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## INTRODUCTION

25 ADHD is a neurodevelopmental disorder characterised by pervasive and impairing symptoms  
26 of inattention, hyperactivity, and impulsivity that interfere with daily functioning and  
27 development (American Psychiatric Association, 2013). ADHD is a common disorder, with  
28 prevalence rates estimating between 5.29% and 7.2% of children worldwide have ADHD  
29 (Polanczyk et al., 2007; Thomas et al., 2015). Children with ADHD may be more likely than  
30 typically developing children to experience sensory processing difficulties (Mangeot et al.,  
31 2001; Dunn & Bennett, 2002). Given that sensory processing difficulties can impact the  
32 development of behavioural, emotional, motor, and cognitive domains, it is important to  
33 identify potential difficulties at an early stage (Jorquera-Cabrera et al., 2017).

### 34 **Sensory processing disorder**

35 Ayres originally theorised that sensory integration dysfunction resulted from difficulties in  
36 processing and organization within the central nervous system (Ayres, 1979). Many models  
37 of sensory processing dysfunction have emerged since Ayre's seminal work in this area (e.g.  
38 Dunn, 2014; Baranek et al., 2001), the most recent of which comes from Bundy and Lane  
39 (2020). Bundy and Lane focus on two major categories of sensory integration: dyspraxia and  
40 sensory modulation dysfunction. Ayres (1979) defined sensory modulation as the central  
41 nervous system's regulation of its own activity. Sensory modulation dysfunction, which  
42 arises when an individual has difficulty regulating sensory input, can be further broken down  
43 into distinct patterns of overresponsivity and underresponsivity (Bundy & Lane, 2020).

44 Both the Diagnostic Manual for Infancy and Early Childhood (Interdisciplinary Council on  
45 Development and Learning Disorders, 2005) and DC:0-5 Diagnostic Classification of Mental  
46 Health and Developmental Disorders of Infancy and Early Childhood (Zero to Three, 2016)  
47 describe disorders of sensory processing, which can be further categorised by sensory

48 overresponsivity, sensory underresponsivity and sensory seeking patterns. There is some  
49 debate over the inclusion of a specific sensory seeking pattern. For example, there is a  
50 suggestion that sensory seeking behaviours may be a compensatory mechanism to moderate  
51 high arousal levels (Liss et al., 2006) or that these behaviours are an outcome of  
52 overresponsivity and underresponsivity (Bundy & Lane, 2020). To date, sensory processing  
53 dysfunction has not been included in the DSM or ICD. However, hyporesponsiveness  
54 (underresponsive) and hyperresponsive (overresponsive) behaviours were added as a criteria  
55 for autism spectrum disorders (ASD) in the latest version of the DSM (APA, 2013;  
56 Niedzwiecka et al., 2019).

57 There is considerable inconsistency in the use of terms surrounding sensory integration,  
58 sensory modulation, and sensory processing. This review will focus on sensory modulation  
59 difficulties (SMD) in line with the overresponsive and underresponsive patterns outlined by  
60 Bundy and Lane (2020), Interdisciplinary Council on Development and Learning Disorders  
61 (2005), and Zero to Three (2016). For the purpose of this review, while specific studies refer  
62 to some of the previously stated terms such as sensory sensitivity and sensation seeking, the  
63 term SMD will be used to describe abnormal sensory modulation in a general sense.

### 64 **SMD and ADHD**

65 Previous research suggests that children with ADHD are more likely to experience SMD  
66 relative to typically developing children (Ben-Sasson et al., 2017; Ermer & Dunn, 1998).  
67 However, it is difficult to distinguish between symptoms stemming from SMD and symptoms  
68 linked to an ADHD diagnosis (Lane et al., 2010). Neither SMD or ADHD are homogenous,  
69 and both are typically diagnosed through observational or behavioural criteria (Koziol &  
70 Budding, 2012). Miller and colleagues (2012) report similarities between sensory modulation  
71 patterns and ADHD subtypes. In particular, the sensory seeking pattern and ADHD

72 hyperactive-impulsive subtype can often both display poor impulse control, and inappropriate  
73 movement and touch; the overresponsive pattern and ADHD inattentive subtype both feature  
74 symptoms of distractibility and difficulty focusing; the underresponsive pattern and  
75 inattentive ADHD subtype both present with a lack of awareness when being spoken to or  
76 following directions. Investigating differences between individuals with ADHD, individuals  
77 with SMD, and those with co-occurring ADHD and SMD is necessary to determine whether  
78 sensory modulation difficulties can be reliably distinguished from the behaviours of ADHD  
79 (Lane et al., 2010; Koziol & Budding, 2012).

80 Sensory modulation difficulties can exacerbate the functional impairments already  
81 experienced by children with ADHD. SMD has been associated with poorer social  
82 participation, increased delinquency and aggression (Mangeot et al., 2001), and increased  
83 anxiety (Reynolds & Lane, 2009) in children with ADHD. Early detection and management  
84 of sensory modulation difficulties can help to improve everyday functioning in children with  
85 ADHD (Ghanizadeh, 2011). Thus, understanding SMD in children with ADHD is an  
86 important initiative to improve long term outcomes in this population.

### 87 **Assessment of SMD in children**

88 A recent systematic review identified 21 available tools for evaluating sensory processing in  
89 all children aged 3-11, of which 15 are supported by psychometric studies (Jorquera-Cabrera  
90 et al., 2017). More recently, there has been an influx in the number of available sensory  
91 assessments, increasing from one publication a year between 2006 and 2009 to seven  
92 publications in 2014 (Jorquera-Cabrera et al., 2017). This may be due to an increased interest  
93 in sensory processing as part of the new DSM criteria for ASD. It may also reflect a focus on  
94 research examining the association between sensory processing and domains such as child  
95 development and mental health (Jorquera-Cabrera et al., 2017; Harrison et al., 2019). The

96 most common method of assessing SMD is through parent-report questionnaires (Soto et al.,  
97 2018) such as Sensory Profile (Dunn, 1999), Sensory Profile 2 (Dunn, 2014), Sensory  
98 Experiences Questionnaire (Baranek, 2018), Sensory Processing Measure (Parham et al.,  
99 2007), Sensory Overresponsivity Scale (Schoen et al., 2008), or Sensory Processing Scale  
100 Assessment (Schoen et al., 2014). Research has also attempted to use physiological measures  
101 to examine sensory overresponsivity (SOR) (Lane et al., 2010; Ben-Sasson et al., 2017). The  
102 most common physiological assessment is the Sensory Challenge Protocol (McIntosh et al.,  
103 1999a). However, although this unique laboratory paradigm has not been standardized, it has  
104 since been used in a number of sensory processing studies, including studies with autistic  
105 children (e.g. Reynolds et al., 2010; Schaaf et al., 2015; Schupak et al., 2016; Bizzell et al.,  
106 2020). Research with ADHD populations has typically focused on examining electrodermal  
107 responses during the Sensory Challenge Protocol. One recent study suggests that caregiver  
108 reports have established differences between children with ADHD and typically developing  
109 controls in terms of SMD but that physiological findings have been less consistent (Lane &  
110 Reynolds, 2019).

### 111 **The current review**

112 There has only been one review to date that has looked at sensory modulation difficulties in  
113 children with ADHD (Ghanizadeh, 2011). As the field of sensory modulation has gained  
114 momentum in recent years (Jorquera-Cabrera et al., 2017), a more comprehensive, up-to-date  
115 systematic review of the literature is timely and necessary. Importantly, no review to date has  
116 considered the influence of the choice of assessment on the detection of SMD in children  
117 with ADHD (Eeles et al., 2013). Given the ongoing debate surrounding ADHD and SMD as  
118 distinct diagnoses, understanding the tools used to assess SMD in this population can provide  
119 further insight as to whether they should be considered distinct disorders. The findings of this

120 review could aid clinicians in selecting the most appropriate tool for measuring SMD in this  
121 population (Miller et al., 2007).

122 The aims of this review are twofold. Firstly, to establish how SMD is assessed in children in  
123 ADHD and whether the choice of measure has an influence on the detection of SMD in this  
124 population. As mentioned previously, there is a suggestion that caregiver reports have  
125 established significant differences between controls and children with ADHD, while findings  
126 are less consistent using physiological measures (Lane & Reynolds, 2019). This review will  
127 systematically review the literature in order to compare measures of SMD across studies of  
128 children with ADHD. Secondly, this review will focus in on studies which include  
129 participants with dual diagnoses of ADHD and SMD and those with SMD only or ADHD  
130 only to investigate whether these diagnoses can exist independently of one another.

