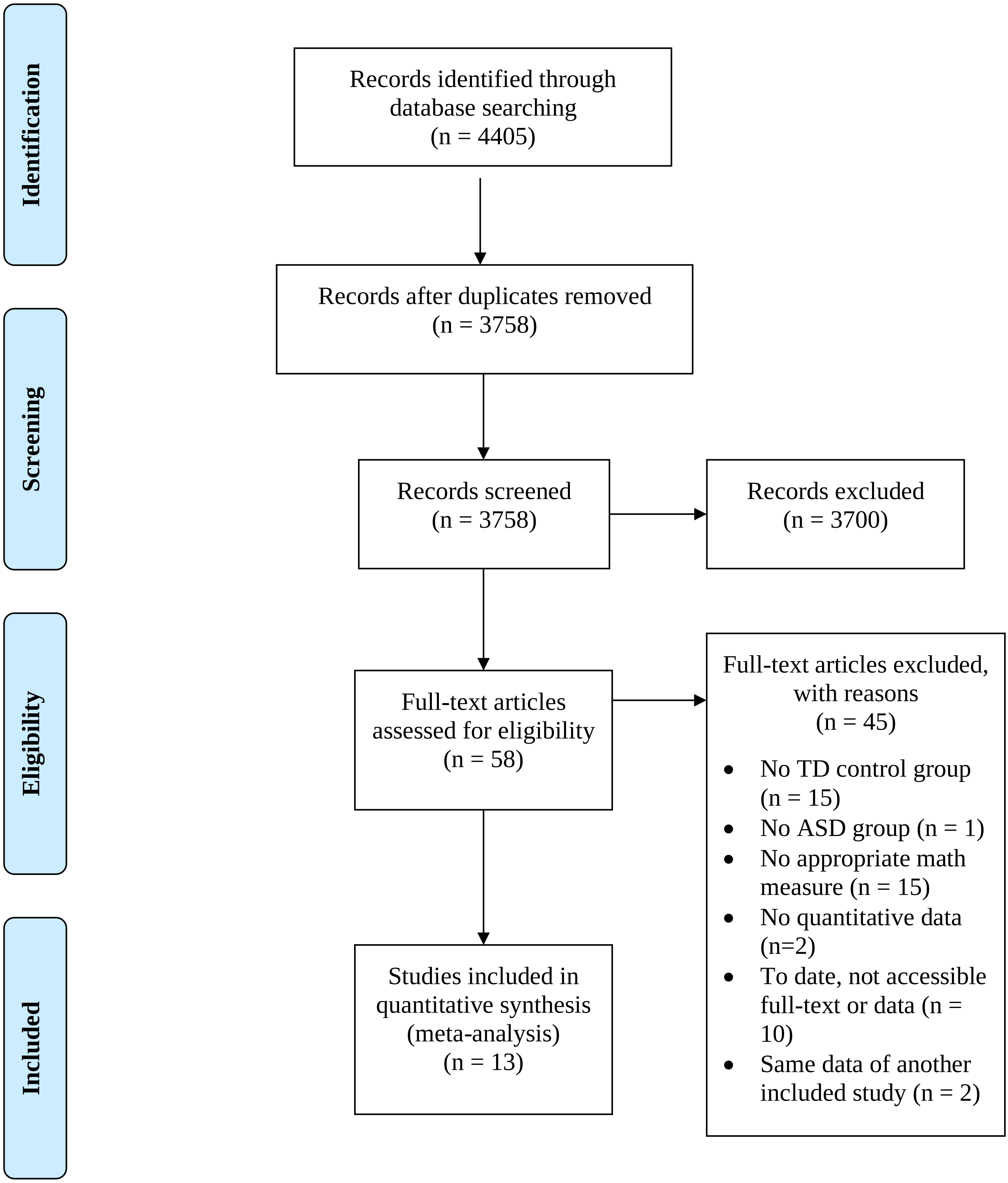
3b. Are there characteristics of the tasks, such as the type of math task (numerical operations vs. math problem solving) or the format of the task (oral vs. written), that moderated the difference between the two groups in math abilities?

3c. Are there characteristics of the participants, such as age, intellectual functioning and WM, that moderated the difference between the two groups in math abilities?

3.2 Method

A systematic search strategy was used to identify relevant studies, following the PRISMA statement (Page et al., 2021). Figure 3.1 shows a flow chart illustrating the search process and the identification of included studies.

Figure 3.1. PRISMA Flow chart illustrating the identification of included studies.



3.2.1 First phase: literature search

A literature search was conducted through the databases PsycINFO, PsycArticles, PubMed and ProQuest combining keywords for math and autism, using the following string of search terms: (“math*” or “mathematics” or "academic achievement" or "word problem*" or "arithmetic problem*" or "arithmetic" or “calculation” or “numeracy”) AND (“autism” or “ASD” or “autistic” or "autism spectrum disorder*" or "pervasive disorder*" or “asperger”). All search keywords have been combined in the same way in each database. Published journal articles, as well as book chapters and unpublished dissertations (the so-called grey literature), were included to manage the possible effects of publication bias. The results were limited by publication year, considering studies published from January 2000. Next, we hand-searched citations in previous relevant reviews and identified 4405 references, of which 647 duplicates were removed.

3.2.2 Second phase: title-abstract screening

Rayyan QCRI, a systematic reviews web application, was employed for the title-abstract screening phase. The records were included according to the following criteria:

1. Studies were written in English and published from January 2000;
2. A group of participants with ASD was included. All participants with ASD met diagnostic criteria according to DSM-III-R, DSM-IV, DSM-5, ICD-10 or ICD-11;
3. A TD comparison group was included; in this phase, we also included abstracts in which the presence of a comparison group was not clearly stated.
4. At least one mathematical task was used. In this phase, we also included abstracts in which unspecified academic achievement measures were mentioned.

References for which the abstracts did not provide enough information on the eligibility criteria were considered for the full-text screening. Following this procedure, 58 references were included in the third phase.

3.2.3 Third phase: full-text screening

The full texts of the included references were retrieved and examined according to the eligibility criteria. In this phase, one specification was added to the previous inclusion criteria: a study was included if it involved at least one measure of math achievement assessed based on school age (from primary school to university). A total of 13 studies were finally included in the meta-analysis. In the full-text screening, 45 studies were excluded for:

- The absence of a group with a diagnosis of ASD (n= 1). Studies with a general group of neurodevelopmental disorders or with participants having only autistic traits were excluded;
- The absence of a control group of TD participants (n= 15);
- Studies using a general academic achievement measure and not a math measure from school age (n= 15);
- Not accessible data or pdf. In this case, the corresponding author was contacted via e-mail (n= 10);
- Studies without quantitative data (n=2)
- Studies or theses with the same data as another included study (n=2).

3.2.4 Inclusion Coding

The relevant information of each included study was coded in a dataset with the following variables: authors, publication year, demographics, sample sizes, ASD diagnostic criteria and instruments, math measures and mean scores, type of math measure (numerical operations vs. word math problems), format of the tasks (written vs. oral), IQ measures and mean scores, IQ and age match for the ASD and TD groups, WM measures and mean scores.

3.2.5 Interrater Reliability

The interrater reliability was calculated for the title-abstract and full text screening. To this end, two authors independently double-screened 25% of both abstracts (n=940) and full texts (n=15). The percentage of agreement was 98.4% (n=15 abstracts in disagreement) and 93.4% (n=1 full text in disagreement) for the abstracts and the full-texts, respectively. All disagreements were resolved by discussion.

3.2.6 Analytic Strategy

The analyses were conducted in accordance with the guidelines provided by Borenstein et al. (2009) and were performed using R software (version 4.0.3) with the *Metafor* package (Viechtbauer, 2010). Hedges' g effect size statistic was calculated to compare mean math performance between groups, with positive and negative *g* indicating the better and poorer performance of the TD group on math tasks, respectively.

Due to the expected heterogeneity between studies, we chose to adopt a random effects model to account for this variability. Random effects models are generally encouraged because have the advantage of assuming that the true effect size varies across studies, depending on some moderators concerning method and sample characteristics (Borenstein et al., 2009). Importantly, in our meta-analysis, there were studies with multiple math tasks, and therefore we also used a multilevel model to address the dependency of effect sizes within studies (Borenstein et al., 2017).

We calculated the following statistics to estimate the heterogeneity across effect sizes: I^2 (with values of 25%, 50%, and 75%, corresponding to small, moderate, and high levels of heterogeneity, respectively), Q, tau squared (τ2), and sigma squared (σ2) (Borenstein et al., 2009; Deeks et al., 2008). Sigma squared (σ2) in the multilevel approach corresponds to Tau squared, is used to assign weights under the random-effects model and indicates the variance of the true effect sizes.

Meta-regressions with random effects were used to test the statistical significance of moderators (Borenstein et al., 2009). Task-related moderators were coded as dichotomous variables: the type of math tasks (numerical operations vs. word math problems) and the format of the task (verbal vs. written). Sample-related moderators were coded as continuous variables: age, intellectual functioning, and WM. As studies adopted different WM tasks with different measurement scales, we used the standardized mean difference between the ASD vs. TD groups on WM tasks as a moderator.

We assessed publication bias using funnel plots and the trim-and-fill method (Borenstein et al., 2009; Duval, 2005). Symmetrical distribution of the studies around the mean effect size on the funnel plot indicates the absence of publication bias (Sterne et al., 2005). To correct for the observed asymmetry, we used the trim-and-fill method (Duval, 2005) to impute missing studies and estimate the summary effect size.

3.3 Results

The meta-analysis included 13 studies with a total of 27 effects. In Table 3.1, we report descriptive statistics for the two groups. Table 3.2 shows a summary of the main characteristics of each included study. All studies compared a group with ASD and a TD group on at least one math measure (for a detailed description of tasks, see Table 3.3). Task type (numerical operations vs. math word problems) and format (oral vs. written tasks), age, FIQ, PIQ, VIQ, and WM scores were considered moderators.

Table 3.1. Descriptive statistics for the groups with ASD and the TD group (standardized scores).

	ASD (N= 533)			**TD (N=525)**		
	M	**SD**	**Range**	**M**	**SD**	**Range**
Age (in years)	11.02	1.78	9.39-14.88	10.82	1.63	9-14.73
Full IQ	107.53	14.27	96.78-120.8	109.68	12.96	97.49-120.31
Performance IQ	109.93	16.49	101.08-119	109.44	13.64	103.59-114.37
Verbal IQ	104.24	15.63	96.11-117.31	110.06	13.45	103.5-121.88
Standardized math tasks	102.91	18.41	82.77-123.25	109.45	15.48	97.97-119
Numerical operations	103.91	19.22	87.61-123.25	109.23	16.21	97.97-117.3
Math word problems	105	17.28	93.67-116.88	110.71	14.67	104.78-119.00
Working memory	98.47	17.52	93.94-102.47	98.18	16.6	92.28-107.48

Note: ASD = autism spectrum disorder; TD = Typical Development; M = mean; SD = Standard Deviation.

Table 3.2. Summary of included studies with direct measures.

Authors	ASD N	TD N	ASD diagnostic criteria	ASD age M	ASD age SD	ASD age Range	TD age M	TD age SD	TD age Range	Math measure	IQ measure	WM measure
Aagten-Murphy et al., 2015	32	32	clinical diagnosis DSM IV; SCQ; ADOS-G	10.28	1.3	7.95-13.28	9.92	1.07	7.82-12.38	Mathematical reasoning WOND	WASI	-
Aagten-Murphy et al., 2015	32	32	clinical diagnosis DSM IV; SCQ; ADOS-G	10.28	1.3	7.95-13.28	9.92	1.07	7.82-12.38	Numerical operations WOND	WASI	-
Aagten-Murphy et al., 2015	28	32	clinical diagnosis DSM IV; SCQ; ADOS-G	10.28	1.3	7.95-13.28	9.92	1.07	7.82-12.38	Nonsymbolic estimation	WASI	-
Aagten-Murphy et al., 2015	32	32	clinical diagnosis DMS IV; SCQ; ADOS-G	10.28	1.3	7.95-13.28	9.92	1.07	7.82-12.38	Numberline 1-100	WASI	-
Aagten-Murphy et al., 2015	32	32	clinical diagnosis DSM IV; SCQ; ADOS-G	10.28	1.3	7.95-13.28	9.92	1.07	7.82-12.38	Numberline 1-1000	WASI	-
Bae et al., 2015	20	20	clinical diagnosis	10.6	0.94	-	10.27	0.54	-	TOMA-2-SP	KBIT-2	-
Bae et al., 2015	20	20	clinical diagnosis	10.6	0.94	-	10.27	0.54	-	MWPS	KBIT-2	-

Bae et al., 2015	20	20	clinical diagnosis	10.6	0.94	-	10.27	0.54	-	Math Vocabulary TOMA-2	KBIT-2	-
Bae et al., 2015	20	20	clinical diagnosis	10.6	0.94	-	10.27	0.54	-	Computation TOMA-2	KBIT-2	-
Bae et al., 2015	20	20	clinical diagnosis	10.6	0.94	-	10.27	0.54	-	Everyday Mathematical Knowledge TOMA-2	KBIT-2	-
Bullen et al., 2020	77	43	clinical diagnosis; ADOS-2	11.38	2.2	8-15	11.6	2.28	8-15	Numerical Operations WIAT-III	WASI-II	WRAML-2 (verbal WM score)
Bullen et al., 2020	77	43	clinical diagnosis; ADOS-2	11.38	2.2	8-15	11.6	2.28	8-15	Problem Solving WIAT-III	WASI-II	WRAML-2 (verbal WM score)
Chen et al., 2018	114	96	clinical diagnosis; ADI-R; ADOS	9.39	1.49	7.01-12.88	9.39	1.09	7.14-12.59	Numerical Operations WIAT-II	WASI	WMBT-C (backward digit recall)
Chen et al., 2018	114	96	clinical diagnosis; ADI-R; ADOS	9.39	1.49	7.01-12.88	9.39	1.09	7.14-12.59	Math Reasoning WIAT-II	WASI	WMBT-C (backward digit recall)
Hiniker et al., 2016	36	61	clinical diagnosis; ADI-R; ADOS	9.66	1.6	7-12	9.6	1.49	7-12	Numerical Operation WIAT-II	WASI	WMBT-C (backward digit recall)
Hiniker et al., 2016	36	61	clinical diagnosis; ADI-R; ADOS	9.66	1.6	7-12	9.6	1.49	7-12	Math Reasoning WIAT-II	WASI	WMBT-C (backward digit recall)

Iuculano et al., 2014	18	18	clinical diagnosis; ADI-R; ADOS	9.6	1.64	7-12	9.59	1.53	7-12	Numerical Operation WIAT-II	WASI	WMBT-C (backward digit recall)
Iuculano et al., 2014	18	18	clinical diagnosis; ADI-R; ADOS	9.6	1.64	7-12	9.59	1.53	7-12	Math Reasoning WIAT-II	WASI	WMBT-C (backward digit recall)
Iuculano et al., 2020	16	16	clinical diagnosis; ADI-R; ADOS	9.46	1	-	9.03	1.75	-	Numerical Operation WIAT-II	WASI	WMBT-C (backward digit recall)
Iuculano et al., 2020	16	16	clinical diagnosis; ADI-R; ADOS	9.46	1	-	9.03	1.75	-	Math Reasoning WIAT-II	WASI	WMBT-C (backward digit recall)
May et al., 2013	64	60	clinical diagnosis DSM IV	9.9	1.83	7-12	9.32	1.71	7-12	Numerical Operation WIAT-II	WISC-IV	-
McCauley et al., 2018	44	36	clinical diagnosis; ADOS-2; SCQ; SRS	12.78	2.1	-	12.83	2.25	-	Numerical Operation WIAT-III	WASI-II	-
McCauley et al., 2018	44	36	clinical diagnosis; ADOS-2; SCQ; SRS	12.78	2.1	-	12.83	2.25	-	Problem Solving WIAT-III	WASI-II	-
McDougal et al., 2020	22	59	clinical diagnosis	11.1	2.91	6.08-16.00	9	1.22	6.92-11.25	Math Composite Score WIAT-II	WASI-II	-

Oliver, 2013	22	23	clinical diagnosis; ASSQ	10.36	1.8	-	11.48	1.78	-	Math Computation KTEA-II	KBIT-2	-
Oswald et al., 2016	27	27	clinical diagnosis; ADOS-2	14.88	1.68	12-17.83	14.73	1.92	12.08-17.67	Problem Solving WIAT-III	WASI-II	WRAML-2 (composite score)
Troyb et al., 2014	41	34	clinical diagnosis; ADOS	13.81	2.67	8.6-20.0	13.87	2.58	9.9-21.7	Applied Problems WJ-III	WASI	-

Note: ASD = autism spectrum disorder; TD = Typical Development; M = mean; SD = Standard Deviation; SCQ = Social Communication Questionnaire; ADI-R = Autism Diagnostic Interview Revised; ADOS =Autism Diagnostic Observation Schedule; ASSQ =Autism Spectrum Screening Questionnaire; SRS = Social Responsiveness Scale; WOND = Wechsler Objective Numerical Dimensions ; WIAT= Wechsler Individual Achievement Test; TOMA-2-SP = Test of Mathematical Abilities Second Edition-Solving Problems; MWPS =Mathematical Word Problems Solving Test; WJ-III = Woodcock-Johnson Third Edition; KTEA-II =Kaufman Test of Educational Achievement Second Edition; WASI= Wechsler Abbreviated Scale of Intelligence; KBIT-2 =Kaufman Brief Intelligence Test Second Edition WRAML-2= Wide Range Assessment of Memory and Learning; WMBT-C =Working Memory Battery Test-Children.

Table 3.3. Description of the tasks (math, intellectual functioning, and working memory tasks) used in the studies included in the meta-analysis.

	Tasks	Description of the task	Studies using this task
Math abilities	The Math Reasoning subtest of the Wechsler Individual Achievement Test, Second Edition (WIAT-II, Wechsler, 2005) and the Problem Solving subtest of the Wechsler Individual Achievement Test, Third Edition (WIAT-III, Wechsler, 2010).	The Math Reasoning subtest of the WIAT-II and the Problem Solving subtest of the WIAT-III involve solving untimed math problems, which are developmentally graded to relate to basic skills, everyday applications (time, money, etc.), geometry, and algebra. The assessor reads aloud instructions to the participant for each problem. The participant is encouraged to use scratch paper and pencil. These subtests have a mean of 100 and a standard deviation of 15 and show strong psychometric properties (for the WIAT-III mean reliability coefficient of .91, and test–retest reliability of .86.)	Math Reasoning (WIAT-II): Chen et al., 2018; Hiniker et al., 2016; Iuculano et al., 2014; Iuculano et al., 2020. Problem Solving (WIAT-III): Bullen et al., 2020; McCauley et al., 2018; Oswald et al., 2016
	The Numerical Operations subtest of Wechsler Individual Achievement Test, Second Edition (WIAT-II, Wechsler, 2005) and Third Edition (WIAT-III, Wechsler, 2010).	The Numerical Operations subtests of the WIAT-II and the WIAT-III assess participants' written arithmetic and calculation skills in an untimed condition. This subtest has a mean of 100 and a standard deviation of 15 and strong psychometric properties including a mean reliability coefficient of .93, and test–retest reliability of .89.	Numerical operations (WIAT-II): Chen et al., 2018; Hiniker et al., 2016; Iuculano et al., 2014; Iuculano et al., 2020; May et al., 2013. Numerical operations (WIAT-III): Bullen et al., 2020; McCauley et al., 2018
	The Mathematics composite score of the Wechsler Individual Achievement Test, Second Edition (WIAT-II, Wechsler, 2005).	The Mathematics composite score is calculated based on the Math Reasoning subtest and the Numerical Operations subtest and shows a mean reliability coefficient and a test-retest reliability of .95.	McDougal et al., 2020
	The Story Problems subtest of the Test of Mathematical Abilities, Second Edition (TOMA-2- SP; Brown et al. 1994).	The TOMA-2-SP is a standardized test including 25 math word problems. Participants are instructed to read word problems and show their answers, completing all the 25 items. The internal	Bae et al., 2015

		consistency reliability of the Story Problems subtest is .89 and the test–retest reliability is .85.	
	The Mathematical Word Problem Solving Test (MWPS; Griffin & Jitendra, 2009; Jitendra et al. 1998).	The MWPS test is a criterion-based arithmetic word problem measure. Participants are required to complete all 12 questions. The maximum total MWPS score is 24. The Cronbach alpha coefficients for the MWPS ranges from .80 to .91 and the test–retest reliability is .63 (Griffin & Jitendra, 2009).	Bae et al., 2015
	The Wechsler Objective Numerical Dimension (WOND; Rust, 1996).	The WOND comprises two subtests. The first subtest, Mathematical Reasoning, consists of verbal based numerical and geometric problems. The second subtest, Numerical Operations, consisted of paper-and pencil arithmetic operations of increasing difficulty. The test yields standard scores (a mean of 100 and a standard deviation of 15) for each subtest and an overall Composite Score. The test-retest reliability is .89 and .85 for mathematical reasoning and number operations, respectively.	Aagen-Murphy et al., 2015
	The Math Computation subtest of the Kaufman Test of Educational Achievement, Second Edition (KTEA-II; Kaufman & Kaufman, 2004)	In the Math Computation subtest of the KTEA-II the participants are required to solve math problems printed in a response booklet. Computation Skills includes addition, subtraction, multiplications, division operations, fractions and decimals, square roots, exponents, signed numbers, and algebra. The final scoring of the measure results in a standard score. The Math Computation subtest reported an average split-half reliability coefficient of .93.	Oliver, 2013
	The Applied Problems subtest of the Woodcock–Johnson III, Test of Achievement (WJ-III; McGrew & Woodcock, 2001)	This subtest measures a student's ability to analyze and solve math problems. Initial items require application of simple number concepts. The majority of items require a student to listen to the problem, recognize the mathematical	Troyb et al., 2014

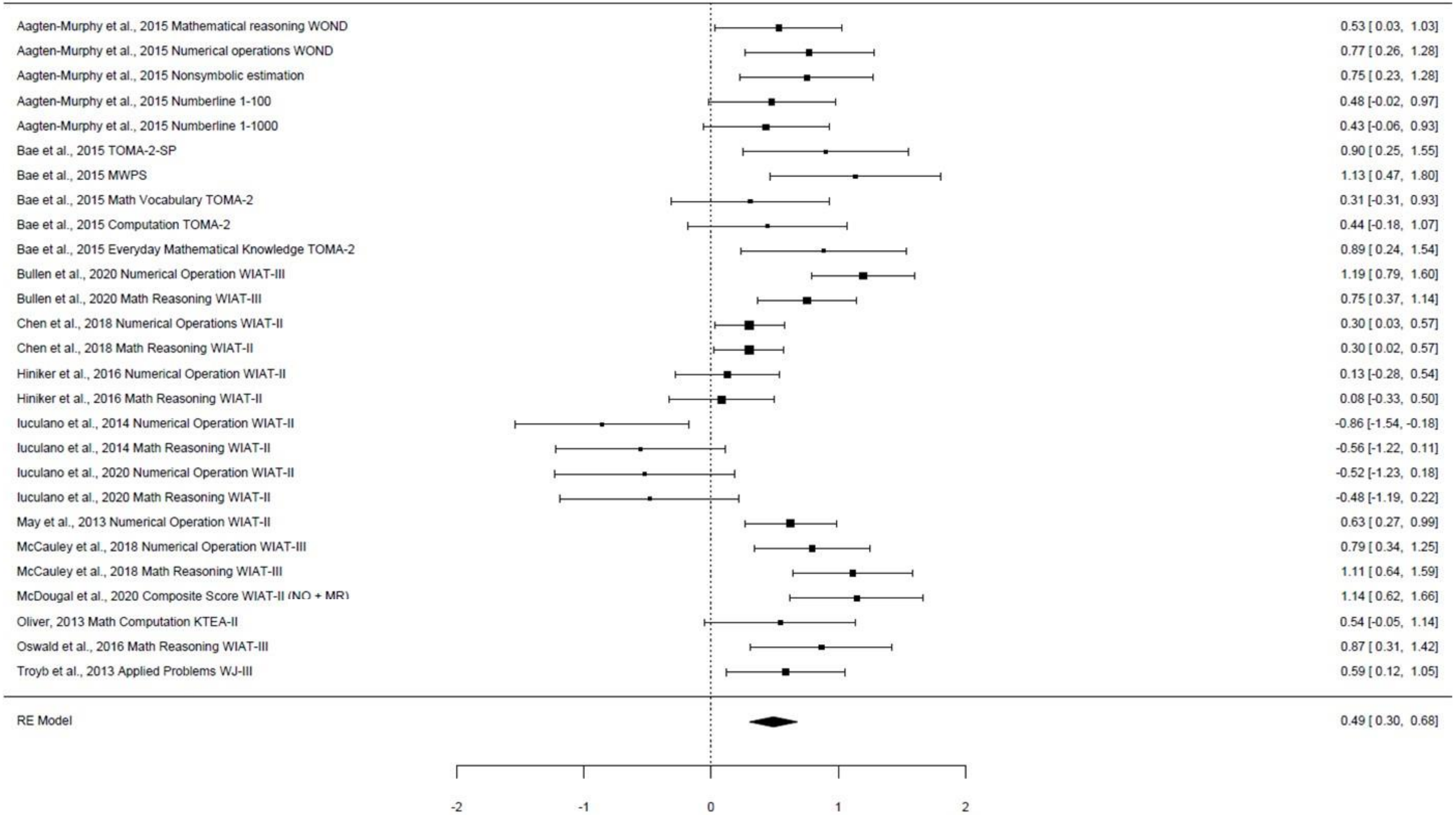
		procedure that must be followed, and perform the appropriate calculations. Woodcock et al. (2001) reported reliability coefficients, estimated by the split-half procedure, for the tests of cognitive ability as being between .60 and .96, with the majority of test reliabilities falling at .80 or higher.	
Intellectual functioning	The Wechsler Abbreviated Scale of Intelligence, First Edition (WASI, Wechsler, 1999) and Second Edition (WASI-II; Wechsler, 2011).	The WASI and the WASI-II are suitable for the evaluation of intellectual functioning in individuals aged 6–90 years. It was used to obtain an estimate of full-scale intelligence (FSIQ-4) including two subtests in the first edition (Vocabulary and Matrix Reasoning) and four subtests in the second edition (Vocabulary, Similarities, Matrix Reasoning and Block Design). This measure has good test-retest reliability for child samples (r = .96) and the FSIQ-4 scores from this measure correlate with the Wechsler Intelligence Scale for Children – Fifth Edition, r = .87 (Raiford, Zhou, & Drozdick, 2016) indicating good concurrent validity.	WASI: Aagten-Murphy et al., 2015; Chen et al., 2018; Hiniker et al., 2016; Iuculano et al., 2014; Iuculano et al., 2020; Troyb et al., 2014 WASI-II: Bullen et al., 2020; McCauley et al., 2018; McDougal et al., 2020; Oswald et al., 2016
	The Wechsler Scale of Intelligence for Children (WISC-IV; Wechsler, 2003)	The WISC-IV measures the intellectual functioning of children and adolescents between the ages of 6 and 16. The test provided a Full Scale IQ score, which correspond to an individual's overall cognitive ability based on the performance on all the subtests that are used to measure the four scales: Verbal Comprehension Index, Perceptual Reasoning Index, Working Memory Index and Processing Speed Index. The study included in the meta-analysis (May et al., 2013) reported the Verbal Comprehension Index (a measure of an individual's ability to understand, learn and retain verbal information and to use language to solve novel problems) and the Perceptual Reasoning Index (a measure of an individual's ability to understand visual	May et al., 2013

		information and to solve novel abstract visual problems). Each of these scores is set to have a mean of 100 and a standard deviation of 15. The internal consistency scores and the test-retest reliability are .97 and .93 for the Full scale IQ, .94 and .93 for the Verbal Index, .92 and .89 for the Perceptual Reasoning Index.	
	The Kaufman Brief Intelligence Test, Second Edition (KBIT-2; Kaufman & Kaufman, 2004)	The KBIT-2 is used to evaluate participants' verbal and non-verbal intellectual functioning from 4 to 90 years of age and can be administered in approximately 20 min. The test provides standardized scores (M = 100, SD = 15) and reported an internal consistency between the .80s and .90s using the split-half reliability coefficients and test–retest reliability coefficients of .88 to .93 for all ages.	Bae et al., 2015; Oliver, 2013
Working memory	The Backward Digit Recall subtest of the Working Memory Test Battery-Children (WMTB-C; Pickering & Gathercole, 2001)	Backward Digit Recall subtest of the WMTB-C is used to assess working memory capacity. Specifically, the experimenter reads aloud a list of digits and the participants are required to repeat them in the reverse order. The test-retest reliability ranges from .53 to .71.	Chen et al., 2018; Hiniker et al., 2016; Iuculano et al., 2014; Iuculano et al., 2020;
	The Wide Range Assessment of Memory and Learning, Second Edition (WRAML-2; Sheslow & Adams, 2003)	The WRAML-2 is used to assess differences in participant working memory abilities. Specifically, in the Verbal Working Memory the participants are required to recall and manipulate words, while in the Symbolic Working Memory subtest they are required to recall and manipulate letters and numbers. Oswald and co-authors (2016) calculated a composite score based on the Verbal and the Symbolic working memory subtest. Internal consistency for the subtests falls within the 0.86-0.93 range.	Bullen et al., 2020 (Verbal WM Score) Oswald et al., 2016 (Composite Score)

