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**INTERPERSONAL SYNCHRONY IN CHILDREN AND
ADOLESCENTS WITH AUTISM SPECTRUM DISORDER:
A SYSTEMATIC REVIEW OF HYPERSCANNING
STUDIES**

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Abstract

Feeling connected and linked to other people is an essential need for humans, as social beings. We learn through imitation and mirroring, and we establish meaningful relationships through affiliative processes. What do these mechanisms have in common? They are based on being in synch with one another.

Synchrony can be observed in behaviour and movements, in physiological changes, but also in brain coupling: when two persons interact, their neural activity tends to become similar, and the more the relationship is tight, the more the interbrain synchronization.

Since synchrony is a key process for learning and for social exchanges, it is important to study how it develops and what happens when it's disrupted. The aim of this study is to provide an overview of biobehavioural synchrony during typical development and which aspects of it are impaired or atypical in Autism Spectrum Disorder. More specifically, the systematic review's aspiration is to present the current efforts to explore inter-brain synchronization in children and adolescents with ASD through hyperscanning techniques.

As this research field is in its early stages, paradigms and experimental procedures are not yet standardized and the future direction should include samples with a broader range of age and symptom severity. Despite that, this line of research could produce interesting advances and a better understanding of the topic, and contingently help clinical practices.

Introduction

Although defining interpersonal synchrony (IS) is a difficult task, the most inclusive definition refers to the temporal alignment of individuals. More specifically, during a social interaction, social partners tend to align their behaviour (symmetry of movements, conversational turn-taking), but also their physiological processes (contingent changes in heart rate) and brain activity (Hoel et al., 2021).

Another difficulty arises from the definition of “temporal synchrony”, because in human relationships interactions are beyond mimicry and perfect alignment, integrating complex dynamics and subsequent phases. Feldman (2007) describes three temporal parameters of synchrony: coherence, as the degree of matching behaviour, lead structure, when the interaction is led by one of the partners and the other follows, and time-lag, because adjusting to the other’s changes can produce a lag of few seconds.

Apart from small differences in the definition of interpersonal synchronization, there is a general consensus in considering this dynamic essential to human relationships and bond formation. Some evidence points towards affirming that just moving in synchrony with other members of the group is sufficient to increase cooperation and affiliation: when subjects march in sync, and not when they walk asynchronously, they perform better in a cooperative game and affirm to feel more connected with the other players (Wiltermuth & Heath, 2009).

Consequently, synchronizing with other people is linked to pro-social behaviour: in Cross’s experiment, when participants march coordinated, the prejudice against other ethnicities is reduced and, after the same task, pro-social behaviours like recycling are improved (Cross et al., 2019).

Biobehavioral synchrony allows people to connect with one another, according to Feldman (2017), in different kinds of relationships: from mother-child attunement to peer socialization and romantic relationships.

Given the importance of being in synch, research has focused on studying these mechanisms from the first stages of development, highlighting the early maturation of the basic systems involved. The quality of interpersonal synchrony in parent-child dyads is related to social and developmental outcomes, like social competence and emotion regulation (Leclere et al., 2014).

It follows that its impairment could cause important developmental outcomes. Studies on IS in atypical development could improve our understanding of the dynamics at play and how in the early stages precursors of social competence change from typical development.

Especially in Autism Spectrum Disorders, the symptom profile includes lack of interest in social interactions, difficulties in communication and synchronization; and mechanisms that should provide the basis of being attuned with others, like the development of Theory of Mind and the Mirror system, are under scrutiny for functioning atypically.

To better understand how being connected with one another can differ in ASD population, studies focused on various levels of synchrony, from simple imitation to spontaneous coordination in naturalistic settings. Beyond overt aspects, synchrony can be approached by addressing coordination of physiological indices and neural networks, to uncover the basis of this complex construct. Therefore, the aim of this thesis is to provide a general framework of interpersonal synchrony in typical and atypical development, as described by the current literature, and then to channel the focus on how inter-brain synchronization can occur in ASD developmental populations, with studies performed with hyperscanning techniques to record brain activity.

In the first chapter, interpersonal synchrony during development is analysed both in typical and ASD populations, from the point of view of the biobehavioural model of synchrony (at motor, physiological and neural level and with the related developmental outcomes).

The second chapter will provide a systematic review of the literature concerning inter-brain synchronization in developmental ASD subjects. Although research in this field has barely scratch the surface of the question, pilot studies can help to trace a path of investigation to deepen our understanding. To better analyse how these studies are

performed, the third chapter will take into consideration the technique used in most of the included papers, functional Near-Infrared Spectroscopy, and its application in developmental research and hyperscanning methods.

Chapter 1: interpersonal synchrony in typical and atypical development

Synchrony can be viewed as a dyadic characteristic, but it is also influenced by individual features. Harris e Waugh (2002) propose a review that analyses child-caregiver synchrony trough infancy, toddlerhood and early childhood. Among the main differences in these stages of development, they highlight the role of the child, that becomes more active and an increasingly sophisticated social partner as time passes.

During the first year of life, mothers tend to attune to their children' changes and to engage their attention. Shared attention is a crucial tool for synchrony, but mutual focus is not enough to define synchrony. Other key features are temporal coordination and contingency, as they enable the two participants of the dyad to coordinate in a dialogue-like interaction, establish a rhythm, and go beyond mimicry.

During this early stage, the caregiver's sensibility and responsivity to the child's signals are vital to establish a pattern and to enable the infant to develop a sense of agency and participation to the dyad (Sroufe, 2006).

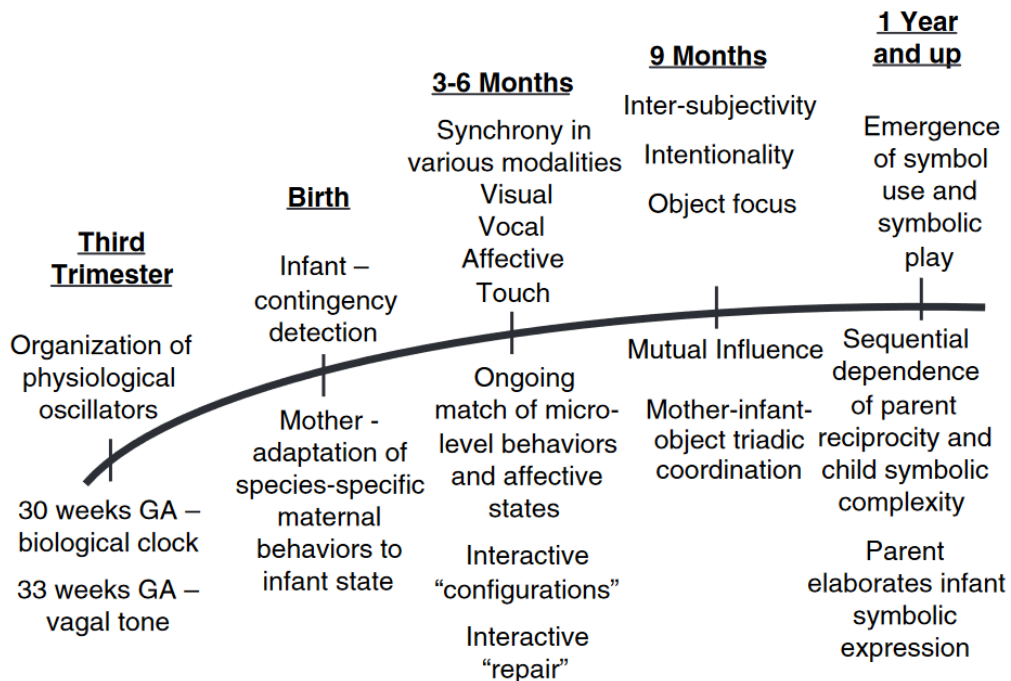
The description of a parent who would promote a secure attachment style could be identifiable with a well-connected, attuned caregiver, ready to interpret and respond to their child's signals.

Synchrony during this sensitive period also helps the infant to develop self-regulation. For example, feeding the child is a form of joint self-regulation promoted by the mother, where the baby can experience that their needs are met, and that the adult can help to ease a temporary situation of discomfort (more on self-regulation in the following sections).

As children grow up, they dispose of a wider repertory of behaviours to communicate and interact, e.g. verbal communication, and synchronous interactions with the caregiver help developing language acquisition and communicative competence.

Feldman (2007) proposes an exhaustive picture of how synchrony between the caregiver and the child develops and changes across the first year.

From Feldman R. (2007). Parent-infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of child psychology and psychiatry*, Vol 48, p. 329-354



Starting from the pre-natal period, physiological rhythms start to develop, and at birth infants are predisposed to synchronize their behaviour with the caregiver’s, and the mother, on her side, is sensitive to her baby’s cues and ready to follow its social signs and adapt to its states. For the infants, this is the first experience of temporal matched interactions, and the basis for stabilize a model that will teach the baby that others’ behaviour can be regular and predictable. Growing up, infants gain proficiency in communication and they progressively learn how to intentionally lead an interaction.

1.1 Biobehavioral synchrony

According to Feldman, we can mainly observe synchrony in four systems: behaviour, autonomic, hormones and brain (Feldman et al., 2012).

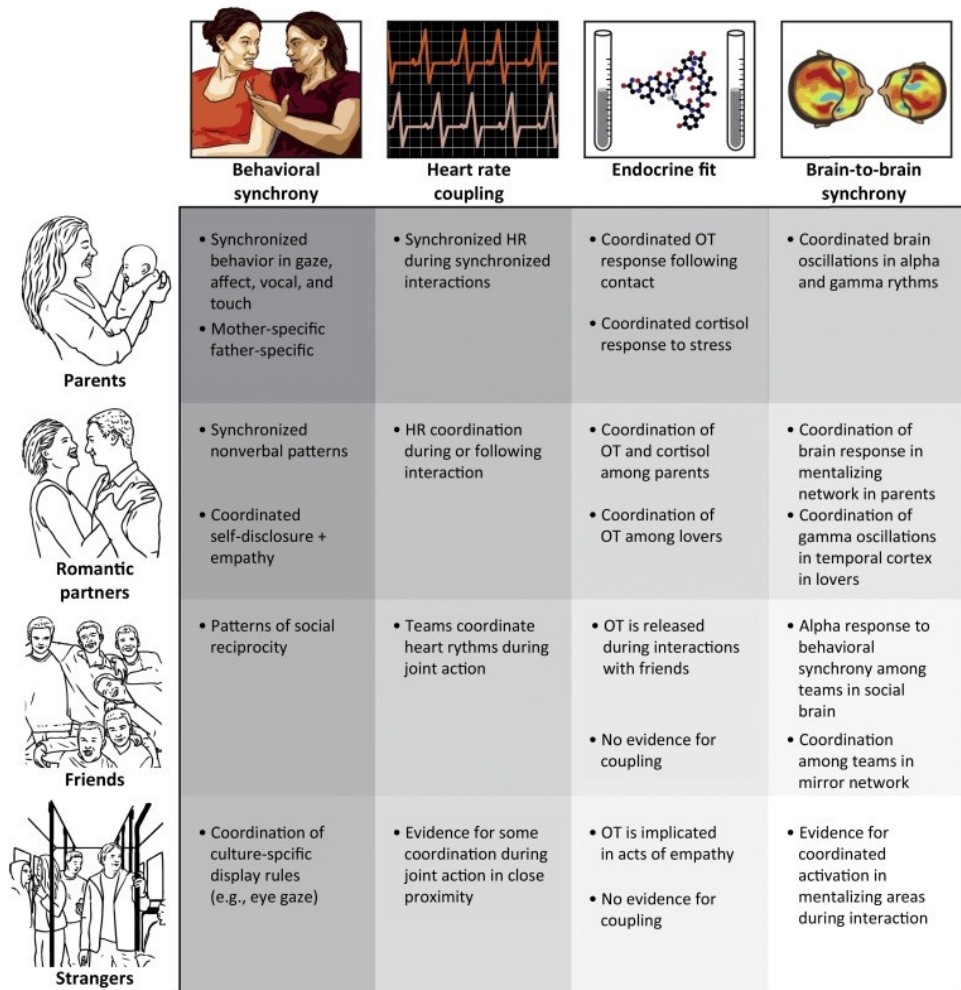
The behavioural system is the most evident, with overt displays of motor coordination, reciprocity and matching gaze and facial expressiveness. The other three systems are

covert biomarkers of the human ability to connect with one another, and they represent the biological correlates of synchronization. Measures like heart rate variability and cortisol and oxytocin levels tend to match in social partners involved in joint activities. Least but not least, brain activation is coherent in areas related to mentalizing, to social cognition, and in general the ability of understanding and predicting other's behaviour and social cues (frontal regions and temporo-parietal regions).

These systems develop from the early stages of life and interact to build the ability to establish relationships and engage in social exchanges.

Different kinds of attachment require different ways of bonding, and through life we experience how engaging in relationships can vary. In the early stages of development, the main interaction is with caregivers, and this attachment model can shape successive relationships. As children grow, they start to interact with peers and friends, and then to engage in a full social life. Hence, the main bond that will be taken into account in this thesis is the one underlying the parent-child dyadic system.

Biobehavioral synchrony in human attachments



Trends in Cognitive Sciences

Figure from: Feldman, R. (2012). Bio-behavioral Synchrony: A Model for Integrating Biological and Microsocial Behavioral Processes in the Study of Parenting. *Parenting*, 12(2–3), 154–164.

