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ORIGINAL PAPER

Executive Functioning: A Mediator Between Sensory Processing and Behaviour in Autism Spectrum Disorder

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Abstract
Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder characterized by impairments in social interaction, executive functioning, sensory-perceptual abilities and behaviour, such as anxious/depressed states, attention problems, aggression, or somatic complains. However, the dynamic relationship between these dimensions remains to be addressed. Therefore, we explored the link between executive functions, sensory processing and behaviour in 79 children and adolescents with ASD. Results showed significant associations between all dimensions—executive functions, sensory processing and behaviour. Furthermore, using structural equation modelling methods, we observed a mediation effect of executive functioning, specifically the domain pertaining to emotion regulation and control, and in the relationship between sensory processing abnormalities and behavioural problems. We discuss the importance of emotion regulation as a mediator between sensory processing and behavioural impairments and its impact in social competence in ASD.

Keywords ASD · Sensory processing · Behaviour · Executive functions · Emotion regulation and control

Introduction

The worldwide prevalence of Autism Spectrum Disorder (ASD) has been increasing over time and it was estimated to be 62/10,000 in 2012 (Elsabbagh et al. 2012). In the United States, for example, the most recent study (Christensen et al. 2019) showed an increase in the overall ASD prevalence among children aged 4 years: 13.4/1000 in 2010, 15.3/1000 in 2012, and 17.0/1000 in 2014. ASD is a neurodevelopmental disorder characterized by the presence of persistent deficits in social communication and interaction, and by restricted and repetitive patterns of behaviour (American Psychiatric Association [APA] 2013). Over recent years, abnormal patterns of sensory-perceptual processing have also been described as a characteristic of the ASD phenotype. Difficulties in sensory processing have been observed in ASD regardless of individuals' age or severity of symptoms (Ben-Sasson et al. 2009) and were recently added as a diagnostic criterion (APA 2013).

Children and adolescents diagnosed with ASD often express distress when exposed to a variety of stimuli (Kern et al. 2007a, b; Tomchek and Dunn 2007; Tseng et al. 2011). Beginning early in life, atypical sensory processing can impact multiple modalities (visual, auditory, touch or olfaction). In addition to the frequently identified sensory alterations, such as auditory, visual and tactile processing, abnormalities in olfactory, gustative and proprioceptive processing have also been described (Gonthier, Longuepee, & Bouvard, 2016; O'Connor, 2012; Thye et al., 2018). In this

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regard, hypo-responsiveness (e.g., unaware of changes in the environment) and hyper-responsiveness (e.g., displaying distress to loud noises) and are commonly described as atypical sensory responses in autism (APA 2013; Ben-Sasson et al. 2009). These difficulties impact children's daily and social life (Liss et al. 2006; Thye et al. 2018). Of note, studies have shown that hypo- and hyper-responsiveness are often associated with general maladaptive behaviour, communication difficulties (Lane et al. 2010), restricted, repetitive and stereotyped interests and behaviours (Chen et al. 2009; Gabriels et al. 2008; Wiggins et al. 2009), less social competences (Hilton et al. 2007, 2010) and impaired language skills (Watson et al. 2011).

Sensory processing dysfunction in ASD has also been associated with executive function impairments in all domais: emotion regulation and control, working memory and planning, as suggested by McCray et al. (2014). For instance, greater sensitivity to stimuli may be explained by fewer strategies to cope with stimulation (Boyd et al. 2009), suggesting that emotion regulation problems may contribute to the observed abnormal reactivity patterns in ASD (Erfanian et al. 2018; Mazefsky and White 2014; Samson et al. 2014). In another line of research, sensory overresponsivity to tactile stimulation was found to modulate social functioning in adolescents with ASD, indicating that hyper-responsivity to sensory stimuli disrupt social cognition (Green et al. 2018). As well, children with ASD who failed to integrate multisensory information from auditory and visual stimuli present greater difficulties in speech processing and, consequently, in integrating social information (Stevenson, et al. 2018). Executive function problems have also been related to sensory processing abnormalities in typically developing children with sensory processing dysfunction (Adams et al. 2015).

Sensory-perceptual abnormalities have also been related to functional alterations in ASD. In particular, abnormal sensory responses were found to predict the presence of repetitive behaviours (Boyd et al. 2009), and the sensory abnormalities have been linked to distinct behavioural disorders, such as isolation, reactivity to change, desinterest and indifference, self-aggression, irritability or emotional lability (Gonthier et al. 2016).

Given this line of evidence, recent studies have proposed executive dysfunction as a cognitive factor contributing to the ASD phenotype (Demetriou et al. 2018). Executive functions were previously associated with behavioural problems in ASD, with greater deficits leading to less social competences and more behavioural problems across time (Berkovits et al. 2017; Demetriou et al. 2018; Leung et al. 2016; Lopez et al. 2005).

Also, executive functioning impairments were found to positively correlate with the severity of ASD-like behaviours, quality of life and adaptive functioning (de Vries et al. 2018; Demetriou et al. 2018; McLean et al. 2014). Greater cognitive impairments have also been related to more restrictive and repetitive behaviours in ASD children. Particularly, alterations in behaviour regulation predicted more restricted and repetitive behaviours, specifically linking cognitive flexibility deficits to more repetitive behaviour symptoms (Kenworthy et al. 2009; McKinnon et al. 2019).