3.3.1 **Overall effect** (research question 3a)

Across the 13 included studies, a significant effect size was estimated, $k = 27$, $g = 0.49$, 95% CI [0.21, 0.77], $p < .001$, $\sigma_1^2 = .18$, $\sigma_2^2 =. 03$, using the random-effects model. These results suggested that in general, there is a small-to-medium difference between the mathematical performance of the group with ASD in comparison with the TD group. The *Q* statistic indicated significant heterogeneity among the studies, $Q(26)= 80.17$, $p < .001$, and the I^2 index of 67.57% indicated moderate heterogeneity. The forest plot for these analyses is shown in Figure 3.2

Figure 3.2. Forest plot for all the studies included in the meta-analysis.



3.3.2 Moderator analyses: measure-related characteristics (research question 3b)

Type of math task (numerical operations* vs. *math word problems). The type of mathematical task, coded as a dichotomous variable, was not a statically significant moderator, $k = 27$, $Q_M = 0.02$ $B = -0.01$, $p = .895$, $\sigma_1^2 = .25$, $\sigma_2^2 < .001$. This indicated that the mean difference between ASD and TD groups (i.e. the effect size) was similar for numerical operations and math word problems (a small effect size for numerical operations, $k = 9$, $g = 0.36$, 95% CI [-0.03, 0.76], $p = .073$, $\sigma_1^2 = .15$, $\sigma_2^2 = .15$; a small-to-medium effect for math word problems, $k = 11$ $g = 0.49$ [0.11, 0.78], $p = .009$, $\sigma_1^2 = .23$, $\sigma_2^2 <.001$).

Type of format (written* vs. *oral). The moderating effect of the type of format, coded as a dichotomous variable, was not statistically significant, $k = 27$, $Q_M = 0.52$, $B = 0.06$, $p = .471$, $\sigma_1^2 = .24$, $\sigma_2^2 <.001$, It indicates that the effect size was similar for written or oral tasks (effect size for written tasks, $k = 13$, $g = 0.36$, 95% CI [0.02, 0.71], $p = .041$, $\sigma_1^2 = .21$, $\sigma_2^2 = .02$; for oral tasks, $k = 8$, $g = 0.41$, 95% CI [-0.05, 0.86], $p = .078$, $\sigma_1^2 = .18$, $\sigma_2^2 = .18$).

3.3.3 Moderator analysis: sample-related characteristics (research question 3c)

Age-related differences. Age, considered as a continuous variable, was a significant moderator, $k = 27$, $Q_M = 5.17$, $B = 0.17$, $p = .023$, $\sigma_1^2 = .16$, $\sigma_2^2 <. 001$, and the increase in age of participants was associated with a larger effect sizes in mathematical measures.

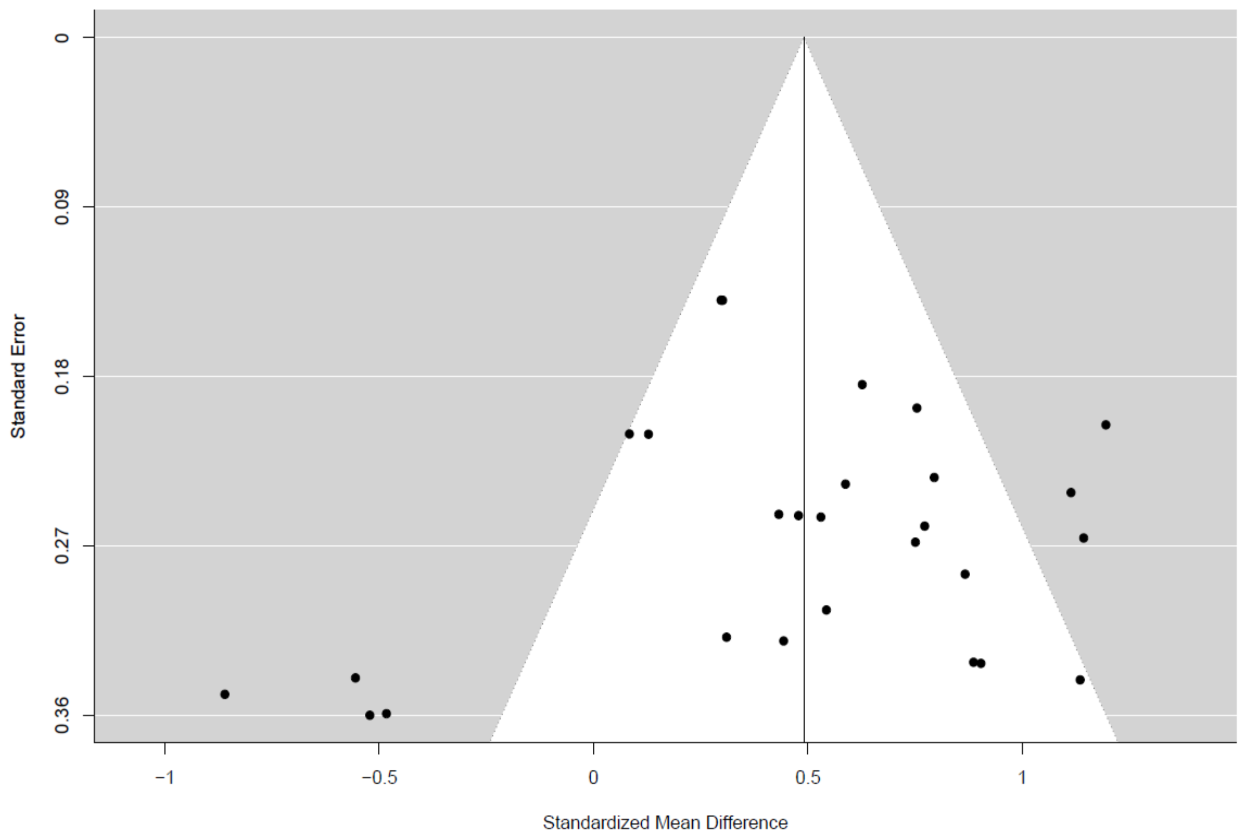
IQ-related differences. The FSIQ and the PIQ score of participants with ASD did not have a significant moderating effect (for FSIQ, $k = 24$, $Q_M = 2.01$, $B = -.0.03$, $p = .156$, $\sigma_1^2 = .24$, $\sigma_2^2 < .001$; for PIQ $k = 21$, $Q_M = 2.98$, $B = -0.05$, $p = .084$, $\sigma_1^2 =. 19$, $\sigma_2^2 < .001$), indicating that a change in FSIQ or PIQ score did not correspond to a change in the effect size in mathematical measures. Instead, the VIQ was a significant moderator, $k = 23$, $Q_M = 48.48$, $B = -0.08$ $p < .001$, $\sigma_1^2 = .002$, $\sigma_2^2 < .001$; an increase in the VIQ score corresponded to smaller effect sizes in mathematical measures.

Working memory. We explored the moderating role of WM using the standardized mean difference between the ASD and TD groups on WM measures. WM had a significant moderating role, $k = 11$, $Q_M = 13.18$, $B = 0.76$, $p < .001$, $\sigma_1^2 = .09$, $\sigma_2^2 <. 001$; an increase in the standardized mean difference between the two groups in working memory measures was associated with an increase in the effect size in mathematical measures.

Publication Bias

In Figure 3.3, the funnel plot is presented. The trim-and-fill procedure (applied to the funnel plot of the random model) did not adjust the previous results, and no asymmetry was observed in the funnel plot, with no missing studies on the left side of the graph.

Figure 3.3. Funnel plot for math measures.



3.4 Discussion

3.4.1 Autism spectrum disorder and mathematical achievement (research question 3a)

The current study aimed to investigate whether participants with ASD differed in math abilities from TD participants. As the literature on this topic is particularly inconsistent, a meta-analytic approach was adopted to provide a more precise estimate of the eventual difference between ASD and TD participants. The results showed a significant small-to-medium difference between the two groups in the performance of math tasks. This finding was in line with some previous studies (Aagten-Murphy et al. 2015; Bullen et al., 2020) showing that people with ASD are more likely to encounter difficulties in math tasks compared with their peers, but it is in contrast with the stereotype of increased mathematical proficiency among students with ASD, which has frequently been upheld in media and some descriptive studies (Baron-Cohen et al., 2007; Soulières et al., 2010).

It should be noted that this finding did not indicate a math deficit in people with ASD in an absolute sense. In fact, analyzing studies that have used standardized math tasks, the math performance of the group with ASD generally fell within the mean of the normative sample. This result is consistent with the review conducted by Chiang and Lin (2007), indicating that most students with ASD have average mathematical ability. However, people with ASD seem to show a relative deficit because their math abilities are significantly lower than those of their peers. This means that students with ASD fall significantly behind their peers. As mathematical achievement has often been related to critical academic and life outcomes (e.g., mental health, employment opportunities, amount of wage, etc.), it is very important to understand the reasons for this gap and identify which factors may impact it (Dowker, 2020).

3.4.2 Task-related moderators of math achievement in autism spectrum disorder (research question 3b)

This meta-analysis found moderate heterogeneity across studies comparing ASD and TD math abilities. Thus, the effect of potential moderating variables was investigated. Interestingly, our results suggested that the difference between the two groups in math performance was not affected by measure-related characteristics, but was significantly affected by sample-related characteristics.

Specifically, the difference between participants with ASD and TD did not vary with the type of math task, suggesting that students with ASD show similar performance on different math tasks. However, it should be noted that this result was obtained considering the two most used tasks, numerical operations, and problem solving. These two tasks may show a similar degree of complexity for students with ASD and share common features: Both tasks are generally evaluated with the corresponding subtests included in WIAT-II or WIAT-III, involve the integration of different processes (e.g., reading comprehension for arithmetic word problems or visuospatial ability for written operations) and both require cognitive flexibility to switch from one type of operation/word problem to another (Daroczy et al., 2015). However, as this result was limited to only two tasks, and not all the studies included both of them, future research should further investigate the profile of participants with ASD across different math domains, including other math tasks like number facts.

The format of the task was not a significant moderator, suggesting that the difference between the two groups was similar in oral and written tasks. As previous literature suggests, both linguistic and graphomotor skills represent areas of weakness of people with ASD (Mody et al., 2013). It could be possible that these skills have a similar impact on math performance and participants with ASD could encounter difficulties in written and oral tasks. However, it is worth noting that most written tasks coincided with numerical operation tasks, whereas most oral tasks coincided with problem-solving tasks. Thus, the results could be a reflection of the type of math task used.

3.4.3 **Sample-related moderators of math achievement in autism spectrum disorder** (research question 3c)

Sample-related characteristics played an important moderating role in explaining the difference between the two groups in math performance. Specifically, age represented a significant moderator, as well as verbal IQ and WM. Concerning the role of age, the results indicated that the difference between the group with ASD and the TD group increased with age. It is possible that, over the years, math achievement requires more abstract and conceptual learning, and therefore students with ASD may encounter more difficulties (Titeca et al., 2014). Moreover, this finding is in line with previous studies (Carrol et al., 2022; Jordan & Levine, 2009), indicating that groups of students with an initial disadvantage are more likely to lag behind their peers and that the resultant discrepancy may increase over the years. In this regard, early interventions for students with ASD are crucial to reduce this gap.

Then, the role of IQ was investigated, exploring in detail the role of full-scale IQ, performance and verbal IQ. Verbal IQ significantly moderated the role of IQ in math performance. Previous studies have shown that WISC-III and WISC-IV verbal subtests are more strongly related to academic achievement than performance subtests (Mayes & Calhoun, 2008). This finding is in line with studies investigating the influence of language on math abilities in TD children and those with ASD (Bullen et al., 2020; Desoete & Roeyers, 2005). Bullen and coauthors (2020) found that lower VIQ was related to lower mathematical achievement in ASD, and Alderson-Day (2014) suggested that early atypical language development in ASD is related to the use of inefficient strategies in verbal problem-solving tasks. Performance and full IQ did not moderate the difference in math performance between individuals with ASD and the comparison group. It should be noted that variability is lower for performance and full IQ than for verbal IQ, and the groups are often matched for nonverbal IQ, reducing between-group variability. The lack of significance for these moderators does not exclude the possibility that they affect math performance.

Crucially, our results showed that also WM represented a significant moderator. It is worth noting that most studies have used measures of verbal WM. As found in previous studies with TD participants, mental manipulation of verbal information appears to be essential for arithmetic and problem solving (Cragg et al., 2017). Furthermore, this finding strengthened the hypothesis that WM and verbal IQ may account for a significant portion of variability in math performance in individuals with ASD (Assouline et al., 2012; Bullen et al., 2020; Chen et al., 2019). However, it is also possible that visuospatial WM could explain a portion of the difference between the ASD and TD groups in math achievement; for example, visuospatial WM could play an important role in decomposition strategies in solving numerical operations but also in generating the mental representation of math word problems (Cragg et al., 2017). For this reason, studies assessing the contribution of visuospatial WM in participants with ASD are needed.

3.4.4 Limitations and Future Directions

Our findings should be interpreted in light of some limitations. In particular, as the heterogeneity across studies was moderate, it is possible that other variables, not considered in the meta-analysis, could explain this heterogeneity. In fact, there are multiple and interacting factors that significantly impact on mathematic achievement: measures characteristics, participants' characteristics, and socio-educational context.

Previous literature suggests that math abilities should be considered a multidimensional construct, and future studies should differentiate specific math components beyond the common numerical operations and word problem solving tasks, investigating, for example, geometry or arithmetic facts. In addition, only a portion of the studies included in the meta-analysis adopted a WM task and most of them used verbal WM tasks with numerical stimuli (i.e., the backward digit span task). As the impact of WM on math abilities may be different with WM tasks without numerical stimuli (Passolunghi & Siegel, 2001; Simanowski & Krajewski, 2019) or using visual WM tasks (Jones et al., 2009; Wang et al., 2022), future research should include different types of WM to better understand its role of in math abilities in students with ASD.

There are several individual factors impacting on math achievement, including cognitive processes, emotional aspects, and, in the case of our meta-analysis, individual differences on core features of autism. Math learning involves both domain-general and domain-specific abilities (Cragg et al., 2014). Domain-general processes concerned not only WM and intellectual functioning, but also other processes, for example, related to executive function. For example, low inhibitory control has been associated with lower math abilities, as it is necessary to suppress an overlearned strategy in favor of a less automatic one or ignore irrelevant data (Ng et al., 2015). People with ASD may have impaired inhibitory processes (Authors et al., 2021), but research on how executive function impacts math abilities in autism is limited (Wang et al., 2022). Similarly, a limited number of studies (Aagten-Murphy et al., 2015; Hiniker et al., 2016; Titeca et al., 2014) investigated the role of domain-specific processes on mathematics in autism, suggesting possible differences in the strength of this association in autism (e.g., in Titeca et al., 2014, verbal subitizing had a higher predictive value in children with ASD than in TD children). It could also be interesting to investigate whether considered moderators differentially contributed to a specific math domain; however, to date few studies have addressed this issue (Bullen et al., 2020; Titeca et al., 2014).

In addition to cognitive domain-general and domain-specific processes, emotional factors may impact on math performance. Math anxiety has been associated with math achievement in typical (Barroso et al., 2021) and atypical (Wu et al., 2014) populations: intrusive and negative thoughts, related with high anxiety, can interfere with WM processing, competing with the other information necessary to complete the task. However, only a study included in the meta-analysis (Oswald et al., 2016) investigated the effect of math anxiety on problem solving and thus further studies are needed.

The heterogeneity among individuals with a diagnosis of ASD could be a potential source of variability in math performance. In DSM-5, ASD is classified as a unique diagnostic group that includes individuals with different cognitive and linguistic functioning and different levels of symptom severity. Although these differences could partially explain the variability in math performance, the presence of a single diagnostic category in the DSM-5 makes it challenging to compare profiles. Exploring differences in core characteristics of autism, such as social difficulties, detail-focused processing, and restricted and repetitive behaviors (RRBs), may help to understand heterogeneity in autism in relation to mathematics. Social difficulties may reduce significant interactions in educational and familiar contexts that can help children develop math knowledge (Fleury et al., 2014). Detail-focused processing may lead to specific areas of strength in math, such as calculations, but may hamper conceptual understanding (Happè & Frith, 2006). RRBs may be associated with learning difficulties, but instructional strategies that incorporate circumscribed interests may enhance motivation and academic outcomes (Harrop et al., 2019).

Importantly, our results cannot be generalized to the entire spectrum of autism, since the studies involved participants with ASD without intellectual disabilities. Another limitation could be found in the restricted variability in the age range of participants. In fact, the studies involved participants between the ages of 6 and 16 years and no studies with older students were found. Moreover, the meta-analysis focused on academic math tasks, so participants should be over six years old; thus, math performance in preschool age was not addressed. To our knowledge, only a study with preschoolers with ASD has available data (Wang et al., 2022), but in this case, the IQ difference between the group with ASD and the TD group was quite large, highlighting the importance of investigating math learning before formal schooling in future studies.

Notably, most of the studies included in the meta-analysis did not report on the inclusion or exclusion of participants with comorbid conditions such as Attention-Deficit/Hyperactivity Disorder, Specific Learning Disorders, or Specific Language Impairments, which may affect math performance in students with ASD. Therefore, the moderating effect of comorbidities on math performance could not be estimated (Bullen et al., 2020; Ibrahim, 2020). Finally, it is worth noted that future meta-analyses could also include other databases, such as general and educational ones, that may yield more results from the literature search process.

3.4.5 Implications

Findings from the current meta-analysis suggest some practical implications. Specifically, the identification of variables moderating math abilities of people with ASD provides useful indications for assessment and educational strategies for this population. In fact, the results suggest the importance of evaluating math abilities in students with ASD and their cognitive processes by being aware of the important role of verbal intellectual functioning and WM. Collecting information on the relative strengths and weaknesses of individuals in both math abilities and cognitive processes may be of fundamental importance for implementing adequate teaching strategies and interventions. For example, given the key contribution of WM for math skills, a successful strategy would be to implement activities that reduce the cognitive load and facilitate the focus on math tasks. In teaching a new or complex math concept, it might be helpful to reduce linguistic and WM demands, create an appropriate setting and use visual aids to support students in remembering the main procedures and focusing on relevant information. This could be an effective strategy, especially for students with ASD, who, as suggested by previous studies, may have WM impairments and generally benefit from a reduction in interfering stimuli and cognitive demands, as well as the use of visual support. Moreover, the gap between students with ASD and their TD peers seems to increase with age. and this highlights the importance of implementing interventions that start as soon as possible and continue throughout the school years.

3.4.6 Conclusion

In conclusion, the meta-analysis contributes to the current literature by providing a deeper understanding of math achievement in autism. Specifically, the results show that people with ASD have poorer math skills than their TD peers and identified some of the main factors that affect this gap between the two groups. Importantly, some characteristics of participants with ASD have a significant moderating role, highlighting the importance of assessing the relative points of strength and weakness in people with ASD, strengthening the interventions that take particular account of their age, verbal intellectual functioning and WM.

4 Inhibitory Control, Working Memory and Math Abilities in autism spectrum disorder

Abstract

The current study investigated inhibitory control and working memory, and their contribution to specific math abilities, in a sample of participants with ASD (N = 33), as compared to a TD group (N = 60). The two groups aged from 6 to 20 years old and were matched for age, sex ratio and visuospatial reasoning. Concerning inhibitory control, results showed a poorer performance of the group with ASD in two of the four tasks used: the Matching Familiar Figures task (MFFT), mainly adopted to measure response inhibition, and the Flanker task, mainly adopted to measure interference control. Mediation analyses showed that basic cognitive processes partially mediated group differences on both tasks, whereas working memory partially explained group differences on MFFT. Moreover, group differences were also found in visuospatial working memory, whereas no difference in verbal working memory was found after controlling for vocabulary effect. Concerning math abilities, the group with ASD showed lower scores on all specific math measures; cognitive processes differently contributed to diverse math abilities, and vocabulary and verbal working memory were stronger associated to specific math abilities in the group with ASD than in the TD group. Findings showed that in general the group with ASD encounters more difficulties in both cognitive processes and math abilities, highlighting some of the factors underlying these differences. Implications for research and clinical assessment intervention were discussed.

4.1 The present study

The primary aim of this study was to investigate inhibitory processes, working memory and specific math abilities in a sample of participants with ASD, as compared with a TD group.

As described in the introduction, studies on inhibitory processes often reported inconsistent results (Geurts et al., 2014) with very few studies adopted both response inhibition and interference control measures (Adams & Jarrold, 2012; Christ et al., 2011; Faja et al., 2016; Geurts et al., 2014;

Weismer et al., 2018) and to date it is not clear if the deficit concerning both the two dimensions. The meta-analysis described in Chapter 2 suggested that the two IC dimensions are impaired in autism with a small-to-medium effect size; however, there is the need to investigate both response inhibition and interference control in the same sample of participants, using more than one measure for each dimension to explore eventual differences related to specific characteristics of a single task. In addition, in previous studies the possible mediating role of other cognitive processes (such as basic cognitive processes or working memory) in explaining differences between the two groups was not explored. As these processes can be impaired in people with ASD (Wang et al., 2017; Zapparrata et al., 2022) and significantly related to inhibitory control (Traverso et al., 2020), they may account for group discrepancies. Therefore, in the first part of this study, we investigate inhibitory processes, comparing a group of ASD participants and a TD group and adopting multiple measures of response inhibition and interference control; in addition, the moderator role of basic cognitive processes and working memory was explored. Specifically, we tried to answer to the following research questions:

4a. Does the group with ASD show a poorer performance than the TD group in both response inhibition and interference control measures?

4b. Are there some other cognitive processes, such as basic cognitive processes or working memory, that explain, at least to some extent, the difference between the two groups in inhibitory measures?

Then, in the second part of this study, we investigated if the group with ASD show poorer math abilities than the TD group. As reported in the introduction, studies often showed heterogeneous results (Chiang & Lin, 2007; Dowker, 2020), with some studies that found poorer math abilities in autism (Bae et al., 2015; Bullen et al., 2020), others that found no differences (Titeca et al., 2014) and still others that found better math abilities in participants with ASD (Iuculano et al., 2014, 2020). The meta-analysis described in Chapter 3 showed a statistically significant difference with a small-to-medium effect size between the two groups, with a poorer math performance in students with ASD. However, previous studies generally used one or two math tasks (mainly numerical operations and math problem solving) and, generally did not include others type of math skills, such as arithmetic facts (e.g., Bullen et al., 2020; Oswald et al., 2016). As some studies suggested that students with ASD could encounter more difficulties in more abstract and complex math tasks that mainly required conceptual knowledge (Cox & Root, 2020; Root et al., 2017), we investigated math abilities in group with ASD and in a TD group, using different tasks intended to measure specific types of math knowledge. Therefore, we adopted a battery of math tasks that included arithmetic facts, mental calculation, mathematical inferences and math problem solving tasks. It is conceivable that the participants with ASD showed more difficulties in the last two tasks (mathematical inference and math problem solving) as they are more complex tasks, requiring more conceptual knowledge than the other two tasks; in fact, arithmetic facts mainly measured factual knowledge and mental calculations mainly measured procedural math knowledge, together with factual knowledge (Cragg et al., 2017).