1.1.1 Physiological synchrony

Physiological and autonomic synchrony, although not as easily detectable as behavioural explicit coordination, underlies the first attempts of attunement in infancy and is the biological foundation for later interactions.

Studies mainly focus on heart rate, breathing and circadian rhythms functions, to understand how these mechanisms are influenced by the presence of other people,

especially during the first months of life, when other complex behaviours have not matured yet (McFarland et al., 2020).

As early as the perinatal period (Bobin-Begue, 2019) and the first days of life, infants are influenced by their mother regarding physiological rhythms, for example the circadian cycle. Establishing basic rhythms is a process guided by the parent, who leads its baby into regulated patterns of activity and rest, and, by doing so, modulates arousal (Thomas et al., 2014, Nishihara et al., 2002).

Biological and physiological alignment in the first months of life is also the precursor of social alignment with the caregiver: better regulation of sleep-wake cycles, for example, is linked to increased flexibility in the infant's interaction with the mother during a stressful situation (modified still faced procedure, in De Graac et al., 2012)

These first reciprocal adjustments are the basis for parent-infant interaction and represent the first form of regulation (exogenous, in this case) and the pillar for future endogenous self-regulation (Bernier et al., 2010).

Furthermore, as the autonomic system is connected to emotional regulation, changing in heart rate and vagal tone suppression are also important to self-regulatory mechanisms: when there are external demands (e.g. stimuli perceived as threats, but also emotional stimuli), the autonomic nervous system regulates autonomic responses to deal with it, decreasing parasympathetic tone and increasing sympathetic tone (Porges et al., 1994).

Variations in heart rate can synchronize: since the first months of life, in the dyad mother-infants (3 months) the heart rate is synchronized during face to face interactions (Feldman et al., 2011), and in Feldman's review (2007b) it is reported that mothers and children who show coordinate behaviour during free play are more likely to be in sync also at the physiological level, i.e. cardiac rhythms, and these children have a better autonomic reaction to stressful situations, measured as an increase in vagal tone suppression.

Abney et al. also uses a still-face paradigm to study self-regulation abilities and found that, when the mother-infant dyad is more in sync (physiological respiratory sinus arrhythmia response, linked to vagal tone response), the child manage to better react to the stressful phase and better self-regulate.

McFarland et al. (2019), recording heart rate changes and behavioural measurements of attention during face-to-face interactions between mothers and infants, highlighted a link between aligned HR periods and behavioural sync, like shared gaze and contingent vocalizations. They also use respiratory contingency to study mother-infant interactions, stating that coordination in breathing rhythm could be an index of shared attention and effective proto-communication, with periods of higher synchrony and moment of disruption and reconstruction. Even in this case, basic autonomic synchronization is seen as a support for behavioural coordination and more complex interactions.

To further state the importance of these mechanisms, not only for the child's self-regulation, but also for the familiar system: physiological synchrony during toddlerhood and early childhood is modulated by risk factors, and higher synchrony is associated with less psychopathologies and maltreatments (DePasquale, 2021).

Moreover, studies that take into consideration adolescents found that higher levels of physiological synchrony are associated with less negative affect and less internalizing symptoms during a discussion between parents and adolescents (for a review, see De Pasquale, 2021).

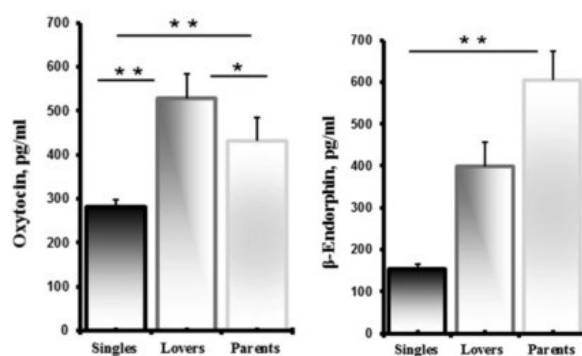
In summary, several research sustain a positive effect of caregiver-child physiological synchronization on self-regulation and its function as a scaffolding for more elaborated social interactions, even if more longitudinal studies are needed in order to have a clearer interpretation of the long-term effects (for a review, see DePasquale, 2021).

Apart from heart rate and circadian rhythms, the invisible synchronization between a dyad can also include hormonal changes, like contingent increases in cortisol, but also in affiliative hormones like oxytocin (Feldman, 2012).

Oxytocin is a hormone involved in bonding and affiliation, linked to maternal behaviours and children care. Feldman et al. (2010) measured oxytocin levels in parents and their children before and after interaction with each other, and they both showed increased levels after playing together. Hence, being in contact can produce a subtle synchronization in hormonal levels, correlated to affiliative behaviour.

Although most of the studies refer only to the mother's level of oxytocin, assessing also the father's level seems to reveal that the couple's oxytocin is similar and linked to more

affectionate touch and proximity to the child, backing the role of this hormone in parental behaviour and in the triadic parents-infant interaction (Gordon et al., 2010). In a study by Ulmer-Yaniv et al. (2016), higher levels of oxytocin in both male and female participants are associated with periods of affiliative bonding (new parents with their children, but also romantic couples, compared to strangers), and with more gaze sharing and affect synchrony, and are also correlated with other biomarkers of reward and affiliation, like beta-endorphins.



1.1.2 Behavioural synchrony

A more evident and visible form of synchrony is the coordination of behaviours, like motor contingency, synchronized and shared gaze, and vocal or proto-conversational turn-taking.

As we are political animals, we are predisposed from birth to pay attention to social cues and human characteristics, for example newborns have a preference for human faces (Viola Macchi et al., 2004), for the face of their mother (Bushneil et al., 1989), and for biological movement (Bardi et al., 2010), and from 4 month-old infants are able to discriminate emotional expressions (Caron et al., 1985).

Already in the perinatal period, newborns are able to coordinate their movements to some rhythmic stimuli, so researchers started to explore if this attitude could also apply to social stimuli and inter-personal coordination. Studies report that infants tend to synchronize their movements with external rhythms, such as the adult's voice and intonation, and with the adult's movement itself. Sensorimotor coordination appears to be an early method to

respond to external stimulation and to communicate and engage with social partners (Provasi et al., 2014).

When infants have gained the ability to walk and are free to explore the space and move during play-time with their mothers, their movement patterns tend to coordinate (locomotor synchronization can take the form of a leader-follower pattern, with the mother adjusting to her child's path, or can be more symmetrical). Like more statical form of motor synchrony (e.g. gaze sharing), but in a wider spatial range, locomotor synchrony has the function to accompany the child in the expansion of its knowledge of the outside world, and to be present during its exploration (Hoch et al., 2021).

Furthermore, interpersonal motor synchrony, operationalised by Bowsheer-Murray et al. (2023) as simultaneous and regular finger tapping, seems to enhance the feeling of affiliation in children.

Generally speaking, a social partner that is coordinated and in sync is preferred, as provides a predictable model for future interactions (Tuncgenc et al., 2015), and 15 months-old are shown to predict social affiliative behaviours between people moving in sync, in contrast with asynchronous pairs (Fawcett & Tuncgenc, 2017).

Another primary form of social interaction is mutual gaze, and subsequently shared gazing. Eye contact is considered an indicator of attention, mutual gazing is a first form of social engagement and its lack can be a precursor to atypical development (Akhtar & Gernsbacher, 2008).

Research findings point that newborns privilege looking at human faces, with a preference for canonical orientation and configuration, and for pictures of faces staring back at them, as opposed to pictures of persons with averted eyes (Farroni et al., 2006).

This infants' propensity to eye contact opens the way to a series of benefits deriving from mutual gaze with the caregiver: it increases positive affect and decreases stress, and it can be a helpful communicative tool (Niedzwiecka et al., 2017). As reported for other forms of synchrony, more mutual gaze between mothers and their infants (4 months old) is correlated with less distress during the still-face paradigm and increased positive affect, suggesting better emotion regulatory skills and a good connection in the dyad (MacLean et al., 2014).

From 3 to 6 months of life, infants start to shift their gaze accordingly to the interactional partner's gaze, thus following its direction. This enables shared attention: the members of the dyad can refer to the same object and the infant can increase its communicative range before developing verbal language (Del Bianco et al., 2018). Joint attention can lead to better attentional skills, and when mothers are more interactive and responsive with their child during play, following their focus, children's play is more advanced (more symbolic and pre-symbolic play), both while interacting with the adult and when alone, showing that a scaffolding and engaged caregiver can promote development (Bigelow et al., 2004).

As being in synchrony is often compared to a dialogue, verbal communication is another interesting area. Even before gaining verbal proficiency, infants and toddlers are capable of engaging in vocal exchanges and proto-conversation. The caregivers' influence is important in this phase, as it is necessary to attune to the infant's vocalization, to understand the emotional content (when possible) and to provide the right response. Being responsive means building a model for the child, a pattern that will be the base for self-regulation, for language development and for turn-taking (Yoo et al, 2018; Oller et al., 2013).

When mothers are more attuned, responding to vocalizations both with speech and with smiles and other non-verbal interactions, infants tend to produce more speech-alike sounds (Gros-Louis et al., 2006), demonstrating how responsiveness is important for language development. Moreover, newborns are already capable of turn-taking, so they are already receptive social partners, and they have a predisposition for interactive and synchronized exchanges (Dominguez et al., 2016).

1.1.3 Brain synchrony

Not unlike behavioural and physiological indices, brain activity can synchronize when a dyad is interacting. To study interpersonal brain connectivity, it is possible to record brain activation simultaneously in two or more people with different techniques, like electroencephalogram, near-infrared spectroscopy, magnetic resonance imaging.

Studying inter-brain synchrony with hyperscanning allows us to explore dyadic dynamics while they are happening and in all the subjects involved, and can help to better

understand the neural correlates of social interactions and how they influence (and are influenced by) coordinated behaviour (Alonso et al., 2024).

In Alonso's review, focused on EEG and fNIRS studies, as they allow more ecological settings (the participants are free to move and can face each other), the analysed papers report more synchrony into brain areas that are considered to support social interaction and mentalization about others' behaviour, like the prefrontal cortex and the temporo-parietal region. All these studies are centred around parent-child interaction, and in these circumstances the increase in inter-brain synchrony is accompanied by higher rates of shared gaze, turn taking or cooperative behaviour.

Some evidence suggests that inter-brain synchronization is not only caused by behavioural coordination, but that more brain coupling could enhance motor coordination: by stimulating the motor cortex of both the subjects with transcranial alternating current stimulation, Novembre et al. were able to measure a facilitation effect in a finger tapping alignment task, suggesting that inter-brain coupling could have a causative effect on other kind of synchrony. Therefore, investigate the neural underpinnings of synchrony with hyperscanning is a new and expanding line of research, and can be applied to the developmental period.

For example, Reindl et al. (2018) reported increased synchrony during a cooperative task (and less during the competitive phase) in child-parent dyads, and not when children are paired with an adult stranger. Although more studies are needed, IBS could be used as an indicator of connection, bonding and shared goals.

Studies on newborn and infants are less common, but there is evidence of neural synchrony between parents and 4 to 6 months old infants, associated to increased preverbal turn taking (Nguyen et al., 2023), and also increased IBS when the mother touches or is in proximity of her child (face-to-face interaction), in respect to a distant condition (Nguyen et al., 2021). Therefore, as seen for other forms of synchrony, IBS appears early in the first months of life and is linked to better connection with the caregiver, with the subsequent advantages for development.

On the contrary, low inter-brain connectivity could mirror a less-than-optimal interaction: higher traits of intrusiveness in the mother's behaviour are associated with less IBS with

her child, while more sensitivity during communication is reflected by higher brain coherence (Endevelt-Shapira & Feldman, 2023).

1.2 Effects of synchrony on development

1.2.1 Prosocial behaviour

As previously stated, inter-personal synchrony between caregiver and child appears to be important for development in various domains, as social behaviour, emotional regulation, communicative skills, and, in a broader way, to establish an attachment style.

Studies on pro-social behaviour focus both on infancy, targeting the interaction between child and caregiver/adult, and on childhood, with more emphasis on peer relationships (Trainor & Cirelli, 2015).

Studies on prosocial behaviour during infancy show that, starting from 14 months of age, infants are more likely to engage in helping behaviours if they are previously bonded in sync with the adult (motor synchrony), compared to the asynchronous condition. In these experiments, helping behaviour is operationalized as picking up an object dropped by the experimenter (Cirelli, 2014).

Moreover, Cirelli (2014b) demonstrated that being in synchrony does not increase social behaviour in general, but it acts as a cue to direct help, as infants are more likely to help the adult they were in sync with, but not a neutral adult, not directly involved in a precedent coordinated interaction with them. This could highlight the role of inter-personal synchrony in affiliative processes.

Apart from the interactions with adults, inter-personal synchrony seems to have an influence also on peer bonding. When age-matched dyads of 4 to 6 years old children play in a musical game in a synchronized condition, helping behaviours increase and the partners share more spontaneous interaction, like smiles and eye contact (Tuncgenç et al., 2016).

Motor coordination in children also enhances cooperation, as dyads of 4-year-olds are faster in completing a task together after moving in synchrony in comparison to dyads that moved in an asynchronous way (Rabinowitch et al., 2017).

