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ORIGINAL PAPER

# Inhibitory Control in Autism Spectrum Disorders: Meta-analyses on Indirect and Direct Measures

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**Abstract**
This manuscript aimed to advance our understanding of inhibitory control (IC) in autism spectrum disorders (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 ($n = 5140$) compared with controls ($n = 6075$). 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 ($n = 1300$). 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.

**Keywords** Autism · ASD · Executive functions · Inhibition · Meta-analysis · Interference control

## Inhibitory Control

From a broad perspective, inhibitory control (IC) is an ability that allows us to control our thoughts and actions, suppressing automatic responses and ignoring distracting stimuli to perform alternative behaviours (Diamond, 2013). IC represents a critical component of executive functions (EF), a set of higher-order cognitive processes necessary to plan, perform, and monitor goal-directed actions in novel and complex situations where automatized strategies can be insufficient or inappropriate (Diamond, 2013; Friedman & Miyake, 2017). Specifically, IC is considered to be one of the three correlated but separable EF components, together with updating (i.e., the ability to actively elaborate the material in working memory by adding new information) and cognitive flexibility (i.e., the ability to shift attention from one mental set to another in a flexible way) (Miyake & Friedman, 2012). Although different taxonomies have been proposed (Friedman & Miyake, 2004; Nigg, 2000; Stahl et al., 2014), there is substantial evidence that IC can be conceptualized as a multidimensional construct, including response inhibition, which reflects the ability to suppress automatic but inappropriate responses, and interference control, which reflects the ability to filter out irrelevant but conflicting information (e.g., Friedman & Miyake, 2004; Gandolfi et al., 2014; Howard et al., 2014; Rey-Mermet et al., 2018).

## Inhibitory Control in Autism Spectrum Disorder

*Autism spectrum disorder (ASD)* is a neurodevelopmental disorder characterized by atypical functioning in social communication, and restricted behaviours and interests, with great variability in the severity and extent of its core symptoms (American Psychiatric Association, 2013). In the 1990s, the cognitive theory of executive dysfunction (Hughes & Russell, 1993; Ozonoff et al., 1994) was proposed to explain both socio-communicative difficulties and repetitive behaviours in participants with ASD. In subsequent years, a number of studies confirmed EF difficulties in ASD (Demetriou et al., 2018), and began to investigate the breadth of impairment, focusing on different EF subcomponents.

Recent evidence suggested that IC difficulties contributed to different ASD features, in both the domain of social communication (Carlson & Moses, 2001; Shiri

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et al., 2018) and repetitive behaviours (Faja & Nelson Darling, 2019; Mosconi et al., 2009; Schmitt et al., 2018). 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 in different EF direct measures, and found that individuals with ASD showed lower performance, with a moderate effect size, in EF tasks and in inhibitory measures. It is also worth mentioning that, in the aforementioned meta-analysis, the authors considered IC as a unitary dimension, while Geurts et al. (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 for 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).

## 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 of 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.

## 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 et al. (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 et al. (2007) and the meta-analysis by Geurts et al. (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.

## 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 focussed on direct measures, while IC has been assessed by indirect measures, such as parental reports (e.g., Faja & Dawson, 2015; Filipe et al., 2020; Gardiner & Iarocci, 2018). Direct and indirect measures have, in fact, been different on several accounts (Biederman et al., 2008; Gómez-Pérez et al., 2016; Gonzalez-Barrero & Nadig, 2019; Mackinlay et al., 2006; Toplak et al., 2013). For example, indirect measures, which are intended to provide an ecological measure of IC, assessed in complex and everyday situations and not in a controlled setting, might be liable to personal biases (e.g., the personal judgements of parents or teachers could somehow affect the results) (e.g., Sachse & Von Suchodoletz, 2008). On the other hand, direct measures could possibly reflect additional error variance or variance influenced by state factors, rather than indexing trait factors. This suggests that direct and indirect measures, despite being correlated, should not be considered equivalent (Gross et al., 2015).

