Tactile sensory processing as a precursor of executive attention: Toward early detection of attention impairments and neurodevelopmental disorders

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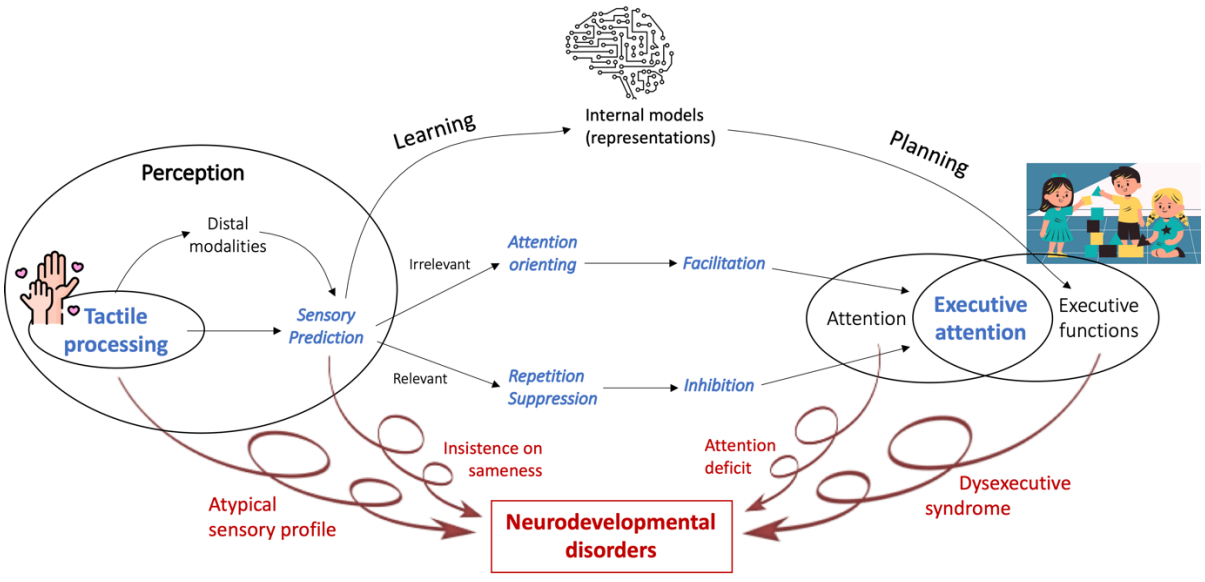
Abstract

Recent studies in developmental neuroscience tend to show the existence of neural attention networks from birth. Their construction is based on the first sensory experiences that allow us to learn the patterns of the world surrounding us and preserve our limited attentional resources. Touch is the first sensory modality to develop, although it is still little studied in developmental psychology in contrast to distal modalities such as audition or vision. Atypical tactile sensory processing at an early age could predict later attention dysfunction, both of them being part of the symptomatology of neurodevelopmental disorders (NDD). We review the state of knowledge on tactile sensory processing and its links with attention, executive attention in particular, and propose that abnormal tactile sensory processing at an early age could provide markers of executive attention dysfunctions, contributing to the early detection of NDD.

Graphical/Visual Abstract and Caption



Tactile sensory perception at an early age could predict the quality of executive attention development and thus provide new leads for the early detection of neurodevelopmental disorders.

1. Introduction

Humans first experience the world through sensory perception, long before birth. During the first weeks of life, sensory perception is actively used by the newborn and infant to make sense of the world, building the first cognitive processes. The tactile modality is the first sense to develop and is the foundation of sensory development (Bremner & Spence, 2017). According to the neuroconstructivist framework, early sensory experiences constrain the construction of brain networks which develop considerably during the first years of life (Karmiloff-Smith, 2009). Variability in perceptual skills at an early age, therefore, affects neural networks underlying attention systems (Rohr et al., 2018) and predicts later cognitive development (Bertenthal & Longo, 2002). Atypical sensory profiles, particularly affecting somesthetic senses, are a frequent feature of neurodevelopmental disorders (NDD) (Cascio, 2010).