1.2.2 Emotional regulation

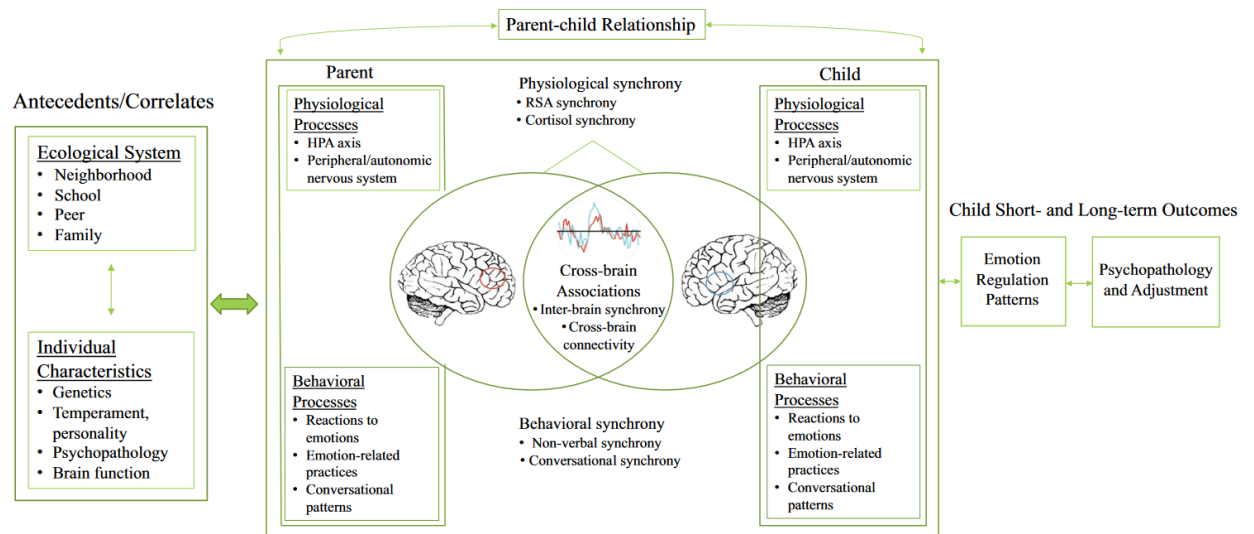
Another important skill that appears to be influenced by the degree of synchronous interaction in the early stages of life is self-regulation.

Emotion regulation can be influenced by external and intrinsic factors, and its aim is to recognize, and then control, redirect or modify emotional arousal to better function. This adaptive ability mostly develops in the first years of life, so early experiences are crucial, and influences social and personal dynamics in adolescence and adult life (Eisenberg et al., 2010).

To analyse this ability, research is starting to focus on dyadic features, such as positive synchrony, in addition to personal characteristics. In fact, emotion regulation is a complex feature, influenced by personal characteristic, such as temperament, by environment (family, peers, school), but also by the relationship between physiological and behavioural processes in the parent-child dyad. Coordinating and adjusting in a parent-child interaction could promote self-regulation, because to maintain the dialogic communication the infant need to practice co-regulation and adaptation, and it is also useful in learning expectations and build behavioural models (Davis et al., 2016).

Ratliff extend the Parent-Child emotion regulation dynamics model (Morris et al., 2018), to include cross-brain correlation of the dyad (see the model in the figure below). The co-regulation that parent and child experience when they interact to reach a goal, is one of the foundations of self-regulatory development and is linked to synchrony in behaviours, physiological states and cross-brain association.

In support to this theoretic frame, Feldman (2007) report that being in synch with the caregiver at 3 and 9 months predicts more self-regulation in the toddler at 2, 4 and 6 years, measures as the ability to follow the mother's prescriptions and restrictions.



The Role of Neurobiological Bases of Dyadic Emotion Regulation in the Development of Psychopathology: Cross-Brain Associations Between Parents and Children (Morris)

Extension of the parent–child emotion regulation dynamics model.

Reindl et al. (2018) also correlate inter-brain synchrony, measured with fNIRS hyperscanning, between child and parent (and not with a stranger adult) to more adaptive emotion regulation during a cooperative game.

1.2.3 Attachment

Synchrony in the dyad parent-child could be an important predictor for the attachment style, as when the caregiver is oriented and receptive of the child’s signals, they start a pattern of responsiveness and implement a model for secure attachment.

In Lindsey et al. (2014), secure attachment between parent and child is associated with more behavioural synchrony (measured in a free-play context), and being in sync was also associated to positive emotions. Of course, secure relationships are not characterized only by synchronized behaviour, but the episodes of asynchrony are less frequent and better handled by the dyad (episodes of reparation of the interactive flow).

In mothers with anxious attachment style, instead, inter-brain correlation with their children is less preponderant during a shared experience. This could mean that if a mother

is too concentrated on her child, she could focus less on the shared task and the exchange could provide less bonding (Azhari et al., preprint).

Markova and Nguyen (2022) extend the study of affiliative interactions and emotional regulation to infants of 4 months, as at that age babies are already able to detect unusual situations and to regulate themselves basing on the attachment model developed (cfr. Still face paradigm). They monitored differences in behaviours, like gaze sharing, and oxytocin levels, during natural interactions and modified interactions (where they asked the mother to be less responsive to the child's cues and needs). Children who experience higher levels of synchronous natural interaction with their mother are more sensitive to detect changes in the partner's behaviour, but also less inclined to negative display of negative emotions, showing a better emotional self-regulation (see the precedent paragraph).

Apart from behavioural synchrony, research on inter-brain synchrony and its relationship with attachment is still in its early stages, and results are not univocal (Miller et al., 2019).

Although studies reported increased IBS during cooperative task and a correlation with positive traits of the relationship (Nguyen et al., 2020), often they don't address the attachment style directly. Nonetheless, this construct is related to other aspects analysed here, like emotion regulation and better social functioning, so we can hypothesize that some of the previous findings could be (directly or indirectly) related to the attachment style.

It is also important to note that the relationship between better synchrony and better attachment style is not causative, or, at least, is not studied only as such, as it is also postulated that being familiar and bonded with someone can increase synchrony. For example, in Reindl et al. (2018), children (5-9 years old) have a better IBS when they perform a collaborative task with their mother, and not with a stranger.

Even though synchrony is a basic communicative skill, whereas attachment is a complex and multifactorial construct, numerous research found a link between them (for an extensive review, see Hoehl et al., 2021).

1.2.4 Communication and language development

Another ability influenced by interpersonal shared experiences is communication and language development. Children learn how to establish a communicative exchange in their parents' arms, via pseudo-dialogical patterns of signal and response, and models of responsiveness. Turn-taking is a mechanism that enables efficiency in conversations, it's based on temporal coordination in the dyad and is the basis for learning how to engage in a verbal exchange.

There are evidences of a link between speech interactions and increased neural activity between mothers and their children: already at 4-6 months of age, increased neural synchrony is related to better turn-taking in proto-conversations between mother and child (Nguyen et al., 2023) and these results are achieved also in studies with preschoolers: in Lotus Lin et al (2023), activity in the alpha and theta band is higher during a social communication interaction than passive listening. Different forms of synchrony and interaction are aligned and contribute to the outcome of the social exchange, so turn-taking is linked to IBS and this coordination with the conversational partner is a key feature in being competent in communication and socializing (Nguyen et al., 2021b).

Other shared experiences, like reading together with a caregiver, can enhance language development, and it is also related to better neural synchronization (measured with fNIRS hyperscanning by Zhai et al., 2023), and this relationship between IBS and shared reading correlates with better learning of novel words (Piazza et al., 2021).

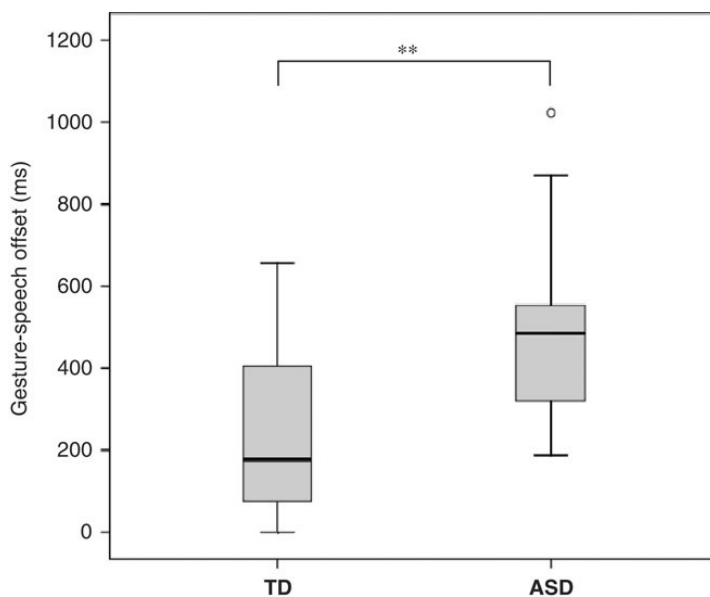
1.3 Biobehavioural synchrony in Autism Spectrum Disorder

The link between synchrony and development is bidirectional, given that synchrony with the caregivers and peers can be helpful to enhance social and behavioural skills, but at the same time being in synch with someone requires a set of aptitudes, so atypical development of some abilities can influence it. For example, while typical children seem to be predisposed for some early social behaviours, like eye contact, children with ASD

are more likely to present an atypical pattern of eye contact and gazing behaviour (Senju & Johnson, 2009).

According to the National Institute of Mental health, “autism spectrum disorder (ASD) is a neurological and developmental disorder that affects how people interact with others, communicate, learn, and behave”. Social deficits are a major component of this disorder and are related to defective communication, difficulties in bonding and in understanding others’ internal processes, as well as being understood (White et al., 2007).

Bloch et al. (2019) propose that interpersonal difficulties in ASD subjects could be influenced by the atypical temporal processing and alignment of movements observed as symptoms. By being clumsier in the movements and having atypical multi-sensory processing, people with autism could experience additional challenges in the delicate and time-sensitive process of synchronization with other social partners.



** $p = 0.01$

In fact, in one of the reported examples, De Marchena and Eigsti (2010) found that, in pairs of TD-ASD adolescents, the frequency of gesture production during a conversation is similar, but the quality differs, as ASD participants show a lack of synchrony between speech content and gestures, and this is related to a lower

communication quality itself.

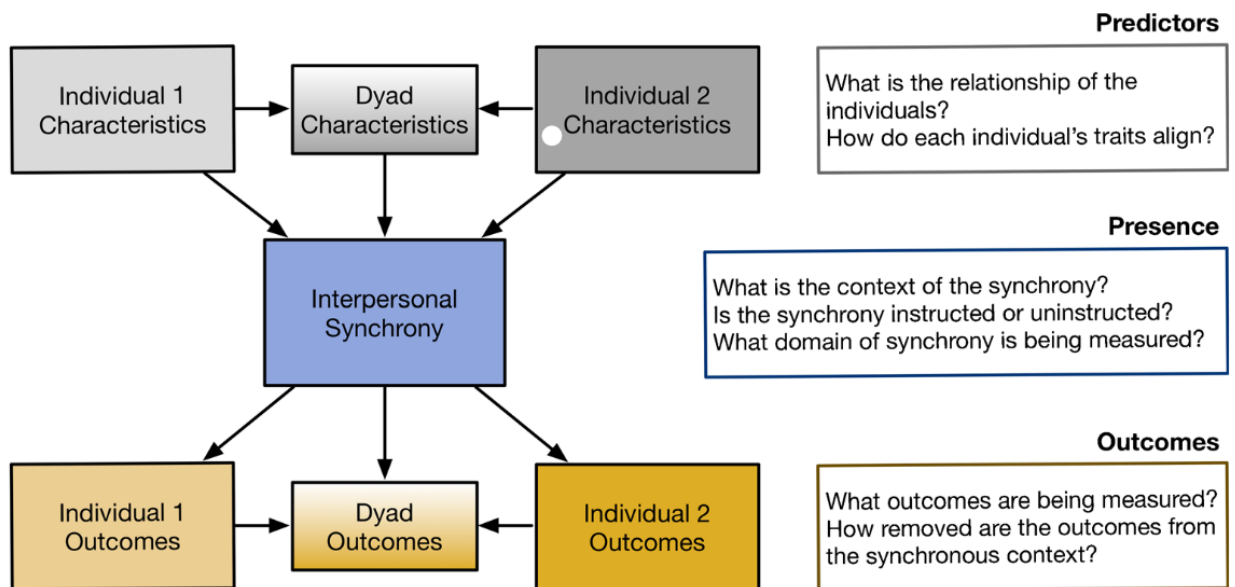
Individual traits, like atypical movement skills and difficulties in following rhythms, could be partially responsible for the reduction of synchronization observed during social interactions (Fitzpatrick et al., 2017).

For example, anomalies in infants’ crying patterns are common in autism, and this influence their capacity to express emotions and also the caregivers’ responses: higher

acoustical frequency of crying that in TD population tend to cause more distress in the listener and could compromise the parent’s ability to adequately respond to its child’s needs (Esposito & Venuti, 2010).

In general, literature points out that interpersonal synchrony is inversely proportional to the severity of autistic traits, but in most of the studies the dyads are composed of TD-ASD pairs, so we know little about dynamics between persons with matched autistic traits (Bowsher-Murray et al., 2022).

Besides personal traits, dyadic characteristics can affect the quality of synchronization: if social expectations are not aligned and predictions of the partner’s behaviour are not accurate, also the perception of synchrony and attunement could be disrupted (McNaughton & Redcay, 2020).