In addition, we examined the contribution of domain-general cognitive processes to math abilities. First, we investigated which cognitive processes (among vocabulary, response inhibition, interference control, verbal and visuospatial WM) contributed to specific math abilities, and if this association differed between the two groups. The previous meta-analysis (Chapter 3) highlighted the role of verbal working memory on explaining group's differences between the two group, but the role of visuospatial working memory and inhibitory measures remained quite unexplored (Iuculano et al., 2020). In summary, the second part of this study aimed to answer to the following research questions:

4c. Are there differences between the group with ASD and the TD group in specific math abilities? Are there relative areas of strength (e.g., arithmetic facts and mental calculations) and areas of weakness (e.g., mathematical inferences and math problem solving)?

4d. Which cognitive processes contributed to specific math abilities? Does this contribution differ between the group with ASD and the TD group?

4.2 Method

4.2.1 Participants

The study involved a group of participants with ASD and a comparison group of TD participants, composed of children, adolescents and young adults. Concerning the inclusion criteria, participants of both groups had to be over six years and scored at or above the average (Scaled Score ≥ 8) on the Matrix Reasoning subtest of the WISC-IV or the WAIS-IV. The choice to use a sample with an age older than six years is due the fact that, at this age, the two dimensions of IC should already be distinguished, although still under development (Usai et al., 2014). Concerning the group with ASD, all participants had a previous formal diagnosis of ASD according to the criteria of the Diagnostic and Statistical Manual of Mental Disorders, 5th edition or 4th edition, Text Revision (APA, 2000) or International Classification of Diseases 10th edition or 11th edition. This formal diagnosis was confirmed by a score above the ASD cut-off (T-score > 60) on the Italian version of the Social Responsiveness Scale, Second edition (SRS-2; Constantino & Gruber, 2012) and a score above the ASD cut-off on the Childhood Autism Rating Scale, Second Edition (CARS-2, Schopler et al. 2010; ASD cut-off corresponds to a score above 28 in the CARS-2-High Functioning Version and above 30 in the CARS-2-Standard Version). Concerning the TD group, only participants without any previous diagnosis and with a T-score < 60 in the SRS-2 were included.

As for the ASD group, 40 participants joined the study; however, only 33 participants were included. In fact, seven of them were excluded because they did not meet the inclusion criteria (n=3 excluded due to the lack of a formal diagnosis of ASD; n=4 excluded due to a scaled score on the Matrix Reasoning subtest ≤ 8). As for the control group, 70 participants joined the study, but we had to exclude from the statistical analysis 10 participants because five of them did not meet the inclusion criteria (n=4 had a previous diagnosis of Learning Specific Disorder, n=1 had a previous diagnosis of Attention-deficit/hyperactivity disorder) and the other five have only completed the first session.

Therefore, the final sample was composed of 93 participants (n = 33 for the group with ASD and n=60 for the TD group). As shown in Table 4.1, the two groups were matched for age and visuoperceptual reasoning measured with the Matrix Reasoning subtest; however, they significantly differed in the Vocabulary subtest (WISC-IV or WAIS-IV), where the TD group obtained higher score than the ASD group.

Table 4.1 Age, Matrix Reasoning and Vocabulary of the group with ASD and the TD group

	ASD group					**TD group**						
	N	**M**	**SD**	**Min**	**Max**	**N**	**M**	**SD**	**Min**	**Max**	**t test**	**Cohen's d**
Age	33	12.42	3.88	6.17	21.35	60	12.27	4.01	6.11	21.15	$t(91) = -0.18$, $p = .857$	-0.04
Matrix Reasoning	33	11.82	2.80	8.00	17.00	60	12.20	2.52	8.00	18.00	$t(91) = 0.67$, $p = .504$	0.15
Vocabulary	33	9.06	4.00	1	15	60	12.03	2.67	6	19	$t(91) = -4.29$, $p < .001$	0.93

4.2.2 Procedure

The study received approval from the University Research Ethics Committee (CERA) of the University of Genoa. Parents who participated in the project were asked to complete and sign the informed consent form. Furthermore, they were asked to complete the SRS-2. This study lasted two years, from November 2020 to December 2022. As the study started in November 2020, during the COVID-19 pandemic, the tasks were adapted to be administered online. This modality was used for the entire duration of the study to avoid possible effects due to administration mode. Each participant was tested individually during online video calls. Specifically, the tasks were administered in four online sessions: the first session included vocabulary, matrix reasoning and backward digit span; the second session included Matching Familiar Figures task, Navon and Go/No-go task; the third session included Mr. Peanut and Flanker task and the fourth session included four math tasks. All the tasks requiring visual materials were administered using screen sharing (Matrix Reasoning, Vocabulary, Matching Familiar Figures task). For Navon, Go/No-go, Mr. Peanut and Flanker tasks a computerized version was used, administered through E-prime Web (Navon and Go/No-go) and Inquisit Web (Mr. Peanut and Flanker); in these cases, the links were sent to participants, and they were asked to share their screen during the task. For participants with ASD, an additional in-person session was included to administer the CARS-2 that required the direct observation of participants' behavior.

4.2.3 Measures

4.2.3.1 Vocabulary and visuospatial reasoning measures

Vocabulary subtest and Matrix Reasoning of the WISC-IV (Wechsler, 2003) were administered to participants between the ages of 6 and 16 years and the same subtests of the WAIS-IV (Wechsler, 2013) were administered to participants over 16 years. Scaled scores were used.

Vocabulary (VC). It is an important indicator of Verbal Comprehension Index and measures participants' verbal fluency and concept formation, word knowledge, and word usage. In this subtest, participants are asked to define a given word. Scaled score ranged from 1 to 19. The WISC-IV Vocabulary subtest (Wechsler, 2003) was administered to participants between the ages of six and 16 years and the WAIS-IV Vocabulary subtest (Wechsler, 2013) was administered to participants over 16 years. Scaled scores were used (range 1-19).

***Matrix Reasoning (MR)*.** It is an untimed core subtest of Perceptual Reasoning Index that measures visual processing and abstract, spatial perception. Participants are shown colored matrices or visual patterns with a missing piece. The participant is asked to select the missing piece from five alternatives. The WISC-IV Matrix Reasoning subtest (Wechsler, 2003) was administered to participants between the ages of six and 16 years and the WAIS-IV Matrix Reasoning (Wechsler, 2013) was administered to participants over 16 years. Scaled score were used (range 1-19).

4.2.3.2 Response inhibition measures

Matching Familiar Figure task (MFFT; adapted from Marzocchi et al., 2010). This task is considered a measure of response inhibition because the participant is required to control the tendency to respond before evaluating which is the correct picture. In this task, a target figure and five alternatives below were shown, and the participant had to select among the five alternatives, which are quite similar to the target, the one that is identical to the target. The task involves five alternatives and is comprised of two practice items and 20 experimental items; for each item, the number of errors (the number of times in which the participant pointed at a wrong picture) was recorded (MFFT errors, expected range 0–100); in addition, the RT for the first response in each trial was recorded (MFFT RT). The test–retest reliability reported for this task in a sample of primary school children was .49 (Marzocchi et al., 2010).

Go/no-go task (Donders, 1969; Malagoli & Usai, 2018). The go/no-go is an inhibition task to assess the ability to stop an automatic response. We used a computerized version of the task in which participants had to press the space bar as fast as they could every time the go stimulus (a blue square) appeared, while they had to stop their response if any other figure was displayed (no-go stimulus). The go stimulus was displayed in 80% of the items. The task consisted of a practice phase of 20 items and a test phase of 100 items. The stimulus duration time was 2000 ms. The dependent accuracy measure was the proportion of no-go items in which participants successfully inhibited their response (Correct No-go, expected range 0–1). We also calculated the RT in the correct items (Go/no-go RT, expected range 0-2000 ms). The Cronbach's alpha reported for this task in a sample of adolescents was 0.70 (Malagoli & Usai, 2018)

4.2.3.3 Interference control measures

Flanker task. This task is considered a measure of interference control. We used a computerized version of the task where stimuli and procedures were similar to those used in previous studies (Christ et al., 2011; Rueda et al., 2004). Participants completed a series of items in which they were shown five fish in one horizontal row and are instructed to pay attention to the fish in the middle, which is the target fish. On each trial, they were asked to respond as quickly as possible as to whether the target fish was looking to the left or right, pressing the left or the right bottom respectively. The other four fish flanking the middle fish (the flankers) can either look in the same (compatible) or the opposite direction (incompatible) as the target fish. The target fish was always located in the same location (i.e., the center of the display) on every trial. For each trial, stimuli were presented until a response was made or until more than 3000 ms elapsed. Each trial was presented after 1500 ms. After an intertrial interval of 1500 ms, a new trial was presented. If a participant responded in less than 200 ms, this was considered an anticipatory error in line with Christ (2011). Children completed two practice blocks of 20 items each (in the first practice block, the target fish was presented alone, while in the second practice block the target fish and the four flanking fish were shown). After these two practice blocks, children completed a total of 120 experimental items (60 compatible and 60 incompatible items) that were randomly intermixed. At intervals of 40 items, children were offered a one-minute break. The proportion of correct responses and the response times in the incongruent and congruent items were recorded. Regarding response times, we only considered RT in the correct items (Flanker accuracy, expected range 0-1; Flanker RT, expected range-200-3000 ms). Split-half reliability ranged from 0.34 to 0.42 was reported in a sample of adolescents (Boot et al., 2019).

Navon task. We used a computerized modified version of the Navon task in which figures, and not letters, were displayed (Fontana et al., 2021). Specifically, stimuli consisted of four figures wherein a large (global) figure was composed of a small (local) version of the same (congruent) or different figure (incongruent). Congruent stimuli included a large heart made of small hearts or a large star made of small stars. There were eight items in each block (with four incongruent and four congruent stimuli presented in a random order); in the first and the third block, participants were required to identify the global figure, while in the second and the fourth block they were required to identify the local figure. The figures were printed in black and presented at the center of the screen on a white background. For each trial, stimuli were presented until a response was made. To measure interference control, the dependent measures were the proportion of correct responses and RT for incongruent items (Navon accuracy, expected range 0-1). Regarding RT, we only considered RT in the correct items. To evaluate the Navon effect, accuracy and RT for local and global condition were recorded. Cronbach’s alphas in the incongruent condition in a TD sample and in a sample of participants with Down Syndrome were 0.69. (Fontana et al., 2021).

4.2.3.4 Working Memory Measures

Backward digit span (BDS; Wechsler, 2003). The Backward digit span task requires the participant to repeat numbers in reverse order. There is no time limit for the participant to respond, but the examiner reads each number out aloud at the rate of one number per second. The task is composed of eight levels with increasing difficulty; each level was composed of two items and the number of digits to remember increases by one every level from two to nine digits. One point was given for each correct trial (Backward digit span, expected range 0-16). The WISC-IV Backward Digit Span (Wechsler, 2003) was administered to participants between the ages of six and 16 years and the WAIS-IV Backward Digit Span (Wechsler, 2013) was administered to participants over 16 years. Row scores were used (range 0-16).

Mr. Peanut. This task is considered a measure of visuospatial WM (Morra & Camba, 2009; Morra, 1994). We used a computerized version of this task. Participants were shown a character, Mr. Peanut, with a number of coloured stickers attached to different parts of his body (e.g., on the right leg, on the nose, etc.) for five seconds. Then, Mr. Peanut disappeared and reappeared without stickers. The participants had to indicate the position and the colour of the stickers as they were presented in the previous figure. There are three items per level (from 1 to 7 stickers). An item is scored as correct if the participants select the correct coloured stickers and locate them in the correct body parts. If a level is successfully mastered (at least one correct attempt per level), participants move up a level. If all 3 attempts per level fail, the test concludes. Test-retest reliability (Pearson's r) calculated in 75 TD children was .39, $p < 0.001$ (Traverso et al., 2015). The total of correct items was registered (Mr. Peanut, expected range 0-21).

4.2.3.5 Mathematical measures

To assess specific math abilities, we used four types of tasks (arithmetic facts, mental calculation, inferences and math problem solving) taken from Italian standardized mathematical batteries. Table 4.2 showed the mathematical batteries that we used according to the age of participants. Arithmetic facts and mental calculation can be administered to the entire age range of our sample, whereas inferences and math problem solving were not available for participants of high school and university. As the number of item and the level of difficulty varied with age, z scores were used for all math tasks.

Table 4.2 Math tasks used according with age.

	6-10 years	**11-14 years**	**14-18 years**	**Over 19 years**
Arithmetic facts	AC-MT 3 (Cornoldi et al., 2020	AC-MT 3 (Cornoldi et al., 2020)	MT-3 Advanced Clinical, (Cornoldi et al., 2017)	LSC-SUA (Montesano et al., 2020)
Mental calculation	AC-MT 3 (Cornoldi et al., 2020	AC-MT 3 (Cornoldi et al., 2020	MT-3 Advanced Clinical, (Cornoldi et al., 2017)	LSC-SUA (Montesano et al., 2020)
Inferences	AC-MT 3 (Cornoldi et al., 2020, available from 2nd grade)	AC-MT 3 (Cornoldi et al., 2020	-	-
Math Problem Solving	AC-MT 6-11 (Cornoldi et al., 2012, available from 3rd grade)	AC-MT 11-14 (Cornoldi et al., 2007)	-	-

Arithmetic facts (AC-MT 3, Cornoldi et al., 2020 for primary and middle school students; MT-3 Advanced Clinical, Cornoldi et al., 2017 for high school students; LSC-SUA, Montesano et al., 2020 for participants over 19 years). This test assesses the ability to memorize and retrieve arithmetic facts (i.e., whether the participant already has the information available in memory and can access it without performing calculation procedures). Participants are orally presented with simple operations, to which they must respond as quickly as possible, within three seconds. Each item can only be repeated once. The number of items and the level of difficulty vary based on the corresponding school grade. Test-retest reliability (Pearson's r) calculated in 215 TD primary and middle school students was .91. The total score was the number of correct items within time limit, transformed into z scores according to test norms for each school grade.

Mental calculation (AC-MT 3, Cornoldi et al., 2020 for primary and middle school students; MT-3 Advanced Clinical, Cornoldi et al., 2017 for high school students; LSC-SUA, Montesano et al., 2020 for participants over 19 years). This task assesses the child's ability to apply mental calculation strategies to arrive at the correct result of an operation. Participants are required to mentally solve operations presented orally, within 30 seconds. Each item can only be repeated once. Test-retest reliability (Pearson’s r) calculated in 211 TD primary and middle school students was .80 The total score was the number of correct items within time limit, transformed into z scores according to the standardized norms for each school grade.

Inferences (AC-MT 3; Cornoldi et al., 2020). This test investigates the partecipant's ability to perform inferential mathematical reasoning, their understanding of mathematical symbols, and the degree of automation of arithmetic procedures and fundamental principles. The subtest is divided into three different tasks. The first one required to solve calculation with figures (e.g., in the operation “flower + flower = 8”, the participant has to understand that one flower is equivalent to 4). In the second task, the participant had to add the missing mathematical symbol in numerical operations. In the last, the third task, there are two operations: one complete, while in the other the result is missing. Students were required to complete the calculation using the second operation as an aid. The total time available for the subscale was two minutes, one minute for the first type of the task and one minute for the other two tasks. Test-retest reliability (Pearson’s r) calculated in 198 TD primary and middle school students was .69. The total score was the number of correct items within time limit, transformed into z scores according to the standardized norms for each school grade.

Math Problem Solving (AC-MT 6-11, Cornoldi et al., 2012; AC-MT 11-14, Cornoldi et al., 2007). In this task participants had to solve arithmetic word problems, presented in a written form. During the task, they were able to write the resolution on a paper. Five math problems were administered to primary students (from 3rd to 5th grade) and ten math problems were administered to middle school students; the time limit for this task was 40 minutes for primary school and 30 minutes for middle school. Chronbach's alphas between .68 to.73 were reported in samples of primary school students. For each solution, one point was given if both the procedure and calculation were correct, and 0.5 point was given if only the procedure was correct. Z scores calculated according to the standardized norms for each school grade were used.

4.2.4 Analytic strategy

All the analyses were performed with Jamovi software, version 2.3.18. The first part of the study aimed to investigate group differences on inhibitory control and working memory (research question 4a). Descriptive statistics and correlations for cognitive variables (Matrix Reasoning, Vocabulary, working memory tasks and inhibitory tasks) were computed. As noted previously, the group with ASD and the TD group significantly differed in the vocabulary score, therefore an analysis of covariance ANCOVA was conducted including vocabulary as covariate, group as independent variable and each measure of IC and WM as dependent variables. Concerning interference control measures, we investigated the congruency effect in the Flanker task. The data were analyzed using a 2 x 2 mixed model ANOVA, with group (ASD or TD) serving as a between-subjects variable, whereas congruency (Flanker congruent or incongruent items) serving as within subject variable. The same analysis was performed for both accuracy and RT on correct items of the Flanker task. Then, we investigated the congruency and the global-local effect in the Navon task. The data were analyzed using a 2 x 2 x 2 mixed model ANOVA, with group (ASD or TD) serving as a between-subjects variable, whereas congruency (Navon congruent or incongruent items) and local-global condition (Navon local or global items) serving as within subject variable. The same analysis was performed for proportion of correct items and RT on correct items of the Navon task.

Then we investigated the role of basic cognitive processes and WM on inhibitory differences between the two groups (research question 4b). Specifically, we conducted a series of mediation to assess if these processes mediated the association between the group and the IC variable. Notably, according to a recent approach to mediation (i.e., the product of coefficients approach), a statistically significant indirect effect is considered indispensable to establish mediation, whereas a significant direct effect from independent variable to dependent variable is not a necessary condition to investigate the mediation effect (Preacher & Hayes, 2004, 2008; Zhao et al., 2010). The bootstrapping method was used (Hayes, 2022; Zhao et al., 2010). Bootstrapping with 5,000 samples was used to generate 95% bias-corrected confidence intervals (CIs). According to this approach, confidence intervals not passing through zero indicated significant effects.

In the second part of the study, descriptive statistics and correlations for math measures were reported. To assess groups' differences in math measures (research question 4c), a t-test for each math ability was conducted to compare the group with ASD and the TD group. Then, we investigated the effect of group (ASD or TD) and domain-general cognitive processes on specific math abilities and examined if the contribution of cognitive processes varied according to the group (research question 4d). To this end, we first investigated zero-order correlations (Pearson) between cognitive processes and specific math abilities. Math abilities variables were expressed in z scores, as different items were administered to different school age. To take the participants different ages into account, we calculated residual scores for each cognitive process running a series of regression analysis with age as predictor and raw score of each cognitive process as dependent variable (Giofrè et al., 2018; Giofrè & Mammarella, 2014). To determine the contribution of group and each cognitive process to specific math abilities, a series of hierarchical linear regression analyses were conducted; each math ability was used as dependent variable, whereas the independent variables were included in two three blocks: group (ASD or TD) and vocabulary in the first block, residual scores of cognitive processes (included one by one in separate regressions) in the second block, while the interaction between group and the cognitive processes was added in the third block. Before running the analysis, we verified that all the necessary assumptions of regression were met, and then, when evaluating the models, we verified there were no collinearity problems (tolerance values were greater than .50, VIF < 2, and condition indices were less than 4.2; see Chiorri, 2010; Durbin-Watson values ranged from 1.5 to 2.2; see Dillon & Goldstein, 1984).

4.3 Results

4.3.1 Descriptive statistics of working memory and inhibitory measures

Table 4.3 showed the descriptive statistics (N, mean, SD, minimum and maximum, skewness and kurtosis) of vocabulary, matrix reasoning, verbal working memory (VWM), visuospatial working memory (VSWM) and inhibitory measures for the total sample. All the participants completed Matrix Reasoning and Vocabulary subtest; for the other tasks, the percentage of missing data was under 10%, except for Go/No-go and Navon task where the percentage of missing data were higher (20.43% for the Go/no-go task, 17.20% for accuracy on Navon task) because they were administered through E-prime Web, which showed incompatibility with some operating systems. For reaction times on correct items of Navon task (missing data around 33%), we excluded participants with reaction times higher than 3 SD, as it was the only computerized task without time limit in stimuli presentation. Zero-order (Pearson) correlations and partial correlations (controlling for age) among all cognitive measures were performed (Table 4.3).

Table 4.3 Descriptive statistics of age, matrix reasoning, vocabulary, working memory and inhibitory measures in the total sample.

Variable	Task	Index	Area	N	M	SD	Min	Max	SK	K
Age	-	-	-	93	12.32	3.94	6.11	21.35	-0.65	0.50
MR	Matrix Reasoning (MR)	Scaled score	Visuospatial reasoning	93	12.06	2.62	8.00	18.00	-0.77	0.50
VC	Vocabulary (VC)	Scaled score	Vocabulary	93	10.98	3.49	1	19	0.93	0.50
BDS	Backward digit span (BDS)	N. of correct items	Verbal Working Memory (VWM)	92	7.23	2.39	0	14	-0.06	1.19
Mr. Peanut	Mr. Peanut	N. of correct items	Visuospatial Working memory (VSWM)	87	7.72	3.09	3.00	16.00	0.59	-0.01
MFFT errors	Matching Familiar Figure task (MFFT)	N. of errors	Response inhibition	89	6.71	6.18	0	26	1.21	0.94
MFFT RT	MFFT	RT at the first response	Response inhibition	85	22.49	11.07	7.47	58.83	1.21	1.43
GNG Correct Go	Go/No-go	Proportion of correct Go items	Stimuli processing	74	0.98	0.04	0.74	1.00	-4.24	19.87
GNG Correct No-go	Go/No-go	Proportion of correct No-go items	Response inhibition	74	0.86	0.14	0.28	1.00	-1.92	4.98
GNG RT	Go/No-go	RT on correct Go items	Stimuli processing	74	440.66	116.17	235.55	732.70	0.75	0.36
Flanker AC	Flanker	Proportion of accuracy on congruent items	Stimuli processing	83	0.94	0.07	0.60	1.00	-2.10	5.68
Flanker AI	Flanker	Proportion of accuracy on incongruent items	Interference control	83	866.86	278.90	404.03	1732.48	0.61	0.11
Flanker RTC	Flanker	RT on correct congruent items	Stimuli processing	83	0.98	0.04	0.70	1.00	-3.58	18.57
Flanker RTI	Flanker	RT on correct incongruent items	Interference control	83	985.51	348.94	427.50	1925.35	0.67	-0.35

Navon AC	Navon	Proportion of accuracy on congruent items	Stimuli processing	77	0.98	0.05	0.69	1.00	20.74	0.54
Navon AI	Navon	Proportion of accuracy on incongruent items	Interference control	77	0.87	0.18	0.31	1.00	1.79	0.54
Navon RTC	Navon	RT on correct congruent items	Stimuli processing	75	1263.43	520.26	572.69	2819.19	0.68	0.55
Navon RTI	Navon	RT on correct incongruent items	Interference control	62	1574.29	787.24	702.92	4163.25	1.50	0.60
Navon AC global	Navon	Proportion of accuracy on global congruent items	Stimuli processing (global condition)	77	0.98	0.07	0.63	1.00	-4.47	21.24
Navon AC local	Navon	Proportion of accuracy on local congruent items	Stimuli processing (local condition)	77	0.99	0.05	0.75	1.00	-3.62	13.13
Navon AI global	Navon	Proportion of accuracy on global incongruent items	Interference control (global condition)	77	0.91	0.18	0.00	1.00	-2.92	9.43
Navon AI local	Navon	Proportion of accuracy on local incongruent items	Interference control (local condition)	77	0.84	0.28	0.00	1.00	-2.04	3.37
Navon RTC global	Navon	RT on correct global congruent items	Stimuli processing (global condition)	76	1241.73	557.10	516.91	3274.75	1.45	2.41
Navon RTC local	Navon	RT on correct local congruent items	Stimuli processing (local condition)	75	1292.13	632.37	500.88	3020.09	1.13	0.68
Navon RTI global	Navon	RT on correct global incongruent items	Interference control (global condition)	70	1300.06	571.62	605.00	3119.59	1.30	1.49
Navon RTI local	Navon	RT on correct of local incongruent items	Interference control (local condition)	66	1813.60	1071.16	646.63	5046.75	1.61	2.43

Note: ASD = autism spectrum disorder; TD = Typical Development; M = mean; SD = Standard Deviation; SK = Skewness; K = Kurtosis; MR = Matrix Reasoning; VC = Vocabulary; BDS = Backward digit span; MFFT errors = number of errors on Matching Familiar Figures Task; MFFT RT = reaction time on Matching Familiar Figures Task; GNG Correct Go = Go/No-go Correct go items; GNG Correct No-go = Go/No-go Correct No-go items; GNG RT = Go/No-go reaction time; Flanker AC = Flanker accuracy on congruent items; Flanker AI = Flanker accuracy on incongruent items; Flanker RTC = Flanker reaction time on congruent items; Flanker RTI = Flanker reaction time on incongruent items; Navon AC = Navon accuracy on congruent items; Navon AI = Navon accuracy on incongruent items; Navon RTC = Navon reaction time on congruent items; Navon RTI = Navon reaction time on incongruent items.

Table 4.4 Zero-order (Pearson) correlations and partial correlations (low triangle), controlling for age among matrix reasoning, vocabulary, working memory and inhibitory measures in the total sample.