Executive attention (EA) is a cognitive construct part of the three attentional networks modelized by Posner and Petersen (1990) and necessary to executive functions (EF), formed by different cognitive processes like inhibition and interference control, cognitive flexibility, and updating in particular (Diamond, 2013). There is increasing interest in the early development of EF because they are critical for school achievement, and because executive impairment is also a common feature of NDD (Ozonoff & Jensen, 1999).

NDD are characterized by developmental impairments in cognitive, motor, affective and social skills. They include various disorders such as attention-deficit/hyperactivity disorder (ADHD), autistic spectrum disorder (ASD), communication disorders (CD), intellectual disability (ID), learning disabilities (LD), and motor disorders (MD). A systematic review by Francés et al. (2022) reports the following worldwide incidence rates: ADHD, 5–11%; ASD, 0.70–3%; CD, 1–3.42%; ID, 0.63%; LD, 3–10%; and MD, 0.76–17%. In European countries such as Spain, the study of Bosch et al. (2021) reports the following incidence rates: ADHD, 9.92%; ASD, 0.70%; CD, 1.05%; ID, 0.63%; LD, 10.0%; and MD, 0.76%. In the United States, the data show an increase in the overall prevalence of disorders between 2014 and 2016 (Zablotsky et al., 2017). The authors also point out the variability of prevalence rates depending on the pathology, the population, and also on the resources available to clinicians for diagnosis.

One of the global public health challenges is to better understand the emergence of NDD to propose early detection and remediation programs (Ozonoff, 2015). Although there is extensive knowledge of the many environmental risk factors for NDD (Arpino et al., 2010; De Felice et al., 2015; Martens & van Loo, 2007) abnormal brain development is often reported as a vulnerability to these subsequent risk factors and precedes clinical impairment (Jeste, 2015). We propose that atypical tactile perception at an early age puts children at risk of developing atypical attention, evolving into dysexecutive syndromes at a later age, these deficits being aspects of the same pathological process in NDD. We review research on tactile sensory processing and EA in young children and consider new research paradigms integrating these two components to provide new markers of EA deficit. Such markers could be used for the early identification of children at risk of EF NDD and other cognitive impairment, and to design new early interventions.

2. SOMATOSENSORY PROCESSING IS THE FOUNDATION OF COGNITIVE DEVELOPMENT

The somatosensory system collects all the information that we receive from our tactile skin receptors (touch, pain, temperature) and proprioceptive receptors in joints and ligaments (head and body position and movement). Touch is the first sensory modality to develop and the first sensations we experience are tactile (Bremner & Spence, 2017). As early as 7 weeks of gestation, the first tactile receptors are mature and somatosensory functions quickly follow. Touch is considered the foundation upon which other perceptive, cognitive, motor and affective functions develop (Ardiel & Rankin, 2010; Lickliter, 2011; Dumont et al., 2018). Because of this sensory scaffolding function, touch is believed to play a critical role in attachment (Weiss et al., 2000) and early sensory-motor development (Fearon et al., 2002), the representation of our own body in space (Serino and Haggard, 2010), and to be the precursor of verbal communication (Hertenstein et al., 2006). A recent review of the importance of touch for all aspects of development can be found in Cascio et al. (2019). Despite the relevance of tactile processing for understanding both typical and pathological developmental courses, early somatosensory development remains poorly exploited in developmental cognitive science, compared with the later-developing modalities of audition and vision. In this section, we address how somatosensory processing, and particularly prediction, is related to attention development.