In the literature on IC in ASD, different studies 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). 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 multilevel approach, which takes into account all of the effects in a single model.

## 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). 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 presented with 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. 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.

As IC is commonly assessed with indirect and direct measures and previous literature has suggested discrepancies between them, 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 between 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 (Gómez-Pérez 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.

## 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 Fig. 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 Fig. 1 for further details).

### 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

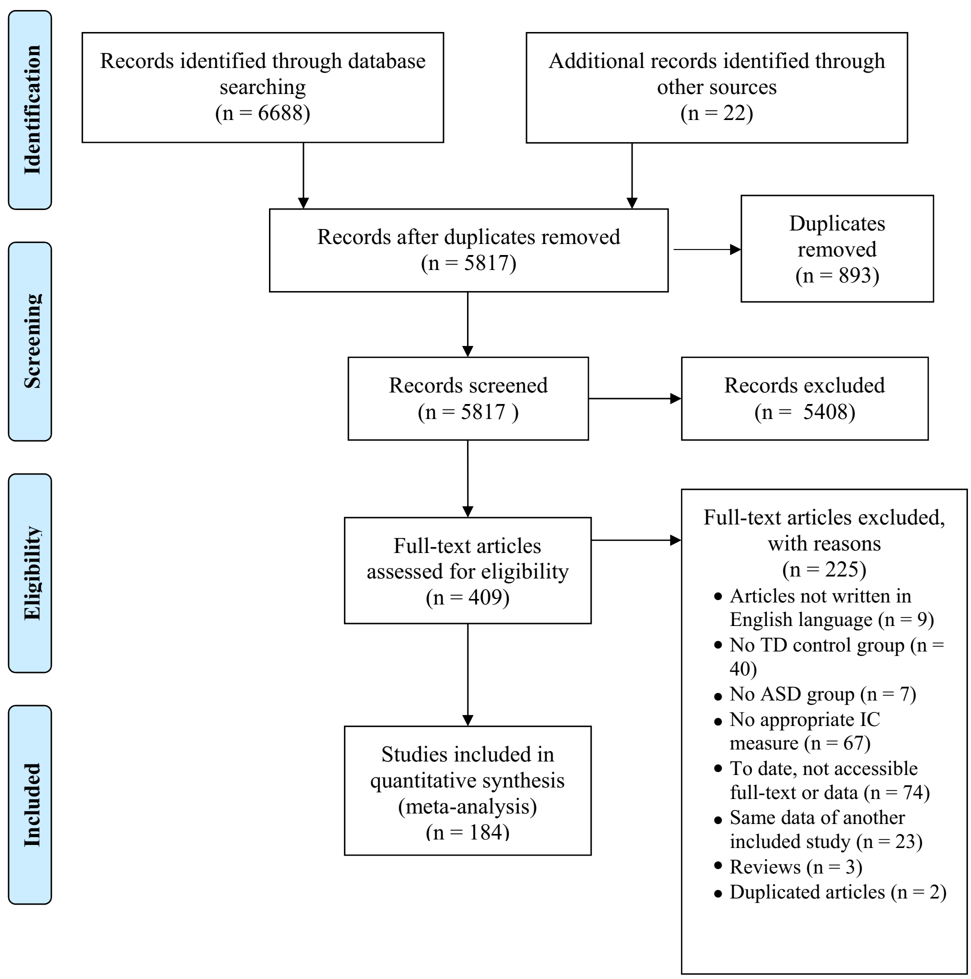


**Fig. 1** PRISMA Flow chart illustrating the identification of included studies

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 (Fig. 1), references were included in the third phase for full text screening.

### 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 (see the Supplemental Material for further details).

### 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.

### 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, 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 et al., 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, 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 et al., 2010).

The heterogeneity across effect sizes was estimated using three statics: $Q$, tau squared ($\tau^2$), 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 ($\tau$) or Tau squared ($\tau^2$) 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 ($\sigma$) 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 et al., 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 et al., 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.