	RM	VC	BDS	Mr. Peanut	MFFT errors	MFFT RT	GNG Go	GNG No-go	GNG RT	Flanker AC	Flanker AI	Flanker RTC	Flanker RTI	Navon AC	Navon AI	Navon RTC	Navon RTI
RM	—	0.39***	0.38***	0.35***	-0.51***	0.29**	-0.05	0.10	-0.26*	-0.03	-0.00	-0.05	-0.09	0.05	-0.03	-0.29*	-0.31*
VC	0.39***	—	0.32**	0.28**	-0.45***	0.10	-0.00	-0.14	-0.29*	0.20	0.17	-0.12	-0.12	0.25*	0.29*	-0.35**	-0.18
BDS	0.34**	0.28**	—	0.35***	-0.35***	0.07	0.18	0.17	-0.11	0.23*	0.24*	-0.17	-0.14	0.02	0.07	-0.18	-0.22
Mr. Peanut	0.30**	0.24*	0.34**	—	-0.31**	0.03	0.13	-0.10	-0.40***	0.22	0.09	-0.16	-0.12	0.04	0.02	-0.20	-0.18
MFFT errors	-0.46***	-0.40***	-0.36***	-0.33**	—	-0.34**	-0.13	-0.08	0.39***	-0.09	-0.19	0.18	0.23*	0.01	-0.12	0.23*	0.20
MFFT RT	0.29**	0.10	0.08	0.04	-0.38***	—	0.11	0.20	0.06	0.01	0.17	-0.01	-0.14	-0.16	-0.09	0.12	0.17
GNG Go	-0.05	-0.00	0.21	0.15	-0.14	0.11	—	0.37***	-0.06	0.51***	0.45***	-0.22	-0.20	0.10	0.03	-0.07	-0.10
GNG No-go	0.10	-0.13	0.19	-0.12	-0.09	0.18	0.36**	—	0.29*	0.08	0.20	0.19	0.19	0.08	-0.01	-0.06	-0.15
GNG RT	-0.23	-0.26*	-0.12	-0.42***	0.37**	0.05	-0.06	0.26*	—	-0.16	-0.10	0.37**	0.33**	-0.22	-0.21	0.25*	0.29*
Flanker AC	-0.03	0.20	0.25*	0.25*	-0.09	0.01	0.50***	0.08	-0.18	—	0.64***	-0.36***	-0.27*	-0.02	0.03	-0.16	-0.17
Flanker AI	-0.00	0.17	0.27*	0.10	-0.21	0.16	0.44***	0.20	-0.11	0.64***	—	-0.40***	-0.41***	-0.08	0.26*	0.06	-0.02
Flanker RTC	-0.04	-0.11	-0.17	-0.17	0.18	-0.01	-0.20	0.18	0.38**	-0.33**	-0.36***	—	0.77***	0.02	-0.12	0.22	0.30*
Flanker RTI	-0.08	-0.11	-0.14	-0.12	0.23***	-0.12	-0.18	0.17	0.33***	-0.25*	-0.38***	0.79***	—	0.08	-0.09	0.14	0.22
Navon AC	0.05	0.26*	0.03	0.05	0.01	-0.16	0.10	0.09	-0.26*	-0.02	-0.09	0.02	0.09	—	0.29*	-0.30*	-0.38**
Navon AI	-0.03	0.29*	0.08	0.03	-0.13	-0.09	0.03	-0.01	-0.24*	0.03	0.25*	-0.13	-0.10	0.28*	—	0.04	-0.25
Navon RTC	-0.26*	-0.32**	-0.18	-0.21	0.23	0.11	-0.06	-0.05	0.26*	-0.15	0.05	0.22	0.14	-0.26*	0.03	—	0.74***
Navon RTI	-0.30*	-0.18	-0.24	-0.20	0.21	0.16	-0.09	-0.15	0.32*	-0.16	-0.02	0.31*	0.21	-0.35**	-0.24	0.80***	—

Note: MR = Matrix Reasoning; VC = Vocabulary; BDS = Backward digit span; MFFT errors = number of errors on Matching Familiar Figures Task; MFFT RT = reaction time on Matching Familiar Figures Task; GNG Go = Go/No-go Correct go items; GNG No-go = Go/No-go Correct No-go items; GNG RT = Go/No-go reaction time; Flanker AC = Flanker accuracy on congruent items; Flanker AI = Flanker accuracy on incongruent items; Flanker RTC = Flanker reaction time on congruent items; Flanker RTI = Flanker reaction time on *incongruent items; Navon AC = Navon accuracy on congruent items; Navon AI = Navon accuracy on incongruent items; Navon RTC = Navon reaction time on congruent items; Navon RTI = Navon reaction time on incongruent items .*p<.05. **p<.01. ***p<.001.*

4.3.2 **Group differences in working memory measures, response inhibition and interference control** (research question 4a)

To assess group differences in working memory, response inhibition measures, an analysis covariance ANCOVA was conducted, with group as independent variable, vocabulary score as covariate and each index of WM and IC measures as dependent variable. Results were shown in Table 4.6.

Concerning WM measures, a statistically significant effect of the group was found in Mr. Peanut, where the group with ASD showed a lower score than the TD group. Instead, the effect of the group on BDS did not remain statistically significant after controlling for the vocabulary score.

Concerning response inhibition, the group with ASD committed more errors in the MFFT and showed longer RTs at the first response than the TD group. Instead, no difference was found in the inhibitory index of the Go/No-task, i.e., the proportion of correct No-go items (commission errors). However, a statistically significant difference was found in the proportion of correct Go items and in the Go/No go RT, an index generally considered as a non-inhibitory basic process, where the group with ASD was less accurate than the TD group. Vocabulary score had a statistically significant effect on MFFT errors, but not on the Go/No-go indices.

Concerning interference control measures, an analysis of covariance ANCOVA was first conducted to investigate the effect of group and the eventual effect of vocabulary. Differences between the groups were found in proportion of correct on congruent and incongruent items in the Flanker task. Vocabulary score had not a statistically significant effect.

Table 4.6. Descriptive statistics of working memory and inhibitory measures in the group with ASD and the TD group and ANCOVA results.

	ASD					TD					ANCOVA			
Task	**N**	**M**	**SD**	**Min**	**Max**	**N**	**M**	**SD**	**Min**	**Max**	**Group effect**	**Effect size**	**Vocabulary effect**	**Effect size**
BDS	32	6.47	2.72	0	13	60	7.63	2.11	4	14	F(1,89)=2.89 *p*=.093	η^2_p= .03	F(1,89)=0.84; *p* =.363	η^2_p=.01
Mr. Peanut	28	6.50	2.90	3.00	13.00	59	8.31	3.03	3.00	16.00	F(1,84)=5.57 *p*=.021	η^2_p= .06	F(1,80)=0.01; *p* =.905	η^2_p<.001
MFFT errors	31	9.32	8.05	0	26	58	5.31	4.37	0	18	F(1,86)= 4.16; *p*=.045	η^2_p= .05	F(1,86)= 3.95; *p* =.05	η^2_p= .04
MFFT RT	28	26.12	11.83	11.82	58.83	57	20.71	10.32	7.47	56.59	F(1,82)= 8.83; *p*=.004	η^2_p= .10	F(1,82)= 5.50; *p* =.021	η^2_p= .06
GNG Go	24	0.97	0.06	0.74	1.00	50	0.99	0.03	0.82	1.00	F(1,71)=6.22; *p*=.015	η^2_p= .08	F(1,71)= 2.12; *p* =.15	η^2_p= .03
GNG No-Go	24	0.88	0.17	0.28	1.00	50	0.86	0.12	0.36	1.00	F(1,71)=0.09; *p*=.769	η^2_p<.001	F(1,71)= 2.62; *p* =.11	η^2_p= .04
GNG RT	24	491.83	140.75	281.48	732.70	50	423.35	101.87	235.55	727.69	F(1,71)=4.15; *p*=.045	η^2_p= .06	F(1,71)=0.02; *p* =.890	η^2_p<.001
Flanker AC	27	0.96	0.07	0.70	1.00	56	0.99	0.02	0.93	1.00	F(1,80)=7.41 *p*=.008	η^2_p= .08	F(1,80) <.001; *p* =.962	η^2_p<.001
Flanker AI	27	0.90	0.10	0.60	1.00	56	0.96	0.05	0.77	1.00	F(1,80)=10.9 *p*=.001	η^2_p= .12	F(1,80)=0.19; *p* =.664	η^2_p<.001
Flanker RTC	27	922.46	323.76	439.97	1732.48	56	840.05	253.32	404.03	1456.93	F(1,80)=2.23 *p*=.140	η^2_p= .03	F(1,80)=0.74; *p* =.393	η^2_p=.01
Flanker RTI	27	1039.26	377.92	513.97	1813.17	56	959.60	334.54	427.50	1925.35	F(1,80)=1.25 *p*=.267	η^2_p= .02	F(1,80)=0.34; *p* =.562	η^2_p<.001
Navon AI	25	0.80	0.21	0.31	1.00	52	0.91	0.16	0.31	1.00	F(1,74)=3.26 p=.075	η2p= .04	F(1,74)=1.21; p =.274	η2p=.02
Navon RTI	16	1672.03	673.77	715.00	2954.11	46	1540.30	827.16	702.92	4163.25	F(1,59)=0.29 p=.594	η2p<.001	F(1,59)=0.01; p =.941	η2p<.001

Note: ASD = autism spectrum disorder; TD = Typical Development; M = mean; SD = Standard Deviation; SK = Skewness; K = Kurtosis; MR = Matrix Reasoning; VC = Vocabulary; BDS = Backward digit span; MFFT errors = number of errors on Matching Familiar Figures Task; MFFT RT = reaction time on Matching Familiar Figures Task; GNG Go = Go/No-go Correct go items; GNG No-go = Go/No-go Correct No-go items; GNG RT = Go/No-go reaction time; Flanker AC = Flanker accuracy on congruent items; Flanker AI = Flanker accuracy on incongruent items; Flanker RTC = Flanker reaction time on congruent items; Flanker RTI = Flanker reaction time on incongruent items; Navon AC = Navon accuracy on congruent items; Navon AI = Navon accuracy on incongruent items; Navon RTC = Navon reaction time on congruent items; Navon RTI = Navon reaction time on incongruent items.

4.3.2.1 Group differences and congruency effect in the Flanker task

Concerning accuracy on Flanker task, a main effect of congruency was evident, with participants generally less accurate in the incongruent condition, as compared to the congruent condition [F(1, 81) = 37.86, p <.001, $\eta^2_p = 0.32$]. Also a main effect group was statistically significant, indicating that the group with ASD a lower accuracy [F(1,81) = 12.43, p <.001, $\eta^2_p = 0.13$]. The interaction between group and congruency was statistically significant [F(1, 81) = 4.62, p = .035 $\eta^2_p = 0.05$]; Bonferroni post hoc tests indicated that the congruency effect was evident in both the group with ASD [t(1, 81) = 5.05, <.001] and the TD group [t(1, 81) = 3.51, p =.004]; in addition the ASD group was less accurate than the TD group in both congruent [t(1, 81) = 2.93, p =.026] and incongruent condition [t(1, 81) = 3.40, p =.006].

Concerning RT, a main effect of congruency was evident, with participants generally slower to respond in the incongruent condition, as compared to the congruent condition [F(1,81) = 44.79, p <.001, $\eta^2_p = 0.36$]. However, the main effect group was not statistically significant, indicating that overall RT did not differ between the group with ASD and the TD group [F(1,81) = 1.17, p = 0.262 $\eta^2_p = 0.02$]. Also, the interaction between group and congruency was not statistically significant, indicating that the two groups did not differ in RT in both congruent and incongruent condition [F(1,81) = 0.01, p = 0.938, $\eta^2_p < 0.001$].

In summary, both the group with ASD and the TD group showed a lower accuracy in the incongruent condition than in the congruent one and the ASD group was less accurate than the TD group in both congruent and incongruent condition of the Flanker task. Instead, no groups differences were found in RT, where participants of the two groups generally were slower in incongruent condition than in congruent condition.

4.3.2.2 Group differences, congruency and global-local effect in the Navon task

Concerning accuracy, a main effect of congruency was evident, with participants generally less accurate in the incongruent condition, as compared to the congruent condition (F(1, 75) = 40.29,

$p < .001$, $\eta^2_p = 0.35$). Also a main effect of group was statistically significant, indicating that the group with ASD showed an overall lower accuracy (F(1,75) = 5.42, $p = .023$, $\eta^2_p = 0.07$). Instead, the main effect of global local condition was not statistically significant, with no difference in accuracy between global and local condition (F(1,75) = 1.82, $p = .182$, $\eta^2_p = 0.02$) and also the interaction between group and global local condition was not statistically significant, indicating that the effect of group was similar in the global and local condition (F(1,75) = 0.88, $p =.350$, $\eta^2_p = 0.01$). There was a statistically significant interaction between group and congruency (F(1,75) = 6.89, $p = .011$ $\eta^2_p = 0.08$); however, Bonferroni post hoc tests showed the accuracy was lower in incongruent condition than in congruent condition in both the group with ASD (t(1, 75) = 5.46, $p <.001$) and TD group (t(1, 75) = 2.27, $p =.010$). in addition, no group differences in congruent (t(1, 75) = 0.16, $p = 1.000$) and also in incongruent condition (t(1, 75) = 2.55, $p =.077$) were found.

Concerning RT, a main effect of congruency was evident, with participants generally were slower in the incongruent condition, as compared to the congruent condition (F(1, 57) = 27.37, $p <.001$, $\eta^2_p = 0.32$). The effect group was not statistically significant, indicating that there was no groups differences in overall RT (F(1, 57) = 2.75, $p = .103$, $\eta^2_p = 0.05$). Also the main effect of global local condition was not statistically significant, with no difference in RT between global and local condition (F(1, 57) = 0.64, $p = .426$, $\eta^2_p = 0.01$). However, there was a statistically significant interaction between congruency and global local condition, with post hoc test indicating slower RT in incongruent local items than in congruent local items (t(1, 57) = -5.07, $p <.001$) but this effect of congruency was not evident in global items (t(1, 57) = -2.55, $p = .082$). In addition, there was also a statistically significant interaction between group and global local condition (F(1, 57) = 6.63, $p = .013$, $\eta^2_p = 0.10$) and Bonferroni post hoc tests showed that the group with ASD was slower than the TD group in the global condition (t(1, 57) = -3.50, $p = .006$); no group differences were found in the local condition (t(1, 57) = -0.09, $p = 1.00$). the TD group was slower in the local condition than in the global condition (t(1, 57) = -3.24, $p =.012$), but this global-local difference was not found in the group with ASD (t(1, 57) = 1.04, $p = 1.00$).

In summary, participants showed lower accuracy in the incongruent condition than in the congruent one and the ASD group was less accurate than the TD group in both congruent and incongruent condition of the Navon task; no difference in accuracy between global and local condition was found. Moreover, participants showed slower RT in the incongruent condition than in the congruent one; instead, no difference between the ASD and TD was found in overall RT, as well as no difference between global and local condition. However, interaction effects showed that the group with ASD was slower than the TD group in global condition and there was a congruency effect only in local condition and not in global condition.

4.3.3 **Mediation Analyses** (research question 4b)

4.3.3.1 The mediating role of basic cognitive processes in group differences in response inhibition and interference control

In the following mediation analyses we investigate the associations between group and response inhibition (MFFT errors) and between group and interference control (Flanker accuracy on incongruent items), using basic cognitive processes (Go-No/Go RT on correct items for response inhibition and Flanker accuracy on congruent items for interference control, respectively) as mediators.

The first mediation analysis was performed to investigate if the association between group (ASD or TD) and response inhibition (MFFT errors) was moderated by a basic cognitive process (Go/No-Go RTs). Therefore, in the model we entered group as independent variable, GNG RT as moderator and MFFT errors as dependent variable. As reported in Table 4.6, group was significantly associated with GNG RT (path *a*), which in turn was significantly associated with MFFT errors (path *b*). As shown in Table 4.7, the direct effect of group on MFFT errors was statistically significant (path *c*), and there was also a statistically significant indirect effect (a*b) of group on MFFT errors mediated by GNG RT. Thus, the group with ASD committed more errors on MFFT and this association was partially mediated by longer RT in the Go/No-go task. Age significantly contributed to GNG RT and MFFT errors.

Table 4.6. Path estimates of mediation analysis (Group – GNG RT – MFFT errors), controlling for age.

			Label	**b (95% BCBCI)**	***SE***	**β**
Group	→	GNG RT	*a*	74.10 (16.94, 132.64)	29.84	0.29
GNG RT	→	MFFT errors	*b*	0.02 (0.01, 0.03)	0.01	0.37
Group	→	MFFT errors	*c*	2.84 (0.01, 6.26)	1.58	0.22
Age	→	GNG RT	-	-16.62 (-21.99, -10.68)	2.91	-0.52
Age	→	MFFT errors	-	-0.35 (-0.76, -0.01)	0.19	-0.22

Note: BCBCI =bias-corrected bootstrap confidence interval; bestimate; SE = Standard error; β = standardized estimate; MFFT errors = number of errors on Matching Familiar Figures Task; GNG RT = Go/No-go reaction time;

Table 4.7. Direct, indirect and total effect of mediation analysis (Group – GNG RT – MFFT errors), controlling for age.

	Label	**b (95% BCBCI)**	***SE***	**B**
Direct effect	*C*	2.84 (0.01, 6.26)	1.58	0.22
Indirect effect	*a*b*	1.38 (0.25, 3.38)	0-78	0.11
Total effect	*c + a*b*	4.22 (1.68, 6.75)	1.29	0.33

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate.

The second mediation analysis was performed to investigate if the association between group (ASD or TD) and interference control (Flanker AI, accuracy on incongruent items) was moderated by a basic cognitive process (Flanker AC, accuracy on congruent items). Therefore, in the model we entered Group as independent variable, Flanker AC as moderator and Flanker AI as dependent variable. As reported in Table 4.8, group was significantly associated with Flanker AC (path *a*), and Flanker AC was significantly associated with Flanker AI (path *b*). As shown in Table 4.9, the direct effect of group on Flanker AI was statistically significant (path *c*), and there was also a statistically significant indirect effect (a*b) of group on Flanker AI mediated by Flanker AC. Thus, the group with ASD was less accurate on Flanker AI and this association was partially mediated by a lower accuracy on Flanker AC. Age significantly contributed to Flanker AC but not to Flanker AI.

Table 4.8. Path estimates of mediation analysis (Group - Flanker AC - Flanker AI), controlling for age.

			Label	**b (95% BCBCI)**	***SE***	**β**
Group	→	Flanker AC	*a*	-0.03 (-0.06, -0.01)	0.01	-0.32
Flanker AC	→	Flanker AI	*b*	1.03 (0.45, 1.31)	0.21	0.61
Group	→	Flanker AI	*c*	-0.03 (-0.05, -0.01)	0.01	-0.17
Age	→	Flanker AC	-	<.001 (0; 0.01)	<.001	0.29
Age	→	Flanker AI	-	<.001 (-.001; <.001)	<.001	0.10

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate; Flanker AC = Flanker accuracy on congruent items; Flanker AI = Flanker accuracy on incongruent item.

Table 4.9. Direct, indirect and total effect of mediation analysis (Group - Flanker congruent-Flanker incongruent), controlling for age.

	Label	**b (95% BCBCI)**	***SE***	**β**
Direct effect	*C*	-0.03 (-0.05, -0.01)	0.01	-0.17
Indirect effect	*a*b*	-0.03 (-0.07, -0.01)	0.02	-0.20
Total effect	*c + a*b*	-0.06 (-0.09, -0.03)	0.02	-0.37

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate.

4.3.3.2 **The mediating role of visuospatial working memory in group differences in response inhibition and interference control.**

In the following mediation analyses we investigate the associations between group and response inhibition (MFFT errors) and between group and interference control (Flanker AI, accuracy on incongruent items), entering VSWM (Mr. Peanut) as mediator.

The third mediation analysis was performed to investigate if the association between group (ASD or TD) and response inhibition (MFFT errors) was moderated by VSWM (Mr. Peanut, number of correct items), controlling for age. Therefore, in the model we entered group as independent variable, Mr. Peanut as moderator, MFFT errors as dependent variable and age was entered as covariate. As reported in Table 4.10, group was significantly associated with Mr. Peanut (path *a*) and Mr. Peanut in turn was significantly associated with MFFT errors (path *b*). The direct effect of group on MFFT errors was significant (path *c)*. As shown in Table 4.11, there was also a statistically significant indirect effect (a*b) of group on MFFT errors mediated by Mr. Peanut. Thus, the group with ASD committed more errors on MFFT and this association was partially mediated by a lower score on VSWM (Mr. Peanut). Age significantly contributed to both Mr. Peanut and MFFT.

Table 4.10. Path estimates of mediation analysis (Group - Mr. Peanut – MFFT errors), controlling for age.

			Label	**b (95% BCBCI)**	***SE***	**B**
Group	→	Mr. Peanut	*A*	-2.24 (-3.37, -1.08)	0.58	-0.33
Mr. Peanut	→	MFFT errors	*B*	-0.53 (-1.04, -0.13)	0.23	-0.28
Group	→	MFFT	*C*	3.02 (0.43, 5.85)	1.38	0.24
Age	→	Mr. Peanut	-	0.43 (0.29, 0.57)	0.07	0.55
Age	→	MFFT errors	-	-0.44 (-0.76, -0.13)	0.16	-0.30

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate; MFFT errors = number of errors on Matching Familiar Figures Task.

Table 4.11. Direct, indirect and total effect of mediation analysis (Group – Mr. Peanut -MFFT errors), controlling for age.

	Label	**b (95% BCBCI)**	***SE***	**B**
Direct effect	*c*	-0.05 (-0.9, -0.02)	0.02	-0.35
Indirect effect	*a*b*	1.18 (0.38, 2.69)	0.55	0.09
Total effect	*c + a*b*	4.19 (1.91, 6.47)	1.16	0.33

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate.

The fourth mediation analysis was performed to investigate if the association between Group (ASD or TD) and interference control (Flanker AI, accuracy on incongruent items) was moderated by VSWM (Mr. Peanut, number of correct items), controlling for age. Therefore, in the model we entered group as independent variable, Mr. Peanut as moderator, Flanker AI as dependent variable and age was entered as covariate. As reported in Table 4.12, group was significantly associated with Mr. Peanut (path *a*), but Mr. Peanut was not significantly associated with Flanker AI (path *b*). As shown in Table 4.13, the direct effect of group on Flanker AI was statistically significant (path *c*), but there was not a statistically significant indirect effect (a*b) of group on Flanker AI mediated by Mr. Peanut. Age significantly contributed to both Mr. Peanut and Flanker AI.

Table 4.12 Path estimates of mediation analysis (Group - Mr. Peanut – Flanker AI), controlling for age.

			Label	b (95% BCBCI)	*SE*	β
Group	→	Mr. Peanut	*a*	-2.07 (-3.22, -0.85)	0.60	-0.31
Mr. Peanut	→	Flanker AI	*b*	<.001 (-0.01,0.01)	<.001	-0.03
Group	→	Flanker AI	*C*	-0.05 (-0.9, -0.02)	0.02	-0.35
Age	→	Mr. Peanut	-	0.43 (0.28-0.56)	0.07	0.54
Age	→	Flanker AI	-	0.01 (0-0.01)	<.001	0.28

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate; Flanker AI = accuracy on incongruent items in Flanker task.

Table 4.13. Direct, indirect and total effect of mediation analysis (Group – Mr. Peanut -Flanker AI), controlling for age.

	Label	b (95% BCBCI)	*SE*	β
Direct effect	*c*	-0.05 (-0.9, -0.02)	0.02	-0.35
Indirect effect	*a*b*	<.001 (-0.01, 0.02)	0.01	0.01
Total effect	*c + a*b*	-0.05 (-0.08, -0.02)	0.02	-0.34

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate.

4.3.4 Serial mediation analyses: the mediating role of basic cognitive processes and visuospatial working memory in group differences in response inhibition and interference control.

The first serial mediation analysis was performed to investigate if the association between Group (ASD or TD) and response inhibition (MFFT errors) was moderated by basic processes (Go/No-go RT on correct items) and VSWM (Mr. Peanut, number of correct items), controlling for age. Therefore, in the model we entered group as independent variable, Go/No-go RT and Mr. Peanut as moderators, MFFT errors as dependent variable and age was entered as covariate. As reported in Table 4.14, group was significantly associated with Go/No-go RT (path a_1) and Go/No-go RT in turn was associated with MFFT errors (path b_1). As shown in Table 4.15, in this first pathway no indirect effect emerged and thus the association between Group and MFFT errors was not mediated by Go/No-go RT ($a_1 * b_1$). Concerning the second pathways, group was associated with Mr. Peanut (path a_2), and Mr. Peanut was significantly associated with MFFT errors (path b_2). In this pathway, an indirect effect was found and thus the association between Group and MFFT errors was mediated by Mr Peanut ($a_2 * b_2$). In addition, the path between the two moderators ($d_{1,2}$), from Go/No-go RT to Mr. Peanut, was statistically significant and there was a serial indirect effect suggesting that the effect of group on MFFT errors was mediated by Go/No-go RT through Mr. Peanut. The direct effect of group on MFFT errors was statistically significant (path *c*).

Table 4.14. Path estimates of serial mediation analysis (Group – Go/No-go RT- Mr. Peanut – MFFT errors), controlling for age.

			Label	**b (95% BCBCI)**	***SE***	**B**
Group	→	Go/No-Go RT	a_1	82.56 (19.12, 152.13)	33.31	0.31
Go/No-Go RT	→	MFFT errors	b_1	0.01 (<.001, 0.03)	0.01	0.25
Group	→	Mr. Peanut	a_2	-2.13 (-3.45, -0.67)	0.70	-0.32
Mr. Peanut	→	MFFT errors	b_2	-0.55 (-1.22, -<.001)	0.31	-0.29
Go/No-Go RT	→	Mr. Peanut	$d_{1,2}$	-0.01 (-0.01, -<.001)	<.001	-0.32
Group	→	MFFT errors	*c*	1.91 (-1.11, 5.67)	1.73	0.15
Age	→	Go/No-Go RT	-	-16.56 (-22.17, -10.65)	2.92	0.53
Age	→	Mr. Peanut	-	0.35 (0.18, 0.51)	0.09	0.45
Age	→	MFFT errors	-	-0.11 (-0.52, 0.32)	0.21	-0.08

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate; MFFT errors = number of errors on Matching Familiar Figures Task.

