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REVIEW

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In and out of synchrony—Behavioral and physiological dynamics of dyadic interpersonal coordination

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Abstract

Interpersonal synchrony, the temporal coordination of actions, emotions, thoughts and physiological processes, is a widely studied ubiquitous phenomenon. Research has already established that more synchrony is not always more beneficial, especially in the fields of emotional and physiological synchrony. Despite this fact, the dominant tone in the literature is that behavioral interpersonal synchrony is a pro-social phenomenon, and hence, in social contexts, more behavioral synchrony is generally considered better. In accordance with that tone, the naturally occurring dynamics of moving in and out of synchrony have rarely been studied or considered as an adaptive state. In the present article, we aim to present a new model of interpersonal synchrony, based on the existing literature assessing synchrony as well as the ideas of complex dynamical systems. At the core of our model is the idea that two tendencies exist simultaneously, one to synchronize with others and another to move out of synchrony and act independently. We suggest that an adaptive interpersonal system is a flexible one, able to continuously adjust itself to the social context. We suggest that the concept of meta-stability might be a marker of such a flexible interpersonal system. Moreover, the model considers both behavioral and physiological aspects in order to provide a more extensive account. We present research implications of the model, as well as a demonstration of the model's applicability to data, and provide code researchers can use to analyze their own data in these methods. Finally, we discuss future directions in detail.

KEYWORDS

dynamical systems, interpersonal synchrony, meta stability, physiological synchrony

1 | INTRODUCTION

1.1 | Interpersonal synchrony

Interpersonal synchrony is defined as the spontaneous rhythmic and temporal coordination of actions, emotions, thoughts and physiological processes between two or more participants (Ackerman & Bargh, 2010; Bernieri & Rosenthal, 1991; Palumbo et al., 2017). Although there is a considerable variability in terms (e.g., behavioral matching, alignment, mirroring; Hasson & Frith, 2016; Vicaria & Dickens, 2016), interpersonal synchrony is usually considered to be a part of a broader term - interpersonal coordination (Bernieri & Rosenthal, 1991). Interpersonal coordination refers to the interdependence between two or more people that can be divided into two main concepts: behavioral mimicry and interpersonal synchrony. Behavioral mimicry occurs when people behave in the same way in a relatively short period of time (for a review see Chartrand & Lakin, 2013). Interpersonal synchrony differs from mimicry in two main ways: (a) In interpersonal synchrony timing is critical, whereas in mimicry the same behavior occurs in a short window of time, but the timing and rhythm of the behavior is not considered; (b) In mimicry individuals' behaviors are similar or even identical, whereas, in interpersonal synchrony, complementary behavior (e.g., turn-taking in conversation) can also be considered synchronized (Ackerman & Bargh, 2010; Chartrand & Lakin, 2013).

Interpersonal synchrony is widespread across various human activities and has recently been suggested as an evolutionary-based mechanism for facilitating social cohesion and bonding (Launay, Tarr, & Dunbar, 2016). Evidence from developmental studies show that parent-infant synchrony is a cornerstone of social development, and most particularly crucial for the development of self-regulation, empathy, and symbolic skills (for a review see, Feldman, 2007). In adulthood, research has shown that interpersonal synchrony has profound social effects such as increased pro-social behavior, improvement in social cognition and pro-social attitudes, and blurring of self-other boundaries (for reviews see Mogan, Fischer, & Bulbulia, 2017; Rennung & Göritz, 2016; Vicaria & Dickens, 2016).

It is worth mentioning that there is some confusion in the literature regarding the specific definitions of synchrony, and as Butler (2011) suggested, it is important to distinguish between types of synchrony discussed, and the way these types are conceptualized and computed. Butler argues that these distinctions denote meaningful aspects of the coupling and the dynamic system. For example, synchrony may sometimes relate to homeostatic-stable (morphostatic) processes and at other times to developing and changing patterns (morphogenic). Otherwise, synchrony can be in-phase or anti-phase (see also section 4). For the scope and purposes of the current article—we will use the term synchrony as it refers to a concurrent co-variation.

Most of the research on interpersonal synchrony focuses on behavioral synchrony, and more specifically on synchrony of body movements. In accordance, we focus here on research that examined bodily motion. Research on this topic has assessed a large variety of movements: laboratory studies of basic synchronous motions such as finger tapping (Hove & Risen, 2009) and chair rocking in shared rhythm (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007), spontaneous synchronization of leg movements in athletes (Varlet & Richardson, 2015), hand-clapping concert halls (Néda, Ravasz, Brechet, Vicsek, & Barabási, 2000), and body movements in natural settings such as conversations (Fujiwara & Daibo, 2016; Gaziv, Noy, Liron, & Alon, 2017; Tschacher, Rees, & Ramseyer, 2014). To sum the above research, it is clear that the behavioral synchrony of body movement occurs under varied settings and is widely studied.

Interpersonal synchrony also occurs at a physiological level, and we will address three main modes of this synchrony

TABLE 1 Types and modes of interpersonal coordination

Behavioral mimicry (also called mimicry or behavioral matching) occurs when people behave in the same way in a relatively short period of time.
Behavioral synchrony (sometimes also referred to as alignment) is the spontaneous rhythmic and temporal coordination of actions (usually body movement) between two or more individuals.
Physiological Synchrony is the spontaneous rhythmic and temporal coordination of physiological processes, comprised of:
1. Autonomic Nervous System (ANS) synchrony is defined as the interdependence or co-variation of ANS activity between two or more individuals over time.
2. Interbrain synchrony is the common neural activity in time across subjects.
3. Hormonal synchrony is the temporal inter-relatedness of hormones' levels between people.

(see Table 1): Autonomic Nervous System (ANS), neural and hormonal (these three forms of physiological synchrony along with behavioral synchrony were identified in a recent review (Feldman, 2017) as the four systems in which interpersonal synchrony occurs). For this article, ANS synchrony is defined as the interdependence or co-variation of ANS activity over time between two or more individuals (Palumbo et al., 2017). ANS activity is usually assessed by measures such as heart rate (HR) and heart rate variability (HRV), respiratory sinus arrhythmia (RSA), cardiological impedance, blood pressure, electrodermal activity (EDA). These measures are usually divided into measures of the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS; Palumbo et al., 2017). For example, EDA is related to the activation of SNS (Boucsein, 2012), whereas RSA is more related to the activation of PNS (Task Force of the European Society of Cardiology, 1996). ANS synchrony is ubiquitous and has been found in many social contexts such as: between therapists and patients, between romantic couples, between children and their parents and even between strangers (for a recent review, see Palumbo et al., 2017).

Neural or brain synchrony is a relatively new avenue of research, that started with the seminal work of Montague et al. (2002) introducing the "hyperscanning" technique. Hyperscanning is when two or more brains' activities are recorded simultaneously (usually by EEG, MEG, fMRI or near-infrared spectrometry (NIRS)) to measure their common activity. The common neural activity in time across subjects is called *interbrain synchronization* and has been found in many settings (for review see Babiloni & Astolfi, 2014). For example, in a study that observed turn-taking during verbal interactions, interbrain synchrony was found in the alpha band in EEG data and in alpha and gamma bands in MEG data (Ahn et al., 2018). Overall, interbrain synchrony has been found in many settings such as: while synchronizing simple movements, talking, playing games and during facial expression communication in couples (Babiloni & Astolfi, 2014).