### 131 **METHOD**

132 The review protocol was registered with PROSPERO (CRD42018091730). PRISMA  
133 guidelines were followed (Moher et al., 2009). The search was conducted by the primary  
134 author with assistance from a librarian at the primary author's institution. Articles were  
135 required to be published in English, based on human research, from the January 1980 to  
136 December 2019. The year 1980 was decided upon as it marked the publication of the  
137 Diagnostic and Statistical Manual III, whereby ADHD was classified. Sample included  
138 children under the age of 18 with a diagnosis of ADHD (see Table 1). After several scoping  
139 searches to develop an appropriate search string, articles were retrieved from PubMed,  
140 CINAHL, and PsycINFO in November 2020. These three databases were selected by  
141 reviewing the common databases used in systematic reviews concerning ADHD and sensory  
142 modulation literature as of June 2020. An example of the search string used is outlined in the  
143 supplementary material (Table S1).

144 In addition to searching the databases, a hand-search was conducted of the reference lists of  
145 the original studies which met the eligibility criteria. The titles and abstracts of studies  
146 identified in the initial search were screened by two of the authors. The full text of the  
147 remaining studies were then screened by the same reviewers independently. Papers not  
148 identified by both reviewers as eligible for inclusion were marked and discussed, with  
149 disagreements resolved through this discussion. Data extraction was completed by the lead  
150 author on the studies which met the inclusion criteria. Quality, scientific rigor, and risk of  
151 bias were assessed using a Risk of Bias Tool developed from the Cochrane Collaboration  
152 (Higgins & Green, 2011) and DeBoth and Reynolds (2017). Each of the studies was rated  
153 based on a series of twelve questions under the broad categories of selection bias,  
154 performance bias, attrition bias, detection bias, and reporting bias. The lead author  
155 determined whether the risk of bias was high or low, or whether there were some concerns  
156 present in each study. A series of twelve questions were rated according to this criteria under  
157 the broader categories of selection bias (four questions), performance or statistical bias (two  
158 questions), attrition bias (two questions), detection bias (three questions), and reporting bias  
159 (one question). Results of the risk of bias assessment are presented in Figure 2 (further details  
160 on risk if bias assessment are present in supplementary material [Figure S1]). Double data  
161 extraction and risk of bias assessments were completed by the second reviewer for a  
162 proportion of the included studies (n=5, 22.73%) to verify that the correct data had been  
163 extracted. This partial double data extraction resulted in a 90% agreement rate, in line with  
164 recommendations outlined by Schlosser (2007), with any disagreements resolved through  
165 discussion.

166 TABLE 1 HERE

167

## RESULTS

168 The initial electronic search yielded 345 results (see Figure 1). Eighteen additional studies  
169 were retrieved through hand-searching the reference lists of included studies. All abstracts  
170 were screened by the lead author and an independent reviewer. After screening of titles and  
171 abstracts, 68 articles were obtained for full-text screening of eligibility. All full-text articles  
172 were assessed by the same two reviewers. Forty-three articles were excluded from final  
173 analysis. The remaining 25 studies, all of which were quantitative, are included in the current  
174 review. Data extraction was completed by the main author and cross-checked by an  
175 independent reviewer. Of the 25 studies, ten were conducted in America, six in Israel, three  
176 in Iran, one in Brazil, one in the Netherlands, one in China, one in Spain, one in India, and  
177 one in Taiwan. Nineteen of the studies used a case-control design to compare children with  
178 ADHD to typically developing controls. Three studies examined a single group of children  
179 with ADHD without matched controls. One study was conducted with a representative birth  
180 cohort, and 2 studies compared children with SMD and ADHD. The age of participants  
181 included across all studies ranged from 3-15 years. The characteristics of the 25 studies are  
182 summarised in Table 2.

183 FIGURE 1 HERE

184 TABLE 2 HERE

### 185 **Critical appraisal**

186 No study was shown to have an extremely high risk of bias (see Figure 2). The most common  
187 concern was that confounding variables were not always collected using valid measures. For  
188 example, May Benson and colleagues (2020) rely on parent report of co-occurring diagnoses,  
189 and did not include a standardised assessment for co-occurring disorders in their population  
190 of children with SPD. The studies of Ghanizadeh (2008, 2009, 2013) utilised newly  
191 developed questionnaires which had not been assessed previously for validity or reliability.  
192 No study was excluded after the risk of bias assessment was carried out.

193 FIGURE 2 HERE

194 **Measures of sensory processing**

195 Of the 25 included studies, n=24 (96%) of studies used a parent-report measure and n=1 (4%)  
 196 used a self-report measure to assess SMD. Five studies (20%) also included a physiological  
 197 measure, while one study (4%) included both a parent-report and behavioural measure. Only  
 198 one study (4%) included parent-report, physiological, and behavioural measures. A summary  
 199 of the main results of each study, including the type of assessment used, is presented in Table  
 200 3.

201 TABLE 3 HERE

202 **Caregiver reports**

203 *Sensory Profile/Short Sensory Profile/Sensory Profile-2*. Fifteen studies administered the  
 204 Sensory Profile (n=7), the Short Sensory Profile (n=5), the Sensory Profile 2 (n=2), or Short  
 205 Sensory Profile 2 (n=1). The seven studies which included the Sensory Profile, developed by  
 206 Dunn (1999), were Ben-Sasson et al., 2017; Dunn & Bennett, 2002; Yochman et al., 2004;  
 207 Cheung & Siu, 2009; Lin et al., 2013; Shimizu et al., 2014, and Iyer et al. (2020). Internal  
 208 consistency of section scores ranges from .47 to .93 (Dunn, 1999). The complete Sensory  
 209 Profile consists of 125 items investigating a variety of sensory categories: general processing,  
 210 auditory, visual, tactile, vestibular, and oral sensitivity processing. A lower score on the  
 211 Sensory Profile is indicative of greater difficulty with sensory processing. All seven studies  
 212 employed various methods of scoring the Sensory Profile. Cheung and Siu (2009) and Lin et  
 213 al. (2013) used the Chinese Sensory Profile, which contains eight subscales – six relating to  
 214 sensory systems and two behavioural subscales. Cheung and Sui (2009) analyse their results  
 215 by item. Similarly, Dunn and Bennett (2002) analysed their results by item, as well as by  
 216 section scores. Lin et al. (2013) converted the results to Z-scores for analysis. Ermer and

217 Dunn (1998) analysed their results by factor scores. Shimizu et al. (2014) and Yochman et al.  
 218 (2004) both analysed their results by factor and section scores. Iyer and colleagues (2020)  
 219 report scores for each sensory quadrant (sensitivity, avoiding, registration, and seeking).  
 220 Despite the varied nature of scoring, all seven studies observed significant differences  
 221 between children with ADHD and typically developing children, with children from the  
 222 ADHD group displaying lower scores (i.e. a higher frequency of issues) of sensory  
 223 processing in some or all subscales. Lin et al. (2013), Shimizu et al. (2014), and Yochman et  
 224 al. (2004) observed no significant difference between the ADHD and control groups on the  
 225 factor of sensory sensitivity. Ermer and Dunn's (1998) discriminant analysis found that  
 226 children with ADHD were best discriminated from controls by a high incidence of sensory  
 227 seeking and inattention/distractibility and a low incidence of oral sensitivity and fine  
 228 motor/perception. Thus, suggesting there was no discriminant difference between groups on  
 229 sensory sensitivity, similar to the aforementioned studies. Lin et al. (2013) and Shimizu et al.  
 230 (2014) also found no significant difference between the ADHD and control groups in terms  
 231 of oral sensitivity. Similarly, Iyer et al. (2020) found that the ADHD group scored  
 232 significantly lower than children with no ADHD symptoms on the sensory seeking quadrant  
 233 only.

234 The Sensory Profile has also been condensed into a Short Sensory Profile (McIntosh et al.,  
 235 1999b), consisting of 38 items. The Short Sensory Profile was used by five studies in this  
 236 review (Manegot et al., 2001; Miller et al., 2012; Engel-Yeger & Ziv-On, 2011; Mimouni-  
 237 Bloch et al. 2018; Yochman et al., 2013), two of which used the Hebrew version of the scale  
 238 (Engel-Yeger & Ziv-On, 2011; Yochman et al., 2013). The Short Sensory Profile consists of  
 239 seven subscales: tactile sensitivity, movement sensitivity, taste/smell sensitivity,  
 240 visual/auditory sensitivity, seeking sensation, auditory filtering, and low energy/weak.  
 241 Internal consistency of the subscales ranges from .70-.90 (McIntosh et al., 1999b). All four

242 studies observed significant differences between children in the ADHD group and those in  
243 the control group for at least five of the seven subscales. Engel-Yeger and Ziv-On (2011),  
244 Mangeot et al. (2001), Miller et al. (2012), and Mimouni-Bloch et al. (2018) found that the  
245 ADHD group scored significantly lower than controls in the subscales of tactile sensitivity  
246 and low energy/weak (with effect sizes ranging from  $d = 0.25$  to  $0.88$  for tactile sensitivity  
247 and  $d = 0.14$  to  $1.43$  for low energy/weak). Miller et al. (2012) divided the ADHD group  
248 into individuals with ADHD and SMD and those with ADHD only (see below for  
249 differences). Children with ADHD alone still scored significantly lower than controls on five  
250 of seven subscales (excluding auditory filtering and seeking sensation). On the other hand,  
251 Mimouni-Bloch et al. (2018) reports a significantly lower score for the ADHD group relative  
252 to controls for all subscales (effect sizes range from  $d = 0.05$  to  $0.64$ ). The largest effect  
253 sizes in Mimouni-Bloch's study were the auditory filtering and seeking sensation subscales  
254 ( $d = 0.64$  and  $d = 0.45$  respectively), in direct contrast to the results of Miller et al. (2012).  
255 Yochman and colleagues (2013) compared children with SMD to those with ADHD only,  
256 without a control group. Yochman et al. (2013) found that the SMD group had significantly  
257 lower scores than the ADHD group for all subscales.