As theorized by Milton (2012) with the definition of “double empathy problem”, it is not correct to emphasize only the autistic traits as components influencing the dyad’s dynamics, and the conceptualization of autism as an absence of theory of mind is outdated. Instead, the responsibility of understanding the other is on both the partners’ shoulders, and the social outcome depends on the alignment of people’s expectations, as the lack of insight into the other’s mind is on both sides.

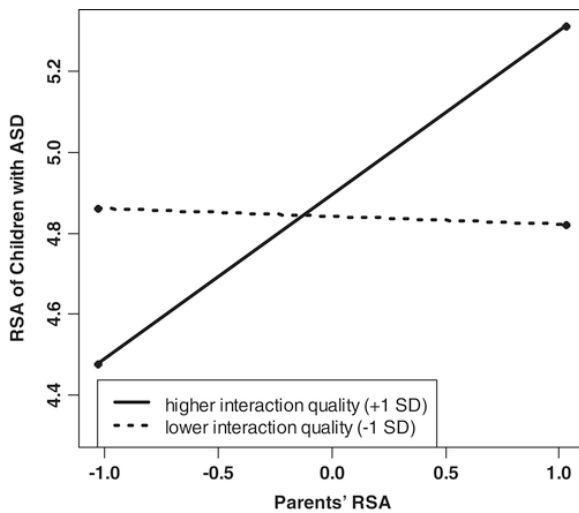
1.3.1 Physiological synchrony in autism

As explained in the previous sections, biological synchrony is a basic and fundamental part of interpersonal synchrony and has a role in development.

Although it is not yet well studied in children with ASD, there are a few papers that report a link between severity of autism symptoms and lower physiological connectivity, mainly in the dyad parent-child.

Baker et al. (2015) measured electrodermal activity in fathers and their children (4-10 years old), as a measure of shared arousal, during play. This pilot study report that a higher covariation in the arousal of the dyad is correlated with lower symptom severity.

In Wang et al. (2020), the measure of choice is respiratory sinus arrhythmia, in line with studies on typical developmental population.



Given that RSA is linked to emotion regulation, it was expected that children with internalizing problems would display less RSA synchrony. Moreover, interaction quality (how the dyads seem to enjoy themselves and interact in a productive and engaged way) is correlated with the coordination of autonomic responses.

Interestingly, the authors propose that matching RSA could be beneficial for the interaction, but only for children with low internalizing problems. Instead, when the internalizing problems are higher, it could be advantageous for the dyad that one partner is able to mismatch (and not back up the dysfunctional activation).

As for cortisol levels, it is unclear if a higher correlation of the levels in the dyad is symptomatic of a better response and beneficial synchrony, or a poor functioning. In Saxbe et al. (2017) parent e child levels of cortisol appear to have a stronger match in father-child dyads in respect to mother-child dyads in the ASD group, but not in the TD group. The explanation given is that mothers tend to make a greater effort in helping their

ASD children to regulate their behaviour and stress levels, while fathers seem to behave the same way with typical and atypical children.

Apart from studies that examine only father-child or mother-child relationships, there is more need of research on triadic interactions and also comparison between the two parents.

As regard oxytocin, studies mainly focus on the children's levels of oxytocin, and not on the possible synchronization of levels. Autism is correlated with disruptions in the oxytocin system, but the low baseline levels of this hormone seem to increase during synchronous interaction with the parents (Feldman et al., 2014).

1.3.2 Behavioural synchrony in autism

When thinking about autism, the preponderant features that come into mind could be social difficulties, lack of communicational skills, restricted interests. Nevertheless, ASD also entails motor impairments, like reduced fine and gross motor coordination, poor performances on tasks requiring balance, postural abnormalities and impaired imitational abilities (Anjana et al., 2011).

According to Trevarthen and Delafield-Butt (2013), children with ASD mainly show difficulties in three types of motor control: single actions, organization of a series of actions, and coordination of multiple actions. These problems in motor control can contribute to social difficulties, by being an obstacle to communication, imitation, understanding of other's intention. Furthermore, postural development can be delayed, and not being able to sit or to crawl and walk can have effects on exploration and learning, but also on social engagement with the caregiver (Nickel et al., 2013).

Regarding the study of motor synchrony, Glass's review (Glass et al., 2023) reports in general a reduced rate in interpersonal synchrony in children with ASD in comparison with control groups. Overall, spontaneous synchrony could be slightly easier to achieve for autistic participants than instructed synchrony, as the latter involves more cognitive overload, attention and movement planning. However, experiments still point out that the tendency to spontaneously align to another's behaviour is still significantly lower than in

TD children. For example, in a rocking chair paradigm with parents, ASD children have worse performances than the control group (Marsh et al., 2013).

Also, adolescents with autisms show less motor synchronization with their parents than controls in a paradigm involving the oscillation of a pendulous, both in the spontaneous and intentional condition (Fitzpatrick et al., 2016).

Regarding infancy, in the experiment of Yirmiya (Yirmiya et al., 2005), siblings of children with autism show decreased synchrony with their mother during interactions led by the infant during free play at 4 months, and at 14 months they display less communicative gestures. More studies are needed on infants with high likelihood to develop autism, in order to intercept early indicators of motor synchrony impairment.

More studied as an early indicator of atypical development, gaze patterns are important for social exchanges and social attention, and it is possible to investigate them from infancy.

Toddlers with ASD are less likely to watch at faces than TD children, and to look at objects attended by others, and this is an early sign of diminished social engagement and less synchronization through mutual gaze (Chawarska et al., 2015).

Another longitudinal study by Jones reports that eye looking is not impaired since the first days of life, but starts declining at two months in children who will later be diagnosed with ASD. This, in the epigenetic theoretic framework, could indicate when an atypical pattern is starting and how an initial vulnerability can shape the subsequent behavioural outcomes (Jones & Klin, 2013).

This limited eye gazing behaviour can lead to less opportunities to interact with the caregiver, less responsiveness from parents and limited opportunity for joint attention and learning. As a basic level process, watching something means giving it attention and allowing the information to enter the system to be processed, so gazing behaviour is informative and has cascading effects on development.

The review Riddiford et al. (2022) reports that increased gaze towards eyes and face is correlated with better social functioning, but other atypical gaze patterns, like paying attention to the mouth, are not linked to worst social performances, but could be a different strategy to overcome initial difficulties in ASD children.

1.3.3 “Social brain” and ASD

Before starting to study interpersonal synchrony and interactions with hyperscanning, as to say during the interaction itself and involving both participants, research also focused on the development of the neural networks that support socialization, aiming to explain how these mechanisms work in Autism.

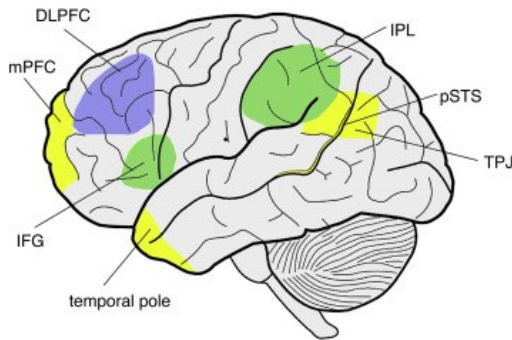
One of the hypotheses to explain social difficulties in ASD is the underconnectivity of higher-order networks in the temporo-parietal and frontal areas and the abnormalities in white matter volume (Just et al., 2012; Gotts et al., 2012). This hypothesis would partially explain how the atypical functioning of regions important for social cognition could generate symptoms ranging from lack of interest in interacting to anomalies in the Theory of Mind, but it is not specific for ASD, as it is observed also in other pathologies, and the experimental results do not conclusively prove this theory.

Alongside with this theory of long-range underconnectivity, at local level overconnectivity is found to be linked with autism, resulting from an abnormal pruning process. An initial overconnectivity and early overgrowth could have an influence on the later pruning processes, leading to abnormal remodelling and atypical overall connectivity (O’Reilly et al., 2017).

Even before talking about networks, the single areas can be object of investigation: in Pelphrey et al. (2011) the early impairments in gaze following and shared attention are attributed to an atypical activation of the superior temporal sulcus, implied in the recognition and attribution of congruent or incongruent intentions and emotions.

A consensus has not been reached for the neural correlates of autism, because its heterogeneity and variety of symptoms makes it difficult to reach a reliable theoretical framework and more studies and larger samples are needed (Di Martino et al., 2009). Despite that, some areas received more attention and are found to function in an atypical manner, like dorsolateral prefrontal cortex, anterior cingulate cortex and premotor areas, with a hypoactivation in the frontal areas observed in studies implying social cognition tasks and executive functions. Amigdala and prefrontal areas are implied in the reward

system activated by social interaction, and their atypical response in ASD is addressed as a signal of impaired social motivation (Chevallier et al., 2012).



In the figure (from Liu et al., 2019): key cortical areas associated with autism.

Yellow: areas associated with Theory-of-mind;

Green: Mirror Neuron system;

Blue: executive function.

With a growing interest in precursors and early signs of autism, recent theories focus more on the basic perceptual, attentional and motor impairments, that are present in the early stages and elicit complex mechanisms of adaptation in the brain development. For example, deficit in disengagement of attention can lead to an overload and difficulties in dealing with all the information entering the system, so it could explain the lack of interest in interaction as a protective mechanism to avoid the overburden (Eisabbagh et al., 2013). In a longitudinal study by Eisabbagh et al. (2012), infants at high risk of autism, who would later be diagnosed, show atypical ERP responses to eye gaze, with no differentiation between direct and averted gaze, in contrast to the responses of the control group and high risk but no diagnose. This atypical sensitivity to eye gaze, detectable at the neural level earlier than with overt behavioural indices, has cascading effects on the possibility of developing joint attention and other learning and social skills. Given that overt signs of atypical behaviour in the first months of life are not homogeneous and are hard to detect, finding a neural signature of high risk of developing autism could improve our understanding.

The following step to indagate the neural basis of atypical socialization is to study how the interaction occurs with more ecological settings and during the said interaction, and focusing on the different contributions of the protagonists.

2 Systematic review

2.1 Search method and inclusion criteria

The databases searched for this review are Scopus, EBSCO and Pubmed, and the searching is conducted up to September 2024. The key words used are: (autis* OR asd OR asc) AND (hyperscanning OR brain sync*) AND (development), and other variants, like “interbrain synchronization” and “interbrain correlation”.

The searching process led to 75 papers in total across all the databases, and, after the elimination of the duplicates, 32 papers remained.

After a first screening phase by title and abstract, all pertinent papers were read, and 8 were found eligible. During the screening phase, 24 papers were excluded due to: reviews or meta-analysis or theoretical (12), no ASD or autistic trait group or no clear differentiation (4), no developmental age (4), no hyperscanning techniques implied (3), no English version available (1).

A total of 8 articles were included at the end of the process.

The main focus of this review is the use of hyperscanning techniques to study interpersonal synchrony in ASD developmental population. Due to this, the papers were selected following these inclusion criteria: all the articles are available in English and are published in peer reviewed journals, all the experimental designs imply the use of an hyperscanning technique to measure inter-brain synchronization. The population under study is aged 0-18 and is diagnosed with ASD or presents high autistic traits, measured via standardised tests.

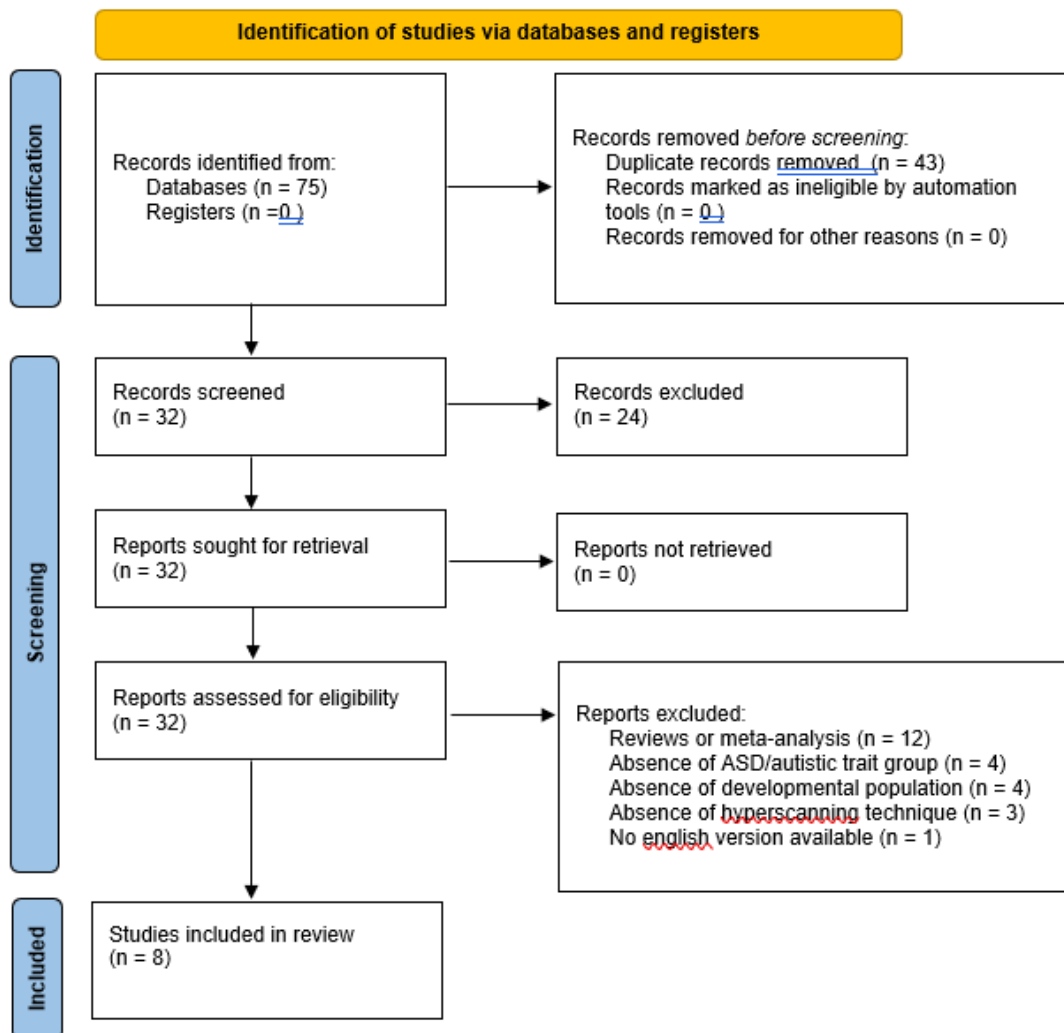
Since the research on this topic is still on its early stages, I decided to include papers that recruit participants based also on the measurement of autistic traits, and not only on a diagnosis of autistic spectrum disorders. In a preliminary phase, studies that focus on the correlation between specific traits and patterns of brain activity and synchronization could help to highlight specific links and to better understand the specific components involved.