2.1. Somatosensory processing and prediction

One of the fundamental mechanisms of cognitive development is sensory prediction. The brain constantly extracts information from its environment to develop internal mental models that will serve to predict future sensory inputs (Friston, 2005). Predictions optimize our cognitive and behavioral resources by anticipating changes in our environment and preparing appropriate responses, resulting in a cognitive and motor economy (Schubotz, 2015). The infant's brain is highly predictive from a young age and prediction guides sensory processing and learning (Baek et al., 2020). From the age of 2 months, infants can anticipate the caregiver's actions, for example when being picked up, and adjust their posture to enter into interaction (Reddy et al., 2013). In a recent study, Dumont et al. (2022) showed that premature neonates can predict a tactile stimulus and that the somatosensory cortex activity is modulated according to the temporal regularity of the stimulation sequence, similar to what has been described in adults (van Ede et al., 2014). Somatosensory representations support body representations (Bremner & Spence, 2017), therefore, they are critical for the development of motor planning and motor control (Assaiante et al., 2014). Sensory prediction then develops in distal modalities such as auditory in 6-months-olds (Emberson et al., 2019) and visual in 12-months-olds (Kouider et al., 2015). Impaired tactile prediction may thus impair both sensory prediction in later developing distal modalities and motor development. In support of this hypothesis, experimental data show that performance in motor control and executive skills such as inhibition and working memory are related in infants (Gottwald et al., 2016), and therefore, may rely on common processes early in life. Indeed, anticipating a stimulus regulates its processing, be it enhancement or suppression depending on the stimulus' relevance (Summerfield et al., 2008), and this process forms the basis of attention, the ability to select and filter relevant sensory inputs depending on context and goals.

2.2. Prediction and executive attention

Attention commonly refers to a state in which we have a level of concentration that allows us optimal filtering of information from the environment (Conejero & Rueda, 2017). During the first months of life, the salience network (SN), consisting of the dorsal anterior cingulate cortex and anterior bilateral insulae (Ham et al., 2013) supports the development of exogenous attention, captured by salient stimuli in the environment, such as being touched. The SN partially overlaps with the alerting and orienting attention networks (Uddin, 2016), as they

were described by Posner and Petersen (1990). Alerting and orienting attention develop first, then they serve as the foundation for endogenous attention, controlled by the subject and directed towards relevant but not salient stimuli. This latest form of attention is called executive attention (EA). The successive development of attention networks (alerting, orienting, and executive attention networks) during the first years of life is associated with behavioral improvements in tasks involving executive functions (EF) such as inhibition of distractors (Holmboe et al., 2008) and tasks combining executive and motor control such as reaching for a hidden object (Diamond, 1990).

EA and EF are related constructs. EA is associated with the fields of attention and cognitive psychology and designates mechanisms that enable regulation between our perceptions and our actions (Rueda et al., 2021). EF is associated with the field of neuropsychology and refers to top-down control mechanisms involved in the modulation of our thoughts and actions when automatic processes are not sufficient. EA is a component of inhibitory control in Miyake's model of EF (Miyake & Friedman, 2012), but it is also a component of Self-Regulation (SR) in Diamond's model (Diamond, 2013). SR is an internal process that allows us to regulate our thoughts, emotions, and behaviors to overcome an internal conflict (Nigg, 2017). Although these models of adult cognition and neuropsychology consider EA as a part of EF or SR, from a developmental standpoint they should be conceived differently. The literature on young children shows that EF and SR are in fact overlapping constructs and that EA is a distinct and earlier process serving as the developmental foundation for the development of these two functions (Garon et al., 2008; Tiego et al., 2020). EA promotes EF and SR by allowing the child to control what sensory information is being processed. It enhances or dampens processing based on contextual or goal-related relevance (Kok et al., 2012), and predictions that were built through previous experience (Bubic et al., 2010). Johansson et al. (2015) confirmed that sustained attention at 1 year of age is predictive of EF and SR at 2 years.

In this section we described why somatosensory prediction is a precursor of multisensory prediction, which allows exogenous forms of attention to emerge and scaffold the development of executive attention, which in turn serves as a developmental step toward SR and EF, fostering learning and higher order cognition. Individual differences in EA appear in early infancy and remain stable across childhood (Johansson et al., 2015), and children with greater EA efficiency have better understanding and performance in school, which promotes academic success and well-adjusted behaviors in the classroom (Blair & Razza, 2007). Therefore, it is important to understand individual differences in the earliest foundations of EA such as

prediction, and this can be achieved in the youngest babies by using the somatosensory modality. In the following section, we review how the constructs discussed above are affected in NDD.