Overall, theoretical and empirical evidence indicate possible relationships between sensory processing, executive functioning and behaviour in ASD. The associations observed in these dimensions may be due to multiple neurobiological mechanisms that contribute to early sensory dysregulation and later, impact social functioning (Thye et al. 2018). A group of impaired characteristics—sensory-perceptual processing, executive functions, and behavioural outcomes—among other factors, are identified as contributors to the autism phenotype (Robertson and Baron-Cohen 2017). Specifically, executive functions assume an important role as they are associated with both altered sensorial-perceptual problems and maladaptive behaviour and communication difficulties (Lane et al. 2010). Therefore, it is important to further examine the role of executive functions as a mediator between sensory processing and behavioural problems, as current evidence is scarce. Indeed, only one study investigated the dynamic association between executive functions, sensory features and behaviour in high functioning children and adolescents with ASD, reporting a non-existant connection between the later two dimensions when executive functioning was considered as a mediator (Boyd et al. 2009). However, the authors addressed this issue with a statistical design and analysis different from the analytic design used in the current study. Therefore, the main goal of this investigation is to examine the relationship between three dimensions—executive function, sensory processing and behaviour—in children and adolescents diagnosed with ASD using structural equation models. Particularly, we are interested in the behavioural manifestations, such as anxious/depressed states, attention problems, aggression or somatic complains, that may derive from impairments in executive functioning and/or sensory processing. For this, we tested the mediating role of executive functions in the relation between sensory processing deficits and behavioural problems using an innovative phenotype ontology approach to assess executive functions (McCray et al. 2014). We hypothesize that executive function deficits will be associated with greater behavioural problems and sensory processing impairments. We also expect that sensory processing deficits will be related to behavioural problems. Based in theoretical evidence, we further hypothesized that executive functioning will act as a mediator in the relationship between sensory processing and behaviour and, thus, we expect that impairments in executive functions may explain how sensory

processing affects behavioural problems in children and adolescents with ASD.

Methods

Participants

Seventy-nine children and adolescents (65 males) with ASD, who were participating in a larger project investigating the relationship between ASD phenotype and genotype enrolled in this study. Participants were between 4 and 16 years old (M = 9.01, SD = 2.9) and were referred from institutions that provide support to families with children diagnosed with this disorder. A psychiatrist and a psychologist performed the ASD diagnosis according to the DSM-5 criteria (APA 2013). Additionally, children and adolescents' clinical history and, when possible, the Autism Diagnosed Interview (ADI-R) and Autism Diagnostic Observation Schedule (ADOS), were used to complement the diagnosis (Lord et al. 2000; Volkmar et al. 2014).

Measures

Sensory Processing (SP)

Child Sensory Profile—2 (CSP-2) (Dunn 2014; Williams et al. 2018) is a questionnaire used to measure children's sensory processing features. Children's parents completed the questionnaire. CSP-2 quantifies the frequency of children´s behaviour in a 5-point likert scale, ranging from "almost never" (1) to "almost always" (5). From CSP-2, 4 subscales are derived: Sensory System, Behavioural System, Sensory Pattern and School Factor. For the purpose of this study only the scores obtained from the Sensory System subscale were used, as these provide an understanding of how children interpret and adapt to the distinct sensory information in the environment. Additionally, significant correlations between this subscale and autism symptoms were previously reported, but were not observed when using the total scale (Kern et al. 2007a, b), discouraging its use (Williams et al. 2018). The Sensory System subscale includes items addressing children's reactivity patterns to distinct sensory modalities: auditory (e.g., hold hands over ears to protect them from sound), visual (e.g., prefers to play or work in low lighting), touch (e.g., becomes irritated by wearing shoes or socks), movement (e.g., rocks in chair, on floor, or while standing), body position (e.g., moves stiffly) and oral sensory (e.g., gags easily from certain food textures or food utensils in mouth) outcomes. Lower scores indicate hypo-responsivity and higher scores indicate hyper-responsivity to sensorial stimuli. Although the sensory profile questionnaire was design for children aged 3–14:11 years, it has been previously used in older children and adolescents (Uljarevic et al. 2016).

Behaviour

Child Behaviour Checklist (CBCL) (Achenbach and Rescorla 2001) is a parent report form used to assess children's emotional, behavioural and social problems and competences. CBCL examines the frequency of behavioural problems in a 3-point likert Scale (0 = behaviour is absent, 1 = behaviour is sometimes present, 2 = behaviour is frequently present). Higher scores indicate greater behavioural problems. Items on the CBCL comprise eight different behaviour syndrome scales: anxious/depressed, withdrawn/depressed, somatic complaints, social problems, thought problems, attention problems, rule-breaking behaviour and aggressive behaviour and two empirically-derived broadband scales—*Internalizing Domain* and *Externalizing Domain*.

Executive Functions

To assess executive functions, we used an autism phenotype ontology proposed by McCray et al. (2014). The authors postulated a concept-based approach to map the most important behavioural features in ASD. This selection resulted from the study of the phenotypic characteristics of individuals affected by ASD and from a detailed content analysis of multiple assessment instruments. Three ontology sections were obtained—personal traits, social behaviours and medical conditions. These sections and their subclasses aimed to capture the main characteristics of ASD behavioural phenotype. In particular, regarding the personal traits ontology section, we selected the executive functioning subclass. Considering this evidence, our study used three executive functioning domains derived from CBCL (Achenbach and Rescorla 2001): (1) emotion regulation and control, (2) working memory and (3) planning. Emotion regulation and control refers to children's ability to direct or govern their own emotions. Working memory assesses children's ability to store and manipulate information to perform complex cognitive tasks, such as learning or reasoning. Planning examines children's ability to engage in complex operations in which sequences of actions must be constantly monitored, re-evaluated and updated. Higher scores obtained in all outcomes indicate greater executive function problems.