258 The Sensory Profile 2 (Dunn, 2014) is an updated version of the Sensory Profile. It contains  
259 86 items, with internal consistency scores ranging from  $0.6$  to  $0.92$  (Dunn, 2014). Unlike the  
260 Sensory Profile, higher scores indicate greater difficulties. Two studies in this review  
261 employed the Sensory Profile 2 (Little et al., 2017; Little et al., 2018). Little et al. (2017)  
262 found that children with ADHD had higher scores (i.e. greater difficulties) on all nine  
263 subscales of the Sensory Profile 2 than typically developing children. The other study  
264 classified children with ADHD into sensory processing patterns (Little et al., 2017). Little  
265 and colleagues observed that of 96 children with ADHD, 13.5% showed increased sensory  
266 seeking, 10.4% showed an intense, aversive pattern, 10.4% showed increased scores in

267 avoidance and registration of sensory stimuli, and 12.5% showed increased sensitivity and  
 268 avoidance. The remaining participants with ADHD (51.3%), showed a balanced profile with  
 269 low frequency of sensory behaviours. Using the Spanish version of the Short Sensory Profile  
 270 2, Delgado-Lobete and colleagues (2020) found increased incidence of atypical sensory  
 271 processing scores for children with ADHD across all sensory processing quadrants and  
 272 patterns (bystander, seeker, sensor, avoider).

273 *Sensory Overresponsivity Scale (SensOR)*. Three studies assessed sensory processing using  
 274 the Sensory Overresponsivity Scale (SensOR), developed by Schoen and colleagues (2008),  
 275 (Ben-Sasson et al., 2017; Reynolds et al., 2010; Lane et al., 2010). The SensOR is a caregiver  
 276 report containing 76 items, all focusing on the overresponsive pattern of sensory processing.  
 277 It encompasses all seven sensory domains: tactile, auditory, visual, olfactory, gustatory, and  
 278 vestibular–proprioceptive. Reliability for the total scaled ranged from a Cronbach’s alpha of  
 279 .74 to .94. The internal reliability within each domain ranged from a Cronbach’s alpha of .65  
 280 to .88. Higher scores on the SensOR are associated with more difficulty in terms of sensory  
 281 processing. The cut-off for the presence of SOR is based on the presence of four or more  
 282 tactile or auditory items (Schoen et al., 2008; Ben-Sasson et al., 2017). Ben-Sasson et al.  
 283 (2017) used items from the auditory and tactile scales of the SensOR only to examine clusters  
 284 of ADHD and sensory overresponsivity (SOR) symptomatology. Children with high levels of  
 285 ADHD symptomatology had significantly higher sensitivity scores (SOR) than those with  
 286 low levels of or an absence of ADHD symptoms. This study also found that 48% of  
 287 participants with elevated ADHD scores on the Child Behaviour Checklist also met criteria  
 288 for SOR. Similarly, Reynolds et al. (2010) found that thirteen participants (54.17%) from  
 289 their ADHD group met the criteria for sensory overresponsivity, based on their SensOR  
 290 scores. Lane et al. (2010) observed that 46% of participants from the ADHD group met  
 291 criteria for SOR.

292 *Sensory Processing Measure.* The Sensory Processing Measure – Home Form was developed  
 293 by Parham et al. (2007) and employed by one study in this review (Pfeiffer et al., 2015). The  
 294 Sensory Processing Measure is a norm-referenced caregiver report. It consists of 8 subscales:  
 295 social participation, vision, hearing, touch, taste and smell, body awareness, balance and  
 296 motion, and planning and ideas. The subscales of vision, hearing, touch, taste and smell, body  
 297 awareness, and balance and motion are combined to represent a total sensory systems score  
 298 (Lai et al., 2011). It has good internal consistency with Cronbach’s alpha ranging from .77 to  
 299 .95 and strong test–retest reliability, with estimates ranging from .94 to .98 (Pfeiffer et al.,  
 300 2015). Pfeiffer et al. (2015) found that for each subscale of SPM, children with ADHD had a  
 301 higher mean score (i.e. more problems) than controls. Pfeiffer and colleagues also reported  
 302 that 64% of those in the ADHD group scored in the range of "some problems" or "definite  
 303 dysfunction", compared to less than 5% of controls who scored in range of "some problems".  
 304 No controls scored in the range of "definite dysfunction".

305 *Evaluation of Sensory Processing Questionnaire.* The Evaluation of Sensory Processing  
 306 Questionnaire was used by one study (Yochman et al., 2013). There are six subscales related  
 307 to specific sensory systems: visual, auditory, tactile, olfactory/gustatory, proprioceptive, and  
 308 vestibular sensory systems. Higher scores indicate fewer sensory problems. Yochman et al.  
 309 (2013) observed that children with SMD scored lower than children with ADHD on three of  
 310 the six subscales (taste and smell, tactile, motion/vestibular).

311 *Touch Inventory for Preschoolers.* The Touch Inventory for Preschoolers is a parent-report  
 312 scale based on children’s typical responses to tactical stimuli and was used by one study in  
 313 this review (Parush et al., 2007). Internal consistency of .89 has been reported (Royeen,  
 314 1987). Parush and colleagues calculated tactile defensiveness (TD) as one standard deviation  
 315 above the mean score of a sample of 60 typical children (2007). Out of 67 children with  
 316 ADHD, 49 children met the criteria for TD (Parush et al., 2007). Mean scores on the Touch

317 Inventory for Preschoolers was 112.30 for the ADHD group, compared to 61.51 for typically  
318 developing controls.

319 *OTA The Koomar Centre Development/Sensory History.* OTA The Koomar Centre  
320 Development/Sensory History questionnaire is a parent-report measure concerning sensory  
321 processing and motor skills in children aged 4-12 years which was used by one study in this  
322 review (May Benson et al., 2020). Each item is scored on a 3-point scale where higher scores  
323 indicate greater functional problems. May Benson and colleagues (2020) focused on the  
324 gravitational insecurity subscale in their study. Gravitational insecurity is a type of  
325 movement-related overresponsivity dysfunction (May Benson et al., 2020). Results showed  
326 that children with SPD+ADHD did not differ from those with SPD only in terms of  
327 gravitational insecurity scores.

328 *Non-standardized measures.* It should be noted that three studies included in this review did  
329 not use standardized measures to assess sensory processing abilities (Ghanizadeh, 2008;  
330 Ghanizadeh, 2009; Ghanizadeh, 2013). However, all of these new measures were assessed for  
331 face validity by a team of three psychiatrists and subjected to a pilot study. One study found  
332 that ADHD subtypes were not associated with scores on the hyposensitivity or  
333 hypersensitivity subscales of the Tactile Sensory Dysfunction Checklist (Ghanizadeh, 2008).  
334 Another study reported that ADHD subtypes were not associated with total scores on the  
335 Auditory Dysfunction Checklist (Ghanizadeh, 2009). Ghanizadeh reported that children with  
336 ADHD who display ODD symptoms were more likely to have oral sensitivity and oral over-  
337 responsivity on the Oral Over- and Under-responsivity Behaviours Inventory (2013). In  
338 interpreting the results of these three studies of non-standardized measures, it should be noted  
339 that all of these studies were single group designs, with no matched control group.

340 **Self-report measures**

341 *Touch Inventory for Elementary School-Aged Children.* The Touch Inventory for Elementary  
 342 School-Aged Children (TIE) is a self-report screening questionnaire for children aged 6-12,  
 343 measuring tactile defensiveness to tactile stimuli. It contains 26 items and has good internal  
 344 reliability, with a Cronbach's alpha of 0.79. One study in this review used the Dutch version  
 345 of the Touch Inventory for Elementary School-Aged Children (Broring et al., 2008). Broring  
 346 and colleagues (2008) observed children with ADHD scored higher (i.e. a greater incidence  
 347 of tactile defensiveness) than controls.