For the same reasons, some of the studies included in this review only tested participants with autistic traits, not providing a proper control group. Although this lack of

homogeneity in the studies is an obstacle to a comprehensive view of the topic, it is also an accurate representation of the current state of this emerging line of research, and the basis for further in-depth analysis.

Due to the complexity of the research area, no distinction was made based on the experimental tasks used to study interpersonal synchrony: some researchers focused on cooperative games, others on joint activities. All the conditions are further analysed below.

Prisma flowchart



Overview of the selected papers:

Author, Year	Title	Task	Measures	Dyads	Take home message
Du B. et al, 2024	Higher or lower? Interpersonal behavioral and neural synchronization of movement imitation in autistic children	Imitation of meaningful and meaningless movements	-analysis of imitation accuracy and behavioural synchrony -fNIRS -autism behaviour checklist (ABC) -social responsiveness scale (SRS-2)	Child-experimenter	Autistic children, compared to TD, showed lower imitation accuracy, behavioural synchrony, and lower neural synchronization
Hasegawa C. et al., 2016	Mu rhythm suppression reflects mother-child face-to-face interactions: a pilot study with simultaneous MEG recording	Face-to-face spontaneous non-linguistic interaction	-MEG hyperscanning -Magnitude of mother and child head motions -Social Responsiveness Scale to assess autistic traits in children and Kaufman Assessment Battery for Children to assess their intelligence -Autism Spectrum Quotient to assess	Mother-child	Mu suppression has been used as an index of perception-action coupling involving the MNS, and is negatively correlated with the severity of autistic symptoms in children with ASD.

			autistic traits in mothers		
Key P. et al., 2022	Greater social competence is associated with higher interpersonal neural synchrony in adolescents with autism	Free-form conversation about a fun day in the past or the future	-EEG hyperscanning -Coding of social behaviour -NEPSY ToM subtest -Social Communication Questionnaire -CASS Assessment (vocal expressiveness, number of question asked etc.)	Adolescent with ASD- adolescent TD (opposite sex)	Greater inter brain synchrony during the conversation was associated with milder social difficulties and lower severity of autism.
Kruppa J. et al., 2020	Brain and motor synchrony in children and adolescents with ASD- a fNIRS hyperscanning study	Computer-based cooperative/competitive game	-fNIRS hyperscanning -response times -percentage of joint wins	Child (8-18 y.o.), TD or ASD- adult (parent vs stranger as control condition)	Motion synchrony is lower in the ASD group. Brain synchrony is different in the parent-child condition in relation to stranger-child only in the TD group, not in the ASD group.

Minagawa Y. et al., 2023	Inter-brain synchrony during mother-infant interactive parenting in 3-4-month-old infants with and without an elevated likelihood of autism spectrum disorder	Hyperscanning during 3 conditions: breastfeeding, mother holding her child, experimenter holding the child (separation as control condition)	-fNIRS hyperscanning -developmental questionnaire (ESIAD) -Postpartum Bonding Questionnaire -Temperament and Character Inventory (TCI) -MacArthur-Bates Communicative Development Inventories -Still Face Paradigm coded with ELAN	Mother-infant	Inter-brain synchrony is significantly greater in the breastfeeding condition in both groups. The high-risk group did not show reduced inter-brain synchrony with the mother, that could be due to the nature of the task (simple motor adjustment could be similar in ASD and TD population).
Tang et al., 2023	Children with autism spectrum disorder perform comparably to their peers in a parent-child cooperation task	Cooperative key-pressing task	-fNIRS hyperscanning - winning ratio - strategy selected	Parent-child	In task performance, there are no great differences between ASD and non-ASD group. Parents of ASD children could be more prone to self-adjust and better explain their game strategy to their children.
Wang et al., 2018	Autism symptoms modulate interpersonal neural synchronization in	Key-press task, cooperating with the	-fNIRS hyperscanning -behavioural performance	child-parent dyads (no	Although showing higher brain synchrony when performing the task together with their

	children with autism spectrum disorder in cooperative interactions	parent or alone (control condition)	-autism spectrum quotient and Wechsler intelligence scale	control group)	parent than alone, higher autistic traits predicts lower synchrony.
Zohu et al., 2024	Autistic traits modulate social synchronizations between school-aged children: insights from three fNIRS hyperscanning experiments	1. watching a video together or alone (cc) 2. read a story together subvocalizing (cc) or vocalizing 3. playing jenga together or just pretending to play (cc)	-fNIRS hyperscanning -autism spectrum quotient	Child-child	Interbrain connectivity is higher in the tasks that require more social interaction. Autistic traits modulate IBC during peer interaction.

Hyperscanning techniques allow to record brain activity simultaneously from different subjects. Just by looking at the publication years of the selected papers (that span from 2016 to 2024), it is possible to see how these techniques are a recent approach, but rapidly expanding.

One of the major advantages of hyperscanning is the possibility of an ecological approach to social settings: instead of recording a single person’s brain activity during interactions, it is now possible to study the complexity of human connections during a real-life social exchange.

Moreover, the latest technologies in this field are increasingly comfortable and portable, less susceptible to motion artifacts and easier to use, in brief more suitable to ecological studies, even with sensitive groups like children or atypical individuals, that would less tolerate invasive and prolonged measurements (Babiloni & Astolfi, 2014).

As seen beforehand, autism spectrum disorder is characterized by some difficulties in social interactions and atypical interpersonal synchrony. Whilst some aspects, like motor synchrony, have been more thoroughly studied (for a comprehensive review and meta-analysis of motor synchrony in ASD, see Carnevali et al., 2023) the underlying neural correlates are less clear.

To better understand the state of the art on this topic, these aspects of the selected papers will be analysed in the following sections: composition of the dyads, tasks applied to study synchrony, hyperscanning technique, ROIs, and results.

2.2 Narrative synthesis of the data

study	Sample size and relationship	ASD diagnosis or traits measure	Task or paradigm	Neuroimaging measure, model and number of channels	Analysis type and ROIs
Higher or lower? Interpersonal behavioral and neural synchronization of movement imitation in autistic children	20 ASD children (mean age 6.085 +/- 1.036) and 20 TD children as control group (mean age 5.101 +/- 1.252)	Diagnosed with DSM-5 Measures of traits: Social responsiveness scale (SRS-2), autism behaviour checklist (ABC), Peabody picture vocabulary test (for intelligence)	Imitation task of meaningful gestures and meaningless movements	fNIRS (NirSmart), 20 channels	Wavelet transform coherence and Granger causality, Bilateral IFG, IPL and TPJ

		and Raven test, movement questionnaire test			
Mu rhythm suppression reflects mother-child face-to-face interactions: a pilot study with simultaneous MEG recording	8 ASD children and their mothers. No control group	Diagnosed, with Autism Diagnostic Observational Schedule-Generic (ADOS), Diagnostic Interview for Social and Communication Disorders (DISCO) and DSM-5 criteria. Severity: Social Responsiveness Scale (SRS)	Real-time video that allows mothers and children to see each-other facial expressions.	MEG (SQUID device), 160 channels for mothers and 151 for children.	Index of Mu suppression (IMS), whole brain
Greater social competence is associated with higher interpersonal neural synchrony in adolescents with autism	34 children and adolescents (10-16 y.o.), paired with opposite-sex, TD peers. No control group	Diagnosed with DSM-5, ADOS. Severity: Social Communication Questionnaire (SCQ) and Theory of Mind	Free form conversation about a given topic	EEG (Electrical Geodesic), 128 channels.	Correlation of theta, alpha and beta amplitudes, on temporoparietal electrodes, bilateral.
Brain and motor synchrony in	18 children with ASD, 41 TD (8-18	Diagnosed by an expert, ADOS.	Cooperative and competitive	fNIRS (ETG-4000 NIRS	Wavelet coherence

children and adolescents with ASD- a fNIRS hyperscanning study	y.o.), paired with their parent or with an adult stranger (control condition)	13 with comorbidity of ADHD.	computer game, paired with the parent / a stranger adult	device), 22 channels	DLPFC and mFPC (bilateral)
Inter-brain synchrony during mother-infant interactive parenting in 3-4-month-old infants with and without an elevated likelihood of autism spectrum disorder	Infants (122.4 days old on average) with elevated likelihood of ASD (16) and typical likelihood (71) with their mothers.	The Elevated likelihood group included infants with at least one older sibling with a diagnosis of ASD, TL had no first-degree relative with ASD.	Breastfeeding, holding condition and separation.	fNIRS (ETG-7000) 44 channels	Wavelet transforms coherence, Temporal, parietal and frontal areas (bilateral)
Children with autism spectrum disorder perform comparably to their peers in a parent-child cooperation task	36 high-functioning ASD children (age 7.96 +-2.16) and 35 non-ASD (age 8.18 +- 2.05) with their parents	Diagnosed ASD. Severity: Childhood Autism Rating scale	Cooperative key-pressing task	fNIRS (ETG-4000), 22 channels	Wavelet transform coherence, Right fronto-parietal region

Autism symptoms modulate interpersonal neural synchronization in children with autism spectrum disorder in cooperative interactions	16 ASD children (age 8.2 +/- 1.7) and their mothers, No control group	Diagnosed with DSM-5 Severity: Wechsler Intelligence Scale, Autism spectrum quotient, SRS	Cooperative key-pressing task and control condition (playing alone with the parent just looking)	fNIRS (TechEn CW6 system), 22 channels	Wavelet transform coherence, Bilateral prefrontal areas.
Autistic traits modulate social synchronizations between school-aged children: insights from three fNIRS hyperscanning experiments	14 ASD children (age 10.4 +/- 1.1) 32 TD children (age 9.9 +/- 1)	Diagnosed, but in this study only the traits are considered in the analysis. Traits: Autism spectrum quotient (AS-Q) and Broad Autism Phenotype Questionnaire	1. watching a video together or alone 2. reading together or alone 3. playing jenga or pretending to play	fNIRS (NIRScout), 19 channels	Wavelet transform coherence, Bilateral fronto and temporoparietal areas

2.2.1 Sample description

article	Type of dyads	Number of ASD subjects	Number of control subjects	Mean age and SD	Sex: male/female ratio
Du et al.	Experimenter-child	20	20	ASD: 6.085 (1.036) Non-ASD: 5.101 (1.252)	ASD: 15/5 Non-ASD: 16/4
Hasengawa et al.	Mother-child	8	no	74.1 months	4/4
Key et al.	Adolescent with ASD-adolescent without ASD	34, paired with matched-age confederates	no	Males: 12.80 (1.50) Females: 13.06 (1.62)	17/17
Kruppa et al.	Parent-child and stranger-child	18	41	ASD: 13.54 (2.96) Non-ASD: 12.66 (2.79)	All males
Minagawa et al.	Mother-infant	16 (high risk)	71 (low risk)	HR: 122.4 days (16d) LR: 122.4 days (16d)	HR: 10/6 LR: 35/36
Tang et al.	Parents-child	36	35	ASD: 7.96 (2.16) Non-ASD: 8.18 (2.05)	ASD: 30/6 Non-ASD: 21/14
Wang et al.	Parent-child	16	no	8.2 (1.7)	15/1
Zhou et al.	Child with ASD-child without ASD	14	Does not have a control group, but 32 TD children	ASD: 10.4 (1.1) Non-ASD: 9.9 (1.0)	ASD: 11/3 Non-ASD: 24/8

This table contains a brief description of the population taken into exam: half of the studies eligible did not include a control group, one of them compared only the autistic traits (Zhou et al.), the other four included a control group (three used age-matched children without ASD, one compared high and low risk infants). None of them tested ASD-ASD dyads, although this could be an interesting perspective to analyse.

In the 8 papers selected, only two investigated peer interactions in children and adolescents, one used dyads composed by the experimenter and children, while the others focused on parent-child dyads. This is in line with the previous statements about the importance of the early synchronous interactions between parents and their children, but the need to be integrated in the social environment and the difficulties of ASD children and adolescents in this regard should not be overlooked, and more studies should involve peers. It could also be interesting to investigate better the relationship with other significative adults, like therapists or teachers.