### 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).

## Results

### Inhibitory Control Effects for Direct Measures

For the first meta-analysis, we selected studies that used direct inhibition measures. In Table S1, we reported the main features of the included studies. Across the 164 studies, an estimated total of 11,215 participants (5140 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], $p < 0.001$, $\sigma_1^2 = 0.008$, $\sigma_2^2 = 0.143$ suggesting that people with ASD had in general a small-to-medium inhibitory deficit. The $Q$ statistic indicated significant heterogeneity among the studies, $Q(273) = 1058.897$, $p < 0.001$, 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 S1.

### Inhibitory Dimensions in Autism Spectrum Disorders

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, $k = 272$, $Q_M = 0.009$, $B = -0.011$, $p = 0.923$, $\sigma_1^2 = 0.094$, $\sigma_2^2 = 0.065$ 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], $p < 0.001$, $\sigma_1^2 = 0.112$, $\sigma_2^2 = 0.040$; while for interference control $k = 25$, $g = 0.436$ [0.128, 0.743], $p = 0.006$, $\sigma_1^2 = 0.350$, $\sigma_2^2 < 0.001$), 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, $k = 274$, $Q_M = 1.121$, $B = -0.061$, $p = 0.290$, $\sigma_1^2 = 0.097$, $\sigma_2^2 = 0.062$ 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], $p < 0.001$, $\sigma_1^2 = 0.140$, $\sigma_2^2 = 0.035$; and for interference control $k = 106$, $g = 0.469$ [0.366, 0.571], $p < 0.001$, $\sigma_1^2 = 0.099$, $\sigma_2^2 = 0.041$).

### Moderator Analysis for Direct Measures: Sample-Related Characteristics

#### 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, $k = 271$, $Q_M = 6.900$, $B = -0.009$, $p = 0.008$, $\sigma_1^2 = 0.088$, $\sigma_2^2 = 0.066$ 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, $k=29$, $Q_M=4.019$, $B=-0.017$, $p=0.045$, $\sigma_1^2=0.076$, $\sigma_2^2=0.045$, and direct measures that were not norms based on age, $k=238$, $Q_M=3.933$, $B=-0.007$, $p=0.047$, $\sigma_1^2<0.001$, $\sigma_2^2=0.151$, 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], $p<0.001$, $\sigma_1^2=0.712$, $\sigma_2^2=0.024$; for children, $k=127$, $g=0.556$ [0.454, 0.658], $p<0.001$, $\sigma_1^2=0.077$, $\sigma_2^2=0.103$; for youth, $k=74$, $g=0.419$ [0.290, 0.548], $p<0.001$, $\sigma_1^2=0.106$, $\sigma_2^2=0.045$; for adults, $k=43$, $g=0.284$ [0.138, 0.431], $p<0.001$, $\sigma_1^2=0.081$, $\sigma_2^2=0.023$). 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 ($k=244$, $Q_M=6.649$, $B=-0.009$, $p=0.010$, $\sigma_1^2=0.105$, $\sigma_2^2=0.042$), but not for interference control tasks ($k=25$, $Q_M=0.355$, $B=-0.009$, $p=0.552$, $\sigma_1^2=0.379$, $\sigma_2^2<0.001$).

### Age-Matching

We also tested moderator effects of sample matching (between ASD and TD) based on age. Age-matching was not a significant moderator, $k=271$, $Q_M=0.819$, $B=0.092$, $p=0.366$, $\sigma_1^2=0.097$, $\sigma_2^2=0.065$, with non-significantly different estimates for age-matched and non-matched samples (for age-matched $k=240$, $g=0.499$ [0.429, 0.569], $p<0.001$, $\sigma_1^2=0.068$, $\sigma_2^2=0.077$, for non-age-matched samples, $k=31$, $g=0.403$ [0.180, 0.626], $p<0.001$, $\sigma_1^2=0.217$, $\sigma_2^2=0.024$). A non-significant moderating effect of age-matching was found for both response inhibition ($k=244$, $Q_M=1.043$, $B=0.105$, $p=0.307$, $\sigma_1^2=0.115$, $\sigma_2^2=0.041$), and interference control tasks ($k=25$, $Q_M=1.020$, $B=-0.518$, $p=0.313$, $\sigma_1^2=0.344$, $\sigma_2^2<0.001$).