348 **Behavioural measures**

349 *Sensory Reactivity Score.* The Sensory Reactivity Score is a rating scale developed to  
 350 quantify both verbal and non-verbal behaviours of touch-related discomfort and agitation  
 351 (Parush et al., 2007). It was used by one study in this review (Parush et al., 2007). Test-retest  
 352 and interrater reliability was examined by coding videos, while construct validity was  
 353 established by six experts from occupational therapy, neuroscience, and psychology  
 354 backgrounds. Ratings of reactivity or discomfort were made by the experimenter while four  
 355 scalp-electrodes were attached for electrophysiological recordings (see below for discussion  
 356 on physiological data). Ratings were on a scale from 0 (no discomfort) to 4 (intense  
 357 discomfort). Children with TD had a mean reactivity score of 3.36 compared to .71 for  
 358 controls.

359 *Fabric Prickliness Test.* This behavioural assessment measures the level of pain evoked by  
 360 the application of prickly fabrics to the skin and was used by one study in this review  
 361 (Yochman et al., 2013). Three types of woollen fabrics (least prickly, mildly prickly, and  
 362 very prickly) were applied to the child's non-dominant forearm in 16 applications (Yochman  
 363 et al., 2013). Children rated their level of pain using the Revised Faces Pain Scale (Hicks et  
 364 al., 2001). 'Pain after-sensation' was measured 15 seconds after the last fabric application and

365 repeatedly every 1 minute until sensation dissipated. Children with SMD reported higher pain  
 366 and a longer ‘pain after-sensation’ period than children with ADHD.

367 *Pinprick Pain.* Yochman and colleagues (2013) also used a series of Von-Frey filaments to  
 368 test pinprick pain. Filaments were applied 9 times with increasing levels of punctuate pain.  
 369 Children were then asked to rate pain intensity using the Revised Faces Pain Scale (Hicks et  
 370 al., 2001). Children with SMD higher scores in response to punctuate pain than children with  
 371 ADHD.

372 **Physiological measures**

373 *Sensory Challenge Protocol.* The Sensory Challenge Protocol (SCP) is a lab paradigm which  
 374 uses electrodermal response to examine sensory stimulation in olfactory, auditory, visual,  
 375 tactile, and vestibular domains (McIntosh et al., 1999a). Stimuli presented to the participants  
 376 include wintergreen oil in a vial (olfactory), a siren at 90 decibels (auditory), a 20-watt strobe  
 377 light at 10Hz (visual), a feather moved across the face (tactile) and the chair tilted back to a  
 378 30-degree angle (vestibular). Electrodermal activity is recorded throughout the procedure (see  
 379 McIntosh et al., 1999a for a detailed description). Five studies in this review employed the  
 380 SCP and results are less homogenous than caregiver reports (Mangeot et al., 2001; Miller et  
 381 al., 2012; Reynolds et al., 2010; Lin et al., 2013; Lane et al., 2010). Three of these studies  
 382 report no significant differences between the ADHD group and relative controls (Miller et al.,  
 383 2012; Lin et al., 2013; Lane et al., 2010). However, Lane et al. (2010) did find that children  
 384 with ADHD+SOR showed higher arousal levels during recovery from the challenge, relative  
 385 to controls. Mangeot et al. (2001) observed a trend towards a significant difference between  
 386 children with ADHD and controls ( $p = .056$ ). Reynolds et al. (2010) used salivary cortisol to  
 387 measure children’s stress responses to the SCP. Reynolds and colleagues (2010) also  
 388 observed a trend towards a significant difference between children with ADHD+SOR and

389 children with ADHD only in terms of cortisol levels over time ( $p = .056$ ). Although,  
 390 Reynolds et al. found no significant difference between the children with ADHD+SOR and  
 391 TD controls in their stress responses to the SCP.

392 *Somatosensory Evoked Potential*. One study in this review used somatosensory evoked  
 393 potential (SEP), electrical activity from the nervous system in response to sensory stimuli, as  
 394 a measure of somatosensory function (see Parush et al. (2007) for experimental procedure).  
 395 Parush et al. (2007) observed that children with ADHD who met criteria for tactile  
 396 defensiveness (as measured by their sensory reactivity score and the Touch Inventory for  
 397 Preschoolers,  $n = 46/67$ ) were distinguishable from children with ADHD who did not meet  
 398 the criteria for tactile defensiveness and typically developing children by larger  
 399 somatosensory evoked potential amplitudes (N13, N20, P23). There was no difference  
 400 between children with ADHD only and controls.

401 **Caregiver reports versus experimental measures**

402 Seven studies included both a caregiver report and a physiological assessment. Of these, three  
 403 studies report that significant differences emerged between groups for the caregiver reports,  
 404 while no significant difference was found between groups for objective measures (Lin et al.,  
 405 2013; Mangeot et al., 2001; Miller et al., 2012). Reynolds and colleagues (2010) report  
 406 significant differences between ADHD+SOR, ADHD, and controls on the SensOR, however  
 407 the difference between ADHD+SOR and controls, and ADHD+SOR and ADHD only both  
 408 fail to reach significance in cortisol responses to the Sensory Challenge Protocol. A  
 409 significant difference does emerge in Reynolds et al. (2010) for the ADHD only and control  
 410 groups on cortisol responses. Similarly, Lane et al. (2010) observed group differences in  
 411 SensOR and electrodermal responses during recovery from the Sensory Challenge Protocol.  
 412 However, no differences emerged between those with ADHD only and the control group

413 (Lane et al., 2010). On the other hand, Parush et al. (2007) report significant differences  
 414 between those with ADHD+TD and ADHD only on both parental-report and physiological  
 415 measures. Likewise, Yochman et al. (2013) did observe differences between SMD and  
 416 ADHD groups on both caregiver-report and behavioural measures.

417 **Separating SMD from ADHD**

418 Six studies in this review included both children with ADHD only and children with both  
 419 ADHD and sensory modulation disorder (SMD). One study looked at children with SPD and  
 420 those with a co-occurring diagnosis of SPD and ADHD. As discussed above, differences  
 421 between ADHD and SMD behaviours are often difficult to distinguish (Ermer & Dunn, 1998;  
 422 Koziol & Budding, 2012). In this review, caregiver report questionnaires observed moderate  
 423 to large effect sizes between groups, whereby participants with SMD or SOR reporting  
 424 poorer sensory modulation. Ben-Sasson and colleagues (2017) observed a large effect size  
 425 ( $d = 3.1$ ) between the ADHD+SOR group and ADHD only group on total SensOR scores, in  
 426 which children with ADHD+SOR reported greater difficulties than those with ADHD only.  
 427 On the other hand, a large effect size was observed between controls +SOR and ADHD+SOR  
 428 ( $d = -1.3$ ), whereby children with SOR only had greater difficulties than children with  
 429 ADHD+SOR. In Lane et al. (2010), the ADHD+SOR group differed significantly from the  
 430 ADHD group on SensOR scores, with large effect sizes ranging from  $d = 0.72$  to  $d = 1.94$ .  
 431 The ADHD+SOR and ADHD groups were not distinguishable based on electrodermal  
 432 responses. Reynolds et al. (2010), observed moderate to large effect sizes when looking at  
 433 differences between children with ADHD+SOR and those with ADHD on the SensOR, with  
 434 Cohen's  $d$  ranging from  $d = 0.33$  to  $d = 2.35$ . A trend towards significance ( $p = .056$ )  
 435 emerged between the two groups in their cortisol levels during the Sensory Challenge  
 436 Protocol. Miller and colleagues (2012) report that individuals with ADHD+SMD scored  
 437 significantly lower than those with a sole diagnosis of ADHD on all subscales of the Short

438 Sensory Profile, however no effect sizes are available. In Miller et al. (2012), those with  
439 ADHD+SMD were excluded from the electrodermal response analysis as too few participants  
440 took part in the Sensory Challenge Protocol. Parush et al. (2007) observed that ADHD+TD  
441 group was distinguishable from ADHD group by larger SEP amplitudes. Finally, both  
442 caregiver reports and behavioural measures were able to distinguish children with SMD from  
443 children with ADHD in Yochman et al. (2013). Children with SPD+ADHD could not be  
444 distinguished from children with SPD only in terms of parent-reported gravitational  
445 insecurity (May Benson et al., 2020).

## 446 **DISCUSSION**

447 This review had two specific aims: (1) to investigate how SMD is measured in children with  
448 ADHD and whether the choice of measure has an influence on the detection of SMD in this  
449 population, and (2) to examine whether symptoms of SMD and ADHD could be distinct  
450 diagnoses. Results will be discussed below in relation to these aims.

