Research in Developmental Disabilities 139 (2023) 104559

Contents lists available at ScienceDirect

Research in Developmental Disabilities

journal homepage: www.elsevier.com/locate/redevdis

Review article

Math abilities in autism spectrum disorder: A meta-analysis

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ARTICLE INFO

Keywords:
Autism
ASD
Math ability
Meta-analysis

ABSTRACT

Background: Studies focusing on math abilities in autism spectrum disorder (ASD) are limited and often provide inconsistent results.

Aim: This meta-analysis was conducted to investigate math abilities in people with autism spectrum disorder (ASD) compared to typically developing (TD) participants.

Methods and procedures: 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.

Outcomes and results: 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.

Conclusions and implications: 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.

What this paper adds?

Students with ASD, even those without co-occurring intellectual disability (ID), often struggle in educational settings and encounter significant difficulties. However, this area of research is not yet fully developed; in particular, studies on math achievement are especially limited and often provide contradictory results. To address the inconsistency of previous findings, in this paper, we conducted a meta-analysis on studies that have investigated mathematical abilities, comparing participants with ASD without ID and a TD group. To the best of our knowledge, this is the first meta-analysis that investigates the mathematical abilities of individuals with ASD compared with TD participants. The results showed a significant small-to-medium difference between the two groups on math tasks, with ASD participants showing a lower performance than the comparison group and highlighted the role of important characteristics of participants.

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https://doi.org/10.1016/j.ridd.2023.104559
Received 3 November 2022; Received in revised form 10 May 2023; Accepted 11 June 2023
Available online 15 June 2023
0891-4222/

1. Introduction

1.1. Autism spectrum disorder and mathematical achievement

Autism spectrum disorder (ASD) is a neurodevelopmental disorder defined by deficits in social communication and restricted or repetitive patterns of behavior, interests, or activities, irrespective of culture, race, ethnicity, or socioeconomic status (American Psychiatric Association, 2013).

Autism is characterized by high heterogeneity, which arises from different levels of symptoms, intellectual and linguistic abilities, and the presence of comorbidities (Zeidan et al., 2022). 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). These students may exhibit some weaknesses that could affect their learning abilities, such as impairments in executive function (EF), which includes high-order processes such as updating working memory, inhibitory control, and cognitive flexibility (Demetriou et al., 2018). They may also display weak central coherence with a detail-focused processing style, difficulties in social abilities and pragmatics, and a tendency to interpret language literally (Happé and Frith, 2006).

Understanding the academic strengths and weaknesses of individuals with ASD is crucial in education. Nowadays, most students with ASD are in regular education settings, with or without additional guidance, and academic achievement in autism is receiving more attention (Dowker, 2020). 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, 2002). However, a greater mathematical proficiency in autism seems to be mostly anecdotal and descriptive (Baron-Cohen et al., 2007). In fact, only a limited number of people with ASD exhibit superior mathematical abilities (Chiang & Lin, 2007; Heavey, 2003; Hermelin and O'Connor, 1990) and mathematical difficulties seem to be more common in students with ASD than in their typically developing (TD) peers (Mayes & Calhoun, 2006).

1.2. 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 example, oral comprehension and fine-motor skills seem to play a key role in impacting on math performance (Peng et al., 2020). As these abilities could be impaired in students with ASD (Fuentes et al., 2009; Mody and Belliveau, 2013), it is possible that their math performance may vary according to the type of stimuli involved (i.e., written or oral). However, this issue remains underexplored. Mayes and Calhoun (2007) suggested a negative association between graphomotor skills and mathematics, measured with the WIAT-III Numerical Operation subtest of WIAT-III; a similar result was found in a study with students with ASD and very high cognitive abilities (full IQ above 120), suggesting that difficulties in fine motor skills are negatively associated with math achievement measured with the Woodcock Johnson III composite score, including equations, simple math facts, and problem solving (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 and 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 ID (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).