Interpersonal synchrony also occurs at the hormonal level, which has also been termed the "endocrine fit" (Feldman, 2017). Hormonal synchrony, the temporal inter-relatedness of hormone levels between people, is usually studied in romantic couples and in child-parent relationships. For example, it has been reported that during the first six months of parenting, maternal and paternal level of peripheral oxytocin (OT) were positively correlated (Gordon, Zagoory-Sharon, Leckman, & Feldman, 2010). Other studies, for example, have found that spouses tend to synchronize their cortisol levels (Liu, Rovine, Cousino Klein, & Almeida, 2013; Papp, Pendry, Simon, & Adam, 2013).

Table 1 summarizes the above-mentioned definitions of different types and modes of interpersonal coordination.

2 | ARTICLE OUTLINE

Research has already established that more synchrony is not always beneficial (Butler, 2015, 2017; Palumbo et al., 2017). This has been acknowledged especially in the fields of emotional and physiological synchrony (e.g., Gates, Gatzke-Kopp, Sandsten, & Blandon, 2015; Levenson & Gottman, 1983). Despite this fact, the dominant tone in the literature about *behavioral* interpersonal synchrony, although usually only implicitly expressed, is that interpersonal synchrony is a pro-social phenomenon, and hence, in social contexts, the more synchrony is generally considered the better (or more pro-social, see Mogan et al., 2017; Rennung & Göritz, 2016; Vicaria & Dickens, 2016). In accordance with the dominant tone, the naturally occurring dynamics of moving in and out of behavioral synchrony is rarely studied, quantified or considered as an adaptive state (Dahan, Noy, Hart, Mayo, & Alon, 2016). But, if it is known that more synchrony is not always better, then how can we quantify synchrony accordingly? What are the contexts for which less behavioral synchrony is actually more suitable? Can moving in and out of synchrony, at times, be socially adaptive? Moreover, if so, what are the parameters that dictate these shifts? In the present article, we aim to deal with these issues and suggest entries and withdrawals from synchrony as a mechanism that describes the adaptive state of the interacting dyad. The current article will present a new model of interpersonal synchrony, which highlights the importance of flexibility in synchrony both at the behavioral and physiological levels. We will do so by considering a systems' perspective. Namely, we will address the interpersonal system as a whole, and our basic unit of research will be the interpersonal system as one social unit, and not each person separately.

In the next section, we will review both the evidence regarding entering and withdrawal from interpersonal synchrony and studies which address the question of how much synchrony is adaptive. Later, we will present our understanding of what is an adaptive interpersonal system, both on behavioral and physiological levels, through the perspective of complex dynamical systems' approach (Marsh, Richardson, & Schmidt, 2009). Then we will present our model. At the core of our model is the idea that two tendencies exist simultaneously, one to synchronize with others and another to move out of synchrony and act independently. We suggest that an adaptive interpersonal system is a flexible one, able to continuously adjust itself to the social context. Finally, we will discuss the model's implications for future research.

3 | IN AND OUT OF SYNCHRONY

In most interpersonal situations, people tend to move in and out of synchrony, rather than remain synchronized endlessly. Indeed, in many studies, behavioral synchrony occurred only in less than half of the time assessed (e.g., Feniger-Schaal et al., 2016; Noy, Dekel, & Alon, 2011). Developmental studies have shown that infant-parent interactions move back and forth from synchronous to a-synchronous behaviors, suggesting that such a pattern might be developmentally more adequate compared to endless synchrony (Feldman, 2007). To the best of our knowledge, only one study directly addressed the issue of withdrawal from behavioral synchrony, tried to adjust a mathematical model (which did not take into account departures from synchrony) to fit the pattern in which people tend to move in and out of synchrony in the "mirror game", a game in which participants were instructed to move handles synchronically (Dahan et al., 2016). These researchers showed that the model that considers both entering and withdrawal from synchrony fits better real data in "mirror game" than previous models. Critically, this research does not deal with the interpersonal meaning of such a phenomenon and its mechanisms.

Additional studies have shown that more interpersonal synchrony is not always more adaptive. Developmental studies revealed that mid-range infant-parent behavioral synchrony is associated with more securely attached children compared to too much or too little synchrony (Beebe & Steele, 2013). Physiological synchrony (measured by heart rate and heart rate variability) between infants and their parents also displays a more complex relationship: while overall increases in the child's arousal were related to an increase in parental arousal, when both parent's and child's arousal was high, the arousal of the parent tended to decrease, which may imply the there are times when withdrawal from synchrony may be adaptive (Wass et al., 2019). Studies of physiological synchrony in couples also provide mixed results: At times physiological synchrony related to more closeness in couples, and during other times it was related to poorer relationship outcomes (Timmons, Margolin, & Saxbe, 2015). In a study that explored the relationship between attachment style in adults and the amount of behavioral synchrony with each other in the "mirror game" (Feniger-Schaal et al., 2016), it was found that securely attached adults synchronize their behavior less than those with insecure attachments. These results were interpreted as reflecting a greater sense of security (in securely attached participants) that allowed individuals the freedom to disengage from synchrony under the assumption that they can re-enter the synchronous mode again. In addition, a study of dyadic problem solving has shown that less spontaneous behavioral synchrony (operationalized as overall body movement measured by video analysis) leads to a better performance (Abney, Paxton, Dale, & Kello, 2015). The authors suggested that reduced synchrony allows for a more flexible interpersonal organization compared to strong synchrony which reflects a more organized and less flexible interpersonal organization, and that such a flexible organization facilitates joint problem solving. Another study explored the relations between interpersonal synchrony, dyadic performance, and subjective feelings during a cooperative dyadic task (Wallot, Mitkidis, McGraw, & Roepstorff, 2016). In the aforementioned task, participants were instructed to build a car model made of Lego bricks together, while their hand movement and heart rate were assessed. Interestingly, hand movement synchrony (but not heart rate synchrony) was negatively related to task performance. Thus, more behavioral synchrony was related to a worse performance outcome. Moreover, hand movement synchrony was related positively to participants' subjective feelings during the task in one condition (when one of the participants was the "boss"), and negatively in another (when the task was more mutual). These results suggest that synchrony may differentially affect discrete aspects of the situation (social aspects vs. task-related aspects), and thus the amount of adaptive synchrony may heavily depend on the context. A recent study emphasized that interpersonal synchrony is not only beneficial (Galbusera, Finn, Tschacher, & Kyselo, 2019). In this study, participants took part in a dyadic body movement task. Interestingly, it was found that while behavioral synchrony was related to increased positive affect it was also related to decreased self-regulation. All these studies provide some support to the idea that more synchrony, both at the behavioral and physiological level, is not always adaptive or beneficial.

Only a small number of studies have shown that the extent of behavioral synchrony is also dependent on the social context. For example, one study reported that participants tend to synchronize their stepping movement less with a confederate that arrived 15 min late, compared to a confederate that arrived on time (Miles, Griffiths, Richardson, & Macrae, 2010). The authors suggested that participants tended to synchronize more when they held more positive (and less negative) feelings toward their co-actor. Another study has shown that participants synchronize their body movement more in an affiliative conversation compared to an argument (Paxton & Dale, 2013).