451 Overall, all studies with a case-control design reported that a proportion of children with  
452 ADHD showed atypical sensory modulation. A key finding of this review is that the type of  
453 assessment used influenced the detection of these differences. Findings show that caregiver  
454 reports and self-reports were more likely to observe differences between children with  
455 ADHD and typically developing children, while results from physiological measures were  
456 less robust. This is similar to observations reported by Lane and Reynolds (2019). Similar  
457 discrepancies between behavioural/parent-report and physiologic measures have been  
458 reported in other domains such as sleep (Corkum et al., 1998) and distress in children with  
459 cancer (Walco et al., 2005).

460 This discrepancy between measures calls for further examination of the validity and  
461 consistency of assessments. For example, the Sensory Profile does not operationally define

462 ‘sensory processing’ and includes items which capture behaviours beyond the scope of  
 463 sensory processing such as emotional and social responses (Koziol & Budding, 2012). Many  
 464 items also overlap with behaviours included in the diagnostic criteria for ADHD and other  
 465 DSM disorders (Koziol & Budding, 2012; Lane & Reynolds, 2019). The user manual of the  
 466 Sensory Profile reports that 43/125 items (34.4%) represent behaviours more commonly seen  
 467 in ADHD (Dunn, 1999; 2014). A similar overlap issue occurs in the Sensory Processing  
 468 Measure (SPM) (Parham et al., 2007). One item from the SPM “Fails to gather belongings or  
 469 otherwise take notice of approaching bus stop” is closely aligned with the DSM criteria of  
 470 “often has trouble organising tasks and activities”. This conceptual overlap may explain more  
 471 robust differences between ADHD and control groups in caregiver reports over physiological  
 472 measures. This, however, does not explain why differences emerged in behavioural tests (e.g.  
 473 pinprick pain test) and not with electrodermal response during the Sensory Challenge  
 474 Protocol. While Parush and colleagues (2007) did observe a significant difference in  
 475 physiological response between children with ADHD+TD and a control group, this was a  
 476 single study with only male participants which warrants replication. Furthermore, parent  
 477 report measures often combine a complex cluster of behavioural observations over a period  
 478 of time, while lab assessments assess a child’s sensory experiences at a single point in time in  
 479 a controlled environment (Tavassoli et al., 2018). Perhaps SMD may be better captured over  
 480 time through caregiver report than a singular lab session. Including additional reports, such as  
 481 those from a teacher’s perspective, may also help to offer a clearer picture of a child’s  
 482 sensory profile. Importantly, the most appropriate measure to use will likely be guided by the  
 483 specific questions being asked by the researcher.

484 Seven studies included participants who had ADHD+SMD or ADHD+SOR and those with  
 485 SMD or SOR only, providing further insight into the differences between these two disorders.  
 486 Six studies were able to distinguish between those with SOR and those with ADHD only

487 based on caregiver reports. One thing to consider is the way in which SMD or SOR was  
488 diagnosed identified within each study. Ben-Sasson et al. (2017), Lane et al. (2010) and  
489 Reynolds et al. (2010), used SensOR scores to both differentiate the groups and also to report  
490 group differences. Similarly, Parush et al. (2007) divided the ADHD group into ADHD+TD  
491 and ADHD only based on their Touch Inventory in Preschoolers score and sensory reactivity  
492 score. In the studies by Yochman et al. (2013), Miller et al. (2012), and May Benson et al.  
493 (2020), children had been diagnosed with SMD prior to participating in the study and as such  
494 had likely undergone further assessment by an occupational therapist regarding sensory  
495 processing. It may be useful for future studies examining populations with both ADHD and  
496 SMD to include an assessment with an occupational therapist (which may include parent  
497 interview and/or skilled observation of child's behaviour), rather than relying solely on the  
498 measure used within the study itself. This is also pertinent given the conceptual overlap  
499 between common sensory assessments such as the Sensory Profile and ADHD criteria.

## 500 **Limitations**

501 There are several limitations to be considered in the interpretation of the current findings.  
502 This review only included articles published in English, resulting in the exclusion of three  
503 studies. The reporting of results from the Sensory Profile was not homogenous. Some studies  
504 reported factor scores, while others only reported section scores. Section scores reflect a  
505 parent's perception of the child's sensory processing, modulation, and behavioural and  
506 emotional responses. Factor scores reflect a parent's perceptions of their child's  
507 responsiveness to sensory input. Factor scores have been found to be more reflective of  
508 symptoms that characterize ADHD in general (Yochman et al., 2004). Moreover, not all  
509 items in the Sensory Profile are included to calculate factor scores (Yochman et al., 2004).  
510 This made it difficult to synthesise the results of the review or to perform a meta-analysis.

511 Thus, the variability observed in this review may be due to the way in which authors report  
512 their results.

513 A further limitation of this area of research is the lack of a universal diagnostic criteria for  
514 SMD and sensory processing difficulties. This review employed the nosology of Bundy and  
515 Lane (2020), the Interdisciplinary Council on Development and Learning Disorders (2005),  
516 and Zero to Three (2016). Although, it cannot be guaranteed that all researchers adopted this  
517 framework when examining sensory modulation in their respective studies. Furthermore, this  
518 theoretical framework was not always employed in the development of the measures  
519 discussed above. Until a cohesive definition and diagnostic criteria are agreed upon for SMD,  
520 it is difficult to perform a meta-analysis.

521 The majority of studies included in this review did not consider DSM subtypes of ADHD.  
522 Given the robust finding that a number of children with ADHD experience SMD, it is  
523 necessary to investigate whether children with particular subtypes of ADHD are more likely  
524 to experience sensory dysfunction. As we move away from a traditional, categorical  
525 diagnostic process to a more dimension-based approach, it may be useful to consider SMD as  
526 a dimension to ADHD, as proposed by Lane and Reynolds (2019). Furthermore, a small  
527 proportion of studies in this review (n=5) did not include a control group of typically  
528 developing children. As such, caution is advised in interpreting these studies.

### 529 **Implications and future research**

530 Sensory processing impairments are important to consider due to the increased incidence of  
531 sensory processing problems reported in children with ADHD, particularly given that  
532 children with ADHD and sensory difficulties are more likely to present with secondary  
533 problems such as clinically significant anxiety (Reynolds & Lane, 2009). The majority of  
534 studies excluded participants with co-occurring disorders such as ASD (see Table 2 for

535 further detail), suggesting that SMD is not the result of co-occurring traits from other  
536 neurodevelopmental diagnoses. Further research should be mindful of the discrepancies that  
537 arise between caregiver reports and experimental measures when investigating sensory  
538 processing issues in ADHD. These inconsistencies between questionnaire, behavioural, and  
539 physiological assessments raise questions as to their validity: Are caregiver reports too  
540 sensitive to sensory processing deficits? Are physiological assessments too conservative? Are  
541 these measures evaluating different aspects of the sensory experience? It is important that  
542 clinicians and practitioners are aware of the different approaches in measuring sensory  
543 processing symptoms in this population, in order to choose the most appropriate tool.

544 Future research should also aim to further understand potential shared neurobiological  
545 underpinnings of ADHD and SMD. There is currently no consistent neuroanatomic  
546 understanding of SMD, although studies have suggested that sensory gating paradigms may  
547 allow for the dissection of the chain of events involved in sensory processing (Davies et al.,  
548 2009). As previously mentioned, SMD is not recognised by the DSM (APA, 2013). Future  
549 research could benefit from focussing on disruptions to normal development rather than  
550 distinct diagnosis, similar to that of the Research Domain Criteria Framework (RDoC)  
551 (Koziol & Budding, 2012). This approach would allow for the consideration of different  
552 factors which may underlie SMD, such as poor self-regulating and executive functioning  
553 skills (Ahn et al., 2004).

#### 554 **Conclusion**

555 This review reports variability in the prevalence of SMD in children with ADHD that is  
556 dependent on the tools used to measure this domain. Studies that employ caregiver-report or  
557 behavioural measures tend to report a greater prevalence of difficulties in sensory processing,  
558 relative to physiological measures. This has important implications for clinicians in the

559 consideration of tools for sensory processing assessment in children with ADHD. When  
560 identifying the most appropriate tool, researchers should be guided by the questions being  
561 asked. If daily behaviours are crucial to consider, caregiver reports might be more appropriate  
562 to examine. If researchers are focused on understanding the physiological underpinnings of  
563 SMD, then physiologic tools are necessary. Finally, this review found differences between  
564 SMD and ADHD in studies examining children with dual diagnoses and SMD only or ADHD  
565 only suggesting that SMD and ADHD can be considered as distinct, but frequently  
566 cooccurring disorders.