Table 4.15. Direct, indirect and total effect of serial mediation analysis (Group – Go/No-go RT- Mr. Peanut -MFFT errors), controlling for age.

	Label	**b (95% BCBCI)**	***SE***	**B**
Direct effect	*C*	1.91 (-1.11, 5.67)	1.73	0.15
Indirect effect $_1$	a_1*b_1	0.99 (-0.06, 2.90)	0.74	0.08
Indirect effect $_2$	a_2*b_2	1.17 (0.13, 2.92)	0.68	0.09
Indirect effect $_3$	$a_1*b_2*d_{12}$	0.36 (0.02, 1.56)	0.34	0.03
Total effect	$c + a*b + a_2*b_2\, a_1*b_2*d_{12}$	-4.43 (1.80, 7.06)	1.34	0.36

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate.

The second serial mediation analysis was performed to investigate if the association between Group (ASD or TD) and interference control (Flanker AI, accuracy on incongruent items) was moderated by basic processes (Flanker AC, accuracy on congruent items) and VSWM (Mr. Peanut, number of correct items), controlling for age. Therefore, in the model we entered Group as independent variable, Flanker AC and Mr. Peanut as moderators, Flanker AI as dependent variable and age was entered as covariate. As reported in Table 4.16, group was significantly associated with Flanker accuracy on congruent items (path a_1) and Flanker AC was associated with Flanker AI (path b_1). As shown in Table 4.17, in this first pathway an indirect effect emerged and thus the association between group and Flanker AI was mediated by Flanker AC ($a_1 * b_1$). Concerning the second pathway, group was associated with Mr. Peanut (path a_2), but Mr. Peanut was not significantly associated with Flanker AI (path b_2). No indirect effect was found. In addition, the path ($d_{1,2}$) from Flanker congruent to Mr. Peanut was not significant and no serial indirect effect was found. The direct effect of group on Flanker AI was statistically significant (path c).

Table 4.16. Path estimates of serial mediation analysis (Group – Flanker AC - Mr. Peanut – Flanker AI), controlling for age.

			Label	**b (95% BCBCI)**	***SE***	**B**
Group	→	Flanker AC	a_1	-0.03(-0.06 –0.01)	0.01	-0.31
Flanker AC	→	Flanker AI	b_1	1.05 (0.47, 1.36)	0.22	0.64
Group	→	Mr. Peanut	a_2	-1.79 (-3.07, -0.46)	0.66	-0.27
Mr. Peanut	→	Flanker AI	b_2	-<.001 (-0.01, <.001)	<.001	-0.15
Flanker AC	→	Mr. Peanut	$d_{1,2}$	9.52 (-2.24, 25.44)	6.80	0.13
Group	→	Flanker AI	c	-0.03 (-0.06, -<.001)	0.01	-0.19
Age	→	Flanker AC	-	<.001 (<.001, 0.01)	<.001	0.29
Age	→	Mr. Peanut	-	0.40 (0.25, 0.54)	0.07	0.50
Age	→	Flanker AI	-	<.001 (<.001, 0.01)	<.001	0.26

Note: BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate; Flanker AI = accuracy on incongruent items in Flanker task; Flanker AC = accuracy on congruent items in Flanker task

Table 4.17. Direct, indirect and total effect of serial mediation (Group – Flanker AC - Mr. Peanut – Flanker AI), controlling for age.

	Label	**b (95% BCBCI)**	***SE***	**B**
Direct effect	c	-0.03 (-0.06, -<.001)	0.01	-0.19
Indirect effect $_1$	$a_1 * b_1$	-0.03 (-0.07, -0.01)	0.02	-0.20

Indirect effect $_2$	a_2*b_2	0.01 (-<.001, 0.03)	0.01	0.04
Indirect effect $_3$	$a_1*b_2*d_{12}$	<.001 (-<.001, <.001)	<.001	-0.01
Total effect	$c + a*b + a_2*b_2\ a_1*b_2*d_{12}$	-0.05 (-0.08, -0.02)	0.02	-0.34

BCBCI =bias-corrected bootstrap confidence interval; b = unstandardized estimate; SE = Standard error; β = standardized estimate

4.3.5 Descriptive statistics and zero-order correlations of specific math abilities

Table 4.18 showed the descriptive statistics (N, mean, SD, minimum and maximum, skewness and kurtosis) of mathematical measures for the total sample; All the scores were normally distributed, arithmetic fact, with z scores ranging from -3.50 to 1.81. Arithmetic facts and mental calculation were administered to all the 77 participants involved in the fourth session of the study, whereas the numerosity were lower for inferences and math problem solving as these tasks were administered to participants from the second (inferences) or third grade (math problem solving) of primary school to the third grade of middle school. In Table 4.19 zero-order (Pearson) correlations among these variables were reported. High correlations among all math measures were found, with values ranging from 0.58 to 0.85.

Table 4.18 Descriptive statistics of math measures.

Task	Index	N	M	SD	Min	Max	SK	K
Arithmetic facts	Accuracy (z scores)	77	-0.42	1.25	-3.50	1.36	-0.69	-0.35
Mental Calculation	Accuracy (z scores)	77	-0.20	1.23	-2.71	1.81	-0.33	-1.14
Inferences	Accuracy (z scores)	55	-0.53	1.35	-2.84	1.71	-0.12	-1.16
Math problem solving	Accuracy (z scores)	45	-0.74	1.17	-2.53	1.58	0.28	-0.86

Table 4.19 Zero-order (Pearson) Correlations of specific math abilities.

	Arithmetic Facts	Mental Calculation	Mathematical Inferences	Math Problem Solving
Arithmetic Facts	-	0.77***	0.85***	0.69***
Mental Calculation		-	0.66***	0.58***
Mathematical Inferences			-	0.78***

Math Problem Solving									-

. *p<.05. **p<.01. ***p<.001.

4.3.6 Group Differences on specific math abilities (research question 4c)

To assess group differences on each math ability, a t-test was conducted to compare the group with ASD and the TD group. Results are reported in Table 4.20; the group with ASD showed lower scores on all the math measures.

Table 4.20. Specific math abilities of the group with ASD and the TD group

	ASD group					TD group						
Task	**N**	**M**	**SD**	**Min**	**Max**	**N**	**M**	**SD**	**Min**	**Max**	**t test**	**Cohen's d**
Arithmetic facts	25	-1.66	1.20	-3.50	1.09	52	0.18	0.71	-1.35	1.36	t (75) = 7.07 ***	2.04
Mental Calculation	25	-1.32	1.10	-2.71	1.17	52	0.34	0.88	-1.73	1.81	t (75) = 7.14 ***	1.74
Inferences	21	-1.66	1.22	-2.84	1.71	34	0.17	0.88	-1.91	1.55	t (75) = 6.41***	1.78
Math problem solving	18	-1.58	0.99	-2.53	1.37	27	-0.17	0.92	-1.46	1.58	t (75) = 4.91 ***	1.49

Note: ASD = autism spectrum disorder; TD = Typical Development; M = mean; SD = Standard Deviation. *p<.05. **p<.01. ***p<.001.

4.3.7 Zero Order (Pearson) correlations between math abilities and domain-general cognitive processes

Table 4.21 showed zero-order (Pearson) correlations between specific math abilities and domain-general processes. Most cognitive variables were statistically significant correlated with all considered specific math abilities; in particular, vocabulary, VWM, VSWM, MFFT errors, Flanker AI, were significantly correlated with Arithmetic Facts, Mental Calculation, Mathematical Inferences and Math Problem Solving. Navon AI was significantly correlated with Arithmetic Facts and Mental Calculation and Matrix Reasoning was significantly correlated with Math Problem Solving. No significantly correlations were found between Go/No-go and math abilities, as well as between RT indices of inhibitory measures (MFFT RT, Flanker RTI and Navon RTI).

Table 4.21. Zero-order (Pearson) correlations among specific math abilities and domain-general cognitive processes.

	Arithmetic Facts	Mental Calculation	Mathematical Inferences	Math Problem Solving
Matrix Reasoning	0.22	0.17	0.17	0.29*
Vocabulary	0.39 ***	0.27*	0.36**	0.54***
BDS	0.35**	0.44***	0.36**	0.46**
Mr. Peanut	0.27*	0.39**	0.38**	0.37*
MFFT errors	-0.25*	-0.33**	-0.28*	-0.41**
MFFT RT	-0.17	-0.13	-0.12	-0.03
GNG No-go	-0.26	-0.15	0.04	0.06
Flanker AI	0.29*	0.32**	0.49***	0.44**
Flanker RTI	-0.05	-0.13	-0.08	-0.01
Navon AI	0.26*	0.27*	0.19	0.29
Navon RTI	-0.15	-0.28	0.1	0.04

Note: MR = Matrix Reasoning; VC = Vocabulary; BDS = Backward digit span; MFFT errors = number of errors on Matching Familiar Figures Task; MFFT RT = reaction time on Matching Familiar Figures Task; GNG No-go = Go/No-go Correct No-go items; Flanker AI = Flanker accuracy on incongruent items; Flanker RTI = Flanker reaction time on incongruent items; Navon AI = Navon accuracy on incongruent items; Navon RTI = Navon reaction time on incongruent items. *p<.05. **p<.01. ***p<.001.

4.3.8 Contribution of group and cognitive processes on specific math abilities (research question 4d)

A series of hierarchical linear regression analyses were conducted with each math ability used as dependent variable. For each dependent variable, the following regression were conducted:

- in the first hierarchical linear regression, the contribution of group and vocabulary was investigated, including them as independent variable in the first step and interaction between the two included in the second step;
- in the other hierarchical linear regressions, group and vocabulary (here used as a covariate as the two groups significantly differed on this measure) were included as independent variable in the first step; residual scores of cognitive processes (included one by one in separate regressions) were included in the second step; the interaction between group and the cognitive process was added in the third step. In these analyses, we did not include as predictors the cognitive variables that were not significantly correlated with any math ability.

4.3.8.1 Contribution of group and cognitive processes on arithmetic facts

In the following hierarchical linear regression analyses, arithmetic facts were used as dependent variable.

Contribution of group and vocabulary to arithmetic facts. The first regression model, with group and vocabulary as independent variable in the first step, explained 51% of variance and both the variable were significantly predictors. In the second step, the inclusion of interaction between vocabulary and group significantly improved the amount of explained variance; the final model explained 54% of variance and showed that the association between vocabulary and arithmetic facts was stronger in the group with ASD than in the TD group.

Contribution of group, vocabulary and VWM to arithmetic facts. VWM, entered as independent variable in the second step, was a significant predictor (the model explained 60% of variance) and significantly improved the amount of explained variance; in addition to the first step in which only group and vocabulary were included. In addition, the interaction between group and VWM in the third block was also a significant predictor, significantly improved the amount of explained variance; the final model explained 63% and showed that the association between VWM and arithmetic facts was stronger in the group with ASD than in the TD group.

Contribution of group, vocabulary and VSWM to arithmetic facts. Also VSWM, entered as independent variable in the second step, was a significant predictor (the model explained 53% of variance) and significantly improved the amount of explained variance, in addition to the first step in which only group and vocabulary were included. The interaction between group and VSWM in the third block was not a significant predictor, did not improve the amount of explained variance; the final model explained 54% of variance and showed that the association between VSWM and arithmetic facts was similar in the two groups.

Contribution of group, vocabulary and inhibitory measures to arithmetic facts All the inhibitory measures, i.e., MFFT errors, Flanker AI and Navon AI and their interaction with group were not significantly predictors of arithmetic facts and did not significantly improve the amount of explained variance.

4.3.8.2 Contribution of group and cognitive processes on mental calculation

In the following hierarchical linear regression analyses, mental calculation was used as dependent variable.

Contribution of group and vocabulary to mental calculation. The first regression model, with group and vocabulary as independent variable in the first step, explained 39% of variance and only group, but not vocabulary, was a significant predictors; in the second step, interaction between vocabulary and group was a significant predictor and improved the amount of explained variance; the final model explained 45% of variance and showed that the association between vocabulary and mental calculation was stronger in the group with ASD than in the TD group.

Contribution of group, vocabulary and VWM to mental calculation. VWM, entered as independent variable in the second step, was a significant predictor (the model explained 48% of variance) and significantly improved the amount of explained variance in addition to the first step in which only group and vocabulary were included. In addition, the interaction between group and VWM in the third block was not a significant predictor and did not improve the amount of explained variance; the final model explained 49% of variance and indicated that the association between VWM and mental calculation was similar in the two groups.

Contribution of group, vocabulary and VSWM to mental calculation. Also VSWM, entered as independent variable in the second step, was a significant predictor (the model explained 43% of variance and significantly improved the amount of explained variance, in addition to the first step in which only group and vocabulary were included. The interaction between group and VSWM in the third block was not a significant predictor, did not improve the amount of explained variance; the final model explained 45% of variance and showed that the association between VSWM and mental calculation was similar in the two groups.

Contribution of group, vocabulary and inhibitory measures to mental calculation. All the inhibitory measures, i.e., MFFT errors, Flanker AI and Navon AI and their interaction with group, were not significantly predictors of mental calculation and did not significantly improve the amount of explained variance.

4.3.8.3 Contribution of group and cognitive processes on inferences

In the following hierarchical linear regression analyses, inferences were used as dependent variable.

Contribution of group and vocabulary to inferences. The first regression model, with group and vocabulary as independent variable in the first step, explained 42% of variance and only group, but not vocabulary, was a significant predictor; in the second step, interaction between vocabulary and group was not a significant predictor and did not improve the amount of explained variance. The final model explained 43% of variance.

Contribution of group, vocabulary and VWM to inferences. VWM, entered as independent variable in the second step, was a significant predictor (the model explained 51% of variance) and significantly improved the amount of explained variance in addition to the first step in which only group and vocabulary were included. In addition, the interaction between group and VWM in the third block was also a significant predictor, significantly improved the amount of explained variance; the final model explained 55% of variance and showed that the association between VWM and inferences was stronger in the group with ASD than in the TD group.

Contribution of group, vocabulary and VSWM to inferences. VSWM, entered as independent variable in the second step, was not a significant predictor (the model explained 50% of variance) and did not improve the amount of explained variance in addition to the first step in which only group and vocabulary were included. The interaction between group and VSWM in the third block was not a significant predictor and did not improve the explained variance; the final model explained 51% of variance.

Contribution of group, vocabulary and inhibitory measures to inferences *Among* inhibitory measures, Flanker AI, included in the second step, was a significant predictor (the model explained 56 % of variance) and improve the amount of explained variance in addition to the first step in which only group and vocabulary were included. The interaction between group and VSWM in the third block was not significant and did not improve the explained variance (the final model explained 57% of variance) suggesting that the association between Flanker and inferences was similar in the two groups. The other inhibitory measures (MFFT errors, Navon AI) and their interaction with group were not significant predictors of inferences and did not significantly improve the amount of explained variance.

4.3.8.4 Contribution of group and cognitive processes on math problem solving

In the following hierarchical linear regression analyses, math problem solving was used as dependent variable.

Contribution of group and vocabulary to math problem solving. The first regression model, with group and vocabulary as independent variable in the first step, explained 41% of variance and both group and vocabulary were significant predictors; in the second step, interaction between vocabulary and group was not a significant predictor and did not improve the amount of explained variance (the final model explained 42% of variance), showing that the association between vocabulary and math problem solving was similar in the two groups.

Contribution of group, vocabulary and VWM to math problem solving. VWM, entered as independent variable in the second step, was a significant predictor (the model explained 52% of variance) and significantly improved the amount of explained variance in addition to the first step in which only group and vocabulary were included. In addition, the interaction between group and VWM in the third block was not significant, did not improve the amount of explained variance (the final model explained 55% of variance) and showed that the association between VWM and math problem solving was similar in the two groups.

Contribution of group, vocabulary and VSWM to math problem solving. VSWM, entered as independent variable in the second step, was not a significant predictor (the model explained 40% of variance) and did not improve the amount of explained variance in addition to the first step in which only group and vocabulary were included. In addition, the interaction between group and VSWM in the third block was not a significant predictor and did not improve the explained variance (the final model explained 44% of variance).

Contribution of group, vocabulary and inhibitory measures to math problem solving. All the inhibitory measures, i.e., MFFT (errors), Flanker AI and Navon AI and their interaction with group were not significantly predictors of math problem solving and did not significantly improve the amount of explained variance.

In summary, vocabulary was significantly associated to arithmetic facts, mental calculation and problem solving, but not to inferences. In both arithmetic facts and mental calculation, this association was stronger in the group with ASD. VWM was significantly associated to all the specific math abilities, and in arithmetic facts and inferences this association was stronger in the group with ASD. VSWM was associated with arithmetic facts and mental calculation and its contribution was similar in the two groups. Among inhibitory measures, Flanker AI was associated with inferences and its contribution was similar in the two groups.

Table 4.22. Hierarchical linear regression analysis.

		Arithmetic facts			**Mental Calculation**			**Inferences**			**Math problem solving**		
		$F(3,73) = 30.44$			$F(3,73) =$			$F(3,51) = 14.60$			$F(3,41) = 11.51$		
		$p < .001$, $R^2_{adj} = 0.54$			$P < .001$, $R^2_{adj} = 0.45$			$P < .001$ $R^2_{adj} = 0.43$			$P < .001$ $R^2_{adj} = 0.42$		
		$R^2\Delta = 0.03^{*}$			$R^2\Delta = 0.06^{**}$			$R^2\Delta = 0.01$			$R^2\Delta < .001$		
	IV	b	*SE*	β	b	*SE*	β	B	*SE*	β	b	*SE*	B
Block 1	Group	-1.68	0.22	**-1.35*****	-1.59	0.24	-1.29***	-1.69	0.30	-1.24***	-1.05	0.30	-0.90**
	Vocabulary	0.09	0.04	**0.21***	0.04	0.04	0.09	0.06	0.05	0.14	0.12	0.04	0.35**
Block 1&2	Group	-3.39	0.77	**-1.29*****	-3.91	0.83	-1.21***	-2.58	1.12	-1.23*	-0.87	1.08	-0.91
	Vocabulary	0.02	0.04	0.05	-0.05	0.05	-0.13	0.02	0.07	0.05	0.13	0.07	0.37
	Group*Vocabulary	0.16	0.07	**0.39***	0.22	0.07	0.52**	0.08	0.09	0.18	-0.02	0.09	-0.05

		Arithmetic facts			**Mental Calculation**			**Inferences**			**Math problem solving**		
		$F(4,71) = 30.59$			$F(4,71) = 18.91$			$F(4,50) = 17.31$			$F(4,40) = 14.10$		
		$p = <.001$, $R^2_{adj} = 0.63$			$p = <.001$, $R^2_{adj} = 0.49$			$p = <.001$, $R^2_{adj} = 0.55$			$p = <.001$, $R^2_{adj} = 0.55$		
		$R^2\Delta = 0.09^{***}, 0.03^{*}$			$R^2\Delta = 0.10^{***}, 0.01$			$R^2\Delta = 0.09^{**}, 0.04^{*}$			$R^2\Delta = 0.10^{**}, 0.03$		
	IV	b	*SE*	β	b	*SE*	β	B	*SE*	β	b	*SE*	B
Block 1	Group	-1.65	0.22	**-1.34*****	-1.60	0.25	**-1.30*****	-1.69	0.30	**-1.24*****	-1.05	0.30	**-0.90****
	Vocabulary	0.09	0.04	**0.21***	0.04	0.04	0.09	0.06	0.05	0.14	0.12	0.04	**0.35****
Block 1&2	Group	-1.53	0.21	**-1.24*****	-1.48	0.23	**-1.20*****	-1.55	0.28	**-1.15*****	-0.96	0.28	**-0.82****
	Vocabulary	0.07	0.03	**0.18***	0.02	0.04	0.06	0.06	0.04	0.13	0.11	0.04	**0.30***
	VWM	0.21	0.05	**0.31*****	0.22	0.06	**0.32*****	0.24	0.08	**0.30****	0.22	0.07	**0.32****
Block 1&2&3	Group	-1.58	0.20	**-1.24*****	-1.51	0.23	**-1.20*****	-1.72	0.28	**-1.16*****	-1.12	0.28	**-0.85*****
	Vocabulary	0.06	0.03	0.15	0.02	0.04	0.04	0.03	0.04	0.08	0.09	0.04	**0.26***
	VWM	0.10	0.07	0.15	0.16	0.08	**0.24***	0.08	0.10	0.11	0.07	0.11	0.10
	Group*VWM	0.24	0.10	**0.36***	0.13	0.12	0.19	0.32	0.15	**0.41***	0.27	0.14	0.39

		Arithmetic facts $F(4,67) = 22.2$ $p= <.001$, $R^2_{adj} =0.54$ $R^2\Delta=0.04^{*}$, 0.01			Mental Calculation $F(4,67) = 15.76$ $p= <.001$, $R^2_{adj} =0.45$ $R^2\Delta=0.05^{*}$, 0.02			Inferences $F(4,46) = 14.08$ $p= <.001$, $R^2_{adj} =0.51$ $R^2\Delta=0.03$, 0.01			Math problem solving $F(4,36) =9.02$ $p= <.001$, $R^2_{adj} =0.44$ $R^2\Delta=0.01$, 0.04		
		B	SE	Beta	B	SE	Beta	B	SE	Beta	B	SE	Beta
Block 1	Group	-1.74	0.23	**-1.43*****	-1.69	0.26	**-1.37*****	-1.88	0.29	**-1.41*****	-1.11	0.32	**-0.94****
	Vocabulary	0.08	0.04	**0.18***	0.03	0.04	0.07	0.06	0.05	0.13	0.14	0.05	**0.35***
Block 1&2	Group	-1.61	0.23	**-1.32*****	-1.53	0.26	**-1.24*****	-1.69	0.31	**-1.27*****	-1.00	0.34	**-0.85****
	Vocabulary	0.07	0.04	0.16	0.02	0.04	0.04	0.06	0.05	0.12	0.14	0.05	**0.34***
	VSWM	0.10	0.04	**0.20***	0.11	0.05	**0.23***	0.11	0.07	0.17	0.06	0.07	0.12
Block 1&2&3	Group	-1.53	0.23	**-1.26*****	-1.44	0.26	**-1.17*****	-1.65	0.32	**-1.24*****	-0.97	0.33	**-0.81****
	Vocabulary	0.07	0.04	0.15	0.01	0.04	0.03	0.06	0.05	0.13	0.14	0.05	**0.36***
	VSWM	0.06	0.05	0.13	0.07	0.05	0.14	0.05	0.10	0.07	-0.06	0.10	-0.11
	Group*VSWM	0.12	0.09	0.25	0.16	0.10	0.33	0.12	0.13	0.19	0.22	0.13	0.42

		Arithmetic facts $F(4,68) = 20.43$ $p= <.001$, $R^2_{adj} =0.52$ $R^2\Delta=<.001$, 0.01			Mental Calculation $(4,68) = 15.48$ $p= <.001$, $R^2_{adj} =0.45$ $R^2\Delta= 0.01$, 0.02			Inferences $F(4,47) = 13.99$ $p= <.001$, $R^2_{adj} =0.50$ $R^2\Delta=0.01$, 0.03			Math problem solving $F(4,37) =9.03$ $p= <.001$, $R^2_{adj} =0.44$ $R^2\Delta=0.03$, 0.01		
		B	SE	Beta	B	SE	Beta	B	SE	Beta	B	SE	Beta
Block 1	Group	-1.68	0.23	**-1.36*****	-1.57	0.25	**-1.28*****	-1.79	0.30	**-1.31*****	-1.02	0.31	**-0.86****
	Vocabulary	0.09	0.04	**0.22***	0.06	0.04	0.15	0.07	0.05	0.16	0.14	0.05	**0.37****
Block 1&2	Group	-1.64	0.23	**-1.32*****	-1.52	0.25	**-1.24*****	-1.73	0.30	**-1.26*****	-0.90	0.32	**-0.76****
	Vocabulary	0.09	0.04	**0.20***	0.05	0.04	0.12	0.06	0.05	0.13	0.12	0.05	**0.33***
	MFFT	-0.02	0.02	-0.07	-0.02	0.02	-0.08	-0.03	0.03	-0.10	-0.05	0.03	-0.20
Block 1&2&3	Group	-1.66	0.23	**-1.30*****	-1.55	0.25	**-1.20***	-1.84	0.30	**-1.26*****	-1.01	0.34	**-0.78****
	Vocabulary	0.09	0.04	**0.21***	0.06	0.04	0.14	0.06	0.05	0.14	0.12	0.05	**0.33***
	MFFT	0.02	0.03	0.08	0.05	0.04	0.19	0.03	0.04	0.14	-0.01	0.05	-0.05
	Group* MFFT	-0.06	0.04	.0.25	-0.11	0.05	-0.25	-0.10	0.05	0.38	-0.05	0.07	-0.21

		Arithmetic facts $F(4,64) = 19.64$ $p= <.001$, $R^2_{adj} =0.52$ $R^2\Delta=0.01, 0.01$			Mental Calculation $F(4,64) = 13.6$ $p= <.001$, $R^2_{adj} =0.43$ $R^2\Delta=0.01, 0.01$			Inferences $F(4,44) = 17.18$ $p= <.001$, $R^2_{adj} =0.57$ $R^2\Delta=0.04^{*}, 0.01$			Math problem solving $F(4,35) =10.7$ $p= <.001$, $R^2_{adj} =0.50$ $R^2\Delta=0.04, 0.01$		
		B	SE	Beta	B	SE	Beta	B	SE	Beta	B	SE	Beta
Block 1	Group	-1.74	0.23	**-1.42*****	-1.76	0.26	**-1.42*****	-1.91	0.30	**-1.39*****	-1.13	0.32	**-0.94*****
	Vocabulary	0.08	0.04	**0.18***	0.02	0.04	0.04	0.07	0.05	0.15	0.14	0.05	**0.37****
Block 1&2	Group	-1.65	0.24	**-1.35*****	-1.67	0.27	**-1.34*****	-1.61	0.32	**-1.17*****	-0.87	0.34	**-0.72***
	Vocabulary	0.08	0.04	**0.18***	0.02	0.04	0.03	0.08	0.05	0.17	0.15	0.05	**0.39****
	Flanker	1.90	1.60	0.11	1.91	1.77	0.10	3.85	1.76	**0.23***	3.26	1.77	0.23
Block 1&2&3	Group	-1.65	0.24	**-1.33*****	-1.67	0.27	**-1.33*****	-1.65	0.32	**-1.20*****	-0.92	0.34	**-0.78***
	Vocabulary	0.07	0.04	**0.16***	0.01	0.04	0.02	0.07	0.05	0.15	0.14	0.05	**0.37****
	Flanker	0.05	2.44	-0.03	0.21	2.72	0.01	0.83	3.41	0.05	0.03	3.95	<..001
	Group* Flanker	4.20	3.25	0.23	2.96	3.62	0.16	4.10	3.98	0.25	4.04	4.41	0.29