### IQ-Related Differences

The FSIQ score of participants with ASD had a significant moderating effect for direct measures, $k=173$, $Q_M=10.598$, $B=-0.013$, $p<0.001$, $\sigma_1^2=0.056$, $\sigma_2^2=0.071$. 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], $p=0.011$, $\sigma_1^2=0.097$, $\sigma_2^2=0.509$; for FSIQ between 70 and 85, $k=8$, $g=0.517$ [0.056, 0.979], $p=0.028$, $\sigma_1^2<0.001$, $\sigma_2^2=0.207$; for FSIQ between 85 and 115, $k=156$, $g=0.489$ [0.405, 0.573], $p<0.001$, $\sigma_1^2=0.074$, $\sigma_2^2=0.066$; for FSIQ above 115, $k=6$, $g=0.293$ [0.081, 0.505], $p=0.007$, $\sigma_1^2=0.001$, $\sigma_2^2=0.001$). Considering response inhibition and interference control tasks, a significant moderating effect of FSIQ emerged for response inhibition ($k=157$, $Q_M=8.518$, $B=-0.012$, $p=0.004$, $\sigma_1^2=0.084$, $\sigma_2^2=0.031$), but not for interference control tasks ($k=14$, $Q_M=1.848$, $B=-0.052$, $p=0.174$, $\sigma_1^2=0.307$, $\sigma_2^2=0.307$).

### IQ-Matching

IQ-matching had a direct moderating effect for direct measures $k=247$, $Q_M=13.020$, $B=-0.285$, $p<0.001$, $\sigma_1^2=0.076$, $\sigma_2^2=0.056$, with a larger effect size for non-matched IQ samples (for IQ-matched $k=181$, $g=0.424$ [0.347, 0.500], $p<0.001$, $\sigma_1^2=0.090$, $\sigma_2^2=0.035$) as compared to non-IQ-matched samples ($k=66$, $g=0.718$ [0.580, 0.857], $p<0.001$, $\sigma_1^2=0.066$, $\sigma_2^2=0.089$). Distinguishing between response inhibition and interference control tasks, a significant moderating effect of IQ-matching emerged for response inhibition ($k=220$, $Q_M=10.568$, $B=-0.265$, $p=0.001$, $\sigma_1^2=0.095$, $\sigma_2^2=0.032$), but not for interference control tasks ($k=25$, $Q_M=1.460$, $B=-0.441$, $p=0.227$, $\sigma_1^2=0.338$, $\sigma_2^2<0.001$).

### 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, $k=50$, $Q_M=0.190$, $B=0.108$, $p=0.663$, $\sigma_1^2=0.087$, $\sigma_2^2=0.155$, for studies with participants with ASD and a comorbidity with ADHD $k=7$, $g=0.551$ [0.015, 1.088], $p=0.044$, $\sigma_1^2=0.336$, $\sigma_2^2=<0.001$; for studies with participants with ASD without a comorbidity of ADHD, $k=43$, $g=0.547$ [0.350, 0.745], $p<0.001$, $\sigma_1^2=<0.001$,

$\sigma_2^2 = 0.266$). This analysis was performed for direct measures only, due to the paucity of studies selectively excluding or including ADHD comorbidity in indirect measures.

## Moderator Analysis for Direct Measures: Measures-Related Characteristics

### 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, $k = 270$, $Q_M = 8.582$, $B = -0.185$, $p = 0.003$, $\sigma_1^2 = 0.073$, $\sigma_2^2 = 0.076$. 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], $p < 0.001$, $\sigma_1^2 = 0.054$, $\sigma_2^2 = 0.077$; a medium effect size for non-computerized tasks, $k = 109$, $g = 0.626$ [0.520, 0.731], $p < 0.001$, $\sigma_1^2 = 0.064$, $\sigma_2^2 = 0.113$).