Procedure

This study was part of a broader research project. Children's parents were contacted and invited for a meeting with the researchers to explain the procedures and objectives of

this study. Those who agreed to participate were given the informed consent. Their participation was voluntary with no monetary compensation. Informed consent was obtained in accordance with the Declaration of Helsinki.

Data Analysis

The statistical analyses were conducted using the *R* statistical environment (R Studio, version 3.5.2, R Core Team 2018). All structural equation models (SEM) analyses were performed using the "lavaan" R package (Rosseel 2012). In the mediation analysis, the bootstrapping method was used to compute standard errors (Hoyle 2012; Shrout and Bolger 2002). The FIML method was selected to deal with missing data (Dong and Peng 2013).

For each instrument, we used the total disaggregated model to check the unidimensionality and reliability of the scales. Unidimensionality was tested by analysing the number of factors emerging in the exploratory factor analysis. Only the CBCL dimension, Thought Problems, showed bidimensionality and was separated into two outcomes. This original subscale has also shown lack of unidimensionality in previous investigations (Medeiros et al. 2017; Pandolfi et al. 2012). Thought Problems was then divided into two subsets, originating two outcomes. The first seemed to assess repetitive and stereotypical behaviours and obsessive–compulsive behaviours, so is referred to as repetitive/obsessive behaviour. The second outcome seemed to be related to the presence of psychotic-like behaviours, so is referred to as psychotic behaviour.

In the confirmatory factor analysis, factor loadings smaller than 0.4 were deleted (Hair et al. 2014). The reliability was assessed through Cronbach's alpha, assuming that values greater than 0.70 indicate acceptable reliability. Regarding executive functions' planning domain, its associated Cronbach's alpha was 0.39, indicating lack of reliability. For this reason, this subscale was not included in the analysis. Table 1 summarizes information about the final distribution of items per factors and their reliability. We recall that all measures regarding both executive functions and behaviour assessment were obtained through the same instrument (CBCL). Therefore, to avoid associations between outcomes from these two domains due to overlapping items, the items used to measure executive functions were excluded from the scales assessing behavioural problems; only after this removal the outcomes pertaining to the behavioural domain were tested for unidimensionality and internal consistency.

For the sake of simplicity, the total parceling technique was then applied to each factor (see Little et al. (2013) for a discussion on item parceling). Given the extensive number of items in the emotion regulation and control domain, a partial parceling strategy was applied, specifying executive functions as a latent variable measured by three indicators. This construct showed good consistency and validity measures: Cronbach's alpha = 0.79, Composite reliability CR = 0.79, and average variance extracted AVE = 0.56 (Fornell and Larcker 1981). Since the scores of the study variables do not have a clear meaning, all of them were standardized and centred for further SEM analyses.

Table 1 Final distribution of items per outcomes and their reliability

	Outcomes	Items	Number of items	Cronbach's alpha
Sensory Processing	Auditory	1–7	7	0.87
	Visual	9, 10, 12, 13, 15	5	0.72
	Touch	17–26	10	0.84
	Movement	27, 28, 30–34	7	0.80
	Body position	35–41	7	0.86
	Oral sensory	44–47, 49, 50	6	0.93
Executive functioning	Emotion regulation and control	1, 3, 14, 27, 41, 68, 74, 86, 88, 95, 104, 109	12	0.87
	Working memory	4, 8, 78	3	0.74
Behaviour	Anxious/depressed	29–33, 35, 50, 52, 71, 91, 112	11	0.92
	Withdrawn/depressed	42, 69, 75, 102, 103	5	0.76
	Somatic complaints	47, 51, 54, 56 a), b), c), f), g), h)	9	0.81
	Social problems	12, 34, 38, 48, 62, 64	6	0.87
	Repetitive/obsessive behaviour	9, 46, 58, 66, 83, 84	6	0.76
	Psychotic behaviour	40, 59, 60, 70, 92	5	0.83
	Rule-breaking behaviour	39, 43, 67, 72, 73, 81, 82, 90	8	0.82
	Aggressive behaviour	16, 22, 23, 37, 57, 86, 87, 94, 97	9	0.86

We hypothesized executive functioning as a mediator in the relationship between sensory processing and behaviour. First, we considered the mediation models obtained for all possible combinations of sensory processing (six outcomes), executive functions (two domains), and behaviour (eight outcomes) (Table 1). All mediation effects were tested separately. In this analysis, several mediation effects of executive functions, emotion regulation and control domain, were observed. However, mediation effects of the working memory domain were not found. This result also occurred in the multiple mediator models (both mediators tested simultaneously). For this reason, only the results from the emotion regulation and control domain are reported.

All outcomes were tested simultaneously in a multiple outcome approach depicted in Fig. 1.

The mediating role of executive function in the relationship between sensory processing and behaviour was then analysed.

Results

Descriptive Statistics of Executive Functions, Sensory Processing and Behaviour

Table 2 shows the descriptive statistics of executive functions, sensory processing and behaviour outcomes. Means and standard deviations were calculated before the standardization process.