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569

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769 Table 1: Inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
<ol style="list-style-type: none"> <li>1. Published in a peer-reviewed journal.</li> <li>2. Written in English language.</li> <li>3. Published between January 1980 and June 2020.</li> <li>4. Sample: Children under the age of 18 who:                             <ol style="list-style-type: none"> <li>a. Have a formal diagnosis of ADHD (through screening measure or clinical diagnosis)</li> </ol> </li> <li>5. Phenomenon of interest: Sensory modulation:                             <ol style="list-style-type: none"> <li>a. Sensory modulation refers to the ability of the central nervous system to regulate neural messages about sensory stimuli. Sensory modulation can be measured through caregiver reports, behavioural or physiological methods.</li> </ol> </li> <li>6. Design:                             <ol style="list-style-type: none"> <li>a. Quantitative study designs included.</li> </ol> </li> <li>7. Evaluation:                             <ol style="list-style-type: none"> <li>a. Outcomes of the studies must be reporting, measuring, evaluating or comparing sensory modulation within this sample.</li> </ol> </li> </ol>	<ol style="list-style-type: none"> <li>1. If not written in English language.</li> <li>2. Published before January 1980.</li> <li>3. Sample: Participants over the age of 18.</li> <li>4. Phenomenon of interest: Sensory modulation:                             <ol style="list-style-type: none"> <li>a. If the results of a sensory modulation measure are not included in the paper.</li> </ol> </li> <li>5. Design:                             <ol style="list-style-type: none"> <li>a. Systematic reviews, literature reviews, and qualitative studies will not be included.</li> </ol> </li> </ol>

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Table 2: Details of included studies.

First author	Sample	Recruitment and diagnosis	ADHD subtypes	Exclusion criteria/Presence of co-occurring disorders	Medication
Ben-Sasson et al. (2017)	922 children (aged 7-11)	Longitudinal birth cohort. Participants grouped into ADHD, SOR clusters based on scores on SOR and CBCL	Not considered.	Children excluded due to genetic disorders, developmental delays, low birth weight, prematurity.	Not considered.
Broring et al. (2008)	47 children with ADHD (mean age 9y 8m), 36 non-affected siblings (mean age 8y 10m), and 35 controls (mean age 9y 5m)	Recruited from the International Multicentre ADHD genes study (IMAGE). ADHD diagnosis supported by Conners Parent and Teacher ADHD rating scale, the Parent and Teacher Strengths and Difficulties Questionnaire and the Parental Account of Children's Symptoms.	All combined subtype.	Exclusion criteria were an IQ <70, diagnosis of autism, epilepsy, general learning difficulties (i.e. severe problems in multiple areas of academic learning), brain disorders, or known genetic disorders.	31 children with ADHD took stimulants, 3 took non-stimulants, and 2 took a combination of stimulants and non-stimulants. All children were off medication at least 48 hours before testing.
Cheung & Sui (2014)	1840 controls (aged 3-10), 72 children with ASD (aged 2.7-	Recruited from child and adolescent psychiatric units,	Not considered.	No information on co-occurring disorders.	Not mentioned.

Delgado-Lobete et al. (2020)	11.6), and 114 with ADHD (aged 4.8-12) 369 controls, 27 children with ADHD, 46 with DCD, and 10 co-occurring DCD and ADHD (all aged 6-12 years)	diagnosed based on DSM-IV criteria. Participants categorised as ADHD group based on ADHD-RS-IV scores.	Not considered.	Children with other neurodevelopmental or learning disorders were excluded.	Not mentioned.
Dunn & Bennett (2002)	70 children with ADHD (aged 3-15) and 70 controls (aged 3-15)	Diagnosed at clinic based on DSM-IV criteria.	Not considered.	23 children with ADHD had ODD, 1 had PTSD, 1 had adjustment disorder, 10 had learning disorders	52 children with ADHD were on medication. For 10 children, medication information was unknown.
Engel-Yeger & Ziv-On (2011)	29 children with ADHD (aged 6-10) - 15 hyperactive/impulsive and 14 inattention, 29 controls (aged 6-10)	Diagnosed by neurologists according to DSM-IV criteria and supported by Conners Parent and Teacher Rating Scales. Recruited from clinic.	15 children were hyperactive-impulsive, 14 children were inattentive	Participants were not receiving any medical treatment which impacted their nervous system and did not suffer from any other chronic health condition or uncorrected sensory loss.	No child used medication.
Ermer & Dunn (1998)	671 controls (aged 3-15), 38 children with autism (aged 3-15), and 61 children with ADHD (aged 3-15)	Diagnosed at University of Kansas ADHD clinic.	Not considered.	No information on co-occurring disorders considered.	Not mentioned.
Ghanizadeh (2008)	81 children with ADHD (aged 6-14)	Referred from outpatient clinic.	Subtypes included as variable in analysis.	Children with a diagnosis of autism,	Children were off medication for at

		Underwent Schedule for Affective Disorders and Schizophrenia for School-Aged Children (based on DSM criteria)		epilepsy, brain disorders or known genetic disorders were not included.	least 4 weeks prior to testing.
Ghanizadeh (2009)	104 children with ADHD (aged 6-14)	Referred from Child and Adolescent Psychiatry Clinic. Underwent Schedule for Affective Disorders and Schizophrenia for School-Aged Children (based on DSM criteria)	N=27 inattentive, n=11 hyperactive/impulsive, n=59 combined.	Children with neurological disorders, seizures, prematurity, history of meningitis, metabolic disorders, or a significant head trauma, and diagnosed hearing problem were not included.	No information provided.
Ghanizadeh (2013)	189 children with ADHD (aged 3.5-15 years)	Diagnosed based on DSM-IV criteria by psychiatrist.	Participants were scored on a hyperactive/impulsive scale and an inattention scale.	ODD and Anxiety symptoms were variables in the analysis. Children with neurological disorders, autism, epilepsy, Down Syndrome, or seizures were excluded.	No information provided.
Iyer et al. (2020)	20 children with inattentive-hyperactive	Categorised as inattentive-hyperactive based on	Inattentive-hyperactive symptoms treated as one group.	Children with a history of neurodevelopmental	Children on medication were excluded.

	symptoms and 56 typically developing children (aged 9-12 years)	Vanderbilt ADHD Diagnostic Parent Rating Scale and Teacher Rating Scale (based on DSM criteria)		diagnosis were excluded.	
Lane et al. (2010)	39 children with ADHD (aged 6-12), 46 controls (aged 6-12)	Underwent clinical evaluation with psychiatrist and/or record review. SensOR scores used to divide groups into ADHD only, typ only, ADHD+SOR and typ+SOR	Not considered.	Children with psychological diagnoses other than ADHD, significant motor impairments such as cerebral palsy, or any known endocrine or metabolic dysfunctions were excluded from this study.	No information provided on number of children taking medication. Parents were asked to withhold their child's ADHD medication (if applicable) for 24 h before testing.
Lin et al. (2013)	20 children with ADHD (mean age 8.64), 20 controls (mean age 9.1)	Referred from local clinic and diagnosed by child psychiatrist. Confirmed by Conners' Parent Rating Scale and occupational therapist.	Not considered.	Children with fragile X syndrome, autism spectrum disorder, mental retardation, Tourette syndrome, Down syndrome, orthopedic conditions, and mental-disorder-related diseases were excluded.	Use of medication was part of criteria for exclusion from the study.
Little et al. (2017)	788 controls, 77 children with ASD,	Information on diagnosis provided by	Not considered.	Children with autism, learning disabilities,	Information not included.

	96 children with ADHD (all aged 3-14)	parents and verified for 69% of sample using record reviews.		intellectual disabilities, and developmental delay included as separate groups in analysis.	
Little et al. (2018)	77 children with ASD, 78 children with ADHD, 84 controls (all aged 3-14)	Information on diagnosis provided by parents and verified for 70% of sample using record reviews.	Not considered.	Children were excluded if they had a dual diagnosis of ADHD and ASD.	No information provided.
Mangeot et al. (2001)	26 children with ADHD, 30 controls (all aged 5-13)	Referred from local clinics, identified by DSM-IV criteria - confirmed by ACTeRs, and attention, activity level, and impulsivity subscales of Leiter International Performance Scale Revised (parent report).	Not considered.	Possibility of co-occurring disorders not considered systematically.	13 children with ADHD taking medication. Medications were discontinued 24-48 hours before testing.
May Benson et al. (2020)	532 children with SPD, 97 children with SPD+ADHD (aged 4-12 years)	SPD diagnosed by occupational therapist; ADHD diagnosis based on parent disclosing previous diagnosis.	Not considered.	Some children in SPD+ADHD group had an additional diagnosis of ASD, LD, or anxiety (exact number not disclosed).	No information provided.