### 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 $k = 273$, $Q_M = 0.335$, $B = 0.038$, $p = 0.563$, $\sigma_1^2 = 0.088$, $\sigma_2^2 = 0.069$, 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], $p < 0.001$, $\sigma_1^2 = 0.093$, $\sigma_2^2 = 0.085$; while for verbal response, $k = 78$, $g = 0.569$ [0.460, 0.677], $p < 0.001$, $\sigma_1^2 = 0.054$, $\sigma_2^2 = 0.064$).

### Type of Index (Accuracy Scores vs. Reaction Times)

Type of index was not a significant moderator, $k = 269$, $Q_M = 1.724$, $B = -0.080$, $p = 0.189$, $\sigma_1^2 = 0.095$, $\sigma_2^2 = 0.066$, 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], $p < 0.001$, $\sigma_1^2 = 0.067$, $\sigma_2^2 = 0.076$; while for reaction times, $k = 58$, $g = 0.406$ [0.246, 0.567], $p < 0.001$, $\sigma_1^2 = 0.237$, $\sigma_2^2 < 0.001$), 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, $k = 242$, $Q_M = 0.831$, $B = -0.063$, $p = 0.362$, $\sigma_1^2 = 0.114$, $\sigma_2^2 = 0.041$, and interference control tasks, $k = 25$, $Q_M = 0.796$, $B = -0.115$, $p = 0.372$, $\sigma_1^2 = 0.343$, $\sigma_2^2 < 0.001$.

### 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, $k = 273$, $Q_M = 0.190$, $B = 0.0289$, $p = 0.663$, $\sigma_1^2 = 0.096$, $\sigma_2^2 = 0.065$, 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], $p < 0.001$, $\sigma_1^2 = 0.089$, $\sigma_2^2 = 0.063$; while for standardized measures, $k = 83$, $g = 0.508$ [0.387, 0.629], $p < 0.001$, $\sigma_1^2 = 0.153$, $\sigma_2^2 = 0.021$), suggesting that in general the inhibitory deficit in people with ASD was found using both unstandardized and standardized measures.

## Inhibitory Control Effects for Indirect Measures

For the second meta-analysis, we selected studies that adopted a questionnaire to measure inhibitory control. In Table S2, we reported the main characteristics of the included studies. Across the 24 studies, an estimated total of 2285 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], $p < 0.001$, $\sigma_1^2 = 0.024$, $\sigma_2^2 = 0.227$, 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, $Q(26) = 136.363$, $p < 0.001$, 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 S2. As it referred to the multilevel model, it provided the reader with a visual representation of all the considered effects.

## Moderator Analyses for Indirect Measures: Sample-Related Characteristics

### 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, $k = 26$, $Q_M = 0.886$, $B = -0.036$, $p = 0.347$, $\sigma_1^2 = 0.115$, $\sigma_2^2 = 0.115$, 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, $k = 14$, $Q_M = 0.041$, $B = -0.013$, $p = 0.841$, $\sigma_1^2 = 0.063$, $\sigma_2^2 = 0.063$, and indirect measures that were not norms based on age, $k = 9$, $Q_M = 0.229$, $B = 0.033$, $p = 0.063$, $\sigma_1^2 = 0.239$, $\sigma_2^2 = 0.239$, 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, $k = 25$, $Q_M = 0.034$, $B = 0.078$, $p = 0.853$, $\sigma_1^2 = 0.118$, $\sigma_2^2 = 0.118$, 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], $p < 0.001$, $\sigma_1^2 = 0.123$, $\sigma_2^2 = 0.123$, for non-age-matched samples $k = 2$, $g = 1.308$ [0.899, 1.717], $p < 0.001$, $\sigma_1^2 < 0.001$, $\sigma_2^2 < 0.001$).