Table 2 Descriptive statistics of the study variables for the total sample

Domains	Outcomes	*n*	*M (SD)*
Sensory processing	Auditory	73	2.94 (1.19)
	Visual	73	1.80 (0.97)
	Touch	73	2.21 (0.97)
	Movement	73	2.17 (0.96)
	Body position	73	1.75 (1.05)
	Oral sensory	73	2.69 (1.48)
Executive functioning	Emotion regulation and control	79	0.75 (0.39)
	Working memory	79	1.34 (0.53)
Behaviour	Anxious/depressed	79	0.39 (0.38)
	Withdrawn/depressed	79	0.61 (0.46)
	Somatic complaints	79	0.21 (0.23)
	Social problems	79	0.54 (0.48)
	Repetitive/obsessive behaviour	79	0.68 (0.43)
	Psychotic behaviour	79	0.15 (0.28)
	Rule-breaking behaviour	79	0.11 (0.15)
	Aggressive behaviour	79	0.48 (0.35)

For sensory processing, children and adolescents presented higher mean scores in the auditory subscale ($M = 2.94$, $SD = 1.19$) and lower mean scores in the body position subscale ($M = 1.75$, $SD = 1.05$). For executive function, participants scored higher in working memory ($M = 1.34$, $SD = 0.53$) than in the emotion regulation

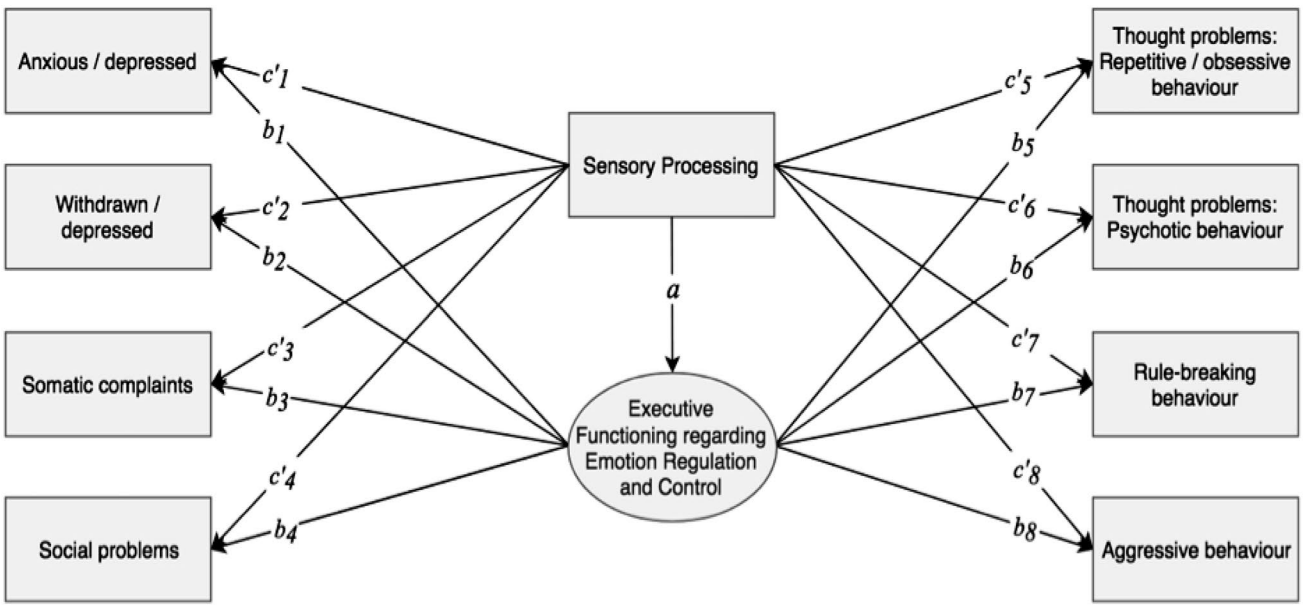

Fig. 1 Mediation model considering a multiple outcome approach. For the sake of simplicity, the three indicators used to define the latent variable *Executive Functioning* are not shown in this figure. Moreover, each endogenous variable is associated with an error but, for simplicity, these errors are also omitted

Table 3 Correlations between executive functions and behaviour

	Executive functions	
	Emotion regulation and control	Working memory
Behaviour		
Anxious/depressed	0.37***	−0.11
Withdrawn/depressed	0.22	0.07
Somatic complaints	0.36**	0.08
Social problems	0.51***	0.22
Repetitive/obsessive behaviour	0.55***	0.36***
Psychotic behaviour	0.25*	0.13
Rule-breaking behaviour	0.38***	0.04
Aggressive behaviour	0.79***	0.24*

Significance: *$p<0.05$, **$p<0.01$, ***$p<0.001$

Table 4 Correlations between executive functions domains and sensory processing

	Executive functions	
	Emotion regulation and control	Working memory
Sensory processing		
Auditory	0.20	0.05
Visual	0.22	0.21
Touch	0.48***	0.54***
Movement	0.45***	0.46***
Body position	0.37**	0.18
Oral sensory	−0.09	−0.14

Significance: **$p<0.01$, ***$p<0.001$

and control domain ($M=0.75$, $SD=0.39$). Finally, for behaviour, participants presented higher mean scores in repetitive/obsessive behaviour ($M=0.68$, $SD=0.43$) and lower mean scores in rule-breaking behaviour ($M=0.11$, $SD=0.15$).