3. SENSORY IMPAIRMENTS AND EXECUTIVE ATTENTION DEFICITS AT THE CORE OF NEURODEVELOPMENTAL DISORDERS

The prevalence of NDD in western countries is increasing (Elsabbagh et al., 2012; Zablotsky et al., 2017). Many factors – genetic, perinatal, and environmental – are involved in the etiology of NDD, and some tend to increase, such as environmental pollution or late pregnancies, which could play a role in this phenomenon. Among them, one possible explanation is that improvements in neonatal intensive care reduce mortality rates in prematurely born children whereas preterm birth is a high-risk factor for atypical neurodevelopment, especially in very preterm infants (<32 weeks) (Ancel, 2009). Cohort follow-up studies such as Epipage-2 in France or Epicure in the UK report increased developmental deficits in a variety of domains: cognitive, motor alterations, and socio-emotional problems which are later expressed in heterogeneous patterns (Twilhaar et al., 2021). Sensory profiles and EF deficits in the preterm population, even without NDD diagnosis, are similar to those found in children diagnosed with NDD regardless of birth status, suggesting common pathological processes in these two populations for these particular domains (Bröring et al., 2017). In this section, we discuss the sensory and executive aspects of NDD symptomatology and how somatosensory processing impairments may be early precursors of attention and executive deficits in NDD trajectories.

3.1. Somatosensory impairments in neurodevelopmental disorders

NDD symptomatology frequently involves atypical sensory processing or modulation, particularly in the tactile modality (Cascio, 2010). Tactile defensiveness, *i.e.*, hyperreactive or aversive reactions to innocuous tactile stimulations, is often reported in ASD, Tourette's syndrome, and ADHD.

In boys with ADHD, Parush et al. (2007) found that tactile defensiveness is associated with deficits in finger discrimination and larger somatosensory evoked potentials (SEP) on the electroencephalogram (EEG). The authors suggest it results from an impaired inhibition of the cortical processing of tactile inputs.

In children with ASD, Tomchek and Dunn (2007) used Dunn's Sensory Profile, a questionnaire designed to quantify sensory processing in different modalities in everyday situations (Dunn & Brown, 1997). Completed by a caregiver, it provides a basis for assessing the impact of sensory processing on the child's performance and quality of life. They found that 95% of children with ASD have sensory processing dysfunction, with greater differences in under-responsiveness or sensory-seeking behaviors, auditory filtering, and tactile sensitivity. Recently, Espenhahn et al. (2021) found that the N140 response, a component of SEP, had a lower amplitude and shorter latency in children with ASD. As for ADHD, the authors propose that an imbalance between excitation and inhibition in the brain underlies these observations. This is consistent with observations in mouse models of ASD: genetic alterations linked with ASD in some human patients cause alterations in mechanoreceptors, leading to impairments in inhibition of peripheral somatosensory neurons in mice (Orefice et al., 2016). This results in impaired tactile discrimination and sensitivity, provoking anxiety and aberrant social behaviors when mice grow up. In parallel, human studies of children and adolescents with ASD revealed overactivation of the neural salience network, suggesting an overinvestment of attentional resources in favor of basic sensory processing (Green et al., 2016). Sensory overload would not allow for investment in social interactions with others and would favor more rigid routines. Hence, tactile processing impairment is not a correlate but a precursor of other autistic symptoms. It is interesting that this seems specific to NDD and not to all behavioral issues: Mammen et al. (2015) found that tactile avoidance in 9 months old infants was not predictive of emotion regulation deficits (neither internalizing nor externalizing symptoms) at 18 months, but was predictive of pervasive developmental disorders symptoms.