Miller et al. (2012)	70 children with SMD, 37 children with ADHD, 12 children with ADHD and SMD, 57 controls	Referred from local clinics. Diagnosed by clinicians.	Three subtypes collapsed and analysed as one group due to small sample sizes.	Excluded if diagnosis of fragile X, autism, mental retardation, Tourette's, Down Syndrome, orthopaedic conditions, or psychiatric diagnosis.	8 children with SMD, 17 children with ADHD and 3 children with ADHD+SMD were taking medication. Medications discontinued evening before testing.
Mimouni-Bloch et al. (2018)	38 children with ADHD, 39 controls (all aged 8-11)	Diagnosis given by paediatric neurologist.	Not considered.	Children with autistic spectrum disorders, physical disabilities, or neurological diseases were excluded from the study.	No information provided.
Parush et al. (2007)	67 children with ADHD, 60 controls (all aged 5-11)	Diagnosis of ADHD if met 8 of 14 criteria on DSM-IV and received scores above standardised cut-off for Conner's Rating Scale. Sorted into ADHD+TD or ADHD only based on scores from TIP and sensory reactivity score.	Not considered.	Sample showed no apparent physical or neurological deficits on the standard assessment protocol (Touwen, 1979).	Children must be free of medication for 1 month prior to testing in order to be included.
Pfeiffer et al. (2015)	20 children with ADHD, 27 controls (all aged 5-10)	Diagnosed by a paediatrician/health professional.	Hyperactive/impulsive scale and inattentive scale scores used in	Children with PDD or ASD diagnosis were excluded from study.	12 children with ADHD were taking medication.

Reynolds et al. (2010)	24 children with ADHD, 24 controls (all aged 6-10)	Diagnosis by psychologist or psychiatrist confirmed by parent. Recruitment of children with ADHD was done under the guidance of a licensed child psychiatrist.	analysis. Children were not grouped based on subtypes. Not considered.	Children with psychological diagnoses in addition to or other than ADHD, significant motor impairments such as cerebral palsy, or any known endocrine or metabolic dysfunctions were excluded from this study.	20 of the 24 children in the ADHDs (n=10) and ADHDt (n=10) groups were currently taking daily medication. Parents were asked to withhold their child's ADHD medication for 24 hr prior to their scheduled laboratory visit.
Shimizu et al. (2014)	37 children with ADHD, 37 controls (all aged 6-11)	Recruited from outpatient clinic, diagnosis confirmed by psychiatric, neurological, and neurophysiological evaluation.	N=8 inattentive, n=7 hyperactive, n=22 combined	N=32 children with ADHD had co-occurring indicators based on CBCL (n=13 affective disorder, n=13 anxiety disorder, n=5 somatic disorder, n=21 ODD, n=22 CD)	Children with ADHD taking medication were excluded from study.
Yochman et al. (2004)	48 children with ADHD, 46 controls (all aged 4-6)	Diagnosed by neuropaediatrician, confirmed by a score of >1.5 SDs above the mean on	Not considered.	Children with any other developmental, physical, sensory, or neurological disorder.	No information provided.

Yochman et al. (2013)	19 children with ADHD only, 19 children with SMD only (aged 6–9)	hyperactive and/or aggressive factors on both teacher and parent Preschool Behaviour Questionnaire ADHD: underwent interview by developmental neurologist, diagnosed according to DSM-IV criteria. SMD: evaluated by occupational therapist.	Not controlled for/considered.	Excluded children with additional physical and/or neurological deficits e.g. cerebral palsy, ASD	Not mentioned whether children taking medication.
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Note: SOR= sensory overresponsivity, ACTerS= ADD-H Comprehensive Teachers Rating Scale, PDD= Pervasive Developmental Disorder, ASD= Autism Spectrum Disorder, CBCL= Child Behaviour Checklist.

Table 3: Main results of included studies.

Study	Type of measure	Name of measure	Main result
Ben-Sasson et al. (2017)	Parent report	SensOR	Cluster analysis revealed an ADHD only cluster (n=38), an SOR only cluster (n=35), an ADHD+SOR cluster (n=35). 48% of those with elevated ADHD symptoms had elevated SOR and 50% of those with SOR had ADHD symptoms. The ADHD+SOR cluster could be differentiated from those with SOR only by their lower tactile scores. Both the SOR and ADHD+SOR groups showed high scores for auditory domain.
Broring et al. (2008)	Self-report	Tactile Inventory for Elementary School-Aged Children	Females with ADHD scored higher on TD than males with ADHD (p<0.002) and female controls (p<0.001). Males with ADHD did not differ from control males (p<0.91).

Cheung & Siu (2014)	Parent report	Sensory Profile (Chinese version)	<p>Overall, children with ADHD had higher TD than control children. 17% of females with ADHD had extreme scores on TIE, only 3% of males with ADHD.</p> <p>Sensory processing scores (of all 8 subscales on CSP) were significantly higher (i.e. better) for controls than ADHD group. Children with ADHD had lower scores (i.e. higher frequency in behaviour) than controls on 118 of 124 items on CSP. When looking at age, children with ADHD showed a significant increase in auditory processing issues and some increases on all subscales bar movement. Suggests that children with ADHD will likely experience a significant processing issue over childhood.</p>
Delgado-Lobete et al. (2020)	Parent report	Short Sensory Profile-2 (Spanish version)	<p>Children with ADHD showed higher scores (more atypical patterns) for all four sensory quadrants (according to Dunn's model) and sensory patterns than typically developing children.</p>
Dunn & Bennett (2002)	Parent report	Sensory Profile	<p>Statistically significant differences (<math>p &lt; 0.05</math>) on 118 of 125 items on SP - lower scores (i.e. higher frequency of issues).</p>
Engel-Yeger & Ziv-On (2011)	Parent report	Short Sensory Profile	<p>Differences in sensory processing performance were manifested among children with both ADHD subtypes relative to controls in most SSP scales - tactile, movement, under-responsive/seeking sensation, auditory filtering, low energy/weak - with values under typical performance range.</p>
Ermer & Dunn (1998)	Parent report	Sensory Profile	<p>Children with ADHD were best discriminated by high incidences of behaviours in Factor 1 (sensory seeking) and Factor 5 (inattention/distractability) and low incidences of behaviours in Factor 4 (oral sensitivity) and Factor 9 (fine motor/perceptual). The incidence or frequency of sensory seeking behaviours may be markedly higher in children with ADHD.</p>

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Ghanizadeh (2008)	Parent report	Tactile Dysfunction Checklist	ADHD subtypes were not found to be associated with hypersensitivity or hyposensitivity scale scores. No differences found in terms of gender.
Ghanizadeh (2009)	Parent report	Auditory Dysfunction Checklist	HES (hypersensitivity) and HOS (hyposensitivity) was not different between ADHD subtypes. ADHD subtype does not appear to be a predictor of auditory dysfunction. No gender differences were found.
Ghanizadeh (2013)	Parent report	Oral Over- and Underresponsivity Behaviours Inventory	ADHD severity did not predict oral overresponsivity. Impulsivity/hyperactivity score did not predict oral underresponsivity, but inattention score did.
Iyer et al. (2020)	Parent report	Sensory Profile	Inattentive-hyperactive group showed significantly lower scores for sensory seeking quadrant only, compared to typically developing group.
Lane et al. (2010)	Parent report and physiological measure	SensOR, Sensory Challenge Protocol	ADHD only group differed from ADHD+SOR group on all domains of SensOR (tactile, auditory, taste, smell, visual, movement). Children with ADHD+SOR differed from typical controls in their ability to recover from the sensory challenge - showed high arousal levels during recovery. While group differences were not significantly different, ADHD+SOR had higher cortisol levels than other groups at measurement points other than baseline.
Lin et al. (2013)	Parent report and physiological measure	Sensory Profile, Sensory Challenge Protocol	Z-scores on the Sensory Profile were significantly lower (more problems) for the ADHD group on all but three subtests (sensory sensitivity, tactile defensiveness, and oral sensory sensitivity). No significant differences in EDR mean magnitude between the two groups.
Little et al. (2017)	Parent report	Sensory Profile 2	Divided participants into 5 sensory subtypes - Balanced (53% of ADHD) low frequency of sensory behaviours, Interested (13.5%) increased sensory seeking, Intense (10.4%) may be averse to many experiences but also difficulty registering, Mellow until... (10.4%) increased