Executive Functions and Behaviour

We analysed the association between executive functions domains and behaviour (Table 3).

A positive and significant correlation was found between emotion regulation and control with almost all behavioural outcomes: anxious/depressed, $r=0.37$, $p<0.001$, withdrawn/depressed, $r=0.22$, $p=0.052$, somatic complaints, $r=0.36$, $p<0.001$, social problems, $r=0.51$, $p<0.001$, repetitive/obsessive, $r=0.55$, $p<0.001$, psychotic behaviour, $r=0.25$, $p=0.026$, rule-breaking behaviour, $r=0.38$, $p<0.001$, and aggressive behaviour, $r=0.79$, $p<0.001$. Also, a positive and significant correlation was observed between working memory and repetitive/obsessive behaviour, $r=0.36$, $p<0.001$, and aggressive behaviour, $r=0.24$, $p=0.032$.

Executive Functions and Sensory Processing

The association between executive functions and sensory processing outcomes were analysed (Table 4).

For emotion regulation and control domain, positive and significant correlations were found with the following sensory processing outcomes: touch, $r=0.48$, $p<0.001$, movement, $r=0.45$, $p<0.001$, and body position, $r=0.37$, $p<0.001$. For working memory domain, positive and significant correlations were found with touch, $r=0.54$, $p<0.001$, and movement, $r=0.46$, $p<0.001$, sensory processing outcomes.

Sensory Processing and Behaviour

We further tested the associations between sensory processing features and behaviour problems. Correlations are depicted in Table 5.

Auditory sensory processing outcome was associated with anxious/depressed behaviour, $r=0.41$, $p<0.001$, withdrawn/depressed behaviour, $r=0.47$, $p<0.001$, social problems, $r=0.38$, $p<0.001$, and repetitive/obsessive behaviour, $r=0.44$, $p<0.001$. Also, visual sensory processing was associated with anxious/depressed behaviour, $r=0.30$, $p=0.01$, withdrawn/depressed behaviour, $r=0.34$, $p=0.004$, social problems, $r=0.35$, $p=0.002$, and repetitive/obsessive behaviour, $r=0.33$, $p=0.005$. Regarding touch sensory processing, significant correlations were observed with anxious/depressed behaviour, $r=0.24$, $p=0.04$, social problems, $r=0.41$, $p<0.001$, repetitive/obsessive behaviour, $r=0.51$, $p<0.001$, psychotic behaviour, $r=0.34$, $p=0.004$, and aggressive behaviour, $r=0.36$, $p=0.002$. An association was observed between movement sensory processing and somatic complaints, $r=27$, $p=0.022$, social problems, $r=0.41$, $p<0.001$, repetitive/obsessive behaviour, $r=0.47$, $p<0.001$, and aggressive behaviour, $r=0.35$, $p=0.002$. For body position sensory processing, we verified correlations with anxious/depressed behaviour, $r=0.29$, $p=0.015$, withdrawn/depressed behaviour, $r=0.35$, $p=0.003$, somatic complaints,

Table 5 Correlations between sensory processing and behaviour

	Sensory processing					
	Auditory	Visual	Touch	Movement	Body Position	Oral Sensory
Behaviour						
Anxious/depressed	0.41***	0.30*	0.24*	0.13	0.29*	0.24*
Withdrawn/depressed	0.47***	0.34**	0.04	0.04	0.35**	0.17
Somatic complaints	0.23	0.15	0.22	0.27*	0.43***	0.16
Social problems	0.38**	0.35**	0.41***	0.41***	0.54**	0.07
Repetitive/obsessive behaviour	0.44***	0.33**	0.51***	0.47***	0.32**	0.13
Psychotic behaviour	0.09	−0.10	0.34**	0.21	0.39***	−0.10
Rule-breaking behaviour	0.05	0.18	0.16	0.13	0.09	−0.02
Aggressive behaviour	0.13	0.12	0.36**	0.35**	0.33**	−0.11

Significance: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

$r = 0.43$, $p < 0.001$, social problems, $r = 0.54$, $p < 0.001$, repetitive/obsessive behaviour, $r = 0.32$, $p = 0.007$, psychotic behaviour, $r = 0.39$, $p < 0.001$, and aggressive behaviour, $r = 0.33$, $p = 0.005$. Finally, an association was found between oral sensory processing and anxious/depressed behaviour, $r = 0.24$, $p = 0.046$.

The Mediating Role of Executive Functioning

Table 6 depicts the mediating role of emotion regulation and control on the relationship between sensory processing features and Behaviour.

Significant indirect effects of auditory and visual sensory processing were found on distinct problematic behaviours—anxious/depressed behaviour, somatic complaints, social problems, repetitive/obsessive behaviour, rule-breaking behaviour and aggressive behaviour. Similarly, significant indirect effects of touch sensory processing were observed on the following behaviours: anxious/depressed, withdrawn/depressed, somatic complaints, social problems, repetitive/obsessive behaviour, rule-breaking behaviour and aggressive behaviour. Significant indirect effects through the emotion regulation and control domain were found between movement sensory processing and anxious/depressed behaviour, withdrawn/depressed behaviour, somatic complaints, social problems, repetitive/obsessive behaviour, rule-breaking behaviour and aggressive behaviour. Again, significant indirect effects through the emotion regulation and control domain were found between body position sensory processing and anxious/depressed behaviour, social problems, repetitive/obsessive behaviour, rule-breaking behaviour and aggressive behaviour. Figure 2 depicts the effects observed between executive functions, sensory processing and behaviour.