Considering this evidence, we suggest two main concepts that will guide our understating of interpersonal synchrony. First, that interpersonal synchrony does not follow a simple rule of "the more the better", but rather needs to be conceptualized in a more elaborated and complex framework, that is considering its different effects in varying contexts. Second, considering the tendency to move in and out of synchrony, there is a great need to understand the interpersonal meaning and mechanisms of such a pattern.

4 | COMPLEX DYNAMICAL SYSTEMS APPROACH TO INTERPERSONAL SYNCHRONY

In order to understand the main contribution of the complex dynamical systems approach to interpersonal synchrony research, we will briefly discuss the approach's main theoretical principals. The "dynamical" part simply refers to looking at temporal changes in behavior. Namely, the main focus is the behavioral change over time, rather than summarizing or averaging the behavior across the entire session (Richardson & Chemero, 2014; Richardson, Dale, & Marsh, 2014). The "complex" part refers to a nonlinear relationship between the system's elements, namely the whole system's behavior cannot be predicted by a reductionist understanding of each element in the system, as the elements do not interact in a linear-additive manner (Richardson & Chemero, 2014; Richardson et al., 2014).

Complex dynamical systems are defined by three main characteristics (Richardson & Chemero, 2014; Richardson et al., 2014). First, they consist of several interacting components. The second characteristic is called "emergence", that is the collective behavior takes a form of some coherent pattern (for discussion on interpersonal collective behavior, also called "interpersonal synergies", see Riley, Richardson, Shockley, & Ramenzoni, 2011), and that pattern cannot be extracted from simple component behavior. Third, this pattern is self-organized and does not require the central (internal or external) organization. The elements of the systems are also considered as "soft-assembled", meaning that the elements' behavior is not fixed, but rather determined by the interaction. Thus, this approach is "interaction dominant", hence the system's behavior emerges from the interaction between its components, which might change under different environmental conditions. Importantly, the term "interaction" refers to the exchange of energy (in physical systems) or information (in human systems). The amount of energy/information exchange is also considered as "coupling strength" (Marsh et al., 2009).

The complex dynamical systems approach has been widely applied to the understating of human social behavior (for a review see, Marsh et al., 2009). Specifically, within this theoretical framework, humans are seen as elements in a social unit, exchanging information, and the system's collective behavior can be understood and modeled. Thus, the different collective patterns that the system can or cannot exhibit were investigated and modeled. For example, one prominent trajectory of research regards the synchrony of oscillatory movements such as finger tapping. The dynamics of interpersonal behavior has been modeled by an equation called the "HKB equation" (Haken, Kelso, & Bunz, 1985; Marsh et al., 2009). This equation made predictions, which were confirmed later in many studies, about what kind of synergetic stable patterns can or cannot emerge. It was predicted that only two patterns, called "in phase" (when the two oscillating movements are in the same relative position) and "anti-phase", (when the two oscillating movements are in the opposite relative position) will emerge into stable states. Another prediction was that coupling strength is positively related to the amount of time the system will persist in stable states (Haken et al., 1985; Marsh et al., 2009). Other paradigms of interpersonal synchrony were investigated as well, such as non-oscillating movements (e.g., Shockley, Baker, Richardson, & Fowler, 2007), paradigms of intentional and unintentional synchrony, and synchrony under different social contexts such as cooperative and-non-cooperative tasks (Marsh et al., 2009). To summarize, the complex dynamical systems approach has been used to study the conditions in which the emergence of collective synchronized patterns of interpersonal interaction might occur, persist, or change.

The emergent patterns of a system can take on three prototypical forms (Tognoli & Kelso, 2014). In the first form, the system's behavior converges into a persistent synergetic stable pattern (or patterns), which means that the elements are synchronized with each other. Such a pattern might be stable under some conditions, whereas under other conditions different stable patterns might emerge (Richardson & Chemero, 2014; Richardson et al., 2014). In the second form, the elements exhibit no energy or information exchange, hence no collective behavior emerges. This is a rather rare condition as it means that the elements are completely isolated from each other. In the third form, the elements are coupled but because they exhibit different intrinsic behaviors, they do not become fully synchronized. In this third form, rather than persistent stable patterns, the system exhibits both synergetic tendencies and segregation tendencies. Thus, the behavior of the system dynamically changes between a more collective mode of behavior (also called quasi-synchrony), and a more segregated the mode of behavior. This form is called "meta-stability" (Kelso, 2012; Kelso & Tognoli, 2009; Tognoli & Kelso, 2014).

We suggest that adaptive interpersonal synchrony is a meta-stable phenomenon (see also Tognoli, Zhang, & Kelso, 2018), namely it contains both tendencies for synergetic action as one social unit and segregation tendencies for each participant to act independently (recently, similar ideas discussed in relation to group dynamics, Zhang, Kelso, & Tognoli, 2018). Thus, at times, the systems tend toward a more coordinated behavior and at times its' elements are almost independent. This also means that the two tendencies exist as latent potentials of the system, and might take place, to various extents, under different conditions. Thus, we suggest that the adaptive interpersonal system should adjust itself to the specific social context, since some contexts require higher level of synchrony (e.g., dancing or playing music together) whereas others might require a lower level of synchrony (e.g., walking together). In order to be adaptive, the system needs to be flexible so it can adjust to changes in the social context.

5 | PHYSIOLOGICAL SYNCHRONY IN RELATION TO BEHAVIORAL SYNCHRONY

The evidence for the relationship between ANS and behavioral synchrony is inconsistent (Palumbo et al., 2017). Although some studies have found an association between ANS and behavioral synchrony (e.g., Feldman, Magori-Cohen, Galili, Singer, & Louzoun, 2011), others have found that ANS and behavioral synchrony are relatively independent (e.g., Codrons, Bernardi, Vandoni, & Bernardi, 2014). A recent review (Palumbo et al., 2017) has concluded that behavioral and ANS synchrony are not always inter-dependent, and at times can occur separately. The authors suggested that ANS synchrony may reflect a shared experience, which is context dependent, and is at least partly independent from behavioral synchrony. One recent study (Zhang, Dumas, Kelso, & Tognoli, 2016) explored the connection between movement synchrony with a virtual player and ANS arousal using skin potential responses (SPR; which is a measure of EDA). This study has shown a positive association between the amount of behavioral synchrony and SPR. The authors also suggested that the relationship between ANS arousal and behavioral synchrony might be bi-directional, though no study has confirmed that hypothesis yet (Zhang et al., 2016).

Koole and Tschacher (2016) have suggested a model of synchrony in psychotherapy that supports the therapist-client alliance and explores the relationship between different types of synchrony (movement, neural, emotional and experiential). According to their model, behavioral synchrony of patient and therapist is underpinned by neural synchrony which dynamically shifts across time and supports alliance. These processes may lead to a co-regulation of emotions and language, which then may promote a better treatment outcome.