### IQ-Related Differences

The FSIQ score of participants with ASD was not a significant moderator for indirect measures, $k = 16$, $Q_M = 0.035$, $B = 0.003$, $p = 0.852$, $\sigma_1^2 = 0.117$, $\sigma_2^2 = 0.117$, 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, $k = 21$, $Q_M = 0.151$, $B = 0.099$, $p = 0.698$, $\sigma_1^2 = 0.111$, $\sigma_2^2 = 0.111$, 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], $p < 0.001$, $\sigma_1^2 = 0.034$, $\sigma_2^2 = 0.034$; for non-IQ-matched samples $k = 7$, $g = 1.259$ [0.691, 1.828], $p < 0.001$, $\sigma_1^2 = 0.253$, $\sigma_2^2 = 0.253$).

## Publication Bias

To examine the effect of publication bias, we used the funnel plot and the trim-and-fill method. In Figs. 2 and 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.

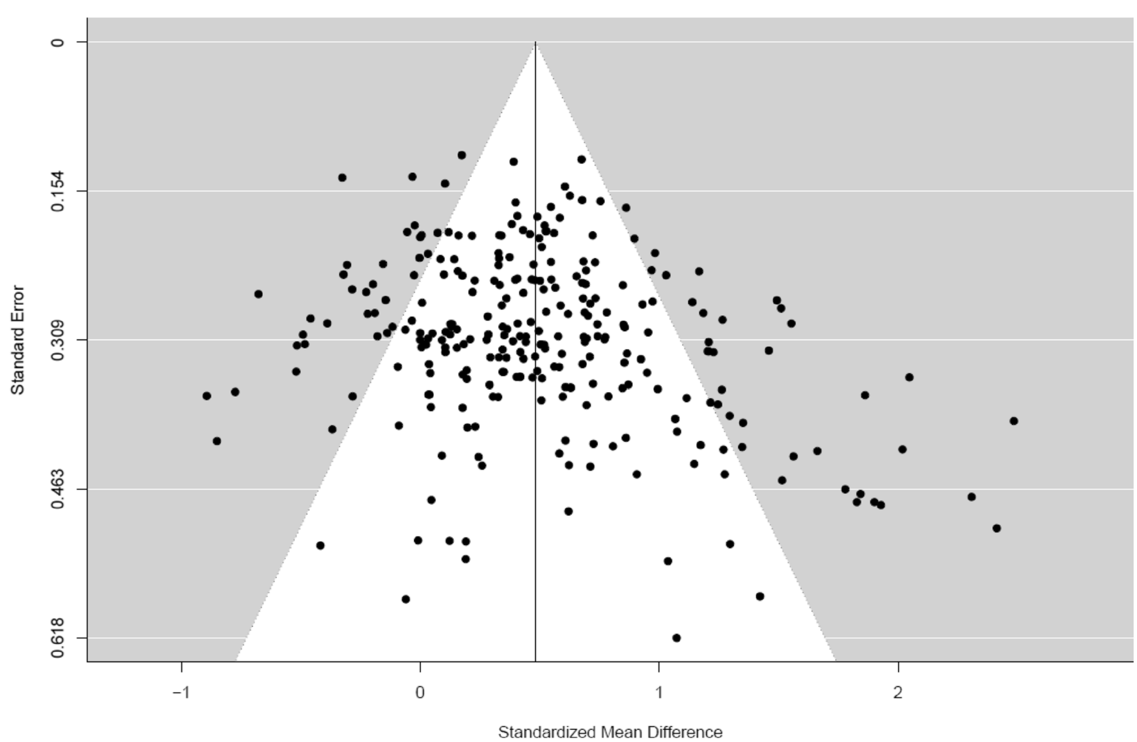


**Fig. 2** Funnel plot for direct measures

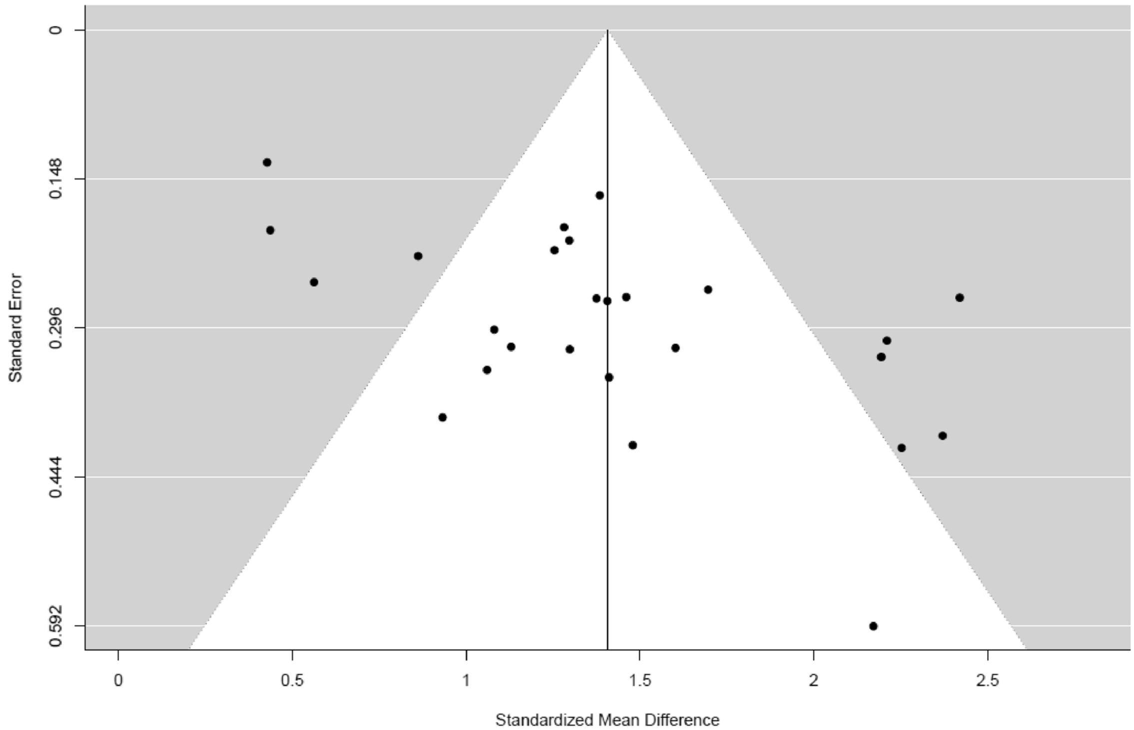


**Fig. 3** Funnel plot for indirect measures

## Discussion

### Inhibitory Control Dimensions in Autism Spectrum Disorders

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., 2014; 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).

### Sample-Related Characteristics

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 (Demetriou et al., 2018; Geurts et al., 2014). 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 (Demetriou et al., 2018; Geurts et al., 2014). 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 et al., 2018), however it shows a distinct maturational process from response inhibition (Vuillier et al., 2016).

As far as response inhibition is concerned, different theories have been proposed for the developmental trajectory of individuals with ASD. To the one hand, some studies seem to indicate an attenuated rate of development in individuals with ASD (e.g., Schmitt et al., 2018). Conversely, other studies showed the opposite results (e.g., Happé et al., 2006). Our results, based on several inhibitory tasks and on a large number of participants from early childhood into adulthood, allows us shed light on the development of response inhibition in children with ASD. In particular, our results suggest that children with ASD demonstrate a delayed development of response inhibition abilities, catching up with children with typical development only when these children reach a plateau in their performances. In addition, it seems that the difference between the two groups in interference control remain relatively stable throughout the development. This finding corroborates the hypothesis that the two IC processes are distinguishable in individuals with ASD.

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 pre-schoolers 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 (Hanson & Atance, 2014; Valeri et al., 2020), 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; Pitzianti 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.

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 (Kanne et al., 2011; Ventola et al., 2014). 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.

### Measures-Related Characteristics

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, 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).

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., 2015). 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 (Gómez-Pérez 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 0.8 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.

### 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., 2018) 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., 2018). 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.

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.

## 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.

## 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.

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