No mediation effect of the emotion regulation and control domain was observed concerning the relationship between oral sensory processing and behaviour or between any other sensory processing modalities and psychotic behaviour.

Discussion

We investigated the relationships between executive function, sensory processing and behaviour in children with ASD, all frequently identified as atypical in this population. We further analysed the mediating role of executive functions in the relationship between sensory processing abnormalities and behavioural problems, using a phenotype ontology approach to characterize executive functions (McCray et al. 2014).

We hypothesized that executive functions in ASD would be associated with previously identified behavioural problems (Berkovits et al. 2017; Kenworthy et al. 2009; Leung et al. 2016; Lopez et al. 2005; McLean et al. 2014). We verified two types of associations: (1) the domain of emotion regulation and control was associated with all behaviour outcomes, and (2) working memory was only associated with repetitive/obsessive and aggressive behaviour.

The pattern of associations observed between emotion regulation and control with distinct behaviour outcomes suggests that children and adolescents who present greater difficulties in directing or governing their own emotions usually display more impaired behavioural problems, such as anxiety, isolation, somatic complaints, aggressive or rule-breaking behaviours. This observation is in accordance with previous evidence, suggesting an association between persisting executive function problems and impaired adaptive functioning, namely problems with attention, communication, planning and social interaction (Charlton et al. 2019; Mazefsky and White 2014; Samson et al. 2014; Wallace et al. 2016).

The association found between working memory and repetitive/obsessive and aggressive behaviour suggests that children's deficits in the ability to store and manipulate the necessary information to accomplish cognitive tasks are mirrored in their behavioural repetitive patterns and frustration (Berkovits et al. 2017; Demetriou et al. 2018; Faja and Nelson Darling 2018; Leung et al. 2016). The association

Table 6 Mediator effects of executive functions: emotion regulation and control mediating the relationship between sensory processing and behaviour (multiple outcome approach)

Sensory processing	Behaviour	*a*	*b*	Direct effect *c'*	Indirect effect		Total effect *ab* + *c'*
					ab	95% CI	
Auditory	Anxious/depressed	.233*	0.449*	0.331*	0.105*	[0.008, 0.289]	0.435*
	Withdrawn/depressed		0.177	0.448*	0.041	[−0.030, 0.123]	0.489*
	Somatic complaints		0.494*	0.148	0.115*	[0.009, 0.290]	0.263*
	Social problems		0.630*	0.259*	0.147*	[0.025, 0.303]	0.405*
	Repetitive/obsessive behaviour		0.685*	0.302*	0.159*	[0.032, 0.333]	0.462*
	Psychotic behaviour		0.357	0.012	0.083	[−0.021, 0.285]	0.095
	Rule-breaking behaviour		0.547*	−0.047	0.127*	[0.013, 0.314]	0.081
	Aggressive behaviour		1.16*	−0.087	0.270*	[0.053, 0.535]	0.182*
Visual	Anxious/depressed	0.222*	0.496*	0.224*	0.110*	[0.009, 0.280]	0.334*
	Withdrawn/depressed		0.238	0.307*	0.053	[−0.023, 0.158]	0.360*
	Somatic complaints		0.529*	0.062	0.118*	[0.011, 0.263]	0.179
	Social problems		0.643*	0.238*	0.143*	[0.023, 0.340]	0.381*
	Repetitive/obsessive behaviour		0.735*	0.184	0.163*	[0.026, 0.337]	0.347*
	Psychotic behaviour		0.433	−0.189	0.096	[−0.010, 0.306]	−0.093
	Rule-breaking behaviour		0.494*	0.091	0.110*	[0.005, 0.294]	0.201*
	Aggressive behaviour		1.16*	−0.096	0.258*	[0.052, 0.532]	0.163
Touch	Anxious/depressed	0.418*	0.565*	0.019	0.236*	[0.061, 0.481]	0.255*
	Withdrawn/depressed		0.414*	−0.090	0.173*	[0.005, 388]	0.083
	Somatic complaints		0.550*	<0.001	0.230*	[0.0.054, 0.456]	0.230*
	Social problems		0.627*	0.154	0.262*	[0.081, 0.504]	0.416*
	Repetitive/obsessive behaviour		0.635*	0.246*	0.265*	[0.108, 0.487]	0.511*
	Psychotic behaviour		0.189	0.254	0.079	[−0.116, 0.314]	0.333*
	Rule-breaking behaviour		0.570*	−0.061	0.238*	[0.014, 0.547]	0.178
	Aggressive behaviour		1.22*	−0.143	0.509*	[0.268, 812]	0.366*
Movement	Anxious/depressed	0.375*	0.629*	−0.079	0.236*	[0.059, 0.483]	0.157
	Withdrawn/depressed		0.398*	−0.072	0.149*	[0.004, 0.303]	0.078
	Somatic complaints		0.496*	0.091	0.186*	[0.027, 0.367]	0.277*
	Social problems		0.623*	0.180	0.234*	[0.060, 0.473]	0.414*
	Repetitive/obsessive behaviour		0.671*	0.218	0.252*	[0.082, 0.436]	0.470*
	Psychotic behaviour		0.305	0.092	0.114	[−0.113, 388]	0.206
	Rule-breaking behaviour		0.566*	−0.058	0.212*	[0.019, 0.475]	0.154
	Aggressive behaviour		1.18*	−0.083	0.442*	[0.184, 0.729]	0.360*
Body position	Anxious/depressed	0.355*	0.499*	0.137	0.177*	[0.030, 0.408]	0.314*
	Withdrawn/depressed		0.162	0.325*	0.058	[−0.073, 0.190]	0.383*
	Somatic complaints		0.366	0.316*	0.130	[−0.013, 0.285]	0.445*
	Social problems		0.526*	0.347*	0.187*	[0.051, 0.381]	0.534*
	Repetitive/obsessive behaviour		0.758*	0.076	0.269*	[0.100, 0.490]	0.345*
	Psychotic Behaviour		0.173	0.317*	0.061	[−0.103, 0.281]	0.378*
	Rule-breaking behaviour		0.580*	−0.091	0.206*	[0.026, 0.463]	0.115
	Aggressive behaviour		1.16*	−0.067	0.413*	[0.170, 0.713]	0.346*
Oral sensory	Anxious/depressed	−0.023	0.594*	0.265*	−0.014	[−0.188, 0.100]	0.251
	Withdrawn/depressed		0.362*	0.193	−0.008	[−0.086, 0.093]	0.184
	Somatic complaints		0.563*	0.182	−0.013	[−0.159, 0.105]	0.169
	Social problems		0.743*	0.113	−0.017	[−0.189, 0.158]	0.096
	Repetitive/obsessive behaviour		0.818*	0.164	−0.019	[−0.202, 0.169]	0.145
	Psychotic behaviour		0.359	−0.085	−0.008	[−0.140, 0.068]	−0.093
	Rule-breaking behaviour		0.529*	−0.002	−0.012	[−0.127, 0.120]	−0.014
	Aggressive behaviour		10.13*	−0.049	−0.026	[−0.245, 0.261]	−0.075