Working memory (WM) contributes significantly to academic achievement in TD children and non-ASD neurobiological disorders

(Fuchs et al., 2020). WM is the ability to hold and manipulate information in mind and is critical for many components of mathematical learning, including holding intermediate results in mind during numerical operations and generating problem representations (Cragg & Gilmore, 2014). Despite the extensive literature on WM and math skills in TD children, relatively little is known about this relationship in autism (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

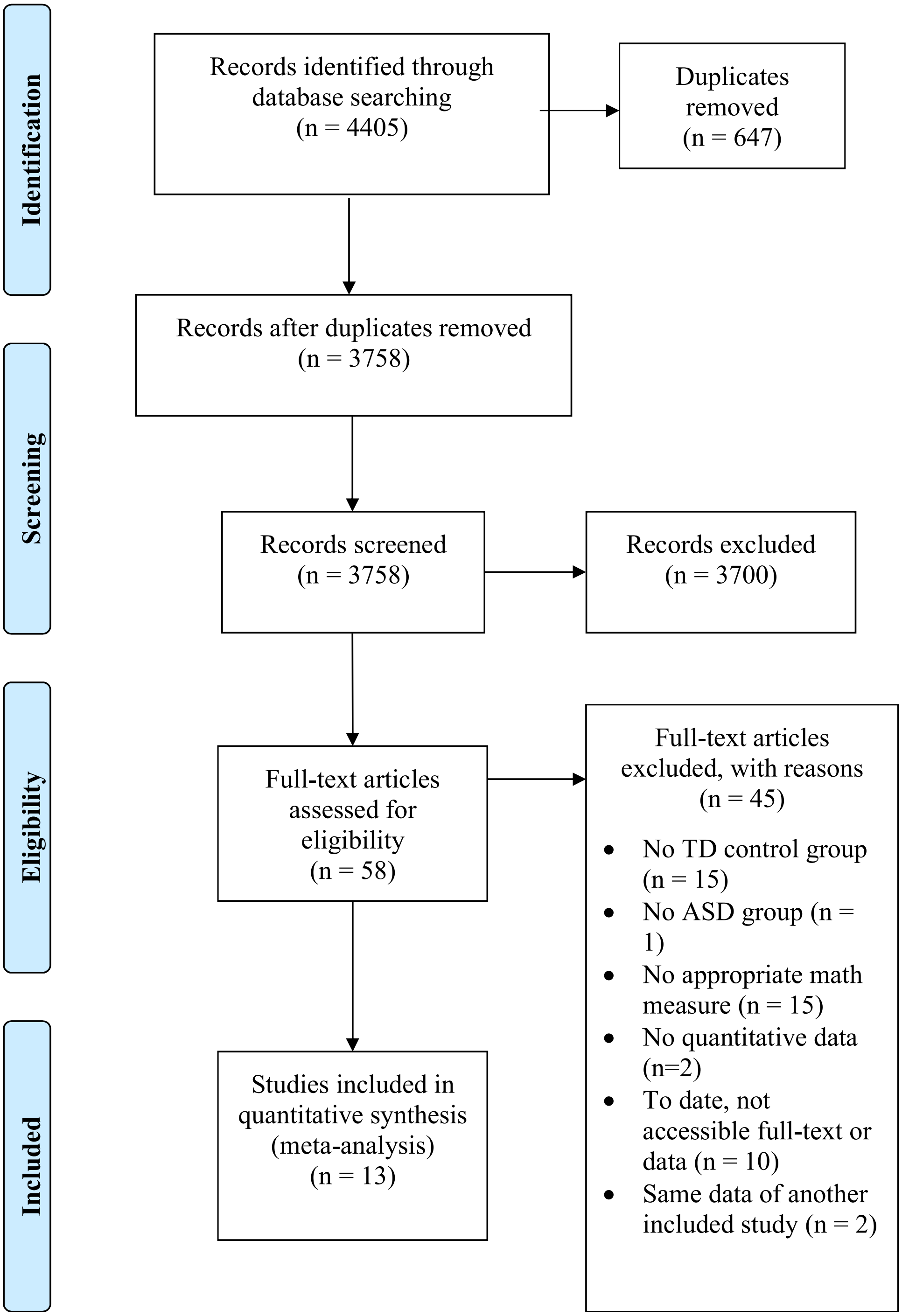

Fig. 1. PRISMA Flow chart illustrating the identification of included studies.

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. However, limited research has focused on the relationship between WM and math abilities in ASD (Bullen et al., 2020; Hiniker et al., 2016; Iuculano et al., 2020; Oswald et al., 2016); therefore, further investigation is necessary.

In summary, there is a need to focus on students' mathematics achievement and factors that may play a significant moderating role. To address the inconsistency of previous findings, in this paper, we conducted a meta-analysis on studies that have investigated the mathematical abilities comparing participants with and without ASD. The meta-analytic approach provides a better estimate of the eventual differences that may exist between ASD and TD participants: in fact, the estimates are more precise because there is an increased amount of data and statistical power; moreover, biases associated with publications can be examined, and potential moderating variables could be investigated.