Regarding the developmental phase, one study chose to test infants at high and low risk of developing autism. This line of research could highlight early indicators of atypical development, and longitudinal studies that start during infancy could help the identification of risk and protective factors, and the clinical development of early paradigms of intervention.

Another partially overlooked period is adolescence, with only one study focusing on it (Key et al.) and others including participants until 18 years of age, but without a specific focus on this period. Interestingly, the only study dedicated to adolescence involves peer interaction, targeting an important shift in the relationships during this age.

As for the ASD diagnosis or ASD traits taken into consideration, there are different approaches in the studies.

Four studies take into account intelligence measures, like Raven test (in Du et al.), Peabody Picture Vocabulary test (in Du et al.), Wechsler Intelligence rating scale (in Wang et al.), Kaufman Assessment battery for children (in Hasegawa et al.).

For the assessment of autistic traits severity, the Social Responsiveness Scale is used in four studies (Du et al., Hasegawa et al., Kruppa et al., Wang et al.), the Autism Spectrum Quotient in two (Wang et al. and Zhou et al.), Social communication questionnaire in two

(Key et al. and Kruppa et al.), the Childhood Autism Rating Scale in Tang et al. and the ABC (autism behavior checklist) in Du et al., and Broad Autism Phenotype Questionnaire in Zhou et al.

For the experiment of Minagawa et al. about infancy, the applied questionnaires regarded the post-partum bonding and development.

On average, studies on ASD children involve high functioning participants, given the technical difficulties of testing on a low-functioning population, such as difficulties in applying the caps or measurement equipment and in choosing a feasible task. Nonetheless, it is important to remember that “autism” is an umbrella term, that can include a wide range of symptom severity and a heterogeneous population, so it would be a challenge, but also an important opportunity, to test on a more diverse sample.

2.2.2 Tasks used to study synchrony

Synchrony can appear in different forms, from motor synchrony to conversational turn-taking. To elicit inter-brain synchronization, different tasks or paradigms can be applied.

The level of active synchronization required can vary, from watching a video together to intentionally coordinate movements, or playing a game that present a shared goal for the dyad.

Starting from the most naturalistic and less active paradigm, the study of Minagawa et al. about infants asked the mothers to feed their children, or just hold them: in the first months of life interactions are crucial, and clearly the leading effort comes from the caregiver. This paradigm allows an ecological view of the first steps of mother-child relationship, as breastfeeding and holding the baby are natural day-to-day situations.

Another paradigm that involved spontaneous synchronization is the one from Hasegawa et al., that simply showed the participants' each other's expressions, allowing them to change their facial expression and thus coordinate. This paradigm consents to focus on emotional face-to-face interactions, relating them to the development of social skills, theory of mind and empathy.

Only one study, by Key et al., investigating peer interaction during adolescence, asked the participants to talk about a given topic, rating the expressiveness and the quality of the conversation, allowing as well to freely coordinate and spontaneously contribute to the mutual synchrony.

Among the studies included in the review, only one paper measured IBS using a motor synchrony task (Du et al.), following the assumption that physiological and brain alignment are linked to coordinated movements, and imitation is not just a reproduction of gestures, but a synchronised interaction. In this case, the interaction was guided by the assigned task and the level of spontaneous regulation was low.

Often used to measure coordination, in three papers the chosen paradigms were centred on cooperative games. In Wang et al., the comparison is between a solo condition, where the child performs the game with the parent just watching, and a joint condition, where the dyad should coordinate to press the button at the same time. In this version of a cooperative paradigm, the difference under evaluation is between playing the same game alone or with another person. In Kruppa et al., the comparison was between a cooperative game and a competitive one, also played with the parent and with a stranger, with the underlying assumption that synchronization would be easier with the caregiver and in the cooperative task.

In Tang et al., the cooperative game is declined in another way, as the parents get to play together first, develop a strategy and then they can share this strategy with their children and play with them. The specific focus of this modified paradigm is to study how the parents' cooperative behaviour can be transmitted to the child and how it can affect the latter.

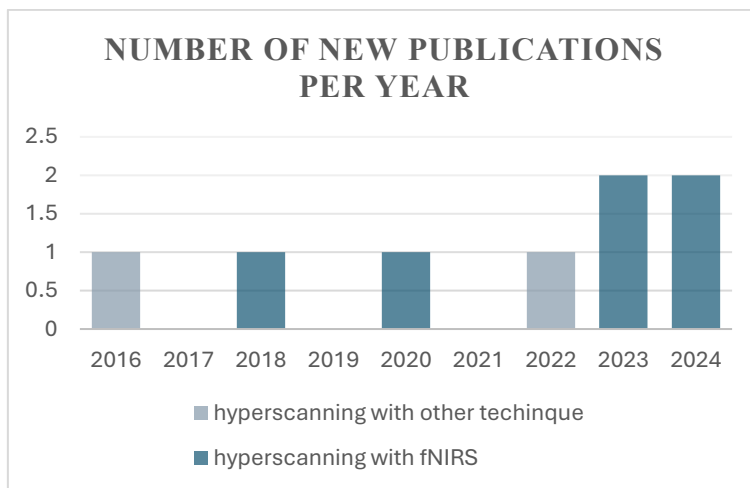
To summarize, three papers adopted a key pressing cooperation task, but with different aims and consequent changes in how the paradigm is implemented.

Lastly, Zhou et al. chose three tasks to study peer interaction between children with and without ASD, ranging from a low level of interaction (watching a video together and rolling on a chair), to a medium one (reading a story aloud) and a higher one (playing together Jenga). For every task, there was a control condition requiring the children to

perform the task alone. It is an interesting way of assessing different levels of spontaneous synchrony.

Overall, the possible paradigms are extremely variable in the degree of active synchronization and spontaneity, and special attention should be paid in providing a reliable control task for the comparison of brain activation.

2.2.3 Hyperscanning techniques and data analysis



In this graphic it is shown how the publications on this topic are progressively growing, although still in the prime of this field. In particular, in the last years the preference appears to be in paradigms involving fNIRS as the chosen technique for hyperscanning.

To assess the different techniques used in the selected papers, it is necessary to summarize first the definition of hyperscanning. “Hyperscan” is a term coined by Montague et al. in 2002, to describe their innovative fMRI paradigm: for the first time, participants’ brain activity is simultaneously acquired while they perform a deception game. According to the authors, the advantages are related to the possibility to investigate the neural processes that lead to understanding the other’s point of view and behaviour, even when we cannot see overt signs of this mentalization (in this case, before the game’s outcome).

This technique was then implemented also for EEG, MEG and fNIRS, to take advantage of the potential of each brain monitoring technique.

For example, Hasegawa et al. chose MEG to test the hypothesis that mu suppression responses, linked to social information processing, could be atypical in the ASD population. They then proceeded to calculate the correlation between mothers' and children's index of Mu suppression.

Key et al. applied an EEG paradigm, because in previous studies (Kinreich et al., 2017 and Perez et al., 2017, cited in Key et al., 2022) electroencephalography has been used to assess the coordination of neural activity during conversation. The subsequent analysis of synchrony was calculated as the correlation of oscillatory amplitudes in theta (4–8 Hz), alpha (8–12 Hz), and beta (12–30 Hz) bands, in the temporoparietal electrodes.

In the remaining six experiments, hyperscanning was performed using functional Near-Infrared spectroscopy, that measures changes in the bloodstream's level of oxygenation. Its application on developmental population is advantageous because the set up is fast and it allows the participants to move. The analysis performed on these data is the Wavelet transform coherence, which will be further explored in the following chapter.

2.2.4 Regions of interest

Among the selected papers, there is a general consensus on the brain regions implied in cooperation and coordination, however, differences in the specific aim or operationalization of the construct of interpersonal synchrony can lead to different choices in the analysis of neural activity.

In the first place, different techniques require specific approaches: in MEG and EEG the coverage is on whole brain, and ROIs are identified to analyse the data, in fNIRS it is possible to only cover specific areas (and it is the most common choice).

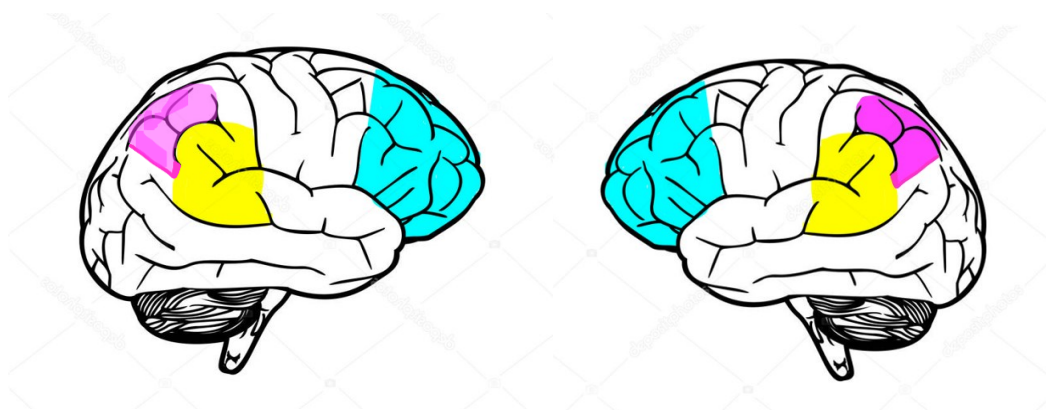
Regarding Hasegawa's study on Mu suppression, the approach is different from the region selection performed for the other techniques: the correlation between the indexes of Mu suppression in mothers and children is calculated in all the brain areas, and as a result, a higher correlation is highlighted in the right precentral area.

In the EEG study of Key et al., the selected region for statistical analysis is the bilateral temporoparietal area: the electrodes in this region are taken into account for hyperconnectivity, instead of all the possible electrode pairs, to reduce the possibility of spurious results.

The fNIRS experiments focus on the prefrontal and temporoparietal regions.

According to previous research, frontal regions are active during cooperation games (Decety et al., 2004) and social behaviour (Rilling et al., 2002), and contain mirror neurons, that allow us to understand each other's intentions (Iacoboni et al., 2005).

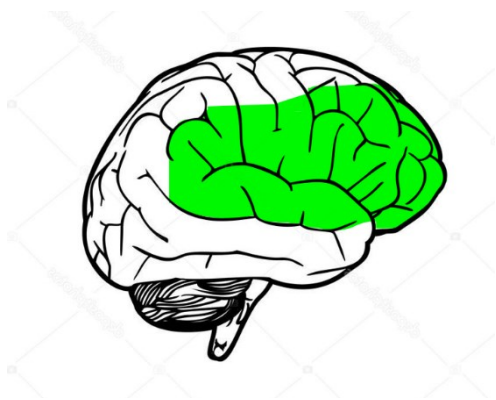
Temporo-parietal junction is another component considered for theory of mind and mentalization about other people, selectively involved in representing what another person is thinking about and mental states (Saxe & Kanwisher, 2003).



■ Du, Zhou

■ Du, Wang, Zhou, Kruppa

■ Du



■ Tang (only the right hemisphere), Minagawa (bilateral)

2.2.5 Results

Given the limited number and heterogeneity of the studies, it is difficult to provide a unified point of view on the results. Nonetheless, it is possible to discuss some commonly emerging patterns.

In general, the experimental conditions differing in quality and quantity of social interaction manage to produce a difference in behavioural and brain synchrony, meaning that the experimental manipulation is working: for example, in Zhou et al. watching a video together vs alone increase interpersonal synchrony.

Regarding the effect of ASD on interpersonal synchrony, there is less agreement among the results.

Three studies compared the performance of ASD children and non-ASD, one of high and low risk of developing autism. The latter was also investigating newborns (Minagawa et al.), and the neural results highlight no difference between the two populations, but interesting correlations between the degree of neural coupling and the measurements of attachment and sensitivity of the mother.

In these three studies, Tang found no difference in the behavioural performance and neural correlates, but reported the tendency of parents of the ASD group to adjust more to their children, to mitigate the effects of a lower level of cooperation in the game. In Kruppa, typically developing children showed increased interbrain coherence when interacting with the parent than with a stranger, while ASD did not show this pattern.

In Du, the task was different, regarding motor imitation: the findings seem to suggest a difference in how children with and without ASD perceive gestures: the non-ASD group

showed a better behavioural performance than ASD (accuracy and behavioural synchrony), and increased INS in meaningless movements, while ASD's INS was higher during the imitation of meaningful movements: the hypothetical explanation could be that non autistic children overestimate their ability to imitate meaningful (more common) gestures, while ASD put more effort into understanding and imitating this kind of motor patterns.

The other studies focused on the relationship between autistic symptoms and interpersonal synchrony, and it is found that higher neural synchrony is correlated with less autistic symptoms and higher theory of mind scores (Key et al.), lower AQ scores, but only in the cooperation condition (Wang et al.), and lower SRS scores (Hasegawa et al.).

Zhou propose a more complex analysis not only on the quantity of interaction, but on the qualitative differences: in the three experiments children with higher or lower autistic traits contribute in different ways to interbrain connectivity, showing that it is not merely a question of increase or decrease, but could be seen as a change in how a person can support the interaction.

To conclude, this line of research is taking its first steps into understanding better interpersonal synchrony, also at the neural level. The first results suggest an atypical response in autistic children, but it is not clear how deep and significant are these changes in comparison to typical development. It would be interesting to focus on early precursors of autism, to detect when and how developmental trajectories vary, and what can be done to address interactional fragilities in ASD.