		Arithmetic facts $F(4,56) = 12.28$ $p= <.001$, $R^2_{adj} =0.43$ $R^2\Delta= <.001, <.001$			Mental Calculation $F(4,56) = 7.87$ $p= <.001$, $R^2_{adj} =0.31$ $R^2\Delta= <.001, <.001$			Inferences $F(4,42) = 7.90$ $p= <.001$, $R^2_{adj} =0.37$ $R^2\Delta= <.001, <.001$			Math problem solving $F(4,34) =6.97$ $p= <.001$, $R^2_{adj} =0.39$ $R^2\Delta= <.001, <.001$		
		B	SE	Beta	B	SE	Beta	B	SE	Beta	B	SE	Beta
Block 1	Group	-1.59	0.27	**-1.30*****	-1.53	0.30	**-1.26*****	-1.67	0.34	**-1.25*****	-1.11	0.33	**-0.94****
	Vocabulary	0.08	0.04	**0.21***	0.03	0.04	0.07	0.05	0.05	0.13	0.12	0.05	**0.34***
Block 1&2	Group	-1.58	0.29	**-1.29*****	-1.49	0.31	**-1.23*****	-1.69	0.35	**-1.26*****	-1.11	0.34	**-0.93****
	Vocabulary	0.08	0.04	0.20	0.02	0.04	0.06	0.06	0.05	0.13	0.12	0.05	**0.34***
	Navon	0.10	0.70	0.02	0.30	0.76	0.05	-0.14	0.84	-0.02	0.02	0.78	<.001
Block 1&2&3	Group	-1.55	0.29	**-1.27*****	-1.47	0.32	**-1.22*****	-1.67	0.35	**-1.25*****	-1.11	0.36	**-0.93****
	Vocabulary	0.08	0.04	0.20	0.02	0.04	0.06	0.05	0.05	0.13	0.12	0.05	**0.34***
	Navon	-0.30	0.98	-0.05	0.01	1.07	<.001	-0.57	1.17	-0.08	0.04	1.07	0.01
	Group* Navon	0.81	1.37	0.12	0.59	1.49	0.09	0.87	1.65	0.13	-0.04	1.54	-0.01

*Note: VWM = Verbal Working memory (Backward digit span); VSWM = visuospatial working memory (Mr. Peanut), MFFT = number of errors on Matching Familiar Figures Task; Flanker AI = Flanker accuracy on incongruent items; Navon AI = Navon accuracy on incongruent items. *p<.05. **p<.01. ***p<.001*

4.4 Discussion

4.4.1 Response inhibition and interference control in autism spectrum disorder: the role of basic cognitive processes and working memory (research question 4a and 4b)

In the first part of the current study, we aimed to examine potential inhibitory difficulties in a group with ASD and a TD group, comparing both response inhibition and interference control measures (research question 4a) and investigate the role of potential mediators in explaining group differences (research question 4b). The findings indicated that the group with ASD exhibited lower inhibitory control in certain tasks that were administered. Specifically, notable differences between the two groups were identified in the Matching Familiar Figure and Flanker task, whereas no significant distinctions were observed in the Go/No-go and Navon tasks. This outcome may partly resemble the results in the study conducted by Christ and coauthors (2011), one of the few studies that evaluated both interference control and response inhibition in participants with ASD. Christ and coauthors (2011) reported significant differences in the Flanker task, while no such disparities were noted in the Go/no-go task. They concluded that a selective inhibitory deficit was linked to interference control rather than response inhibition. However, in their study, each inhibitory dimension was assessed using a single task. In our study, the use of more than one task for each inhibitory control dimension enabled a more complex understanding. This approach revealed that inhibitory control difficulties in the ASD group appeared to be unrelated to a specific inhibitory dimension. In fact, lower inhibitory abilities were observed within one of the two response inhibition tasks (MFFT) and one of the two interference control tasks (Flanker task). Thus, the results seemed to be in line with previous meta-analyses (Geurts et al., 2014; Tonizzi et al., 2021) that found an inhibitory deficit in both IC dimensions; however, the current study suggested these difficulties are evident only in certain IC tasks and alternative explanations may account for this finding.

Concerning response inhibition, it is conceivable that the Go/No-go task assessed a simpler form of response inhibition as compared to the MFFT: in the former task participants had to refrain from pressing the spacebar when a certain stimulus appeared, whereas the latter task required the integration of different cognitive processes. These processes encompassed visuospatial working memory to hold in mind the representation of target stimuli, visual search to explore various alternatives, and the control of impulsive responses (Marzocchi et a., 2010). In this regard, mediation analyses suggested that both basic processing speed (RT on Go items in the Go/No-go task) and visuospatial working memory partially explained the differences between the two groups in the MFFT. This finding is in line with the idea, expressed in the neurobiological model of Minshew and coauthors (Minshew & Goldstein, 1998; Minshew et al., 1997), that individuals with ASD might encounter more challenges in complex tasks, where the gap with TD participants was more evident. However, this view could be integrated considering that also basic cognitive processes may be impaired in autism, as suggested by a recent meta-analysis (Zapparrata et al., 2022), and impact on inhibitory performance of individuals with ASD. The serial mediation showed a cascade effect of basic cognitive processes on response inhibition through visuospatial working memory. This result supported previous studies indicating that individual differences in stimuli processing had a direct effect on working memory capacity, which, in turn, was a direct determinant of individual differences in other cognitive domains (Fry & Hale, 1996; Tourva & Spanoudis, 2020). Concerning interference control, significant group differences were evident in the Flanker task, whereas no differences were found in the Navon task. In the Flanker task, the discrepancies arise even at a more basic level, particularly in terms of accuracy in the congruent condition, suggesting possible difficulties in associating stimuli with the correct response items. Notably, accuracy on congruent items in the Flanker task partially account for group differences in incongruent items. This observation suggests that the differences between the groups in interference control are, in part, explained by disparities at the fundamental stimulus processing level that exerts a cascading effect on the ability to control conflicting stimuli. This difficulty observed in the group with ASD could be interpreted by adopting the model proposed by Ridderinkhof and coauthors (Ridderinkhof & van der Molen, 1995; Ridderinkhof et al., 2021) in which perceptual information processing occurs through two simultaneous pathways. The first pathway involves attentive processing, implying target stimulus selection and activating a stimulus-response translation process. Concurrently, information is processed through a second pathway involving a direct route where response selection processes are activated not only by the target stimulus but also by distractors. When distractors and target are associated with different responses (i.e., incongruent condition), response competition arises. In our study, lower accuracy in incongruent conditions, resulting from this competition, is observed in both groups. However, in the group with ASD, there might be also a difficulty related to the first attentive process concerning the association between the target stimulus and the correct response. This difficulty could somehow explain the lower accuracy even in the congruent condition. Instead, in the Navon task no statistically significant difference between the two groups were found in those indices that are generally considered interference control measures (accuracy and RT on incongruent items); in this task the only significant difference between the two groups was found in the RTs in global condition, suggesting a faster performance of the TD group in identifying global stimuli, as compared to the group with ASD, in line with previous literature that showed greater difficulties in autism in perceiving global stimuli (Frith & Happé, 1994; Guy et al., 2019; Muth et al., 2014). It is possible that discrepancies in interference control was found only in the Flanker task and not in the Navon task due to specific features of the two tasks. Flanker is a longer task, requiring more sustained attention and notably there was a time limit (2000 ms) in stimuli presentation (Christ et al., 2011). Therefore, there is a constraint and faster stimulus prestation rate than in the Navon task. As indicated by previous studies, stimulus presentation rate significantly impacted on inhibitory control abilities in individuals with ASD; for example, Raymaekers and coauthors (2004) found that individuals with ASD performed more poorly than the comparison group when the presentation rate of the stimuli was fast (1000 or 2000 ms) but not when it was slow (6000 ms). This methodological aspect might influence performance, impacting even the basic cognitive processes, and should be controlled in future studies.

4.4.2 Math abilities in autism spectrum disorder: the contribution of domain-general cognitive processes (research question 4c and 4d)

The second part of the study aimed to examine specific mathematical abilities (research question 4c) and how they be influenced by domain-general cognitive processes (research question 4d) in a group with ASD and a TD group. The results demonstrated lower performance of the group with ASD in all four mathematical tasks we used, confirming the findings of the meta-analysis (described in Chapter 3) that did not identify significant differences based on the type of math task. However, in this study, the task type encompasses not only numerical operations and math problem solving, but also arithmetic facts and the ability to make mathematical inferences. Apart from identifying a generalized deficit across various mathematical abilities, the results provide valuable insights to better understand the contributing processes to these abilities, both in typical development and autism. Overall, the obtained results were closely in line with the model proposed by Cragg and coauthors (2017); in fact, our study also observed a fundamental role of verbal working memory, which represents a significant predictor for all specific math tasks. Additionally, the study assessed vocabulary as well, which was also a significant predictor for all evaluated mathematical abilities, except for inferences. In line with the research conducted by Cragg et al. (2017), both verbal and visuospatial working memory were found to be involved in arithmetic facts and calculations - mainly assessing factual knowledge and procedural knowledge, respectively. On the other hand, only verbal working memory was associated with tasks requiring more conceptual knowledge, like inferences and mathematical problem-solving. This finding supports the notion that working memory is crucial for accessing information stored in long-term memory, suggesting that conceptual information is predominantly stored in a verbal format (Cragg et al., 2017). Students with low verbal working memory capacity are less likely to choose a retrieval strategy in math problem solving tasks and are also likely to retrieve them less accurately (Andersson, 2010; Geary et al., 2012). Arithmetic facts, however, might also contain a visuospatial component, likely linked to their presentation format or the use of visual aids (e.g., to memorize times tables) during encoding (Cragg et al., 2017; Macchitella et al., 2023).

Notably, the current study showed that these relationships may have a different strength in the group with ASD and the TD group. In fact, in arithmetic facts and inferences the effect of verbal working memory was stronger in the group with ASD, whereas in mental calculation and math problem solving the contribution was similar in the two groups. A quite similar result was found considering vocabulary, as its contribution was stronger for the group with ASD in arithmetic fact and mental calculation, whereas was similar in the two groups in math problem solving. The fundamental role of vocabulary and verbal working memory confirmed the results from the previous meta-analysis (Chapter 3) and previous studies with participants with ASD (Bullen et al., 2020; Hiniker et al., 2016; Iuculano et al., 2020). It is well known that language and working memory facilitates knowledge retrieval from long-term memory during mathematics performance (Peng et al., 2020). However, in typical development, as students cumulatively build their mathematics knowledge, the direct retrieval of arithmetic facts from long-term memory can reduce cognitive load and, therefore, working memory demands (Peng & Lin, 2019). Thus, when the retrieval of arithmetic facts becomes more automatic, verbal ability and working memory become less relevant. However, the current study seemed to suggest a different pattern for students with ASD; their performance on arithmetic facts was predicted by both verbal ability and verbal working memory, with a stronger association than in the TD group (Peng et al., 2020; Zoccolotti et al., 2021). Thus, for students with ASD, arithmetic facts seemed to be more challenging and less automatized than their peers and their retrieval rely on verbal resources. Instead, the contribution of both vocabulary and verbal working memory to math problem solving was similar in the two groups. This result was in line with previous studies suggesting that the direct retrieval of general knowledge stored in long-term memory can enhance the understanding of word problems (Fuchs et al., 2015; Peng & Lin, 2019). The results showed that solving math problems was generally a complex ability that place high demands on working memory for both students with ASD and their TD peers.

Moreover, we examined how inhibitory control was related to specific math skills. Differently from Cragg's model (2017), we didn't find inhibitory control contributing to arithmetic facts or mental calculation. However, it's worth noting that in Cragg's study, only a response inhibition task with numerical stimuli was a significant predictor, while the response inhibition task without numerical stimuli wasn't linked to any math variables. In our study, inhibitory tasks didn't involve numerical stimuli because it's known that these are more closely related to math tasks (Passolunghi & Siegel,2001; Simanowski & Krajewski, 2019; Szucs et al., 2013). Additionally, unlike most previous studies, we used not only response inhibition measures but also interference control measures. This allowed us to see how the ability to filter out irrelevant stimuli supports more conceptually-based math skills such as mathematical inferences. Thus, it's possible that interference control, rather than just response inhibition, might play a significant role in certain areas of math learning (Passolunghi & Siegel, 2001; Traverso et al., 2019). Moreover, the results suggest that the association between interference control (in our case, accuracy on incongruent Flanker items) and mathematical inferences is statically significant and similar in both the group with ASD and the TD group.

4.4.3 Limitations and future directions

The study's findings should be considered in light of some limitations. First, the limited sample size of the group with ASD reduces statistical power and the wide age range prevents control over confounding variables, such as varying treatment types and durations based on participant cohorts. Importantly, our results cannot be generalized to the entire spectrum of autism since our study only involved participants with ASD without intellectual disabilities. Regarding the procedure, online administration posed challenges due to participants' lack of appropriate technology or incompatible computers with the E-prime software for computerized tasks (Go/No-go and Navon). To ensure controlled assessment, all tasks, including computerized ones, were conducted via screen sharing. Lastly, there are limitations related to the tests used. Using only two tasks (Reason Matrix and Vocabulary) to investigate intellectual domains is a limitation due to session length. We selected the most representative tasks from these domains to avoid participants' overwhelming. Also concerning working memory measures, the use of more tasks for verbal and visuospatial working memory may allow to better understand the specific contribution of each component; in addition, it's important to note that verbal working memory task was a digit span task and therefore the use of numerical stimuli could have increased the association with math tasks. Moreover, the inhibitory tasks lack a common methodology (e.g., only the MFFT was non-computerized), making direct comparisons more complex. In future research, it will be important to systematically investigate which aspects related to different inhibitory tasks emerge as influential variables. In addition, a larger sample size would have also allowed the investigation of the contribution of each domain-general processes, while controlling for the effect of the others. The current study has investigated the contribution of cognitive factors to mathematical skills; however, an important limitation was the lack of analysis on the role of other factors, such as emotional and socio-demographic ones. Considering that individuals with ASD are at risk for developing anxiety (Spain et al., 2019; van Steensel and Heeman, 2017; White et al., 2009) it is possible that the level of anxiety contributes to explaining the mathematical difficulties observed in participants with autism. However, the relationship between emotional, cognitive factors, and mathematical skills in autism is still poorly explored. To our knowledge, the study conducted by Oswald and coauthors (2016) was the first to examine the relationship between anxiety and math achievement in ASD, showing that test anxiety significantly accounted for unique variance in math problem-solving across the whole sample. In this case, test anxiety and math anxiety were considered; however, other forms of anxiety could have been investigated, such as social anxiety. In fact, social could play a significant role in explaining cognitive and academic difficulties of students with ASD, considering both the difficulties they encounter in the social domain (Lord et al., 2018; Spain et al., 2019) and findings of previous studies suggesting that performance in tasks requiring a relationship with the experimenter is lower than in computerized tasks (Dichter & Belger, 2007; Ozonoff, 1995).

Another important limitation that needs to be addressed in future studies is the possibility of gender differences in math abilities. In our study, the percentage of female participants in the group with ASD was not sufficient to explore such differences. However, this could be a relevant aspect to investigate in future studies for various reasons. In fact, in typical development, gender differences in mathematics are still a subject of debate. Females tend to be underrepresented in mathematics and more broadly in STEM fields (Cheryan et al., 2017; Stoet & Geary, 2018). Some previous studies and meta-analyses have identified a small effect size in favor of males in mathematics performance (Giofrè et al., 2020). Furthermore, possible gender differences may also impact working memory and inhibition. In this case, males tend to show some advantages in WM measures (Halpern & Wai, 2000) and more demanding inhibitory tasks (Usai et al., 2022) in both studies with typically developing individuals and those with participants with ASD. Interestingly, Demetriou and coauthors (2021) suggested that gender differences in autism may, in part, be understood by an atypical profile of executive function in females. However, how gender may modulate the association between cognitive predictors and math abilities in autism remains an open question to be addressed in future studies.

The findings of the present study also suggested practical implications. To provide effective education that enhances academic achievement in students with ASD, a deeper understanding of factors influencing individual differences in academic performance is required, considering both domain-general and domain-specific processes (Bullen et al., 2022; Chen et al., 2018; Wei et al., 2015). Additionally, these students benefit from general education, but they may need multidimensional assessments to pinpoint strengths, weaknesses and additional support to improve academic outcomes of students with ASD (Bullen et al., 2022). Moreover, it is crucial to translate research findings into intervention strategies. On one hand, it is essential to adopt compensatory strategies such as reducing linguistic working memory demands, facilitating task focus, creating suitable settings with the use of visual aids to support students in remembering procedures and focussing on relevant aspects. Acknowledging basic stimulus processing difficulties, which can result in longer processing times and greater cognitive resource utilization, is also important (Zapparrata et al., 2022). Furthermore, focussing on the automatization of procedures and strategies that can reduce the cognitive load could be a valid aid to those students with difficulties in WM. On the other hand, it's important to implement interventions that enhance these abilities. In atypical development, interventions have been successful in enhancing executive function in children with neurodevelopmental disorders (Kerns et al., 2017; Macoun et al., 2020). However, in autism research, limited efforts have been made in this direction (De Vries et al., 2015; Wass & Porayska-Pomsta, 2014). Recently, Macoun and coauthors (2021) tested a game-based cognitive training program (Caribbean Quest) to enhance attention and executive function in school-aged children with ASD. Their results showed improvements in visual working memory and selective attention, as well as transfer effects on math fluency. This intervention combined process-specific activities (targeting cognitive functions systematically through graded tasks, adaptive difficulty, intensity, and repetition) and compensatory strategies (enhancing underlying cognitive abilities' efficiency and effectiveness). They also integrated video-game play with metacognitive strategy instruction by an adult trainer. Future evaluations of such training methods are necessary to better understand guidelines to support cognitive and academic outcomes in students with ASD.

In conclusion, the current study suggested the importance of considering both domain-specific and domain-general aspects from a multidimensional perspective, even in the context of atypical development. Advancing toward integrating domain-general processes and domain-specific abilities is crucial in research involving atypical development to better understand these complex skills and the reasons behind the challenges faced by students with ASD.

5 Discussion

The current dissertation aimed to better understand domain-general top-down processes, specifically inhibitory control and working memory, and their connection to learning outcomes, particularly in the domain of mathematics, in autism spectrum disorder. The decision to focus the investigation on these aspects arose from the significant inconsistencies observed in autism research (Geurts et al., 2014; Dowker et al., 2020). The field still lacks a comprehensive understanding of whether distinct differences truly exist between individuals with ASD and those with typical development, as well as the specific factors influencing this variability. Moreover, executive function had a substantial influence over one's ability to adapt to the demands of daily life and impact on academic outcomes in both typical and atypical development (Bertollo & Yeris, 2019; Demetriou et al. 2019; Wallace et al., 2016). Also, proficiency in mathematical skills significantly impacts an individual's academic and professional trajectories (Jordan & Levine, 2009; Whitby & Mancil, 2009). Furthermore, studies with typical developing samples suggested that domain-general cognitive processes, including inhibition and working memory, actively contribute to mathematical learning (Cragg et al., 2017; Traverso et al., 2021). Nonetheless, how this relationship varies across distinct mathematical competencies remains quite unclear and has received limited exploration in autism research.

Summarizing the main findings, the first study (Chapter 2) of this dissertation aimed to meta-analyse previous studies investigating inhibitory control in participants with ASD, as compared with a TD group. Two meta-analyses were conducted; the first focused on direct measures and explored important moderators: the type of IC dimension (response inhibition vs. interference control), sample-related characteristics and measure-relates characteristics. The second meta-analysis focused on indirect measures and investigated moderators concerning sample-related characteristics.

The second study (Chapter 3) aimed to meta-analyse previous studies investigating math abilities in participants with ASD, as compared with a TD group and explored the moderating role of both measures-related characteristics and sample-related characteristics.

In the third study (Chapter 4) we investigated inhibitory processes, comparing a sample of participants with ASD and a TD group. Different measures of response inhibition and interference control were adopted to investigate if the group with ASD had a generalized inhibitory impairment; moreover, the moderating role of basic cognitive processes and working memory in explaining groups differences was analysed. Subsequently, in the second part of the study, we assessed potential math difficulties in the group with ASD compared to the TD group. Given indications that students with ASD might struggle more with complex math tasks, we evaluated math abilities in both groups using specific tasks (arithmetic facts, mental calculations, inferences and overall math skills) targeting different math knowledges. Then, we examined how domain-general cognitive processes (including vocabulary, response inhibition, interference control, verbal and visuospatial working memory) contributed to these specific math abilities, also considering potential differences in these associations between the two groups.

Concerning inhibitory control, results from the meta-analysis (Chapter 2) showed a small-to-medium inhibitory impairment in the group with ASD in direct measures, with no significant difference between response inhibition and interference control dimension. An increment of age and intellectual functioning was associated with a decrease in groups difference in response inhibition measures; the presence of an ADHD comorbidity had not a significant moderating effect. In addition, the difference between the group with ASD and the TD group was larger in paper-and-pencil tasks than in computerized tasks. In indirect measures a large inhibitory deficit was found, not impacted by any participants' characteristics. The study described in Chapter 4 added other information on inhibitory processes in autism; comparing different response inhibition and interference control measures, results confirmed that the inhibitory deficit of the group with ASD was not related to a specific IC dimension, but it was not evident in all IC tasks. Notably, basic cognitive processes and visuospatial working memory partially accounted for these group differences.

Concerning math abilities, results from the meta-analysis (Chapter 3) showed the group with ASD performed lower than the TD group with a small-to-medium effect; groups difference was not moderated by task-related characteristics and thus was similar in math numerical operation and math problem solving tasks and in math tasks with oral or written format. Instead, sample-related characteristics were significant moderators; an increment of verbal intellectual functioning and verbal working memory were associated to a reduction of the differences between the two groups, whereas an increment of age was associated with an increment in the groups difference. The results from the study described in Chapter 4 were in line with the findings of the meta-analysis, showing a general math deficit of the group with ASD, evident in all specific math abilities that we have investigated. In addition, the results showed that domain-general cognitive processes were differently associated with specific math abilities. Verbal working memory was associated to all the math measures, and also vocabulary contributed to all math skills, except for inferences, supporting the findings emerged from the meta-analysis described in Chapter 3. In addition, visuospatial working memory contributed to arithmetic facts and mental calculation, while interference control contributed to mathematical inferences. Interestingly, the strength of these associations partially differed between the group with ASD and the TD group. In fact, the contribution of vocabulary to arithmetic facts and mental calculation was stronger in the group with ASD, whereas these associations were similar for the two groups in math problem solving. Also the contribution of verbal working memory to arithmetic facts and inferences was stronger in the group with ASD, and similar in math problem solving.

5.1 Considering the multidimensionality of inhibitory control: the moderating role of age and intellectual functioning varied according to inhibitory dimensions and method of assessment

As previously stated, the meta-analysis revealed similar impairments in both response inhibition and interference control among participants with ASD, indicating difficulties in both stopping prepotent responses and filtering out conflicting information. Despite these similar impairments, distinctions emerged in how age and IQ affected response inhibition and interference control, highlighting the multidimensional nature of inhibition. Specifically, only response inhibition, not interference control, was influenced by age and IQ. Older age and higher IQ were associated with smaller differences between the group with ASD and the TD group, indicating that response inhibition deficit in autism was more pronounced in younger ages and lower IQ. Thie age and IQ effects were absent in interference control. These findings supported the idea of distinct developmental trajectories for response inhibition and interference control in autism and typical development (Luna et al., 2004, 2007; Vuillier, et al., 2016; Williams et al., 1999). Response inhibition seems to have an extended developmental period in individuals with ASD compared to those with typical development, while differences in interference control between the two groups appear consistent throughout development (Richardson et al., 2018).

Age and IQ had also distinct effects on both direct and indirect measures. Specifically, direct measures, particularly those assessing response inhibition, were influenced by age and IQ, whereas indirect measures were not affected. These findings might support the distinction between the two measurement types. Questionnaires are designed to detect difficulties in everyday life contexts, and it's plausible that such impairments might be less influenced by developmental changes (Gomez-Perez et al., 2016; Gross et al., 2014). Moreover, since questionnaires assess adaptation to daily conditions, they could be less affected by intellectual function, in line with previous studies where a significant relationship between IQ and daily functioning level wasn't identified (Ventola et al., 2014; Kanne et al., 2011). However, it's important to interpret these findings cautiously since indirect measures are mainly employed with children and young adolescents and typically within a normal IQ range. Additionally, most indirect measures have not been validated for individuals with IQs below 70. Given the growing popularity and some advantages of using also indirect measures, especially to include more studies in future meta-analyses, this issue warrants further investigation in the future.