1.3. The present study

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 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 (verbal 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: 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).

2. Method

A systematic search strategy was used to identify relevant studies, following the PRISMA statement (Page et al., 2021). Fig. 1 shows a flow chart illustrating the search process and the identification of included studies.

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 gray 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.

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.

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. The coding procedure and exclusion criteria were described in detail in the Supplementary Material.

2.4. 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.

2.5. 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; Chap. 9). 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. For further details on the statistical analyses, such as the adopted strategies, interpretation of indices, and funnel plot, please see the Supplementary Material.

3. Results

The meta-analysis included 13 studies with a total of 27 effects. In Table 1, we report descriptive statistics for the two groups. Table S1 shows a summary of the main characteristics of each included study. All studies compared a group with ASD and a TD group

Table 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.

on at least one math measure (for a detailed description of tasks, see Table S2). Task type (numerical operations vs. math word problems) and format (oral vs. written tasks), age, FIQ, PIQ, VIQ, and WM scores were considered moderators.

3.1. Overall effect

3.1.1. Moderator analyses: measure-related characteristics

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 Fig. 2.

3.1.2. Moderator analyses: measure-related characteristics

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], $p = .009$, $\sigma_1^2 = .23$, $\sigma_2^2 < 0.001$).

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], $p = .078$, $\sigma_1^2 = .18$, $\sigma_2^2 = .18$).

3.1.3. Moderator analysis: sample-related characteristics

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, $k = 24$, $Q_M = 2.01$, $B = -0.0.03$, $p = .156$, $\sigma_1^2 = .24$, $\sigma_2^2 < 0.001$; for PIQ $k = 21$, $Q_M = 2.98$, $B = -0.05$, $p = .084$, $\sigma_1^2 = .19$, $\sigma_2^2 < 0.001$), 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

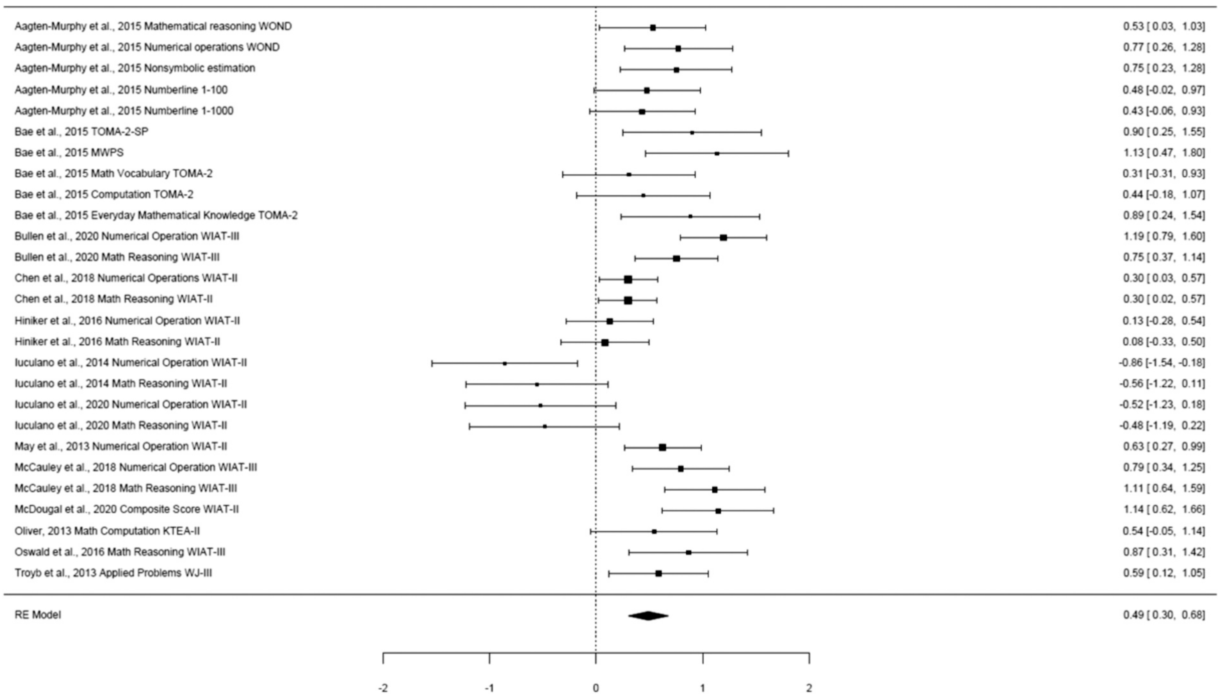

Fig. 2. Forest plot for all the studies included in the meta-analysis.