It is also fundamental to extend these studies to larger and more diverse samples, and to involve typical developing children for comparison, but also interactions between children with autistic traits. It would also be interesting to expand the study of synchrony towards peer interaction and other social contexts.

From the methodological point of view, there is not yet an established model for hyperscanning techniques. There is a general consensus on the brain areas involved in synchrony, but different experimental tasks can involve slightly different networks. The tasks themselves are heterogeneous and can differ in the amount of interaction between persons (from passively watching a video together to a conversation or a game) and in the type of synchrony (motor or cooperation in a game, for example, but also spontaneous

or inducted). Moreover, applying neuroimaging or other kind of measurements to children can add complexity, as the development of different regions has to be taken into account, and also the analysis of the collected data can be challenging.

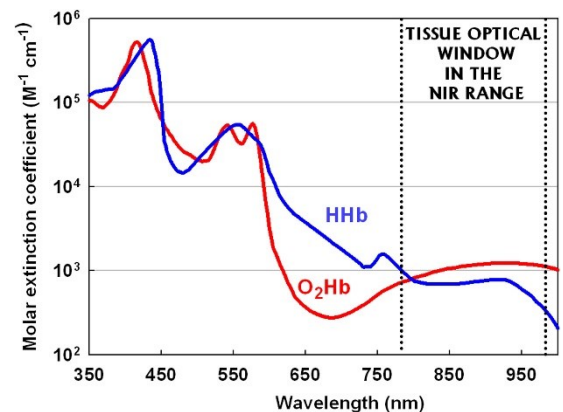
Chapter 3: Functional Near Infrared Spectroscopy: applications in the developmental population

3.1 functional Near-Infrared Spectroscopy

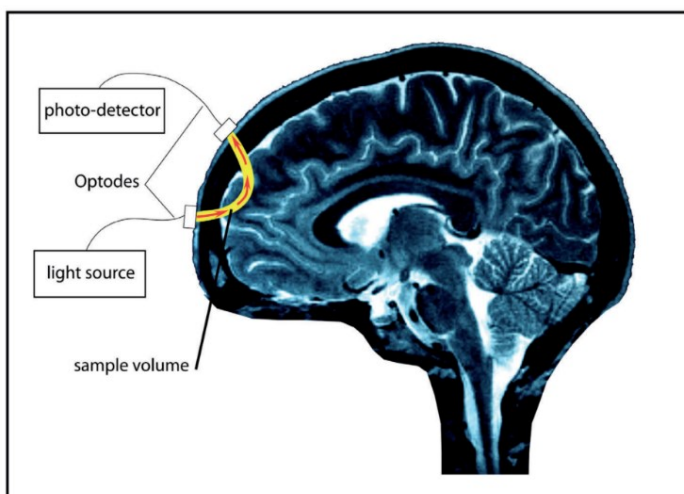
Functional near-infrared spectroscopy is a non-invasive technique used to measure brain hemodynamics and to consequently infer neural activity.

These measurements rely on the human tissues property to partially absorb and partially scatter near-infrared light, and the fact that the absorption spectrum of haemoglobin changes accordingly to the amount of oxygen that it carries (Ferrari et al., 2012).

The main functioning is based on sources (light emitting diode) of near-infrared light, that shine through the scalp and skull, reach the cortex and it is then captured by a detector, also positioned on the scalp. By knowing the amount of light that has been absorbed during this journey, it is possible to calculate the changes in concentration of oxygenated and deoxygenated haemoglobin, as these two chromophores have different optical properties (absorption spectra) (Boas et al., 2014).



In Quaresima and Ferrari, 2016

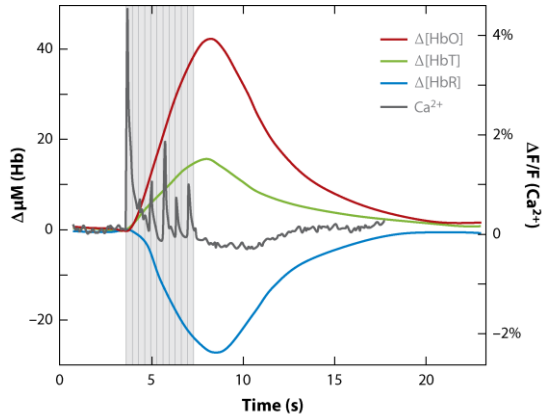


In Bright, 2012

The most diffused instruments use continuous wave technology, that measures the intensity of the light emerging from the tissue and compares it to the emitting source, and usually they imply the use of two wavelengths: although there are different analysis and simulations that report varying

results, the most used wavelengths are 830 nm, paired with 690 or 760 nm. From the

resulting light detected, it is possible to calculate the concentration of oxygenated and deoxygenated haemoglobin with the modified Beer-Lambert law, that takes into account the loss of light intensity, the absorption in different tissues, path factors and other coefficients (Scholkmann et al., 2014).



Like magnetic resonance imaging, fNIRS measures the metabolic response of increased oxygenation in the areas more activated, known as blood oxygenated level dependant (BOLD) response. Changes in the amount of oxygenated and deoxygenated haemoglobin (respectively HbO and HbR) are an indirect measure of the neural response, as they are

produced by neurovascular coupling (Hillman, 2014): in fact, cerebral blood flow increase in connection with neural activity, through a complex series of interactions involving neurons and the vascular system, where increased brain activity requires more supplies in glucose and oxygen, that cause vasodilatation and increased blood flow (Quaresima & Ferrari, 2016).

While the temporal resolution of fNIRS is comparable to fMRI's, because they are both based on the same metabolic response, spatial resolution is restricted to the space between source and detector, and the depth is limited to few centimetres, allowing to detect only cortical activity (Scarapicchia et al., 2018). Reachable depth is influenced by light's wavelength, which, in turn, is limited by the optical window of the chromophores, and by the distance between the optodes: the source and the detector must be placed in order to maximize the penetration (the greater the distance, the greater the penetration), but also to minimize the loss of detected light (the greater the distance, the greater the loss), and usually the recommended distance is of 3 centimetres in adults (in Bright, 2012). As photons propagate in different directions and the light is scattered while penetrating the tissues, the brain area covered by the source-detector pair is predicted via simulations and head models, the most famous of which is the Monte Carlo simulation of coverage (Quaresima & Ferrari, 2019).

Another notable limitation consists in the artifacts produced by cardiac pulsation, Mayer waves and all the physiological interferences. Passing through the scalp and skull, the amount of NIR light detected is influenced by haemodynamic changes that do not originate in the brain: this noise source can be partially removed during the data preprocessing, but can also be attenuated directly during the data collection. It is in fact possible to add short channel detectors, placed closer to the source of light (few millimeters), consequently measuring only light passing through the superficial tissues: in this case, this short optode distance allows to detect only extra-cerebral haemodynamic changes, and to regress it from the total signal, cleaning it from artefacts (Brigadoi & Cooper, 2015).

Zhou et al. (2020) compared two different approaches to reduce the noise component from the signal, with and without short channels: a short channel subtraction method with the general linear model and an anti-correlation correction. Both the analysis significantly reduce systemic noise from the fNIRS signal, but the GLM method with short channels is more efficient in improving the quality of the signal.

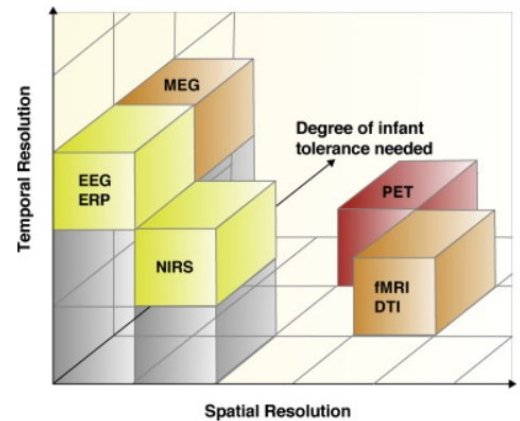
Apart from the aforementioned drawbacks and challenges, near-infrared spectroscopy can offer advantages: it's cheaper than other techniques, its setup requires less time, it can be portable and resistant to movements, and these characteristics make it suitable for different populations and experimental settings (Pinti et al., 2020). In comparison, fMRI is more expensive and requires the participant to stay still and confined in the scan environment, preventing the experimental design to include highly ecological situations, and EEG necessitates significantly more time to prepare for and is equally not suitable for moving around (Cutini & Brigadoi, 2014). Moreover, fNIRS measurements can be performed in combination with other practices, for example magnetic and electrical brain stimulation, because it does not interfere with these magnetic objects or fields.

3.2 Use of fNIRS in the developmental population

The characteristics of a quick setup and the possibility to move without interfering significantly with the signal acquisition make the fNIRS suitable for infants and children, to better understand neural activation in early developmental stages. Furthermore, skull and tissues are less thick in children than in adults, and light can penetrate better (Gervain et al., 2023).

Wilcox and Biondi (2015) in their review identified three principal domains investigated with fNIRS during development:

processing of objects, processing of social information and language development. In these fields would be in fact relevant to research how infants start to explore and form knowledge of the outside world, and the possibility to examine their brain activity and specialization can be used in this direction. In particular, it could be possible to compare different age groups to understand how brain activation changes during time, and in the early stages how domain general and domain specific mechanisms can shape different ways of learning. For example, in the studies reviewed it appears that specialization of the right hemisphere for face recognition is already present at 5 months, but only for frontal views, while for profile views it starts at 8 months, following the infants' advancement in recognizing social stimuli from different perspectives.



From Lloyd-Fox et al., 2010

Table 7.1 Relative attributes of the three most widely used neuroimaging techniques for the study of infant brain development.

Technique	fNIRS	EEG	fMRI
Type of response measured	Changes in HbO ₂ and HHb concentration	Neuronal excitation	Changes in BOLD (mainly HHb concentration)
Spatial localization of response	Good	Relatively poor	Very good
Time locking of response	Good	Very good	Relatively poor
Acquisition of signal	Milliseconds	Milliseconds	Seconds
Timing of signal	Seconds	Milliseconds	Seconds
Participant State	Awake/asleep	Awake/asleep	Asleep/immobile
Experimental Setting	Infant on parent's lap/seated or mobile	Infant on parent's lap/seated or mobile	Infant wrapped up on bed in MRI scanner
Freedom of movement of participants	Relatively high	Relatively high	None
Freedom of movement of equipment	Yes	Yes	No
Length of preparation of participants	Short	Short/Medium	Long
Length of experiment	Short	Short	Long
Instrumentation noise	None	None	High—ear protection needed
Cost of study	Fairly low	Fairly low	Relatively high

Another example of learning processes indagated with fNIRS is the study of Benavides-Varela et al. (2017) on early word recognition: already in newborns, in an ecological setting with auditory interferences, there are signatures of encoding and habituation responses, and consequent recognition of words lateralized in the right hemisphere.

From Kadosh, K. C. (2024). *Oxford Handbook of Developmental Cognitive Neuroscience*.

An additional positive contribution of fNIRS is the ecological validity that this technique can preserve: although video-recorded stimuli are more precise and predictable, live social stimuli are more interactive, more salient for children, and can elicit different responses from 2D versions (Gervain et al., 2023).

Advancements in the study of the developing brain encourage researchers to focus on early signs of atypical development and to investigate how and when the developmental trajectory deviates from the typical path. fNIRS is suitable for studies with children with autism for the aforementioned reasons, and also because fMRI could be too claustrophobic and restraining for this population and too noisy to study language perception and its impairment (Zhang and Roeyers, 2019). Furthermore, it is suitable to study early indicators of ASD in infants at high risk to develop it, because it can be adapted for infants.

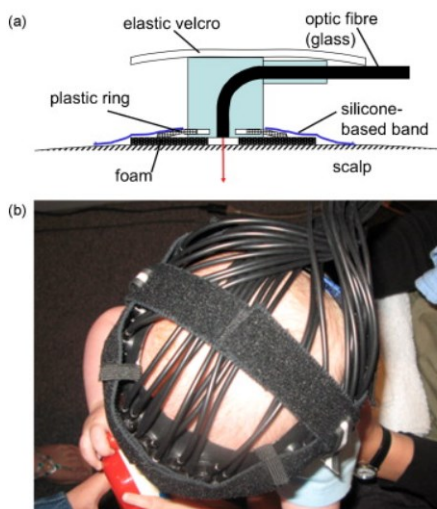
For example, 4-6 months old, who will later be diagnosed with ASD, showed diminished activity measured with fNIRS in the temporal and inferior frontal areas when attending to social stimuli, if compared to infants at high risk but who will not be diagnosed (Lloyd-Fox et al., 2018). Other studies on autism focus on the correlates of abnormal sensory perception and processing, on atypical brain connectivity (both in infants at high risk and in diagnosed children), social difficulties (e.g. face processing and social stimuli), confirming and deepening our understanding (for an extensive review, see Liu et al., 2019).

But in order to collect data from developmental population, some adjustments in the setup and analysis are required. As a relatively recent technique, the problem of fNIRS methodology and best practices has not been fully addressed, and the question becomes even more pressing when applied to infant studies. In the meta-analysis by Gemignani et al. (2023), results from studies conducted with fNIRS on infants are found to replicate reliably, nonetheless the issue of lack of standardization persists, with additional challenges like a larger amount of missing data for children, shorter experimental designs (to maintain their focus), unclear rejection criteria.