In the recent paper by Espenhahn et al. (2021), it was particularly interesting that differences in SEP correlated with parent-reported tactile reactivity in both ASD and typical children, supporting a dimensional approach to NDD and their somatosensory precursors. Even before the age of a possible diagnosis, abnormal sensory profiles are also more prevalent in children at high risk of NDD because of premature birth (Wickremasinghe et al., 2013). In addition to untimely stress on all physiological systems, first sensory experiences are modified due to the premature rupture with the intrauterine environment. Tactile stimulation is altered by the medical environment and care protocols (blood sampling or punctures for example) that impair sensory integration (Dumont et al., 2018). Chorna et al. (2014) showed that in children born before 30 weeks of gestational age, sensory reactivity was abnormal at the age of 24 months. Responses to tactile deep pressure and vestibular stimulation were most frequently affected, as

confirmed by (Crozier et al., 2015). Longitudinal studies of preterm neonates showed that sensory processing was predictive of later cognitive development and the onset of ASD symptoms from the age of two years (Vlaeminck et al., 2020). In very preterm neonates, lower tolerance of handling at birth was associated with tactile sensitivity and poorer executive functioning at 4 years (Meether et al., 2021).

Sensory processing impairment, and particularly somatosensory, is a common feature of the symptomatology of children with NDD, mainly ASD and ADHD, and of children at high risk of NDD such as prematurely born infants. We now need to address the mechanisms mediating the relationship between somatosensory processing and NDD, taking into account the variety of syndromes. EEG studies in ADHD show increased SEP amplitude (Parush et al., 2007), whereas in ASD they found decreased amplitude and shorter latency (Espenhahn et al., 2021). The discrepancy may come from other aspects of the stimulation, such as varying attentional demands exerting opposite effects on somatosensory processing depending on the disorder. In the previous section, we described how somatosensory prediction is the first building block of attention, the core mechanism of EF. Comparing SEP in ADHD and ASD patients for either expected or unexpected auditory stimuli, Gonzalez-Gadea et al. (2015) observed opposite frontal responses: ASD patients had increased frontal activity to expected stimuli and reduced activity to unexpected stimuli, whereas ADHD patients exhibited the opposite pattern. In other words, ASD patients dedicated more attention to predictable events, while ADHD patients favor unpredicted events. Both disorders build atypical attentional processes on atypical sensory processing but in different ways. This is consistent with differences in executive functioning observed in these populations as they grow up.

3.2. Executive and attention deficits in neurodevelopmental disorders

EF and attention impairments partially overlap across the various NDD (Otterman et al., 2019). Executive dysfunction has been demonstrated in ASD, mainly poor cognitive flexibility, for example using the Wisconsin Card Sorting Test (WCST) and its version for preschool children, the Dimensional-Change Card-Sort task (DCCS) (Dichter et al., 2010), but also planning difficulties (Hill, 2004). Shifting and planning impairments explain the insistence on sameness that leads to highly distressing situations for children with ASD and their families. Authors proposed that attention deficits would be the underlying cause of EF deficits in ASD patients, but also the cause of their difficulties in processing social information in all sensory modalities.