Little et al. (2018)	Parent report	Sensory Profile 2	<p>scores in avoidance and registration, Vigilant (12.5%) increased sensitivity and avoidance.</p> <p>ADHD group were significantly different on all sensory systems than control group (<math>p &lt; 0.001</math>) - with ADHD group showing higher scores (i.e. greater difference).</p>
Mangeot et al. (2001)	Parent report and physiological measure	Short Sensory Profile, Sensory Challenge Protocol	<p>ADHD group showed significantly lower scores on 6 of 7 subscales (bar movement sensitivity) on Short SP. There was a trend for a significant difference by group in EDR, with ADHD group showing greater reactivity for sensory stimuli (<math>p &lt; 0.056</math>).</p>
May Benson et al. (2020)	Parent report	The Koomar Center Developmental/Sensory History	<p>Children with SPD only and children with SPD+ADHD did not significantly differ in terms of their gravitational insecurity scores.</p>
Miller et al. (2012)	Parent report and physiological measure	Short Sensory Profile, Sensory Challenge Protocol	<p>Children with a Dual Referral had significantly poorer raw scores compared to ADHD children (<math>p &lt; 0.01</math>) and SMD children (<math>p &lt; 0.02</math>) on the Seeks Sensation subtest. Children with a Dual Referral also had significantly poorer raw scores than ADHD children on Tactile, Visual/Auditory, Low Energy/Weak, and Movement subtests (at least <math>p &lt; 0.05</math>). ADHD+SOR group excluded from analysis of EDR as only <math>n=6</math> completed SCP. EDR magnitudes greater for SMD children than ADHD children to auditory, visual, and movement stimuli. No differences in EDR magnitude between ADHD and typ. dev. children in any domain.</p>
Mimouni-Bloch et al. (2018)	Parent report	Short Sensory Profile	<p>SSP total score was significantly lower than controls (and true for all subtests). The largest effect sizes were observed in auditory filtering and seeks sensation. In the ADHD group, 65.8% of children had atypical SSP performance range, only 2.6% of controls did.</p>

Parush et al. (2007)	Parent report, behavioural, and physiological measure	Touch Inventory for Preschoolers, Sensory reactivity score, Somatosensory Evoked Potential	ADHD group divided into 2 subgroups: TD+ (n=46) and TD- (n=21) based on TIP and Sensory Reactivity scores. 69% of ADHD group met TD criteria based on TIP score. ADHD+TD+ group distinguishable from ADHD+TD- group and control group by larger central SEP amplitudes (N13, N20, P23).
Pfeiffer et al. (2015)	Parent report	Sensory Processing Measure	For each subscale of SPM, children with ADHD had a higher mean score (i.e. more problems) than controls. Subscales are social, visual, hearing, touch, body, balance, and planning. 64% of ADHD group scored in range of "some problems" or "definite dysfunction", compared to less than 5% of controls who scored in range of "some problems". 0 controls scored in range of "definite dysfunction".
Reynolds et al. (2010)	Parent report and physiological measure	SensOR, Sensory Challenge Protocol	13 of ADHD group had SensOR score 2 SDs above mean for at least 1 subscale. 62% of children in ADHDs group had tactile OR and 54% had auditory OR. There was a borderline significant difference between ADHDs and ADHDt groups on SCP (p=0.056), and a significant difference between ADHDt (blunted) and typical groups (p=0.014). No significant difference between ADHDs and typical group (p=0.934). Effect sizes also generally small between ADHDs and typical group.
Shimizu et al. (2014)	Parent report	Sensory Profile	Significant differences found between ADHD and control groups on 11 of 14 SP sections (bar oral processing, modulation of movement affecting activity level, and modulation of visual input affecting emotion/activity level). Also significant differences between groups on 7 of 9 SP factors (bar oral sensitivity and sensory sensitivity). No significant differences found between ADHD subtypes on

Yochman et al. (2004)	Parent report	Sensory Profile	<p>sections or factors expect multisensory - combined scored lower than hyperactive or inattentive.</p> <p>ADHD group had significantly lower scores on 6 of 9 factors (not low endurance-tone, poor registration, and sensory sensitivity) and 11 of 14 sections (not vestibular processing, endurance-tone, or emotional responses). Between 6.5-15% of controls had deficits on various factors and 4-11% for sections. In contrast, 12.5-65% of ADHD group had deficits on factors and 8-65% for sections.</p>
Yochman et al. (2013)	Parent report and behavioural measure	Sensory Challenge Protocol, Evaluation of Sensory Processing Questionnaire, Fabric Prickliness Test, von Frey Monofilament Test (Pin prick)	<p>Significant differences were found between the groups on the overall Von-Frey filament test score (<math>Z = -2.24</math>; <math>p = 0.026</math>). The children with SMD reported higher scores as a response to punctate pain (median = 60) compared to children with ADHD (median = 30). Significant differences were found between the groups in the level of pain elicited by the application of the fabrics (<math>Z = -2.367</math>; <math>p = 0.018</math>), such that children with SMD reported higher scores (median = 16) compared to children with ADHD (median = 4). In addition, significant group differences were found in the measures of pain “after-sensation” (<math>Z = -2.803</math>; <math>p = 0.005</math>). After the application of the last fabric of the FPT, the after-pain sensation in children with SMD lingered longer (median = 2 min, 15 s) than the children with ADHD (median = 15 s). The results indicate that the scores for the SMD group were significantly lower than the scores of the ADHD group in three of the six subtests (i.e., taste and smell, tactile and motion /vestibular) on ESP.</p>

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Notes: SOR= sensory overresponsivity, TD= tactile defensiveness, EDR= electrodermal response.

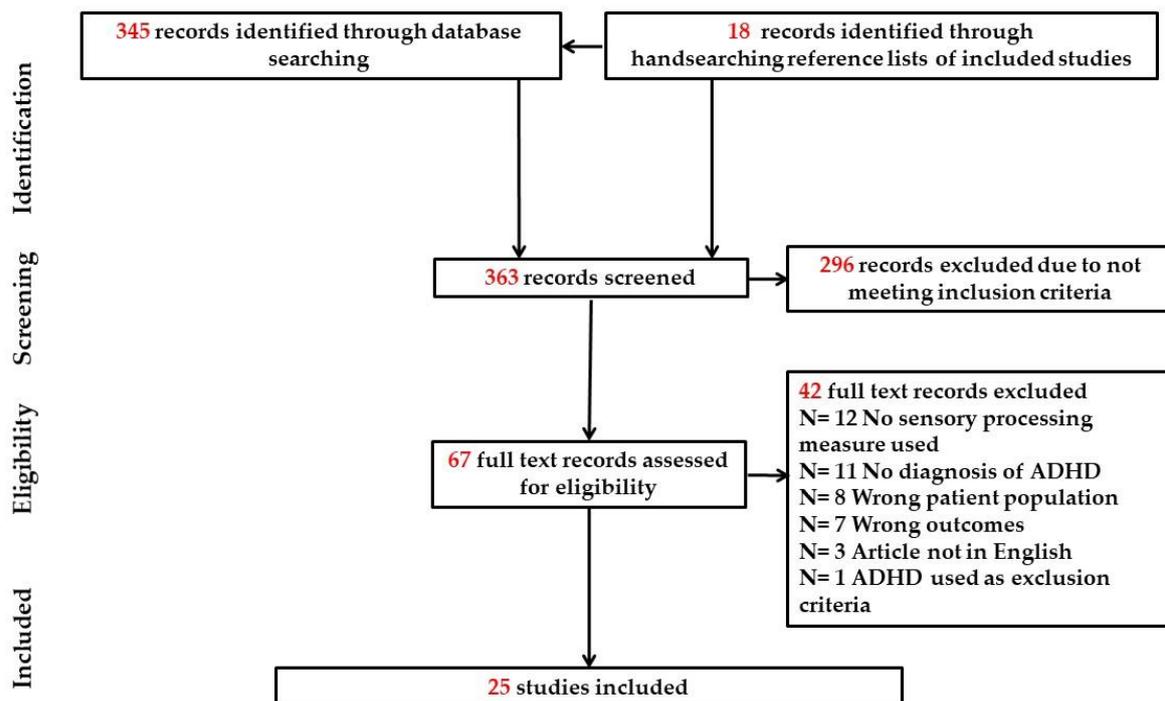


Figure 1: PRISMA flow diagram of study selection.

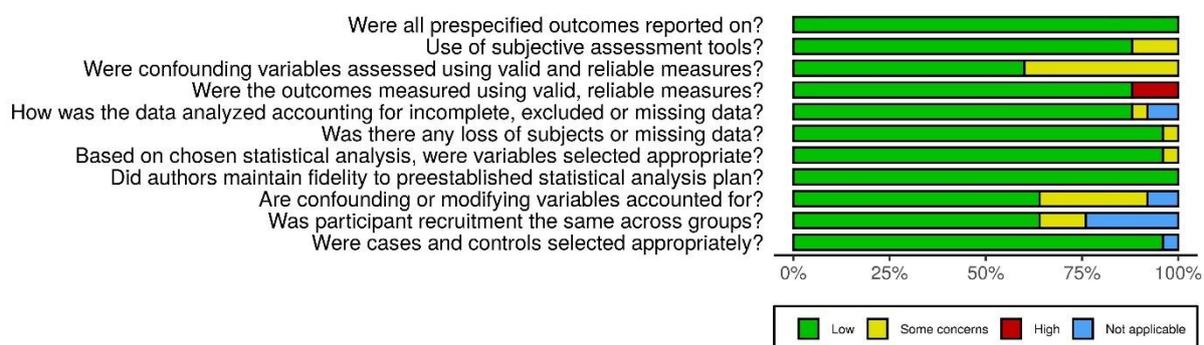


Figure 2: Risk of bias summary.