Among the technical aspects that need to be considered when applying fNIRS to infants, it is still not clear if the optimal wavelengths used in adults are also optimal for children, and if it is sufficient to calculate a proportionated distance of the optodes based on the same considerations made for adults, or if the different skull and scalp thickness and vasculature should arise special concerns (Aslin et al., 2005). For example, with a source-detector distance of 3 cm, the penetration of NIR light should be of 3-5 mm for adults, and 10-15 mm in newborns (Gervain et al., 2011).

Another issue is related to movement artifacts: even if fNIRS is relatively resistant to movement, it is still important for the cap not to slip or lose the contact between scalp and optode. Aslin revise the main solutions adopted, starting with the creation of probe-holders specifically designed for children and adapted to be more stable, then, during the processing of the data, artifacts can be removed with automatic algorithms or statistical techniques, aiming to eliminate signal if it has shared variance.

Unlike studies in adults, it is more challenging to prepare the child for the experiment, so



From Lloyd-Fox et al., 2010

it is crucial to have an equipment specifically studied to be ready when in place (caps with a stable optode placement and that do not require adjustments of the signal) and to not distract the participant during the trials and still provide robust data (Lloyd-Fox et al., 2010).

For example, the Birkbeck/UCL laboratory designed a specific headgear that improved signal quality and reduced the quantity of excluded channels, that is also lighter and less uncomfortable (in the figure).

Regarding the study design, usually infant studies use a block design, with the presentation of experimental stimuli alternating to a baseline condition (Lloyd-Fox, 2024). As for adults' studies, the design should consider effects of adaptation and anticipation, but the number of trials should additionally take into account the higher probability of discarding trials (due to children moving or not complying with the experiment). Usually, an additional step in the preprocessing pipeline of children's data require to discard all the trials in which the participant is not paying attention to the stimuli

(e.g. analyse the video-recording of the session and mark when the child is looking away) (Lloyd-Fox et al., 2010).

After data collection, also preprocessing steps should be adapted for infants' data. Gemignani compared different pipelines for data analysis and highlighted theoretical difficulties that arise (Gemignani & Gervain, 2021). The first obstacle is the intrinsic difference in the haemodynamic response function in infancy compared to the adult canonical response, due to the developmental changes that occur in brain development and neurovascular coupling in the first months of life: the implication is that the haemodynamic function could be atypical, but during preprocessing it should not be overly corrected to approximate it to the adult's data.

Regarding the haemodynamic response, literature also reports inverted responses (when HbO decreases and HbR increases after stimulus presentation) in infants and young children. In adults, the explanation for this phenomenon is usually errors in the choice of stimuli (the control condition elicits more activity than the main condition), or that the region is inhibited. It is not clear how these factors influence infants' responses, but it is reported that HRF changes in function of the cortical region investigated and the cognitive function elicited in children (Issard & Gervain, 2018) and it is suggested that the choice of different wavelengths (with less distance between the lower and higher length) could influence the registration of HbO and HbR (Cristia et al., 2013).

The majority of the studies report HbO changes, and not HbR, because these changes are more similar to adults', and have a better signal-to-noise ratio (Lloyd-Fox et al., 2010).

Moreover, motion correction techniques that work well on adults might not be the best option for children's data, and different options should be taken into consideration depending on the specific age of the subjects and the amount of noise in the dataset. Overall results from the comparison performed by Gemignani and Gervain seem to report a trade-off between being restrictive in deciding whether to include noisy trials or not and having a better quality of the HRF, thus the decision should be made based on the amount of data collected and their noisiness, with further research needed to better specify filtering parameters revised for developmental studies.

To analyse the data, there are two main approaches: time series analysis, based on the averaging of trials, compared with t-tests to the baseline and with analysis of variance if the comparison is between different conditions. The second method is inspired by fMRI analysis, and uses the General Linear Model approach, calculating how fNIRS data are correlated with a predictor: with children’s data the problem is to have a reliable HRF to compare to (Gervain et al., 2011).

3.3 Hyperscanning and development: methods and challenges

As stated in the first chapter, interpersonal synchrony during development can facilitate the acquisition of different skills and abilities, like emotion regulation, cooperation and prosocial behaviour, and it’s predictive of better attachment. Studying synchrony at the neural level is therefore useful to understand the underlying processes.

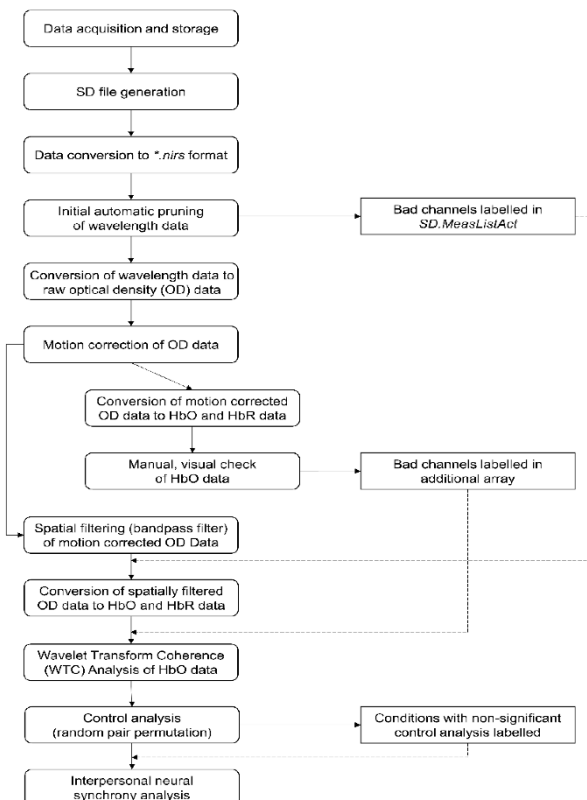
Experimental tasks can include continuously mutual interaction (like finger tapping or a key-pressing task) and turn-based interaction (communication or turn-taking games) (Liu & Pelowski, 2014), and specific tasks can be employed to study interpersonal

coordination in children and toddlers. Parent-child interaction can be studied during conversations and information sharing, but also, at earlier stages, during non-verbal exchanges, like gaze sharing and episodes of affective touch (Bi et al., 2023).

Here we report an example of pipeline adopted to preprocess and analyse data acquired during an hyperscanning fNIRS experiment on parent-child interaction, provided by Nguyen et al. (2021c). Data are collected during a cooperative and competitive problem-solving task, with 5-6 years old playing with their mothers.

In hyperscanning paradigms with fNIRS, one device can be split between two participants (the

two different sets of optodes originating from the same device) or two devices can be



used and synchronized. The advantage of the first method is not having to synchronize multiple devices, but the participants are linked, and therefore unable to freely move.

After data collection, the preprocessing phase usually starts with a quality check of the channels and eventual pruning. Raw wavelength data can then be converted to optical density, and motion correction methods and band-pass filters can be applied, and then another conversion to concentration changes in HbO and HbR.

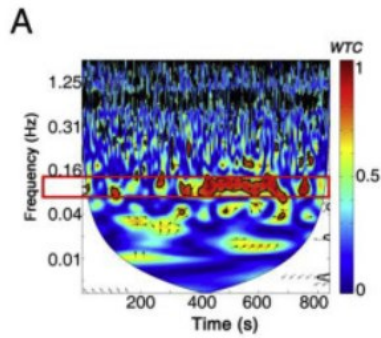
The most used model to calculate interbrain synchronization is the Wavelet Transform Coherence (WTC), but other methods of correlations are possible. For example, with Pearson correlation it is possible to analyse how neural data covary together, but only in a linear relationship (it can't show a directional interaction, if present), but the adaptation of Cross correlation can compute time lagged influences (Hakim et al., 2023). Methods based on the General linear model logic can also be applied, for example with cross brain GLM neural data from one participant of the hyperscanning are used as predictor for the data of the other participant, with the possibility to include time regressors as well.

For coherence, the data are represented in the time-frequency domain (thus giving more information than correlation analysis, based only on the time domain), and Wavelet Transform coherence is indicated for non-stationary data, like biological signals. One of the advantages is that it can reflect out-of-phase interactions (when the participants' activity is not perfectly aligned).

The continuous wavelet transform is useful to highlight patterns and changes of the frequencies over time, as it calculates the coherence and phase lag of the two time series. Even if the main use until now has been to calculate in-phase synchrony, WTC has the potential to take into account also lagged synchronization and anti-phase synchronization (Gvirts Problovski et al., 2023).

Another advantage is that WTC is less sensitive to HRF shape, that can change in different brain regions and in different ages, and this is particularly useful when comparing activation in participants of different age groups (Gvirts Problovski et al., 2023).

WTC usually adopt the Morlet wavelet as the mathematical function used to analyse the signal, that fit particularly well to neural data and their oscillatory nature and it's localized in time and space (Chang & Glover, 2010; Torrence & Compo, 1998).



The visual representation is a heat map (in the figure an example from Pan et al., 2018) of the coherence in HbO signal from the same channel in the two participants of the dyad. The colors, ranging from blue to red, display how low or high is the coherence for each frequency (y axis) for each point in time (x axis).

There is still debate on how to choose the frequencies to compute, because the relationship between frequency and indirect registration of brain function is not clear: it is possible to use frequencies based on the task-frequency, or use computational methods to calculate the frequencies that differentiate between task and rest. In Nguyen et al. (2021c), the frequency is decided based on the most task-relevant, and the general recommendation is to avoid frequencies related to physiological noise (for example, cardiac pulsation at 1 Hz).

These methods assess functional hyperconnectivity, while for effective hyperconnectivity (incorporating causality of interaction) other calculations are needed, for example Granger causality (Scholkman et al., 2013).

Another challenge regards the differentiation between similarities in neural responses due to the presentation of similar stimuli to both the participants and the genuine similarity due to the interaction in the dyad. To overcome this problem, some analysis add a partial correlation coefficient (when calculating the correlation), or another approach is to create random pairs, to compare how brain activity is influenced only by the environment and how on the other hand is created by the real interaction (Czeszumski et al., 2020).

To move forward from tentative interpretations of synchronized activity, experimental designs could integrate multiple sources of information, for example collecting behavioural data and analysing how well overt synchronized interactions couple with brain activation (Hamilton, 2021). Furthermore, a better understanding of the integration of different sources of data and a solid basis for interpretation of brain activation could help to implement studies with naturalistic interactions, and lower the need for strict trials and restricted ways of engaging in social exchanges.

If in typical adults the basic assumption is that during social exchanges the person is trying to control their own behaviour and at the same time understanding and predicting the other's behaviour, using hyperscanning in children could shed light on how this prediction mechanisms develop and modify throughout life cycle.

In summary, hyperscanning has the potential to design studies on real interactions, from the simultaneous point of view of all the actors involved, but it still needs a solid framework on how to analyse the data, and more importantly how to draw conclusions from the results collected.

Conclusions

To be in synch with the people around us in everyday life is a crucial social skill, but in certain situations can also be a struggle. Investigating how this ability can differ in atypical development can sensitize both the common perception about ASD people's interactions and clinical efforts to establish interventions and guidelines.

The aim of this review is to summarise where we are in the study of inter-brain synchronization in developmental population with ASD. The picture emerging from hyperscanning studies is still blurry, but it can be a draft with useful hints for future directions.

The main take home message could be that we have a general consensus on social difficulties in ASD, and this is also evident in atypical patterns of inter-brain correlation, with unusual connections and different patterns of brain activity.

Nonetheless, there is still a lack of standardization on methodological questions, regarding for example how to analyse and interpret the data, or even how to collect them. The diversity of symptoms and levels of functioning in ASD is an additional challenge, with studies often performed on high functioning children, leaving out of the picture more severe cases.

Moreover, social skills and needs can rapidly vary during childhood and adolescence, and research should aim to cover these changes and expand our knowledge about social interactions not only with the caregiver, but also with peers and other meaningful adults. Interpersonal synchrony with parents is the foundation of future interactions during infancy, but interactions with persons less aware of autistic traits or less incline to comply with it are everyday occurrence, especially during school and childhood, and it is therefore useful to better comprehend how these exchanges unfold.

The current perspective is also focused on more structured forms of interaction, like cooperative games and tasks, because the extent of present research has not formed yet enough basis to freely explore different settings. After the consolidation of solid paradigms and a deeper understanding of results, it would be possible to increase variability and to cover more naturalistic interactions. Hyperscanning with fNIRS can still

be seen as an improving factor for ecological studies, as it allows participants to move and interact without being overly confined. The lack of homogeneity in the papers is therefore partially due to the recent introduction of these paradigms, and partially to the intrinsic heterogeneity of both ASD subjects and the definition of synchrony itself.

Hyperscanning techniques demonstrated to be useful to analyse neural correlates of interpersonal synchrony and connections, and, by doing so, to address specific research questions. With the rapid improvements happening in this field and the researchers' attention to the establishment of guidelines, it will be possible to explore thoroughly the topic of brain synch in ASD population.

In this review, only eight papers met the inclusion criteria, depicting the state of the art as still insufficient to draw decisive conclusions. In particular, research's paradigms were so different that was not possible to make a satisfactory meta-analytic summary. It was although possible to detect some trends in the Regions of Interest included (mainly prefrontal and temporoparietal), the tasks used (cooperative and competitive games), the dyads selected (parent-child) and the preferred hyperscanning technique (fNIRS, with Wavelet Coherence Transform as analysis of synch).

Despite the lack of homogeneity, it is important to start collecting the pieces of knowledge at our disposal, and to organize them in a structured effort to have a clear understanding of the current situation and the future directions needed to refine the picture.

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