The Attention Network Test (ANT) is designed to assess the efficiency of Posner's attention networks and was adapted for children by Rueda et al., (2004). Using the ANT, Mutreja et al. (2015) found that children with ASD had specific impairment in orienting and executive attention, not alerting. Imaging studies showed that attention performance in ASD may be sustained by compensatory mechanisms in alternate brain networks (Vaidya et al., 2011), resulting in a coupling between orienting and executive attention in ASD patients (Keehn et al., 2010), whereas these networks are independent in typically developing children. As a consequence of the chronology of the development of attention networks, the orienting impairment in ASD causes a secondary impairment in EA, resulting in EF deficits. ADHD on the other hand is by definition an attention deficit, reflected in inhibition deficits, for example tested by Go/No-Go or stop signal tasks (Senderecka et al., 2012), and everyday difficulties in behavioral regulation and learning (Barkley, 1997). Using the ANT, Fabio and Urso (2014) described a specific EA impairment in children with ADHD compared with controls, but also compared with children with low attention without ADHD in routine screening questionnaires, confirming that EA deficit is a specific marker of NDD, not any developmental difficulty. It is important to note that attention deficits in ADHD also impair performance in task-switching (Rauch et al., 2012) and that 30% of children with ASD also present comorbid ADHD, cumulating flexibility and inhibition impairments (Craig et al., 2016). Children who have poorer EF when they start first core learnings in kindergarten are at greater risk for learning difficulties in elementary school (Morgan et al., 2019), compromising later academic success. LD are frequently comorbid with ADHD but can be expressed distinctly (Mayes et al., 2000). Consistent with the link between motor and executive development, resulting from their common foundations in somatosensory processing, children with developmental coordination disorders or other motor difficulties also have poorer performance on executive tasks (Leonard et al., 2015). The heterogeneity of symptoms among patients with the same disorder, the frequent co-morbidity of NDD in the same patient, and the overlap of symptoms among NDD, strongly suggest they have common organic etiological factors and physiopathological pathways (Taurines et al., 2012). These issues make early NDD detection and diagnosis a challenge when we consider each syndrome separately, but represent an opportunity if we assume a cross-syndromic approach and search for the early, sensory foundations of attention deficits. The neural mechanisms involved in atypical information processing in these populations are still poorly understood yet they could provide relevant information for developing appropriate therapeutic approaches.

Efforts to prevent NDD in high-risk populations, such as premature neonates, highlighted the high prevalence of dysexecutive syndromes and attention impairments in these children (Johnson & Marlow, 2011; van de Weijer-Bergsma et al., 2008). Even in the absence of a diagnosed NDD, children who were born preterm tend to perform lower on attentional and executive tasks such as problem-solving, cognitive flexibility, inhibitory control, or processing speed tasks (Hodel et al., 2017). Inhibitory control at 20 months predicts attentional abilities and school performance at 8 years of age and is particularly impaired in very premature babies (Jaekel et al., 2016). Studies using the ANT in children who were born preterm but were not diagnosed with NDD showed a significantly higher correlation between the orienting and executive networks (Pizzo et al., 2010), similar to what was reported in children diagnosed with ASD (Keehn et al., 2010).

Adams et al. (2015) found that in preschool children born prematurely, sensory symptoms measured using the Short version of Dunn's Sensory Profile were associated with lower working memory and inhibition in a battery of EF tasks and a parental hetero-questionnaire, the Behavior Rating Inventory of Executive Functions – Preschool version (BRIEF-P).

Cognitive training programs at preschool age have shown positive effects in children without pathology (Rueda et al., 2012) and seem to alleviate the symptoms of children with ADHD (Vibholm et al., 2018). However, the long-term effects of these programs and their generalization to everyday situations are still controversial. For this reason, we need to better understand the early basis of atypical developmental trajectories, to target appropriate processes for remediation. Considering that NDD share common impairments in attention yielding overlapping executive symptoms, and that attention develops from sensory prediction processes of which somesthesis is the earliest foundation, can somatosensory processing be used as a marker of a patient's vulnerability to any NDD, and a target for early intervention?

4. PERSPECTIVES FOR EARLY MARKERS AND SCREENING TOOLS

In the second section, we described a developmental process leading from somatosensory prediction to multisensory prediction, to successive forms of attention of which the latest, EA, supports EF. In the third section, we described common impairments in EF across NDD and in a population at high risk of NDD, prematurely born children, and the link between EF deficits and EA deficits in these populations. The chronology we presented explains why screening tools focusing on NDD symptoms are ineffective in very young children: clinical symptoms

build upon other deficits that are not syndrome-specific. In this section, we present efforts being made to provide better markers and early screening tools using a cross-syndromic approach, and we offer new perspectives on how to use tactile sensory processing as the earliest cognitive marker to detect a risk of NDD in vulnerable babies.