5.2 Greater inhibitory difficulties in indirect measures and noncomputerized tasks: hypotheses on social demands and environmental stimulation

An interesting result, emerging from the meta-analysis on inhibitory measures, was that the larger differences between participants with ASD and TD were found in indirect measures, as compared with direct measures, and in noncomputerized tasks, as compared to computerized ones. There are different hypotheses that may explain these results. In fact, it is conceivable that these differences may be attributed to certain biases in the compilation of indirect measures (i.e., questionnaires) which, especially in the case of participants with disabilities, could lead to a higher and more generalized estimation of difficulties (Gomez-Perez et al., 2016). Moreover, direct measures seem to be superior computerized tests can be more accurate in estimating abilities (Gross et al., 2014). However, a potential explanation that considers both the difference between indirect and direct measures and between computerized and non-computerized tests relates to the fact that people with ASD might encounter greater challenges in using their inhibitory processes within more complex and dynamic contexts, where both social demands and the quantity of stimuli are more substantial. This hypothesis was in line with previous studies (Dichter & Belger, 2007; Nakahachi et al., 2006; Ozonoff, 1995; Ozonoff & Strayer, 2001) that found lower differences between the group with ASD and the TD group in computerized tasks, suggesting that computer-based testing removes both the social and verbal aspects from the assessment process, which may be the cause of the better performance for individuals with autism, as compared to paper-and-pencil assessment. Specifically, emotional factors may play a significant role in influencing the performance of participants with ASD on executive function tasks requiring social demands. Students exhibiting high levels of social anxiety may experience constraints on their cognitive resources, as their concurrent worries linked to others' judgement (Amir & Bomyea, 2011; Leigh et al., 2021; Norton & Abbot, 2016). This finding has been observed from a young age, with variations in anxiety affecting performance on tasks that demand higher levels of executive function (Cheie & Visu-Petra, 2012; Ng & Lee, 2015; Ursache & Raver, 2014). This underscores the importance of considering aspects related to social anxiety when examining executive functions and inhibitory control in individuals with ASD, who are at an increased risk of developing anxiety disorders, as indicated by recent reviews and meta-analyses (Spain et al., 2019; van Steensel and Heeman, 2017).

In addition to minimize social demands, computerized assessments may show other different advantages for participants with ASD. Given the challenges that individuals with ASD often face in processing stimuli (Zapparrata et al., 2022), minimal distractions, consistent interface, and predictability of computerized interactions might be important advantages for them. Support for the effectiveness of computer use in boosting motivation among children with ASD can be observed in different studies (De Vries et al., 2015; Macoun et al., 2021; Wallace et al., 2016) and suggested that computers have the potential to divert the attention of children away from self-stimulatory behaviors (Williams et al., 2002). Additionally, computerized assessments have the advantage of filtering out extraneous sensory information and distracting stimuli. This lower quantity of environmental stimuli could potentially account for higher scores from computerized tasks. As discussed in the following paragraph, difficulties in stimuli processing could influence inhibitory abilities of participants with ASD.

5.3 Considering the impurity of inhibitory measures: the indirect effect of stimuli processing and working memory

A problem frequently addressed and intrinsically linked to the assessment of executive function, particularly inhibitory ones, is the impurity of these measures (Friedman, 2019). Therefore, considering which other cognitive processes might be involved in such measures is essential for a better understanding of the observed difficulties. The meta-analysis described in Chapter 2 focused on the inhibitory indices of the tasks but did not include, among the moderators, other cognitive processes in addition to intellectual functioning, such as working memory or basic indices typically used to measure stimulus processing. This last aspect is relatively understudied, especially in research involving autism, despite previous studies have suggested difficulties in stimulus processing in autism (Zapparrata et al., 2022) and despite the recognized importance of basic processes for executive function (Grynszpan et al., 2007; Moore & Calvert, 2000). The study reported in Chapter 4 highlighted the role of these aspects. In particular, discrepancies between the group with ASD and the TD group were evident in various basic processes. Concerning response inhibition, group discrepancies were evident in RT and accuracy in Go responses in the Go/no-go task and, concerning interference control, in congruent responses in the Flanker task. Notably, difficulties in basic cognitive processes explained a significant portion of group differences in the inhibitory indices, including both response inhibition (MFFT errors) and interference control measures (Flanker accuracy on incongruent items). A similar mediating effect is observed with working memory in the Matching Familiar Figure task, a response inhibition task that requires the integration of diverse cognitive processes (Marzocchi et al., 2010). It's conceivable that in inhibitory tasks, there might be a cascade effect of fundamental cognitive aspects and in more complex tasks this effect might also occur through the mediation of working memory. In the Matching Familiar Figure task, in fact, we observe how the differences between the two groups are explained by a serial mediation of basic cognitive processes and visuospatial working memory.

Taken together, results on inhibitory measures suggested the importance of distinguishing between "competence" and "performance" (Zoccolotti et al., 2021). Within this framework, "competence" is the general capacity within a particular domain, while "performance" arises from the interplay between competence and the distinctive features of the task. The main difference between competence and performance lies in the fact that the former is task independent, while the latter is task specific and therefore related to specific features of the task. This distinction was event more salient considering the impurity of inhibitory measures, in which different aspects, in addition to inhibitory processes, can be involved (Friedman, 2019). Therefore, in future research, it will be important not only to focus on determining the presence of inhibitory difficulties but also to systematically understand the factors that can influence them simultaneously, efforts should be directed towards enhancing the psychometric properties of such measures (Löffler et al., 2022). Finally, it is essential to understand the developmental and academic outcomes negatively influenced by inhibitory difficulties (Polo-Blanco et al., 2022).

5.4 Generalized mathematical difficulties and the contribution of verbal cognitive processes.

In Chapter 4 we investigated the role that inhibitory processes, along with working memory and vocabulary, play in contributing to math abilities in participants with ASD and TD. The results of the meta-analysis (Chapter 3) and the study (Chapter 4) was consistent in finding general lower math abilities in participants with ASD, generalized to different math abilities. In addition, both the meta-analysis and the study highlighted the role of verbal working memory and verbal ability (measured with VIQ in the meta-analysis and with Vocabulary in the study) in contributing to these differences. Interestingly, in the study, verbal working memory was a significant predictor of all the specific math abilities we have measured, and vocabulary contributed to all math abilities, except inferences. In arithmetic facts their contribution was stronger for the group with ASD; in this group, a stronger association was also found between verbal working memory and inferences and between vocabulary and mental calculation. These findings can be integrated into the perspective proposed by Zoccolotti and colleagues (2021), derived from the instance theory of automatization formulated by Logan (1988). According to this theoretical framework, the process of automatization is acquired through the repetitive exposure to a stimulus. In the first phase named "obligatory encoding", repetition leads to the formation of an "instance representation" of the specific stimulus that was stored in long term memory. In the second phase named "obligatory retrieval", through subsequent repetitions, information becomes directly accessible. In accordance with this theory, it's conceivable that students with ASD might exhibit a lower capacity to consolidate instances. This could subsequently impact their academic performance; specifically, in the math domain a reduced level of automatization might hinder the acquisition of arithmetic facts, consequently impacting the efficiency of calculation (Marinelli et al., 2021; Zoccolotti et al., 2021). However, the situation changes when it comes to mathematical problems. This complex skill requires the involvement of domain-general cognitive processes, such as verbal knowledge and working memory, in a similar way in the group with ASD and in the TD group.

5.5 Implications and conclusions

The outcomes of the current dissertation suggested practical implications concerning both assessment and intervention strategies for students with ASD. Both inhibitory and math difficulties were not considered core features of autism; however, they significantly impact on daily and academic functioning (Bertollo et al., 2020; Pugliese et al., 2020) and, therefore, an accurate evaluation of these processes, together with the identification of efficient intervention strategies is essential (Macoun et al., 2021). Previous chapters underscored the need to view these abilities multidimensionally, not just identifying difficulties but understanding interacting factors. Employing diverse assessment methods proves advantageous in comprehensively evaluating inhibitory skills in individuals with ASD. Indirect and direct measures exhibit complementary properties, with indirect measures capturing real-life inhibitory processes suitable for screening potential inhibitory difficulties negative impacting on daily situations. Conversely, direct measures more precisely estimate inhibitory process efficiency (Toplak, 2013). In direct assessment, computerized tasks offer advantages such as precise reaction time estimation, but including traditional tasks administered by a clinician can address the relational dimension's influence on inhibitory abilities.

Adopting a multidimensional perspective and identifying moderating variables influencing cognitive and academic abilities in individuals with ASD offers valuable insights for educational strategies. For example, considering the important role of working memory and verbal intellectual functioning can support effective teaching approaches. Anticipating and understanding activities, schedules reduce cognitive load and improve students' ability to participate and respond to classroom or task demands (Leigh et al., 2021). Establishing routines, creating written schedules, and using priming techniques, like exposing school assignments before presentation, have also proven effective; in addition, students with ASD require explicit instruction to learn new skills and visual supports, modelling and the use of highly familiar or automatized information and vocabulary are crucial (Fleury et al., 2014).

Furthermore, it's important to also consider the differential role of age on these abilities. Specifically for inhibitory control, we have observed that especially for response inhibition, the differences are significantly larger in preschool age, a period known to be crucial for the development of executive function (Traverso et al., 2015). As for mathematical skills, the results suggest that the difficulties faced by group with ASD increase with age, highlighting the need for early and continuous interventions to addressing the widening gap between ASD students and their typically developing peers.

It is worth note that, up to date, interventions on cognitive and academic skills for students with ASD do not include strategies to manage and overcome emotional difficulties even though it has been proved that the anxiety can negatively affect their abilities (Finnane, 2011). In fact, although recent research shows that those students face great difficulties in both EF and mathematics and are at-risk of developing anxiety (Spain et al., 2018), interventions focus on their cognitive and learning skills and not on their attitudes and emotions in dynamic and social context like school environment and more specifically towards testing and mathematics. For example, it will be important to consider that executive difficulties may be particularly relevant to social anxiety. This becomes particularly evident when one considers the school context where classrooms are fundamentally social and performance settings and students are surrounded by their peers and may well be expected to answer a question, read aloud or write texts. Situations such as these are likely to generate anxiety for socially anxious individuals (Leigh et al., 2021). Cognitive behavioral therapy (CBT; Wood et al. 2009) and mindfulness training (Spek et al., 2013) have been found to be effective treatments for anxiety in ASD and, therefore, future research in these areas may help to compliment educational interventions for students with ASD.

Moreover, being interested in mathematics can be considered as a variable which affects positively math achievement (Zhang & Wang, 2020). Yet, the motivation of students with ASD is a crucial but, nonetheless, a difficult challenge (Georgiou et al., 2018). It is crucial because, by definition, students with ASD have limited and recurrent interests and difficult because these students are vulnerable to various factors (e.g., sudden changes or sensorial stimuli in the environment) that affect their motivation and concentration. In addition to integrate students' interests in the activities to support a certain skills, it is known that computerized training can increase motivation in participants with ASD and reduce relational demands; however, in order to enhance the generalizability of the results, it is also essential the incorporation of the use of technology in small-group training, adopting different methods of assessment to test the efficacy of the training (Grynszpan et al., 2007; Moore & Calvert, 2000; Beaumont & Sofronoff, 2008).

In conclusion, the current dissertation showed how a multidimensional investigation of domain-general processes, and in particular inhibitory processes and working memory, and their interactions with mathematical learning can reveal detailed insights to address gaps in autism research. These findings could promote educational interventions and enhance our understanding of this neurodevelopmental disorder.

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7 Appendix

Table A1. Summary of included studies with direct measures.

Authors	**N ASD**	**N TD**	**Age ASD** (in years)		**Age TD** (in years)		**Age-matching**	**IQ-Matching**	**Hedges' *g*[a]**	***SE***	**Task name**
			Mean	SD	Mean	SD					
Abu Akel et al., 2018	15	32	8.93	2.05	9.93	1.83	Yes	No	0.522	0.101	Stroop Colour-Word
Adamo et al., 2014	46	36	10	1	10	1	Yes	Yes	0.330	0.050	Go/no-go
Adams & Jarrold, 2009	24	24	13.5	1.7	9.9	0.18	No	Yes	-0.389	0.085	Stroop Colour-Word
Adams & Jarrold, 2009	24	24	13.5	1.7	9.9	0.18	No	Yes	-0.035	0.083	Animal Stroop
Adams & Jarrold, 2012	15	15	14.5	1.7	9.1	1.06	No	Yes	0.304	0.135	Stop Signal
Adams & Jarrold, 2012	15	15	14.5	1.7	9.1	1.06	No	Yes	-0.283	0.135	Flanker
Agam et al., 2010	11	14	28	10	27	8	Yes	Yes	0.807	0.175	Antisaccade
Altgassen & Koch, 2014	22	22	25.82	7.08	25.64	5.44	Yes	-	0.000	0.091	Go/no-go
Altgassen et al., 2012	25	25	21.80	6.68	21.80	6.06	Yes	-	-0.459	0.082	TOL

Ambery et al., 2006	27	20	37.6	14.6	33.5	12	Yes	Yes	0.364	0.088	Stroop Colour-Word
Ambrosino et al., 2014	19	19	11.5	1.2	11.1	1.6	Yes	Yes	0.432	0.108	Go/no-go
Ames & Jarrold, 2007	17	17	14.12	1.48	6.44	0.58	No	Yes	1.215	0.139	Stroop-like Dog-Pig
Andersen et al., 2015	34	45	11.6	2.0	11.4	1.5	Yes	Yes	1.029	0.058	Stroop Colour-Word
Baez et al., 2012	15	15	35.46	11.86	35.7	11.52	Yes	No	0.507	0.138	Hayling Test
Baez et al., 2012	15	15	35.46	11.86	35.7	11.52	Yes	No	0.039	0.133	Flanker
Baez et al., 2012	15	15	35.46	11.86	35.7	11.52	Yes	No	0.035	0.133	Flanker
Bigham, 2010	60	37	7.9	1.51	4.68	1.31	No	-	0.509	0.045	Luria's Hand Game
Biscaldi et al., 2016	18	33	10.98	1.76	10.69	1.88	Yes	Yes	0.345	0.087	Stop Signal
Biscaldi et al., 2016	10	33	10.07	1.92	10.69	1.88	Yes	Yes	1.296	0.150	Stop Signal
Bishop & Norbury, 2005	14	18	8.3	0.99	8.56	1	Yes	Yes	1.351	0.156	Opposite Worlds
Bishop & Norbury, 2005	9	18	8.3	0.99	8.56	1	Yes	Yes	1.147	0.191	Walk/ Don't walk
Boland et al., 2019	36	44	14.5	1.8	14.5	2.4	Yes	Yes	0.085	0.051	Flanker

Boland et al., 2019	36	44	14.5	1.8	14.5	2.4	Yes	Yes	0.142	0.051	Flanker
Bonli 2005	9	19	4.33	-	4.08	-	Yes	No	0.725	0.173	Delayed Response
Bonli 2005	9	19	4.33	-	4.08	-	Yes	No	0.608	0.170	Stroop-like Day-Night
Bonli 2005	9	19	4.33	-	4.08	-	Yes	No	1.929	0.230	Luria's Tapping Task
Bonli 2005	18	16	5.67	-	5.67	-	Yes	No	2.019	0.178	Delayed Response
Bonli 2005	18	16	5.67	-	5.67	-	Yes	No	0.846	0.129	Stroop-like Day-Night
Bonli 2005	18	16	5.67	-	5.67	-	Yes	No	1.246	0.141	Luria's Tapping Task
Bonli 2005	11	6	8.17	-	7.83	-	Yes	No	1.037	0.289	Delayed Response
Boxhoorn et al., 2018	23	23	10.04	2.3	9.77	2.4	Yes	Yes	-0.116	0.087	Go/no-go
Boxhoorn et al., 2018	23	23	10.04	2.3	9.77	2.4	Yes	Yes	2.485	0.154	Incompatibility task
Brady et al., 2017	34	34	18.86	-	18.9	-	Yes	Yes	0.679	0.062	Stroop Colour-Word
Brady et al., 2017	34	34	18.86	-	18.9	-	Yes	Yes	0.467	0.060	TOL

Brunsdon et al 2015	145	142	13.49	0.69	12.79	1.10	No	No	0.675	0.015	Luria's Hand Game
Cage et al., 2016	33	33	10.96	2.11	10.24	2.00	Yes	-	0.228	0.061	Go/no-go
Chan et al, 2011 b	16	19	7.98	1.9	8.3	1.98	Yes	Yes	0.350	0.117	Go/no-go
Chan et al, 2011 b	16	19	7.98	1.9	8.3	1.98	Yes	Yes	0.994	0.129	CPT-II
Chan et al., 2009	13	29	10.78	1.84	9.53	1.9	Yes	Yes	0.037	0.111	CPT-II
Chan et al., 2009	16	38	10.54	1.73	9.31	2.2	Yes	No	-0.062	0.089	Go/no-go
Chan et al., 2011 a	20	20	10.75	2.07	9.8	1.88	Yes	Yes	0.593	0.104	CPT-II
Chan et al., 2011 a	20	20	10.75	2.07	9.8	1.88	Yes	Yes	0.005	0.100	Stroop Colour-Word
Chantiluke et al., 2015	19	25	14.7	2.0	13.4	2.4	Yes	Yes	-0.179	0.093	Stroop Colour-Word
Christ et al., 2007	16	45	8.2	1.6	11.3	3.4	No	No	1.459	0.102	Stop Signal
Christ et al., 2007	15	48	8.2	1.6	11.3	3.4	No	No	2.048	0.121	Stroop Computer Task
Christ et al., 2007	16	45	8.2	1.6	11.3	3.4	No	No	1.207	0.097	Flanker
Christ et al., 2007	16	48	8.2	1.6	11.3	3.4	No	No	0.954	0.090	Stroop Card Task
Christ et al., 2011	28	49	13.1	2.8	13.3	2.7	Yes	No	0.157	0.056	Go/no-go
Christ et al., 2011	28	49	13.1	2.8	13.3	2.7	Yes	No	0.655	0.059	Numerical Stroop

Corbett & Constantine, 2006	15	15	10.1	2.04	9.56	1.89	Yes	No	2.308	0.222	Flanker
Cox et al., 2016	17	27	18.28	2.29	16.59	0.55	No	-	-0.516	0.099	CPT
Cui et al., 2012	11	11	7.43	-	7.37	-	Yes	Yes	0.907	0.201	Response Inhibition Task
Cui et al., 2012	11	11	7.43	-	7.37	-	Yes	Yes	0.712	0.193	Modified Colour-Word Stroop
Czermainski et al., 2014	11	19	11.73	1.9	11.42	1.8	Yes	-	1.075	0.163	Modified Colour-Word Stroop
Daly et al. 2014	7	7	-	-	-	-	-	-	0.191	0.287	Stroop Colour-Word
Davids et al., 2016	30	30	58.6	7.8	59.4	8.3	Yes	Yes	-0.226	0.067	Go/no-go
Davidson, 2016	21	21	10.82	1.42	11.08	1.05	Yes	Yes	0.000	0.095	TOL
Davidson, 2016	21	21	10.82	1.42	11.08	1.05	Yes	Yes	0.091	0.095	Go/no-go
Dawson et al., 2002	72	39	3.62	0.36	2.26	0.74	No	-	0.331	0.040	Flanker
de Vries & Geurts, 2014	74	74	10.6	1.4	10.4	1.1	Yes	Yes	0.400	0.028	(DNMS) Delayed nonmatching to sample
Dierst-Davies, 2005	30	30	13.70	1.39	13.73	1.46	Yes	Yes	0.682	0.071	Stop task

Drayer, 2008	6	6	4.7	-	4.64	-	Yes	No	-0.060	0.333	Stroop Colour-Word
Drayer, 2008	6	6	4.7	-	4.64	-	Yes	No	1.074	0.381	Stroop-like Day-Night
Drayer, 2008	12	7	5.41	-	5.55	-	Yes	No	0.621	0.236	TOH-R
Drayer, 2008	12	7	5.41	-	5.55	-	Yes	No	1.297	0.270	Stroop-like Day-Night
Drayer, 2008	11	17	6.62	-	6.38	-	Yes	No	1.174	0.174	TOH-R
Drayer, 2008	11	17	6.62	-	6.38	-	Yes	No	2.413	0.254	Stroop-like Day-Night
Duerden et al., 2013	13	15	25.9	3.7	29	6.9	Yes	Yes	1.347	0.176	TOH-R
Faja et al., 2016	28	33	9.2	1.5	9.6	1.3	Yes	Yes	0.733	0.070	Go/no-go
Faja et al., 2016	28	33	9.2	1.5	9.6	1.3	Yes	Yes	0.432	0.068	Flanker
Faja et al., 2016	23	24	9.2	1.5	9.6	1.3	Yes	Yes	0.133	0.085	Flanker
Faja et al., 2016	23	24	9.2	1.5	9.6	1.3	Yes	Yes	0.126	0.085	Stroop Colour-Word
Faja et al., 2016	25	32	9.2	1.5	9.6	1.3	Yes	Yes	-0.145	0.071	Stroop Colour-Word
Fitch et al., 2015	20	17	12.92	2.09	13.37	1.43	Yes	Yes	0.582	0.113	Stop task
Fitch et al., 2015	20	17	12.92	2.09	13.37	1.43	Yes	Yes	0.561	0.113	Stroop Colour-

											Word Interference (D-KEFS)
Gardiner et al., 2017	24	19	5.57	1.12	4.87	1.32	Yes	Yes	0.033	0.094	D-KEFS Tower Test
Gardiner et al., 2017	24	19	5.57	1.12	4.87	1.32	Yes	Yes	0.208	0.095	Stroop Boy-Girl
Gardiner et al., 2017	24	19	5.57	1.12	4.87	1.32	Yes	Yes	0.442	0.097	Go/no-go
Gardiner et al., 2017	24	19	5.57	1.12	4.87	1.32	Yes	Yes	0.388	0.096	P-CPT
Garon et al., 2018	16	133	3.78	0.47	3.06	0.58	No	-	0.361	0.070	Monkey Tower
Garon et al., 2018	18	83	5.26	0.6	4.52	0.37	No	-	0.973	0.072	Tricky box
Geurts & Vissers, 2012	23	23	63.6	7.5	63.7	8.1	Yes	Yes	0.743	0.093	Tricky box
Geurts et al., 2004	41	41	9.4	1.8	9.1	1.7	Yes	No	0.732	0.052	SART
Geurts et al., 2004	41	41	9.4	1.8	9.1	1.7	Yes	No	0.684	0.052	Change Task
Geurts et al., 2004	41	41	9.4	1.8	9.1	1.7	Yes	No	0.374	0.050	Circle Drawing Task
Geurts et al., 2009	18	22	10.3	1.6	10.3	1.4	Yes	Yes	0.419	0.103	Opposite Worlds

Geurts et al., 2020	50	51	65.8	5.6	69.7	5.6	No	Yes	0.340	0.040	Go/no-go (Emotiona l)
Goddard et al., 2014	63	63	12.55	2.81	12.10	2.26	Yes	Yes	0.490	0.033	TOL
Goddard et al., 2014	63	63	12.55	2.81	12.10	2.26	Yes	Yes	0.407	0.032	Stroop Colour-Word
Goddard et al., 2014	63	63	12.55	2.81	12.10	2.26	Yes	Yes	0.584	0.033	Junior Hayling Test
Goldberg et al., 2005	17	32	10.3	1.8	10.4	1.5	Yes	No	0.107	0.090	TOL
Goldberg et al., 2011	11	15	10.4	1.6	10.5	1.2	Yes	Yes	1.901	0.227	Stroop Colour-Word
Goldstein et al., 2001	103	103	18.15	10.14	18.96	10.10	Yes	Yes	-0.326	0.020	Go/no-go
Goldstein et al., 2001	103	103	18.15	10.14	18.96	10.10	Yes	Yes	-0.032	0.019	Stroop Colour-Word
Golshan et al., 2019	15	15	9.8	1.65	9.46	1.4	Yes	Yes	1.662	0.179	CPT
Gomez-Perez et al., 2016	34	34	9.35	1.28	9.26	1.46	Yes	Yes	0.407	0.060	Inhibition (Nepsy-II)
Gonzalez-Gadea et al., 2015	24	19	10.38	1.97	11.63	2.43	Yes	Yes	0.278	0.095	Stroop Colour-Word
Gooskens et al., 2019	26	53	11.33	1.07	10.76	1.15	Yes	Yes	-0.321	0.058	Hayling Test

Han & Chan, 2017	19	28	11.6	3.02	12.0	2.33	Yes	Yes	0.154	0.089	Stop Signal
Han & Chan, 2017	19	28	12.1	2.35	12.0	2.33	Yes	No	0.684	0.093	Go/no-go
Hanson & Atance, 2014	25	25	5.86	1.49	4.86	0.93	No	No	0.856	0.087	Go/no-go
Hanson & Atance, 2014	25	25	5.86	1.49	4.86	0.93	No	No	0.282	0.081	Stroop Black-White
Happè et al., 2006	25	26	10.9	2.4	11.2	2.0	Yes	Yes	-0.190	0.079	TOH
Hill & Bird., 2006	22	22	31.09	13.14	33.45	4.54	Yes	Yes	0.417	0.093	Go/no-go
Hill & Bird., 2006	22	22	31.09	13.14	33.45	4.54	Yes	Yes	0.352	0.092	Hayling test
Hogeveen et al., 2018	34	45	10.44	1.66	10.93	1.34	Yes	Yes	0.474	0.053	Stroop Colour-Word
Hopkins et al., 2017	12	12	10.8	-	10.3	-	Yes	-	1.274	0.200	AX-CPT
Hoyland et al., 2019	49	49	15.6	2.4	15.6	1.8	Yes	-	0.000	0.041	Hayling test
Ikeda et al., 2014	9	21	15.44	1.38	8.46	0.52	No	-	-0.368	0.161	Go/no-go (visual cued)
Ikeda et al., 2014	9	21	15.44	1.38	8.46	0.52	No	-	-0.851	0.171	Animal stroop (Real animal size)
Ikeda et al., 2018 a	22	22	12.9	2.8	13.6	2.2	Yes	No	0.442	0.093	Animal stroop

											(Pictorial animal size)
Ikeda et al., 2018 a	22	22	12.9	2.8	13.6	2.2	Yes	No	0.285	0.092	Go/no-go (with direct gaze)
Ikeda et al., 2018 b	20	24	10.0	2.8	9.6	1.9	Yes	Yes	0.125	0.092	Go/no-go (with averted gaze)
Ishii-Takahashi et al., 2014	21	21	30.8	7.2	28.8	5.5	Yes	Yes	0.505	0.098	Go/no-go
Jahromi et al., 2013	20	20	4.91	0.96	4.18	0.93	No	-	0.345	0.101	Stop Signal
Jahromi et al., 2019	18	20	4.8	0.09	4.18	0.93	Yes	-	0.294	0.107	Stroop-like Day-Night
Jahromi et al., 2019	18	20	4.8	0.09	4.18	0.93	Yes	-	0.949	0.117	Stroop-like Day-Night
Johnson et al., 2007	19	18	12.2	2.4	11.1	1.9	Yes	Yes	1.263	0.130	Luria's Hand Game
Johnston et al., 2011	24	14	27.8	8.7	28.7	11.1	Yes	Yes	0.490	0.116	SART
Johnston et al., 2011	24	14	27.8	8.7	28.7	11.1	Yes	Yes	-0.519	0.117	Stroop Colour-Word