Few studies have found associations between neural and behavioral synchrony (Babiloni & Astolfi, 2014). For example, two studies have found synchronization of neural activity in the prefrontal cortices measured by Near Infra-red Spectroscopy Hyper-Scanning (NIRS) during synchronization of button press movements (Cui, Bryant, & Reiss, 2012; Funane et al., 2011). Synchronization of neural alpha band frequency activity measured by EEG, localized in right centroparietal scalp regions, has also been found during synchronization of hand movements (Dumas, Nadel, Soussignan, Martinerie, & Garnero, 2010). In a recent study (Kinreich, Djalovski, Kraus, Louzoun, & Feldman, 2017), behavioral and neural interpersonal synchrony has been found. Specifically, behavioral and neural synchrony was assessed during naturalistic social interaction, and it has been found that moments of behavioral synchrony (measured by gaze and affect expression) were temporally correlate with neural synchrony in gamma frequency measured by EEG, localized at the temporal-parietal regions. Neural synchrony has also been found to be higher in romantic couples compares to strangers. In another study, both fingertip movement and neural activity measured by EEG were synchronized after cooperative interaction (Yun, Watanabe, & Shimojo, 2012). The synchronized neural activity was in beta and theta frequency, and has been localized at inferior frontal gyrus (IFG), anterior cingulate (AC), parahippocampal gyrus (PHG), and post-central gyrus (PoCG), regions that have been found to be related to implicit social cognitive process and anticipation of somatosensory events. Interestingly, the synchronized neural activity was found in a much faster timescale (milliseconds) than the phenomenon of behavioral synchrony, hence they have concluded that neural and behavioral synchrony are dynamically linked, and not a mere consequence of one another (Yun et al., 2012).

Evidence for relationships between hormonal and behavioral synchrony are somewhat less studied and comes mainly from the research of attachment bonds. For example, it has been found that interactions characterized by higher affect synchrony were followed by higher parent-child OT synchrony (Feldman, Gordon, & Zagoory-Sharon, 2010). The model of bio-behavioral synchrony (Feldman, 2012, 2017; Gordon & Feldman, 2015) suggests that from infancy throughout life, affiliative bonds are characterized by synchrony in multiple levels (behavioral, hormonal, autonomic nervous system, neural, etc.), and these different levels are part of a *bio-behavioral matrix*, representing different aspects of social connection.

Overall, the evidence for the relation between behavioral and physiological synchrony is inconsistent. These evidence might imply that the relation between behavioral and physiological synchrony is non-linear, and as Palumbo et al. (2017) suggested, they might be context dependent. A computational study has shed another light on these relations (Vallacher, Nowak, & Zochowski, 2005). This study has found that interpersonal behavioral synchrony is stabilized by two different trajectories (Vallacher et al., 2005). The first one is very strong coupling, in which the behavior soon becomes synchronized with almost no need to synchronize the internal states. The second trajectory is slower and consists of moderate coupling and gradual synchronizing of both internal states and behavior. The first trajectory is based on strong mutual influence which causes almost immediate synchrony, but because the internal states are not similar, the system is not flexible, and synchrony might disappear under different contexts. Moreover, the second trajectory is based on the mutual adjustment of internal states, which causes more stability under changing contexts.

In light of the above, first we highlight the fact, that just as behavioral synchrony, physiological synchrony does not follow a linear trajectory of the more, the better. Second, we propose that much more research is needed in order to reach a crystallized understanding of the complex relationship between physiological and behavioral synchrony, and how context may influence this relationship. Future studies should aim to elucidate exactly how physiological and behavioral coupling can contribute to adaptive functioning.

6 | OUR MODEL OF BEHAVIORAL AND PHYSIOLOGICAL SYNCHRONY

We present a novel model of interpersonal behavioral and physiological synchrony. At the core of our model, is the notion that the interpersonal system inherently contains two latent potentials: to act as one synergetic social unit and to act independently (Figure 1). The extent to which these potentials come into action depends on the social context. At times, there is a greater attraction toward a synergetic action whereas at other times a more independent action is more suitable (Figure 2). Thus, the model does not focus on the external characteristics of the social context (competitive, affiliative, etc.) but rather on the latent potentials for synchronized/independent action. Importantly, we claim that the adaptive interpersonal system is characterized by flexibility, namely, it has the ability to change and adapt to different social contexts. In addition, behavioral synchrony is not only affected by social context, but is also affected by and affects physiological (ANS activity, neural activity, hormones) synchrony in a bi-directional way. In the following section implication of the model for future research will be discussed.

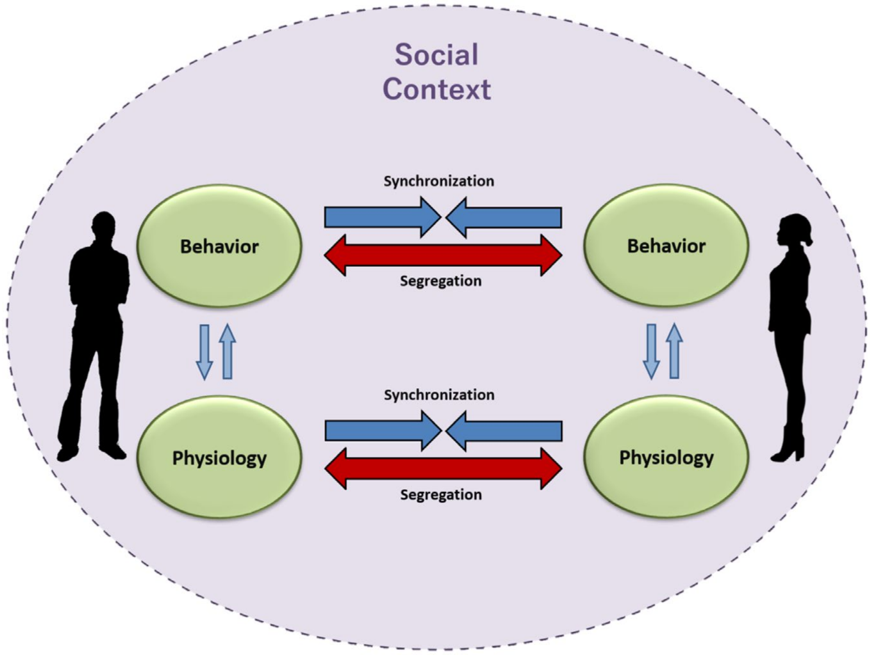

FIGURE 1 At the core of our model is the idea that two tendencies exist simultaneously, one to synchronize with others and another to move out of synchrony and act independently. The blue arrows represent synchrony whereas the red arrows represent segregation