4.1. Assessing early executive functions and executive attention

For many years, researchers have proposed tools to measure EF in preschoolers, such as a modified Stroop with animals instead of words (Wright et al., 2003), and many of them are now part of standard evaluation batteries in clinical practice. Through new tasks suitable for very young children and the contribution of neuroimaging techniques, we are getting a better understanding of EF and their underlying brain substrates from the end of the first year of life until the preschool period, even before children can give verbal responses (Fiske & Holmboe, 2019). Holmboe et al. (2008) developed the Freeze-Frame task, to assess inhibitory control during infancy and childhood. This visual inhibition task requires inhibiting peripheral visual distractors around a central animated stimulus. Performance on this task at 9 months predicts later success at 24 months of age. In continuity with this work, Holmboe et al. (2021) proposed a new task to measure inhibitory control during toddlerhood, the early childhood inhibitory touchscreen task (ECITT). In this task presented on a touchscreen, participants have to press the button presenting a happy face, a rewarded location. Sometimes, the happy face is presented in the other location and it requires toddlers to inhibit the prepotent location to give the correct response. Through accuracy and reaction times in the different conditions, this task provides information about inhibitory control development and can also be used from around 9 months of age. There is currently no data on how sensitive these new EF tasks are to NDD risk. Future studies should aim at comparing EF emergence in toddlerhood with other markers of risk and long-term outcome.

The use of computerized play tasks is also a promising way to better understand the early stages of EA development by combining behavioral and cerebral measures in very young children (Berger et al., 2000). The ANT, designed to assess the efficiency of the three attention networks in adults, was adapted for children to better understand the early development of EA in particular from the age of 6 years (Rueda et al., 2004). The participant must determine the direction of a central stimulus (left or right) presented between distractors (“flankers”) by pressing buttons on a keyboard. This task involves inhibiting the flankers’ information when it

is incongruent with the target, but other parameters such as valid or invalid spatial cues also allow the assessment of alerting and orienting attention. Using the ANT, Rueda et al. (2012) showed EA improvement in 5-year-olds after several sessions of computerized attention training. Recently, a version of the ANT was proposed for even younger children, from 3 years of age (Casagrande et al., 2022). In this version, the target information is not the direction of the central animal but its color, flankers having opposite colors. It will be interesting to see in the future how this new EA assessment applies to NDD screening and relates to other aspects of development, notably sensory processing.

4.2. Tactile sensory processing as an early marker of EA deficit and NDD vulnerability

Developmental cognitive research has recently focused on the theoretical framework of predictive coding (see Box) to explain NDD symptomatology. Authors proposed for example that impaired prediction abilities may be at the core of ASD, explaining repetitive behaviors, planning deficits, and insistence on sameness (Palmer et al., 2017; Sinha et al., 2014; Van de Cruys et al., 2014). Children with ASD would have more difficulty adjusting to their environment and perceiving its regularities, and symptoms would reflect attempts to control or compensate for an unpredictable environment. Using a bimodal auditory-visual paradigm and functional brain imaging, Emberson et al. (2017) showed that 6-months old infants who were born preterm showed a reduced occipital response to predicted visual stimuli, suggesting that prediction impairment may be an early marker of high risk of NDD. As mentioned in section 3.1, Gonzalez-Gadea et al. (2015) observed opposed patterns of response enhancement in the brains of ASD and ADHD patients based on stimulus predictability. The nature of prediction deficits in NDD is debated (Van de Cruys et al., 2014) and beyond the scope of this article, but authors agree on the importance of sensory prediction for the development of attention, and the feedback role that attention plays in regulating sensory processing once the child transitions from externally directed attention towards endogenous, *i.e*. executive, attention. In babies, when a stimulus is perceptually salient, it attracts attention regardless of relevance. As EA comes into play, when a task requires sustained attention to a stimulus, it is made salient by internal top-down processes and the response is enhanced, whereas when attention is not required the response is dampened (Kok et al., 2012). Early in life, sensory processing scaffolds the development of attention through predictive mechanisms, and later, attention in turn regulates sensory processing.