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.

3.2. Publication bias

In Fig. 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.

4. Discussion

4.1. Autism spectrum disorder and mathematical achievement

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).

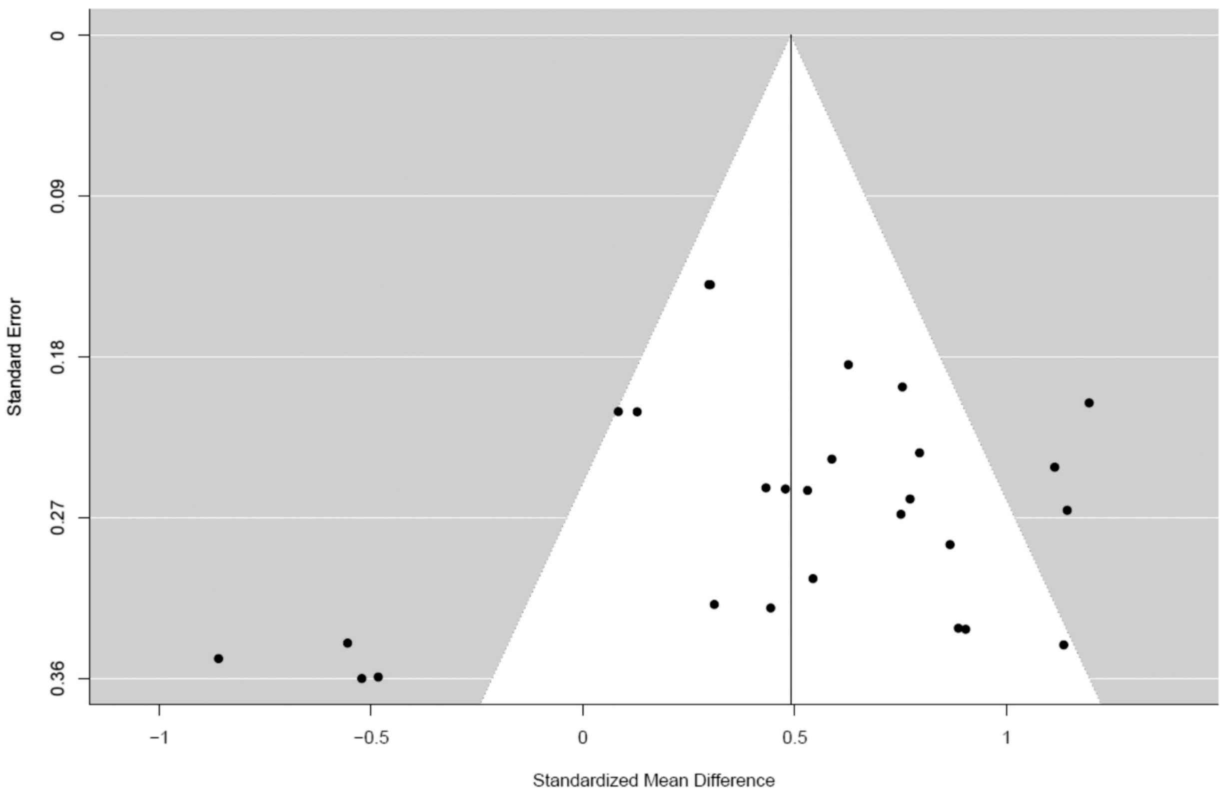

Fig. 3. Funnel plot for math measures.

4.2. Moderators of math achievement in autism

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 and Belliveau, 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.

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 (Carroll 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.

4.3. 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. Executive function involves top-down processes regulating human behavior, such as inhibitory control, that allow individuals to ignore distractions and suppress overlearned strategies. 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 functions impact 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 (Happé and 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.

4.4. 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.

5. 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.

Funding

The authors did not receive any specific funding.

CRediT authorship contribution statement

Irene Tonizzi: Conceptualization, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Maria Carmen Usai**: Conceptualization, Writing – review & editing, Project administration, Supervision.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ridd.2023.104559.

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