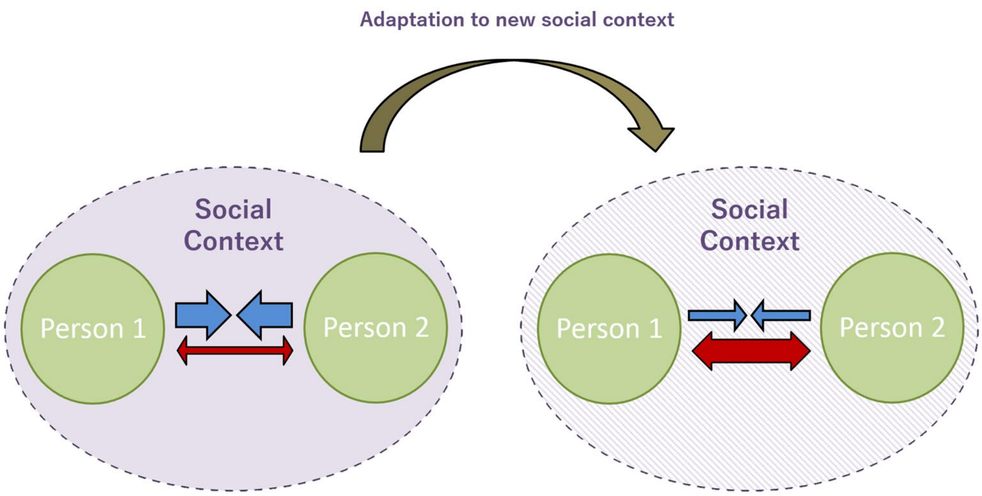

FIGURE 2 The blue arrows represent synchrony whereas the red arrows represent segregation. The size of the arrows represents the amount of synchrony/segregation tendencies in the system. The figure shows that an adaptive interpersonal system should adjust itself flexibly to the social context. For example, in the left context, more synchrony is adaptive compared to the right context, where more segregation is adaptive

7 | IMPLICATION FOR INTERPERSONAL SYNCHRONY RESEARCH

7.1 | Taking into account the latent potentials of the social context

We suggest that in order to properly investigate the system and its elements' different states, namely its tendency for both collective and independent behavior, one should deliberately manipulate these two potentials of the system simultaneously and not just the social context in general. Some studies investigated the differences in interpersonal synchrony in different social contexts (e.g., Tschacher et al., 2014) but critically, we found no study that included and manipulated both tendencies, and not only the pull for synchrony. We claim that such a generalized definition of the social context does not consider these latent potentials of the interpersonal system (for collective and independent behavior), and hence might lead to conclusions that disregard the full complexity of the interpersonal system. For example, a manipulation that simultaneously requires the participant to finger-tap with its co-actor and with an external rhythm might enable to manipulate these both the potential to synchronize and the potential to move out of dyadic synchrony.

7.2 | Meta-stability and "pink noise"

We suggest that adaptive interpersonal systems are "meta-stable" and their behavioral signal might have a unique characteristic. As previously explained, in the meta-stable system, the elements of the system are not completely synchronized, nor do they function independently. Importantly, if each element in the system acts independently it will result in a completely disordered system's functioning. Alternatively, if the elements are completely synchronized, then the system's functioning would be fully organized and predictable (Delignières & Marmelat, 2012; Van Orden, Kloos, & Wallot, 2011). Meta-stability is, thus, considered to reside between these two states, between order and disorder. Importantly, the variability in meta-stable systems is not regarded as "noise" (that comes, e.g., from inaccurate measurements) but rather as an inherent part of the system (Van Orden et al., 2011). Meta-stable systems usually exhibit a form of "Pink Noise"[1] (also called sometimes 1/f noise or fractal time; Delignières & Marmelat, 2012; Kello, Anderson, Holden, & Orden, 2008; Van Orden et al., 2011).

Pink noise is considered as an indication for complex systems that exhibit meta-stability (Kello et al., 2008), and has been found in many cognitive functions such as visual search, lexical decision, color and shape discrimination, etc. (Kello et al., 2008; Wijnants, 2014). For example, Kello et al. (2008) found 1/f pink noise in the acoustic aspect of speaking. In their study, participants were asked to repeat the word "bucket" 1,000 times. The acoustic fluctuations were measured and found to follow a form of pink noise, which was interpreted as reflecting a meta-stability in the speaking process. Such a pattern has also been found in self-esteem fluctuation that was measured daily (Delignières, Fortes, & Ninot, 2004). Meta-stable patterns are also claimed to play a crucial role in neural activity (Tognoli & Kelso, 2014), allowing flexible functioning, of both independent and interdependent neural functions, that can adjust and change even in the absence of external information. Interestingly, pink noise characterizes many living functions such as heartbeat and body temperature (Van Orden et al., 2011; Wijnants, 2014). Moreover, unhealthy functioning tends to move from pink noise toward whiter or browner noise, and certain human functions (like walking) tend to move toward a pinker noise as they approach their mature and more adaptive state (Van Orden et al., 2011). Thus, we suggest that meta-stable interpersonal synchrony, characterized by "pink noise", should be more flexible and adaptive to changing task demands or environment.

7.3 | Considering different levels of interpersonal synchrony simultaneously

We suggest that future studies of interpersonal synchrony should consider several levels (behavioral, physiological, neural, hormonal) of synchrony simultaneously. Although interpersonal synchrony has several levels (behavioral, physiological, neural, hormonal), as we discussed previously, most of the research on interpersonal synchrony usually focused on one or two levels at a time. This is probably, at least partly, the result of technical difficulties (e.g., most of the neural measures are too sensitive to study natural body movement), but nevertheless, our model emphasizes the importance of measuring interpersonal synchrony in a multi-level design. Otherwise, the meaning of the results might not be fully understood.

8 | A BRIEF EXAMPLE OF OUR MODEL APPLICABILITY

In this section, we will demonstrate a possible application of the proposed model. We also provide a Matlab code (The MathWorks, Inc., R2019A) in our supplementary files that will allow other researchers to analyze their data in the same methods we propose here. Our analyses will be on a sample of 18 youth (ages 7.7–16.8 years) with high functioning Autism Spectrum Disorder (ASD) and their parents—mother or father. Participants were seen twice during face-to-face interactions yielding a final sample size of 36 data points. Participants were part of a larger study described in detail elsewhere (See Gordon et al., 2013, 2016). Participants and their parents were videotaped in a dyadic conversation twice and asked to discuss a memory related to a shared joyful experience or to engage in planning a fun future activity for 5 min. These videos were later micro-analyzed continuously by trained coders for gaze behavior in each partner. Behavioral coding was done via a well-validated microanalytical scale used previously to code for communicative behaviors in children with ASD (Berman, Ventola, & Gordon, 2018; Ostfeld-Etzion, Golan, Hirschler-Guttenberg, Zagoory-Sharon, & Feldman, 2015), using specialized software (Noldus, Waggenigen, The Netherlands) to analyze behaviors continuously. Two trained research assistants performed the coding. Inter-rater reliability was over .85 for 10% of all interactions. Coders noted every time each of the interacting partners started and stopped looking at their partners. This later allows us to compute an "eye-contact" measure assessing the duration of time each dyad engaged in gaze synchrony. As there was no significant effect of the

[1]Pink noise is a function in which the size of change in data is inversely related to the frequency of the data. Thus, if F is the frequency of the data, and S(f) is the change in the data, then $S(f) \approx 1/(f)^{\alpha}$, and $\alpha \approx 1$. When the data tend towards a more ordered (also called Brown Noise) or disordered patterns (also called White Noise), then α is increasing or decreasing, accordingly (Delignières & Marmelat, 2012; Van Orden et al., 2011).

research manipulation of the larger study on gaze behavior in this sample, the behavioral data from both visits are reported here together.