Since the earliest sensory modality is tactile, and because tactile processing is specifically affected in NDD and preterm neonates, the time has come to search for early somatosensory processing markers of neurodevelopment. Rational and positive tactile stimulation is increasingly considered in neonatal intensive care units as a tool that provides many benefits to vulnerable neonates: improved physiological constants, shorter hospital stays, faster weight gain, and more favorable overall motor and cognitive outcomes (Field et al., 2004; Ardiel & Rankin, 2010). For example, multiple "therapeutic touch" interventions are an essential component of the widespread Neonatal Individualized Developmental Care Assessment Program (NIDCAP) (Diego et al., 2009). These approaches do not specifically target one type of processing in particular, although they probably address the need for predictability implicitly: massage and caresses are naturally rhythmic interactions.

Recent studies focused more directly on the question of somatosensory prediction and regulation of somatosensory processing based on temporal parameters in premature neonates. Dumont et al. (2017) showed that neonates born more premature and with smaller birth weight, and therefore more at risk of NDD, had less efficient habituation to tactile stimuli at 35 weeks of corrected gestational age. In a follow-up study, they showed that somatosensory cortex activation is modulated according to the temporal regularity of the stimulation sequence as early as 33 weeks of gestational age (Dumont et al., 2022). This suggests that atypical tactile sensory regulation could allow us to identify neonates at risk of an atypical developmental trajectory and perhaps deploy very early sensory intervention methods. We will need to examine the link between somatosensory prediction in premature neonates and outcome, in both diagnosed and not diagnosed children, following a dimensional approach of EA and EF measurement, and a cross-syndromic approach of NDD.

We are still lacking studies addressing the link between early somatosensory processing and attention, but Weiss et al. (2018) showed that brain anticipatory activity of school-aged children (6-8 years) during a somatosensory selective attention task correlated with their performance at EF evaluations. This is highly encouraging and needs further investigation, especially at preschool age when EA is rapidly developing. It will also be important to examine this relationship in children with various NDD, not only ASD and ADHD but also developmental coordination and learning disorders for example. Providing a better understanding of the role of tactile sensory processing from the earliest age in relation to the development of EA, EF, motor control, and NDD diagnosis may make it possible to propose early screening and determine better intervention programs for all children.

Sidebar title: Predictive coding theory

The predictive coding theory is a theoretical framework of cognition based on the Bayesian theorem, aiming to explain how sensory inputs are processed and more generally how the brain works as inherently predictive (Friston, 2005). It postulates that the human brain constantly compares new sensory stimuli from primary cortices with internal models built by higher-order cortices from previous sensory inputs. If the input matches the prediction, it stabilizes the mental model of the stimulus by learning its characteristics, otherwise, a prediction error is fed back to update the probabilistic model. This theory provides a basis to understand sensory prediction and repetition suppression (the suppression of the cerebral response to a repeated, innocuous stimulus). Repetition suppression is the consequence of the internal stability of the model (Grill-Spector, 2006). Neural responses to stimuli can be enhanced or attenuated depending on their predictability and relevance to the subject's needs.

Conclusion

We reviewed knowledge on the place of somatosensory processing as the foundation of multisensory cognition, and its links with attention, executive attention in particular, and executive functions. We emphasized the developmental sequence that they form during typical child development, and detailed how neurodevelopmental disorders are associated with atypical or impaired performance at every step of this sequence, leading to clinical syndromes years later. We presented the emergence of new research on preschoolers' EF and EA assessment, and on the role of somatosensory processing, in particular prediction, as a precursor of attention. Finally, we proposed avenues of work to complete the picture with the links between somatosensory processing, early attention development, and cognitive outcome in both typically and atypically developing children. We propose that abnormal tactile sensory processing at an early age could provide markers of executive attention dysfunctions, which may promote new early screening programs for attention disorders and NDD. Research in these domains remains scarce and needs to be further explored, particularly in the preschool period, when EA is rapidly growing and is strongly required for core academic learning.

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