The significance was assessed through the 95% bootstrap confidence interval (CI). The total effect is the sum of the direct and indirect effects. The asterisk indicates significant results, i.e., that 0 is not contained in the 95% bootstrap CI

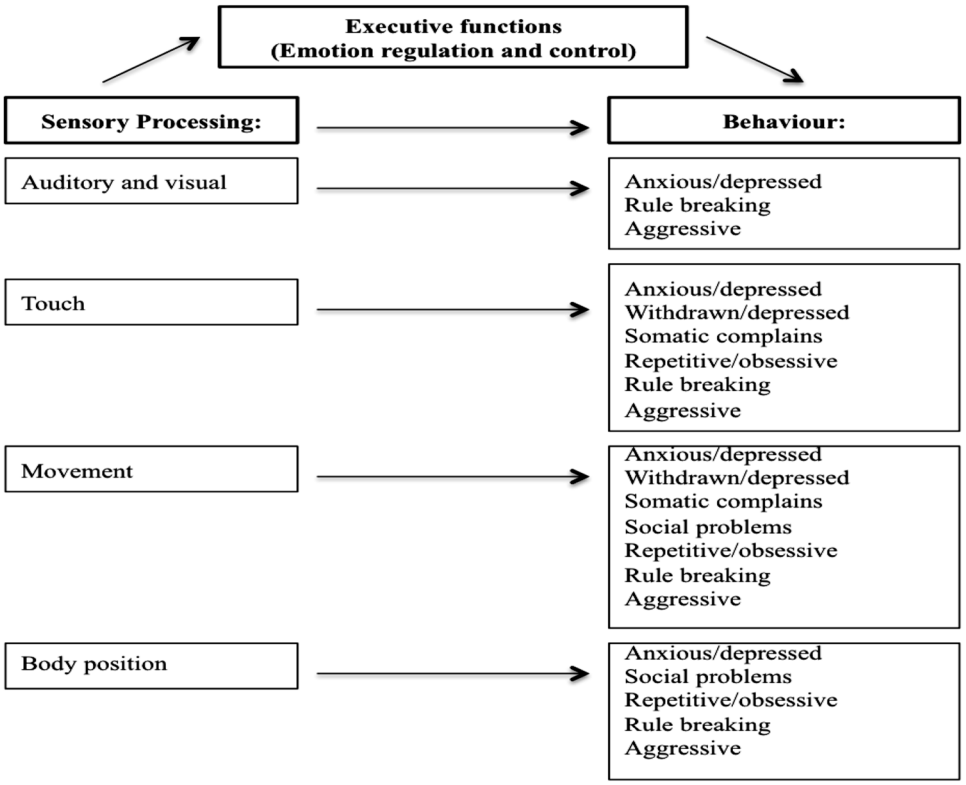

Fig. 2 Path figure of the effects observed between executive functions, sensory processing and behaviour

between executive functions and behaviour in ASD seems to be further supported by recent neuroimaging findings that illustrate an association between alterations in working memory brain networks and memory difficulties in ASD (Barendse et al. 2018) and by a relationship between reduced resting-state functional connectivity at visual, control and default mode networks and stereotyped and restricted behaviours (Barendse et al. 2018; McKinnon et al. 2019).