The level of functioning and symptom severity of ASD was assessed using the Social Responsiveness Scale (SRS; Constantino et al., 2003). This questionnaire consists of 65 items scored from 0 (never true) to 3 (almost always true) which assess the child's behavior in areas that characterize autistic spectrum disorders, social characteristics and stereotypical behaviors, and reflect a single grade that assesses their social functioning. Higher scores indicate greater social dysfunction, and a score higher than 75 is considered severe and strongly related to ASD.

According to our synchrony model, we hypothesized that the number of times a dyad moves in and out of gaze synchrony will be a marker of adaptive interpersonal systems (representing flexibility—in this case, quantified by the SRS scores), whereas the total duration of gaze synchrony may not be associated with SRS. In addition, a more flexible interpersonal system may be meta-stable and hence its "eye-contact" signal will be well represented by the form of "pink noise". Finally, the proximity to "pink noise" will be associated with SRS scores.

8.1 | Data pre-processing

First, we created a "synchrony timeline" for each interaction. Namely, for each .01 s (the highest potential resolution of our micro-coding system), when both child and parent looked at each other (eye-contact), they were assigned a synchronized state ("1"), while otherwise, we assigned the dyad with an a-synchronized state ("0"). This gaze synchrony timeline provides a continuous representation of the child-parent eye-contact behavior. From the synchrony timeline, we extracted two indices: the total amount of time there was eye-contact in each dyad and the number of times each dyad switched states from eye-contact to no eye-contact.

8.2 | Data analysis and results—Pink noise

In order to assess if pink noise (or 1/f noise) represents our gaze synchrony timeline, we conducted a Detrended Fluctuation Analysis (DFA; Peng, Havlin, Stanley, & Goldberger, 1995). This method allows the estimation of the scaling exponent α, while $S(f) \approx 1/(f)^{\alpha}$. When $\alpha \approx 1$, the signal is considered to look like "pink-noise".[2] DFA is widely used in assessing the scaling exponent of signals in many areas of research (e.g., Bellenger, Arnold, Buckley, Thewlis, & Fuller, 2019; Hardstone et al., 2012; Hausdorff & Peng, 1996; Hausdorff, Zemany, Peng, & Goldberger, 1999). In the current study, we preformed DFA of the synchrony timeline, with a MATLAB (The MathWorks, Inc., R2019A) Detrended fluctuation analysis script (Magris, 2018). For each gaze synchrony timeline, we assessed the scaling exponent α. The DFA was preformed using 15 time windows ranging from 150 hundredth of second to 1,500 hundredth of second, logarithmically equally spaced (in this analysis the time windows is inversely related to the frequency, so that the larger the window the lower the frequency). We chose these windows because this was the maximal range in which the scaling exponent α behavior was rather linear. One dyad was excluded from the analysis since it had too little synchrony time (less than 5% of the entire conversation). The scaling exponent α range was between .82 to 1.18 with average of 1.03, which is indeed the representative of $\alpha \approx 1$: pink noise and is in line with our hypothesis.

Next, we tested if a more flexible interpersonal system will be meta-stable and hence its signal will be in the form of "pink noise". We expected lower SRS scores to be associated with a more flexible gaze-synchrony timeline, and hence assessed the relationship between SRS scores and the scaling exponent α that we derived for each eye-contact timeline. See Figure 3 for a description of the relationship between SRS scores and α in all dyads.

We used a mixed linear model. The scaling exponent α was the dependent variable and SRS was the independent variable with fixed effect. We assigned repeated observations from the same participant to a random effect analysis in this model. The model was[3]:

$$\alpha \sim 1 + \text{SRS\_total\_Standard} + (1 + \text{SRS\_total\_Standard} \mid \text{Observation}).$$

In this model, the fixed effect of SRS was significant ($b = .003$, $t = 2.75$, $p = .009$), which means that subjects with lower SRS scores have lower scaling exponent α. See Figure 3.

8.3 | Data analysis and results—In and out of synchrony

In order to assess the association between social functioning and the number of entries and withdrawals from synchrony, we conducted a mixed model analysis with the number of times of entries and withdrawals from eye-contact as a dependent variable and SRS score as an independent variable with fixed effect. As we had more than one observation for each subject, we grouped observations

[2]For further explanations on "pink-noise" see, http://www.scholarpedia.org/article/1/f_noise

[3]In this equation α is the scaling exponent, "SRS_total_Standard" is the standardized SRS score and "observation" is the grouping variable. The phrase in the brackets means we have introduced a random effect for both intercept and slope of "SRS_total_Standard", with the subject as a grouping variable.

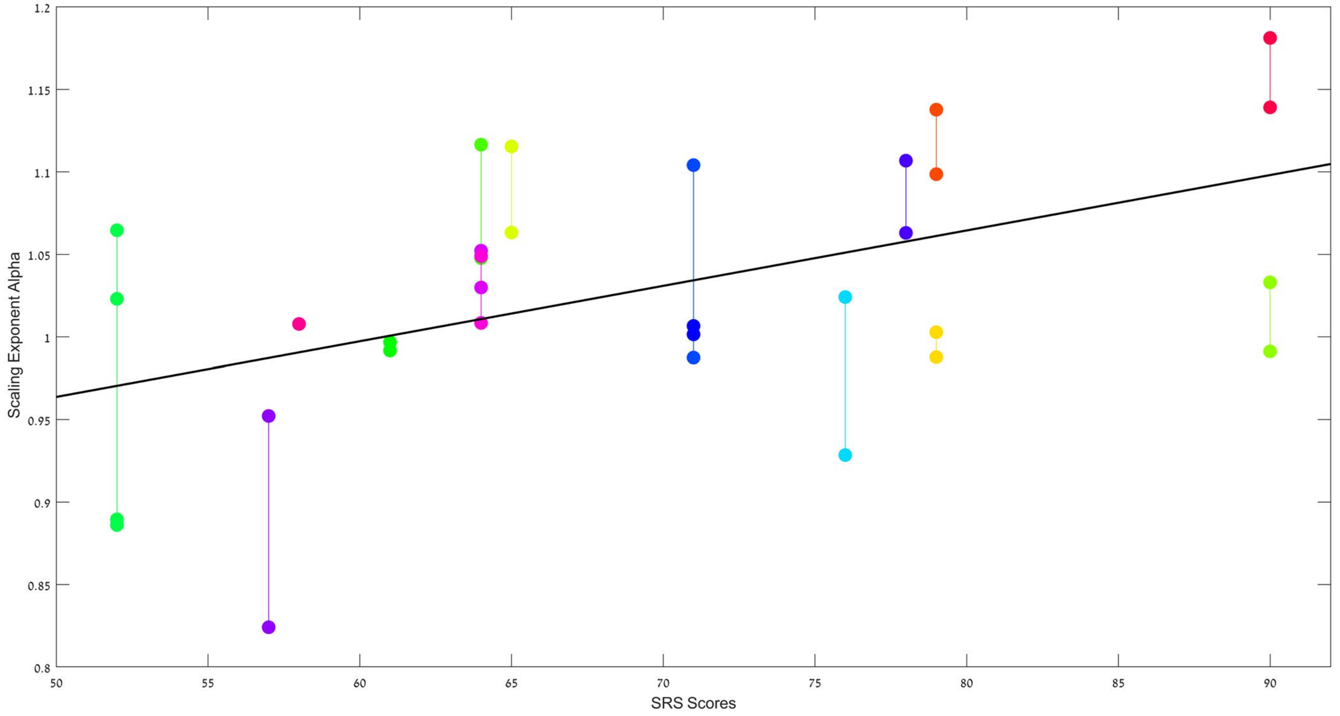

FIGURE 3 The relationship between the scaling exponent Alpha and SRS Scores. Observations from the same participant are displayed with markers in the same color, with a horizontal line between them. The black trend line represents the fixed effect of SRS scores in the model