Johnston et al., 2011	24	14	27.8	8.7	28.7	11.1	Yes	Yes	-0.094	0.113	Hayling Test
Joseph et al., 2005	37	30	7.11	1.9	8.3	2.1	Yes	Yes	0.310	0.061	Matching Familiar Figures
Joseph et al., 2005	36	29	7.11	1.9	8.3	2.1	Yes	Yes	0.565	0.065	Stroop-like Day-Night
Joseph et al., 2005	37	31	7.11	1.9	8.3	2.1	Yes	Yes	0.502	0.061	Knock-Tap (Nepsy-II)
Karalunas et al., 2018	97	301	11.34	2.49	9.48	1.59	No	No	0.174	0.014	TOL
Kiep & Spek, 2016	99	35	38.03	9.39	39.16	11.44	Yes	Yes	-0.054	0.039	Stroop Colour-Word
Kiep & Spek, 2016	40	25	34.92	10.71	36.14	10.78	Yes	Yes	-0.285	0.066	TOH
Kilicaslan et al., 2010	21	18	12.44	2.87	11.96	2.36	Yes	Yes	0.105	0.103	TOH
Kilicaslan et al., 2010	21	18	12.44	2.87	11.96	2.36	Yes	Yes	0.481	0.106	Stroop Colour-Word
Kohli et al., 2019	20	21	50.2	5.9	50.8	6.9	Yes	Yes	0.924	0.108	CPT
Koolschijn et al., 2017	45	49	51.32	12.29	50.47	11.83	Yes	Yes	0.983	0.048	Stroop Colour-Word
Koolschijn et al., 2017	27	39	51.32	12.29	50.47	11.83	Yes	Yes	-0.198	0.063	Flanker

Kouklari et al., 2018 a	79	79	11.27	2.56	10.80	2.49	Yes	Yes	0.755	0.027	Flanker
Kouklari et al., 2018 a	79	79	11.27	2.56	10.80	2.49	Yes	Yes	0.678	0.027	Go/no-go
Kouklari et al., 2018 b	32	32	10.34	1.29	10	1.35	Yes	No	1.139	0.073	TOL
Kretschmer et al., 2014	21	21	10.22	1.55	9.83	2.36	Yes	-	-0.483	0.098	Stroop Colour-Word
Kuijper et al., 2015	46	38	9.3	1.1	9.0	1.9	Yes	Yes	0.032	0.048	Go/no-go
Kuiper et al., 2017	31	39	32.26	14.6	30.58	6.35	Yes	Yes	0.099	0.058	Stop Signal
Kushki et al., 2013	12	17	11.3	2.3	10.9	2.3	Yes	No	1.562	0.184	Emotional stop signal task
Kushki et al., 2014	40	36	12.0	2.9	12.5	2.9	Yes	No	0.694	0.056	Stroop Colour-Word
Landsiedel & Williams, 2020	21	20	34.84	11.42	38.24	13.19	Yes	Yes	0.183	0.098	Stroop Colour-Word
Lee et al., 2009	11	10	10.17	1.57	11.01	1.78	Yes	Yes	0.259	0.193	Stroop Colour-Word
Lemon et al., 2011	10	8	11.1	3.6	12.1	4.2	Yes	No	0.047	0.225	Go/no-go
Lemon et al., 2011	13	14	11.0	3.0	10.7	2.3	Yes	No	1.269	0.178	Stop task
Leno et al., 2018	41	42	13.77	1.08	12.79	1.61	No	No	1.167	0.056	Stop task

Liang, 2015	6	10	11.8	3.5	12.3	2.6	Yes	-	1.422	0.330	TOH
Lopez et al., 2005	17	17	29.1	8.0	29.4	11.4	Yes	Yes	0.510	0.121	Stroop Colour-Word
Lopez et al., 2005	17	17	29.1	8.0	29.4	11.4	Yes	Yes	0.042	0.118	Stroop Colour-Word
Lopez et al., 2005	17	17	29.1	8.0	29.4	11.4	Yes	Yes	1.115	0.136	California Tower
Lopez, 2015	6	10	8.3	1.1	8.0	0.77	Yes	Yes	0.123	0.267	Distracter Interference Task
Lopez, 2015	6	10	8.3	1.1	8.0	0.77	Yes	Yes	0.191	0.268	Response Inhibition Task
Lopez, 2015	6	10	8.3	1.1	8.0	0.77	Yes	Yes	-0.418	0.272	Distracter Interference Task
Lopez, 2015	6	10	8.3	1.1	8.0	0.77	Yes	Yes	-0.009	0.267	Response Inhibition Task
Lundervold et al., 2016	9	134	10.3	0.9	9.7	0.9	Yes	Yes	0.178	0.119	CPT-II
Lundervold et al., 2016	11	134	10.6	0.7	9.7	0.9	No	Yes	0.024	0.098	CPT-II
Ma et al., 2019	20	20	11.86	2.27	5.06	0.42	No	Yes	0.710	0.106	Stroop-like Day-Night

Magnuson et al., 2019	25	30	10	2	9.6	1.8	Yes	Yes	0.342	0.074	Go/no-go (Emotional)
Mahone et al., 2006	24	60	10.0	1.6	9.8	1.4	Yes	No	0.176	0.059	Controlateral Motor Response Task
Mahone et al., 2006	24	60	10.0	1.6	9.8	1.4	Yes	No	-0.026	0.058	Conflicting Motor Response Task
Mahone et al., 2006	24	60	10.0	1.6	9.8	1.4	Yes	No	1.493	0.072	Statue test (NEPSY)
Maister et al., 2013	14	14	12.2	0.6	12.1	0.2	Yes	Yes	0.177	0.143	Stroop Colour-Word
Martinez et al., 2017	21	21	12.67	2.6	12.95	3.0	Yes	Yes	0.866	0.104	CPT-II
Martinez et al., 2017	21	21	12.67	2.6	12.95	3.0	Yes	Yes	0.505	0.098	Stroop Colour-Word
McCrimmon et al., 2012	24	12	-	-	-	-	-	Yes	0.290	0.126	Stroop Colour-Word
McCrimmon et al., 2012	9	21	-	-	-	-	-	Yes	0.197	0.159	Stroop Colour-Word
McCrory et al., 2007	24	27	13.02	1.15	12.55	1.12	Yes	Yes	0.851	0.086	Hayling Test

Mosconi et al., 2009	18	15	17.7	10.8	19.9	11.5	Yes	Yes	0.629	0.128	Antisaccade
Mutreja et al., 2016	14	52	8.09	2.17	7.73	1.38	Yes	Yes	-0.138	0.091	Child ANT
Mutreja et al., 2016	14	52	8.09	2.17	7.73	1.38	Yes	Yes	0.697	0.094	Child ANT
Narzisi et al., 2013	22	44	9.77	3.65	-	-	Yes	-	1.185	0.079	Inhibition (Nepsy-II)
Oerlemans et al., 2013	140	127	12.4	3.0	11.0	3.6	No	Yes	0.391	0.015	Go/no-go
Oswald, 2012	40	40	14.64	2.05	14.64	2.19	Yes	Yes	-0.003	0.050	Flanker
Overweg et al., 2018	44	41	9.4	2.2	9.2	2.0	Yes	Yes	0.328	0.048	Flanker
Ozonoff & Jensen, 1999	40	29	12.6	3.4	12.1	3.0	Yes	No	0.693	0.063	TOH
Ozonoff & Jensen, 1999	40	29	12.6	3.4	12.1	3.0	Yes	No	0.398	0.061	Stroop Colour-Word
Ozonoff & Strayer, 1997	13	13	13.9	2.5	13.1	1.4	Yes	Yes	1.779	0.215	Stop Signal
Ozonoff et al., 1991	23	20	12.05	3.19	12.39	3.04	Yes	Yes	1.862	0.134	TOH
Ozonoff et al., 1994	14	14	12.43	2.47	12.15	1.73	Yes	Yes	0.045	0.143	Go/no-go
Ozonoff et al., 2004	79	70	15.7	8.7	16.0	7.6	Yes	Yes	0.862	0.029	TOL (online)
Pankert et al., 2014	17	17	11.6	1.5	11.7	1.2	Yes	Yes	0.723	0.125	Go/no-go
Pankert et al., 2014	17	17	11.6	1.5	11.7	1.2	Yes	Yes	0.418	0.120	Go/no-go

Pastor-Cerezuela et al., 2020	40	40	6.77	0.93	6.82	1.05	Yes	Yes	0.969	0.056	Counting Stroop
Pastor-Cerezuela et al., 2020	40	40	6.77	0.93	6.82	1.05	Yes	Yes	0.547	0.052	Auditory Attention test
Pellicano et al., 2017	30	30	4.44	1.02	4.42	0.88	Yes	Yes	0.931	0.074	Less is More
Pellicano, 2007	30	40	5.63	0.97	5.47	0.95	Yes	Yes	0.549	0.060	Luria's Hand Game
Pellicano, 2007	30	40	5.63	0.97	5.47	0.95	Yes	Yes	0.848	0.063	TOL
Pellicano, 2010	37	31	5.66	0.87	5.43	1.05	Yes	Yes	1.511	0.076	TOL
Pitzianti et al., 2016	13	13	10.69	2.1	11.85	2.7	Yes	Yes	1.843	0.219	Stroop Colour-Word
Pitzianti et al., 2016	13	13	10.69	2.1	11.85	2.7	Yes	Yes	0.861	0.168	TOL
Pitzianti et al., 2016	12	13	10.25	2.0	11.85	2.7	Yes	Yes	1.828	0.227	Go/no-go
Pitzianti et al., 2016	12	13	10.25	2.0	11.85	2.7	Yes	Yes	1.515	0.206	TOL
Pooragha et al., 2013	15	15	9.33	1.79	10.13	2.44	Yes	Yes	1.067	0.152	Go/no-go
Prat et al., 2016	16	17	25.3	5.0	25.6	7.2	Yes	Yes	0.195	0.122	Stroop Colour-Word
Robinson et al., 2009	54	54	12.5	2.8	12.1	2.3	Yes	Yes	0.524	0.038	Go/no-go
Robinson et al., 2009	54	54	12.5	2.8	12.1	2.3	Yes	Yes	0.528	0.038	TOL

Robinson et al., 2009	54	54	12.5	2.8	12.1	2.3	Yes	Yes	0.431	0.038	Stroop Colour-Word
Rommelse et al., 2015	30	22	12.1	3.0	12.8	3.4	Yes	Yes	-0.220	0.079	Junior Hayling Test
Rommelse et al., 2015	57	54	12.2	2.4	12.2	2.7	Yes	Yes	-0.023	0.036	Response Organizati on Objects (ANT)
Rommelse et al., 2015	41	70	11.4	3.1	12.2	3.6	Yes	Yes	0.119	0.039	Response Organizati on Objects (ANT)
Ross et al., 2019	16	18	20	1.55	20.28	1.87	Yes	-	0.417	0.121	Response Organizati on Objects (ANT)
Russell et al. 1999	19	19	13.8	2.2	7.3	0.2	No	-	0.361	0.107	Stop Signal
Russell et al. 1999	19	19	13.8	2.2	7.3	0.2	No	-	0.679	0.111	Stroop-like Day-Night
Sachse et al., 2013	30	28	19.2	5.1	19.9	3.6	Yes	Yes	0.712	0.073	Stroop-like Day-Night
Sachse et al., 2013	30	28	19.2	5.1	19.9	3.6	Yes	Yes	1.265	0.083	Stroop Colour-Word

Samyn et al., 2015	31	148	12.83	1.41	12.73	1.48	Yes	No	0.459	0.040	Stroop Colour-Word
Samyn et al., 2015	31	148	12.83	1.41	12.73	1.48	Yes	No	0.073	0.039	Go/no-go
Sanderson & Allen, 2013	31	31	13.6	1.9	8.8	1.4	No	Yes	-0.677	0.068	Animal Stroop
Schaeffer, 2020	26	23	10.01	2.03	10.0	2.01	Yes	Yes	0.463	0.084	Go/no-go
Schmitt et al., 2017	121	76	12.3	4.7	13.5	5.8	Yes	Yes	0.104	0.021	Luria's Hand Game
Schmitt et al., 2017	121	76	12.3	4.7	13.5	5.8	Yes	Yes	0.606	0.022	Stop Signal
Schmitz et al., 2006	10	12	38	9	39	6	Yes	Yes	0.244	0.185	Stop Signal
Schmitz et al., 2006	10	12	38	9	39	6	Yes	Yes	0.091	0.184	Go/no-go
Schmitz et al., 2006	10	12	38	9	39	6	Yes	Yes	0.623	0.192	Stroop Colour-Word
Schurink et al., 2012	28	28	10.6	1.5	10.5	1.3	Yes	-	0.588	0.075	Stroop Colour-Word
Shafritz et al., 2015	15	15	18.1	-	18.4	-	Yes	Yes	0.326	0.135	TOL
Shi et al., 2020	23	23	12.22	1.95	12.78	1.26	Yes	No	1.228	0.103	Go/no-go
Shi et al., 2020	23	23	12.22	1.95	12.78	1.26	Yes	No	1.208	0.103	SART
Shi et al., 2020	23	23	12.22	1.95	12.78	1.26	Yes	No	0.496	0.090	Walk/ Don't walk

Shi et al., 2020	23	23	12.22	1.95	12.78	1.26	Yes	No	1.203	0.103	Opposite Worlds
Shi et al., 2020	23	23	12.22	1.95	12.78	1.26	Yes	No	0.131	0.087	Opposite Worlds
Shi et al., 2020	23	23	12.22	1.95	12.78	1.26	Yes	No	0.774	0.093	Stroop Colour-Word
Sinzig et al., 2008	20	20	10.9	3.1	13.1	3.0	Yes	Yes	0.105	0.100	Stroop Colour-Word
Sinzig et al., 2008	20	20	14.3	3.0	13.1	3.0	Yes	Yes	0.154	0.100	Go/no-go
Sinzig et al., 2014	26	29	6.70	1.18	5.19	1.1	No	No	0.781	0.078	Go/no-go
Sivaratnam et al., 2018	26	27	8.77	2.00	9.02	1.80	Yes	Yes	0.527	0.078	Go/no-go
Solomon et al., 2008	31	32	12.3	2.5	12.2	2.5	Yes	Yes	0.516	0.066	Inhibition (Nepsy-II)
South et al., 2010	24	21	14.03	2.4	14.23	2.83	Yes	Yes	0.578	0.093	POP task
South et al., 2010	24	21	14.03	2.4	14.23	2.83	Yes	Yes	-0.490	0.092	Flanker
Suzuki et al., 2017	11	12	11.43	1.5	10.36	1.98	Yes	Yes	0.582	0.182	Flanker
Troyb et al., 2014	43	34	13.85	2.68	13.87	2.58	Yes	Yes	-0.306	0.053	Flanker
Troyb et al., 2014	43	34	13.85	2.68	13.87	2.58	Yes	Yes	-0.156	0.053	Stroop Colour-Word
Troyb et al., 2014	43	34	13.85	2.68	13.87	2.58	Yes	Yes	0.328	0.053	Stroop Colour-Word

Tsai et al., 2011	16	16	7.85	0.8	7.5	0.85	Yes	-	0.788	0.135	TOL
Tye et al., 2014	19	26	11.69	1.7	10.56	1.79	Yes	Yes	0.051	0.091	Endogenous Posner Task
Tye et al., 2014	29	26	10.53	1.69	10.56	1.79	Yes	Yes	0.008	0.073	CPT-Flanker
Vaidya et al., 2011	15	18	10.78	1.29	10.96	1.26	Yes	Yes	0.608	0.128	CPT-Flanker
Vaidya et al., 2011	15	18	10.78	1.29	10.96	1.26	Yes	Yes	0.631	0.128	Stroop-like Arrow Task
Valeri et al., 2020	27	27	5.13	0.53	5.13	0.53	Yes	Yes	0.688	0.078	Stroop-like Arrow Task
Van Eylen et al., 2015	50	50	12.21	2.58	12.48	2.72	Yes	Yes	0.498	0.041	Stroop-like Day-Night
Van Eylen et al., 2015	50	50	12.21	2.58	12.48	2.72	Yes	Yes	0.006	0.040	Go/no-go
Van Eylen et al., 2015	50	50	12.21	2.58	12.48	2.72	Yes	Yes	0.160	0.040	Flanker
Van Eylen et al., 2015	50	50	12.21	2.58	12.48	2.72	Yes	Yes	0.217	0.040	Flanker
van Hulst et al., 2018	32	32	10.7	1.4	10.1	1.1	Yes	Yes	0.333	0.063	TOL
Vara et al., 2014	15	15	15.5	1.2	15.6	1.3	Yes	Yes	0.696	0.141	Stop Signal

Velasquez et al., 2017	19	22	25.84	4.39	29.03	9.40	Yes	Yes	0.015	0.098	Go/no-go
Velazquez et al., 2009	15	16	10.8	3.4	11.1	2.6	Yes	Yes	0.596	0.135	Go/no-go
Vertè et al., 2005	61	47	9.1	1.9	9.4	1.6	Yes	No	0.897	0.041	Change Task
Vertè et al., 2005	61	47	9.1	1.9	9.4	1.6	Yes	No	0.722	0.040	Circle Drawing Task
Vertè et al., 2005	61	47	9.1	1.9	9.4	1.6	Yes	No	0.560	0.039	Opposite Worlds
Vertè et al., 2006	63	82	8.7	2.0	9.2	1.7	Yes	No	0.547	0.029	Change Task
Voelbel et al., 2006	38	13	10.16	1.92	10.77	1.48	Yes	No	0.855	0.110	Stroop Colour-Word
Wallace et al., 2009	28	25	15.74	2.10	16.36	1.83	Yes	Yes	0.619	0.079	TOL
Weismer et al., 2018	48	71	9.5	1.2	9.3	1.0	Yes	No	0.520	0.036	Flanker
Weismer et al., 2018	48	71	9.5	1.2	9.3	1.0	Yes	No	0.383	0.036	Go/no-go
Weismuller et al., 2015	18	15	9.4	2.4	10.6	3.25	Yes	Yes	-0.894	0.134	Tower Test
Weismuller et al., 2015	18	15	9.4	2.4	10.6	3.25	Yes	Yes	-0.774	0.131	Tower Test
White et al., 2009	45	27	9.58	1.44	9.88	1.32	Yes	Yes	0.481	0.061	MHSCT-C
Wichers et al., 2019	17	17	30	11	27	9	Yes	Yes	0.470	0.121	Go/no-go
Wilson et al., 2014	84	82	26.0	7.0	28.0	6.0	Yes	Yes	0.626	0.025	Go/no-go

Xiao et al., 2012	19	16	10.11	2.08	9.69	1.74	Yes	Yes	0.871	0.126	Go/no-go
Xiao et al., 2012	19	16	10.11	2.08	9.69	1.74	Yes	Yes	0.344	0.117	Stroop Colour-Word
Xiao et al., 2012	19	16	10.11	2.08	9.69	1.74	Yes	Yes	0.195	0.116	Stroop Colour-Word
Yang et al., 2009	20	26	8.1	3.5	8.0	3.1	Yes	No	0.771	0.095	Numerical Stroop
Yasumura et al., 2014	11	15	10.51	2.3	9.56	1.51	Yes	Yes	0.230	0.159	Stroop Colour-Word
Yasumura et al., 2014	11	15	10.51	2.3	9.56	1.51	Yes	Yes	-0.090	0.158	Stroop Colour-Word (Reverse)
Yerys et al., 2009	28	21	9.7	2.12	10.3	1.76	Yes	Yes	0.408	0.085	Walk/ Don't walk
Yerys et al., 2009	21	21	9.7	2.12	10.3	1.76	Yes	Yes	0.519	0.098	Walk/ Don't walk
Yerys et al., 2013	21	23	10.22	1.81	10.62	1.55	Yes	Yes	0.689	0.096	Go/no-go
Yi et al., 2014	25	25	7.66	1.56	7.68	1.72	Yes	No	0.741	0.085	Stroop-like Day-Night
Yi et al., 2014	25	28	7.66	1.56	5.79	1.34	No	Yes	0.702	0.080	Stroop-like Day-Night

Yoran-Hegesh et al., 2009	23	43	15.1	3.6	15.5	0.6	Yes	-	0.219	0.067	Stroop Colour-Word (Reverse)
Yoran-Hegesh et al., 2009	23	43	15.1	3.6	15.5	0.6	Yes	-	1.553	0.085	Stroop Colour-Word (Reverse)
Yuk et al., 2018	19	19	10.52	1.45	10.34	1.32	Yes	No	0.329	0.107	Inhibition (Nepsy-II)
Zandt et al., 2009	16	18	10.97	2.42	11.94	2.74	Yes	Yes	0.404	0.120	Walk/ Don't walk

Note. CPT = Continuous Performance task; SART = Sustained Attention to Response Test; TOH = Tower of Hanoi; TOL =Tower of London.- not available.
[a] positive effects indicate a better performance of the TD group over the ASD group.

Table A2. Summary of included studies with indirect measures.

Authors	**N ASD**	**N TD**	**Age ASD** (in years)		**Age TD** (in years)		**Age-matching**	**IQ-Matching**	**Hedges' *g*** [a]	***SE***	**Measure**
			Mean	SD	Mean	SD					
Berenguer et al., 2018	30	37	8.39	1.3	8.54	1.2	Yes	Yes	0.563	0.063	BRIEF Inhibit scale
Drayer, 2008	12	7	5.41	-	5.55	-	Yes	No	2.171	0.350	BRIEF Inhibit scale
Faja & Dawson, 2015	21	21	6.83	0.59	6.69	0.63	Yes	Yes	1.411	0.119	CBQ

											Inhibitory control scale
Filipe et al., 2020	15	15	7.44	1.21	7.27	1.44	Yes	Yes	1.479	0.170	BRIEF Inhibit scale
Gardiner & Iarrocci, 2018	59	67	10.07	2.09	9.44	1.73	Yes	Yes	1.282	0.038	BRIEF Inhibit scale
Gioia et al., 2002	54	208	10.8	3.0	10.9	3.3	Yes	-	1.384	0.027	BRIEF Inhibit scale
Golshan et al., 2019	15	15	9.8	1.65	9.46	1.4	Yes	Yes	0.932	0.148	CHEXI Behavioural Inhibition
Hilvert et al., 2019	24	28	10.09	2.0	10.08	1.07	Yes	No	1.081	0.089	BRIEF Inhibit scale
Hovik et al., 2017	34	50	11.9	2.3	11.6	2.0	Yes	Yes	1.696	0.067	BRIEF Inhibit scale
Hutchison et al., 2016	33	28	11.64	2.8	10.43	3.22	Yes	-	2.194	0.105	BRIEF Inhibit scale

Jahromi et al., 2013	20	20	4.91	0.96	4.18	0.93	No	-	1.060	0.114	BRIEF-P Inhibit scale
Kloosterman et al., 2014	30	40	14.9	2.25	14.39	1.69	Yes	No	1.406	0.072	BRIEF Inhibit scale
Konstantareas & Stewart, 2006	19	19	6.16	-	6.37	-	Yes	-	2.253	0.172	CBQ Inhibitory control scale
Macari et al., 2017	165	92	2.21	0.48	2.07	0.46	Yes	No	0.428	0.017	TBAQS Inhibitory Control
Rohr et al., 2020	36	36	11.2	1.4	10.5	1.7	No	Yes	1.460	0.070	BRIEF Inhibit scale
Rohr et al., 2020	49	49	10.3	1.5	10.3	1.2	Yes	No	2.419	0.071	BRIEF Inhibit scale
Ros & Graziano, 2019	37	31	-	-	-	-	-	-	2.210	0.095	BRIEF Inhibit scale
Rosello et al., 2018	52	37	8.59	1.38	8.54	1.26	Yes	Yes	0.862	0.050	BRIEF Inhibit scale

Rosenblum et al., 2019	26	27	10.88	1.18	10.98	1.1	Yes	Yes	1.602	0.100	BRIEF Inhibit scale
Samyn et al., 2015	31	148	12.83	1.41	12.73	1.48	Yes	No	1.297	0.044	EATQ-R Inhibitory control scale
Samyn et al., 2015	31	148	12.83	1.41	12.73	1.48	Yes	No	0.437	0.040	ECS Impulsivity scale
Troyb et al., 2014	38	32	13.85	2.68	13.87	2.58	Yes	Yes	1.375	0.071	BRIEF Inhibit scale
Van Eylen et al., 2015	50	50	12.21	2.58	12.48	2.72	Yes	Yes	1.254	0.048	BRIEF Inhibit scale
Vanegas, 2013	22	25	9.83	1.41	9.00	1.17	Yes	Yes	1.129	0.099	BRIEF Inhibit scale
Winsler et al., 2007	33	28	11.0	2.3	10.3	3.2	-	-	2.194	0.105	BRIEF Inhibit scale
Yerys et al., 2009	28	21	9.7	2.12	10.3	1.76	Yes	Yes	1.298	0.101	BRIEF Inhibit scale

Yerys et al., 2009	21	21	9.7	2.12	10.3	1.76	Yes	Yes	2.370	0.162	BRIEF Inhibit scale

Note. ASD = autism spectrum disorder; N = number of participants; TD = typically developing. BRIEF= Behavior Rating Inventory of Executive Fucntion: CHEXI = Childhood Executive Functioning Inventory; CBQ = Children's Behavior Questionnaire; TBAQ-S = Toddler Behavior Assessment Questionnaire-Supplemental.

- not available; [a] positive effects indicate a better performance of the TD group over the ASD group.

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