With respect to the relationship between executive function deficits and sensory processing abnormalities, we found that the emotion regulation and control domain was associated with movement and body position, and the working memory domain with touch and movement. This suggests that children and adolescents with greater difficulties in emotion regulation and control, as well as in working memory abilities, are likely to display greater deficits in body and movement and touch and movement sensory dimensions, respectively. Our results are consistent with other studies (Adams et al. 2015; Erfanian et al. 2018) showing the relationship between executive functions patterns and sensory processing abnormalities. This evidence suggests that increase sensory reactivity to touch or body movement may be linked to more emotion regulation difficulties in ASD children. Moreover, displaying under or over reactive responses to touch, poor balance and reduce endurance (Kenworthy et al. 2009) may be related to emotion regulation problems, which, in turn, may lead to disrupted social competences and involvement with the environment (Green et al. 2018; Stevenson et al. 2018).

Along the same line, we found that sensory processing abnormalities being associated with behavioural problems, as was previously reported (Gonthier et al. 2016; Miguel et al. 2018). Specifically, auditory, visual, touch, movement, body position and oral sensory deficits were associated with distinct behavioural problems, such as anxious/depressed behaviour, social problems, repetitive/obsessive behaviours or aggressive behaviour. Our results suggest that difficulties in all sensory processing modalities impact children's behaviour and, consequently, daily and social life (Chen et al. 2009; Hilton et al. 2007, 2010; Lane et al. 2010; Liss et al. 2006; Thye et al. 2018; Watson et al. 2011; Wiggins et al. 2009).

Finally, we observed a strong mediation effect of executive functions in the interplay between sensory processing and behavioural outcomes. More precisely, we found that executive functions at the emotion regulation and control level mediated the relationship between sensory processing abnormalities and behavioural problems. Thus, it seems that higher cognitive level processes (executive functions through emotion regulation and control) exert an effect on how sensory information is processed and, consequently, on how children and adolescents with ASD respond to that stimulation through their behaviour. Emotion regulation and control have been described as children's ability to control

their emotional reactions, impulses and self-injury behaviour in ASD (McCray et al. 2014). Emotion regulation abilities are key factors involved in social interaction competences, which can be understood as the ability to re-organize physiological and behaviourally in order to attend to environment stimuli and social situations (Charlton et al. 2019; Patriquin et al. 2019; Porges et al. 2013). These competences are influenced by executive functioning (Miyake et al. 2000). In order to successfully address social interactions, children must be able to regulate and control emotional responses and, consequently, their behaviour. In ASD, impaired emotion regulation and control abilities comprise behavioural alterations such as overreaction to environment, frustration, tantrums, aggression or disruptive behaviour that seem to negatively influence their ability to respond adequately to social situations (McCray et al. 2014). Our findings are consistent with previous evidence suggesting that poor regulation of emotions may be a common factor underlying sensory processing abnormalities and behaviour manifestations (Mazefsky and White 2014). Considering our results, it is possible that children and adolescents with ASD with altered sensory processing responses to stimuli are more likely to show deficits in emotion regulation and control, which has cascading effects on a variety of behaviour problems in response to social environments.

Thus, it is possible that the relationship observed between sensory processing and behaviour in ASD may be related to higher cognitive processing difficulties, particularly, the ability to regulate and control their emotional processes. Postulating this mediation of higher cognitive functions on sensory abormalities and behavioural problems, these alterations may need to be taken into account when considering clinical intervention approaches in this disorder (Pfeiffer et al. 2018).

These results, however, are not consistent with other findings, that have reported no relationship between executive function, sensory processing abnormalities and behaviour problems (Boyd et al. 2009). This may be due to methodological differences, as no mediation model was employed. Future studies addressing this issue are needed. Another limitation refers to the fact that the severity level or the level of supported required (e.g. support, substantial support or very substantial support) of our ASD participants were not considered as an inclusion/exclusion criteria. Given that ASD is a spectrum disorder, there may be significant gaps between portions of the group related to support required, which may influence the score obtained in each assessment measure. Also, we assessed both executive functions and behavioural outcomes with the same questionnaire and only caregiver reports were used in this study. Therefore, observational and/or laboratory measures of executive functions, sensory processing and behavioural outcomes are necessary to validate our findings. The small sample size used in the SEM approach is also a limitation in this study. While SEM is the most recommended method to assess mediation effects, is important to notice that, although adequate sample sizes in SEM research depend on many key properties of the model (Wolf et al. 2013), sizes smaller than 100 are generally considered small in SEM. Small samples are associated with inflated standard errors and thus, with low statistical power. As a result, it can happen that our sample size have limited us to detecting large effects, a fact that strengths the findings of this paper (Combs 2010). However, it must be acknowledge that some of the non-significant results of this study may have shown significance with increased samples. Also, the participants' age range is broad (4–16) and specific behavioural manifestations may vary according to age (Esbensen et al. 2009). In this sense, it is recommended that future studies used larger sample sizes and control for possible age effects.

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Author Contribution MFP was responsible for the manuscript preparation, data collection, edited and reviewed the manuscript. CM performed data analysis, edited and reviewed the manuscript. SC edited and reviewed the manuscript. VC was responsible for data analysis, manuscript preparation and reviewed the manuscript. RMR edited and reviewed the manuscript. MT edited and reviewed the manuscript. AC was responsible for funding acquisition, supervised data collection, edited and reviewed the manuscript. AS conceptualized the study, edited and reviewed the manuscript. All authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Written informed consent was obtained from all parents of individual participants included in the study.

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