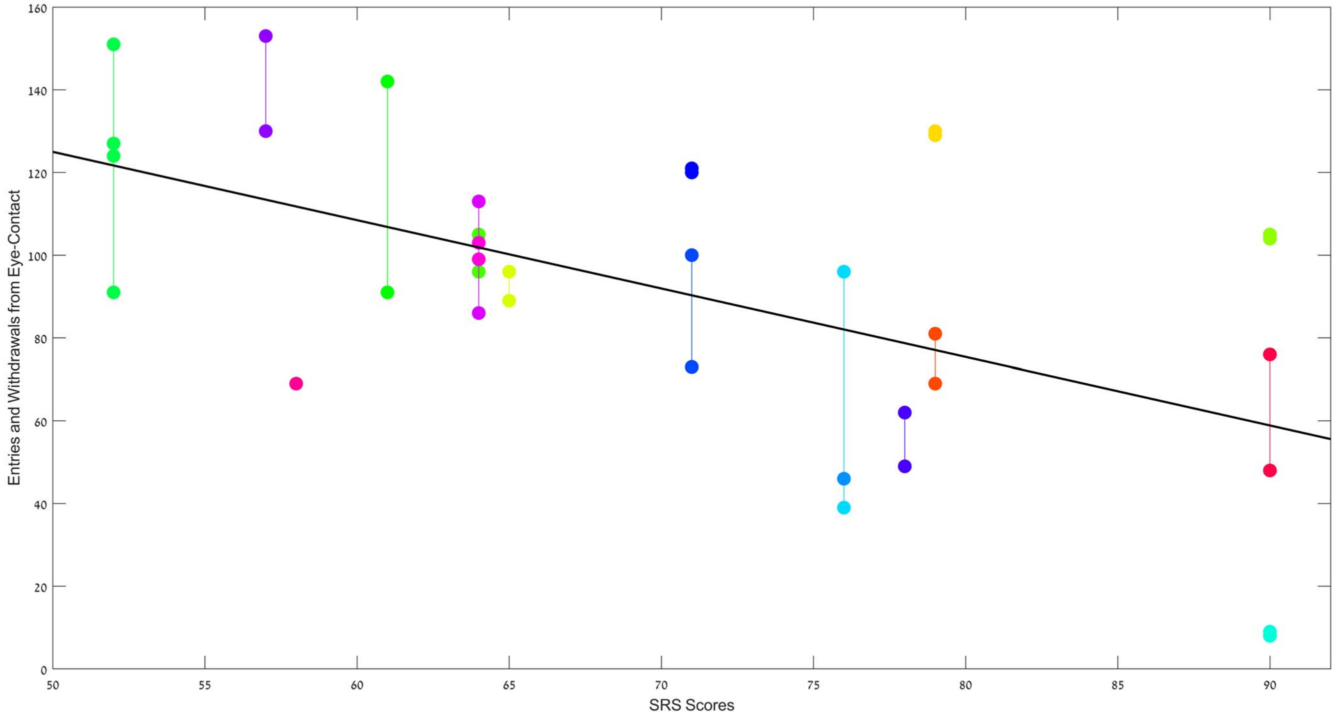

FIGURE 4 The relationship between the number of entries and withdrawals form eye-contact and SRS Scores. Observations from the same participant are displayed with markers in the same color, with a horizontal line between them. The black trend line represents the fixed effect of SRS scores in the model

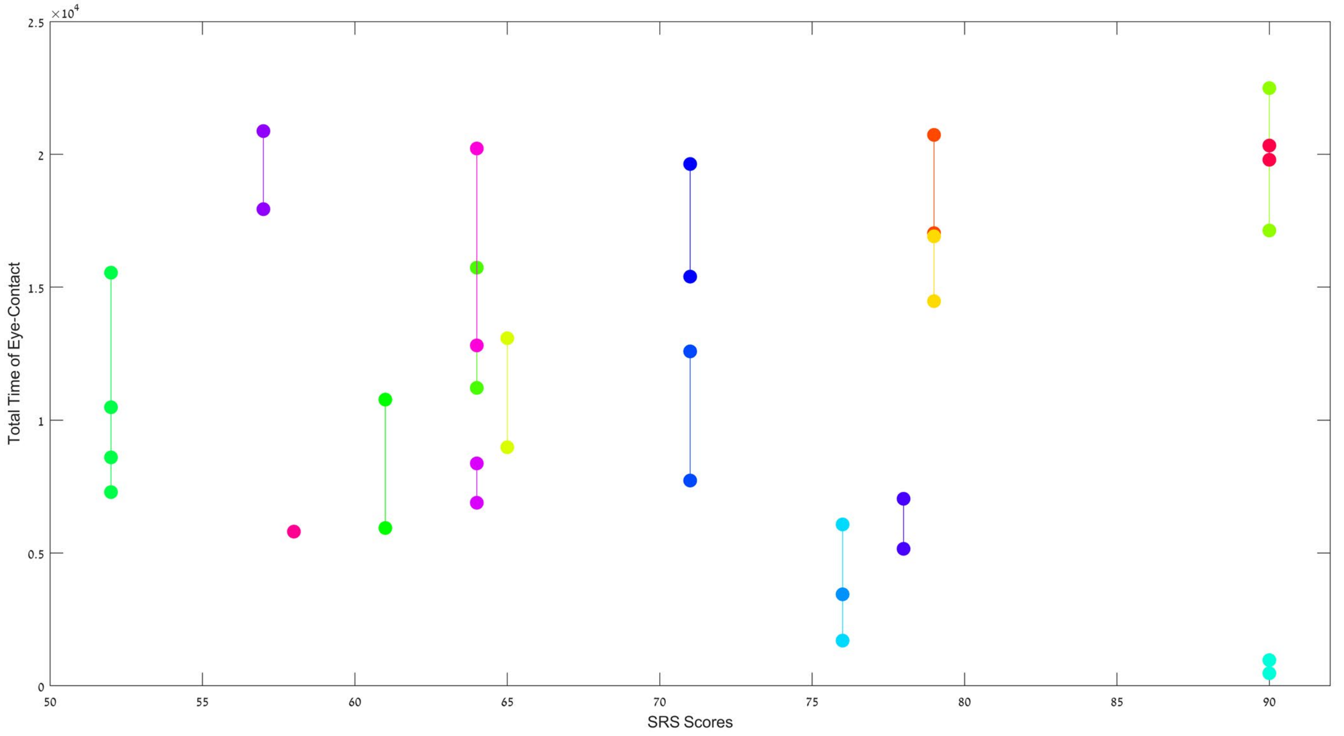

FIGURE 5 The relationship between the total duration of eye-contact and SRS Scores. Observations from the same participant are displayed with markers in the same color, with a horizontal line between them. A trend line is not presented as there was no significant effect of SRS in the model

from the same participant with a random effect in the model. The model was[4]:

$$\text{In\_Out\_Times} \sim 1 + \text{SRS\_total\_Standard} + (1 + \text{SRS\_total\_Standard} \mid \text{Observation}).$$

In this model, the fixed effect of SRS was significant ($b = -1.65$, $t = -2.56$, $p = .015$), which means that dyads with children who have lower SRS scores, move in and out of gaze synchrony more times compared to dyads with children who have higher SRS scores. See Figure 4.

Similarly, we assessed the relationship between social functioning level and the total time of eye-contact. We conducted a mixed model analysis with the total synchrony time of gazing as a dependent variable and SRS as an independent variable with a fixed effect. The model was[5]:

$$\text{Synchrony\_Time} \sim 1 + \text{SRS\_total\_Standard} + (1 + \text{SRS\_total\_Standard} \mid \text{Observation}).$$

In this model, we did not find a fixed effect of the SRS score ($b = -12.03$, $t = -.08$, $p = .93$) See Figure 5. As we are aiming to predict a null effect in the current model, we are underpowered to do so in our current sample size. For that reason, we further compared the above-mentioned model (total synchrony model) to a non-predictive model that does not include the main predictor of the total duration of synchrony. We define the non-predictive model as:

$$\text{Synchrony\_Time} \sim 1 + (1 \mid \text{Observation}).$$

Then we compared the two models' Akaike information criterion (AIC) and Bayesian information criterion (BIC). The non-predictive model's AIC and BIC are 721.52 and 726.27 (respectively), while the total synchrony model's AIC and BIC are 724.18 and 733.68 (respectively). The fact that the AIC and BIC coefficients are lower for the non-predictive model means that the non-predictive model is a better fit to the data than the total synchrony model. Moreover, the AIC scores allow us to estimate the probability that the total synchrony model minimizes information loss (Burnham & Anderson, 2002), and this probability is only .26—a low number. These results are unlikely in the case that the total synchrony model represents a false negative.

[4] In this equation "In_Out_Times" is the number of times the dyad enters and withdrawals from synchrony, "SRS_total_Standard" is the standardized SRS score and observation is the grouping variable (used to identify repeated observations for the same dyad).The phrase in the brackets means we have introduced a random effect for both intercept and slope of "SRS_total_Standard", with the dyad as a grouping variable.

[5] In this equation "Synchrony time" is the total amount of time of synchronized gaze, "SRS_total_Standard" is the standardized SRS score and observation is the grouping variable. The phrase in the brackets means we have introduced a random effect for both intercept and slope of "SRS_total_Standard", with the dyad as a grouping variable.

8.4 | Discussion

In this proof of concept, we provide a clear example of how the model we propose in the current article can be applied to real data. We were able to show that more synchrony is not always a good predictor of social functioning, and in fact, overall synchrony time was unrelated to SRS scores, whereas two indices of system flexibility were significantly associated with the reported level of social functioning of children with ASD. Additionally, we show here that the scaling exponent α is a good representation of the eye-contact timeline, and that better functioning in children with ASD is related to a lower α in the range of pink noise (namely the scaling exponent was close to 1).

These results exemplify our main point: in order to reach a more crystallized understanding of interpersonal synchrony, one should look at the flexibility of the synchronous system, mainly entries and withdrawals from synchrony. These initial results from a very small sample demonstrate concrete ways of assessing flexible dynamics in interpersonal synchrony that go beyond the average and relate to meaningful aspects of functioning in the system.

8.5 | Limitations

We provide a very initial demonstration of a computation method guided by our model. We are well aware that the data we provide here is from a relatively small sample, and hence we are extremely underpowered to predict results, especially null results which comprise a part of our claims. It is clear that our results should be taken very cautiously and need to be replicated before more solid conclusions can be made.

9 | CONCLUSIONS

In real-life situations, people tend to move in and out of interpersonal synchrony and a "perfect" continuous synchrony is rarely achieved. Based on the ideas of complex dynamical systems (e.g., Kelso, 2012; Kelso & Tognoli, 2009; Marsh et al., 2009; Tognoli & Kelso, 2014) we present here a theoretical model for interpersonal synchrony that focuses on these dynamics. At the center of the model is the idea of two interpersonal tendencies, one toward synchronization and the other toward segregation. These two tendencies act simultaneously and also depend on the social context: some contexts require higher level of interpersonal synchrony, while other contexts require a relatively low level of interpersonal synchrony. This is, of course, a dynamic process, hence the social context is constantly changing. The adaptive interpersonal system should allow flexibility to move between more and less synchronized states. We believe that in the current article, we presented some promising ways of assessing this flexibility, and demonstrated their potential applicability.

Our model also emphasizes the importance of considering multiple levels of synchrony, behavioral as well as physiological. As we discussed previously, the meaning of interpersonal synchrony in one level is not separated from the synchrony in other levels. For example, behavioral synchrony in the absence of physiological synchrony might be a sign for a relatively non-adaptive interpersonal system, while high behavioral synchrony accompanied by some physiological synchrony might be a sign for a more adaptive system.

Future research might address a few issues. First, testing our model puts forward some technical difficulties, that still require technical solutions. There is a need to develop laboratory paradigms for controlling these two tendencies. Such a laboratory setting requires putting the study's subjects on a constant tension between the attraction toward synchronization and the attraction toward segregation. Importantly, we suggest that such tension describes better real-life social interactions. Moreover, testing multi-level synchrony, including both behavioral and physiological levels, is complicated since some physiological measures (e.g., neural activity) are very sensitive to body movement. Second, the model presented here takes a system perspective, and a future study should also expand the understanding of intra-personal mechanisms. For example, attention toward co-actor might increase interpersonal synchrony (Richardson et al., 2007; Temprado & Laurent, 2004), hence one might hypothesize that allocating attention to or from co-actor might be a way of increasing or decreasing synchrony, respectively. Future research should not only develop a better understanding of these intra-personal factors, but also develop a more elaborated theoretical framework, that considers both inter and intra-personal level. Third, the meaning of the above mentioned three physiological levels of interpersonal synchrony is not fully understood (e.g., what is the meaning of ANS synchrony vs. neural synchrony) and so is the relations between them. The future model might consider these different levels more specifically. Finally, the idea that the adaptive interpersonal system should be flexible (and, as we discussed previously, in many cases meta-stable) might shed light on different parts of the interpersonal synchrony field. For example, from the developmental perspective, one might ask if healthy mother-infant relations are meta-stable, or from the team perspective, which enable or disable the development of flexible team performance.

CONFLICT OF INTEREST

We declare no conflict of interest.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the Supporting Information section.

This MATLAB code provides an example of data analysis of one child-parent eye-contact

This MATLAB function computes the “synchrony timeline”, overall synchrony time and the number of times each dyad switched states from eye-contact to no eye-contact, from raw data

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