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THEORETICAL REVIEW

# Measurement of interpersonal physiological synchrony in dyads: A review of timing parameters used in the literature

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## Abstract

When individuals share interpersonal connections, such as the bond between a mother and child or between a therapist and their client, they often exhibit measurable coordination of some physiological response patterns during their interactions known as *interpersonal physiological synchrony* (IPS Butler, 2011; Palumbo et al., 2016; Tscacher & Meier, 2019). However, as there is no single definition of IPS in the literature, researchers across fields have not established a standardized method for its study. This paper outlines methodological considerations that researchers should take into account when designing studies of IPS. Due to the inherent temporal component of synchrony analyses, we direct particular focus to the issue of measurement timing. Synchrony is described across multiple physiological processes, including electrodermal skin activation, cardiac function, respiration, and neural oscillatory activity, and we make specific recommendations for each. Across physiological measures and analytic strategies, we recommend that when determining an experimental timeframe in which to isolate periods of dyadic IPS, researchers should account for the timing of both the biological systems of interest and the psychological processes theorized to underlie their activity in that particular context. In adopting this strategy, researchers can ensure that they capture all of the fluctuations associated with a psychological process of interest and can add to the growing body of literature examining physiological correlates of interpersonal bonds.

**Keywords** Interpersonal physiological synchrony · Interpersonal bonds · Empathy · Autonomic response · Neural oscillations · Research methodology · Temporal analysis · Timing

## Introduction

Humans possess a basic need for social interaction, evidenced by decades of research across scientific disciplines (Adolphs, 2003; Baumeister & Leary, 1995; Riess, 2017). Fulfillment of these social needs is typically supported by multiple human capacities such as empathy (i.e., the ability to understand the emotions of others in reference to one's self), which can in turn promote prosocial behavior (Adolphs, 2003; Carr et al., 2003; Riess, 2017). It has been argued that the natural human capacities undergirding social ability begin developing through a series of physiological adaptations in infancy, including a tendency to fix one's gaze on eyes and faces (Carr et al., 2003; Riess, 2017; Soto-Icaza et al., 2015). These behavioral patterns that center on the physical presence of other individuals are thought to contribute to a child's gradual transition towards being able to conceptualize an individual's psychological presence (i.e., theory of mind, social perspective-taking), a capacity that is necessary to acknowledge and engage others as social agents (Feldman, 2006, 2012; Soto-Icaza et al., 2015). Contexts in which these social-perceptual capacities are later put into practice have also been associated with multiple unconscious physiological responses, such as changes in resting heart rate (Patriquin et al., 2019; Porges, 2009; Thayer & Lane, 2000, 2009; Smith et al., 2017). Thus, the evolution of a clear biological basis for developing the skills necessary for interpersonal bonding serves as evidence for its relative importance as a human drive.

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## Psychophysiological measures of social dynamics

The *belongingness hypothesis* states that human social drive arises from an innate psychological need to form positive social bonds that are long-lasting and significant (Baumeister & Leary, 1995). It has long been known that to be deprived of social bonds can have significant psychological ramifications, such as increasing one's feelings of loneliness and experiences of depressive symptoms (Cacioppo & Cacioppo, 2014; White et al., 2020; Won & Kim, 2016). However, as human psychological states can be difficult to reliably characterize or quantify using purely behavioral measures, many researchers have used measures of central nervous system activity as a proxy. One such measure is *interpersonal neural synchrony (INS)*, a phenomenon in which neural activity is temporally aligned between individuals engaged in interpersonal interactions in which there is high concordance in their affect and behaviors, suggestive of strong interpersonal bonds (Anders et al., 2011; Kinreich et al., 2017; Liu et al., 2016; Lu & Hao, 2019; Mu et al., 2016; Nguyen et al., 2020, 2021; Stratford et al., 2012; Zhang et al., 2018).

The growth of INS research is predominantly associated with advances in hyperscanning techniques across most neural recording technologies (e.g., electroencephalography [EEG], functional near-infrared spectrography [fNIRS], etc.), methods that have allowed researchers to simultaneously record neural activity for more than one participant within a behavioral context of interest (Liu et al., 2016; Montague, 2002; Vanutelli et al., 2017). While the precise interactional qualities that generate INS remain an open matter of debate, it often has been found to correlate with increased mutual responsiveness and social bonding (Lu & Hao, 2019; Stratford et al., 2012; Zhang et al., 2018). Given the known links between the brain and various cognitive and psychological processes, INS can thus serve as a valuable biomarker for characterizing social interactions (Lu & Hao, 2019; Nguyen et al., 2020; Vanutelli et al., 2017).

## Autonomic activity as a measure of social dynamics

Since the early 20th century, scientists have used measures of the autonomic nervous system (ANS) to characterize psychological processes through their associated physiological effects (Ricksher & Jung, 1907). The ANS enables rapid, adaptive biological changes in response to the immediate metabolic demands of one's internal (i.e., psychological, physiological) and external (i.e., physical) contexts, making it a sensitive metric for the body's state of functioning (Adolphs, 2003; Critchley, 2005, 2009; Won & Kim, 2016). Both branches of the ANS, the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS), have been examined in the context of behavior, affect, and psychological state due to the inherent interconnectivity of branches of the central and peripheral nervous systems (Beissner et al., 2013; Critchley, 2005, 2009; de Morree et al., 2012; Giuliano et al., 2015; Smith et al., 2017). SNS activity is associated with states of arousal, implicated in behavioral responses corresponding to stress, anxiety, and other psychological or cognitive states marked by increased metabolic needs (de Morree et al., 2012; Giuliano et al., 2015; Murata et al., 2021). The PNS is often linked to top-down self-regulation; its high activity during resting states is tied to maintaining steady rates among automatic functions (Gates et al., 2015; Gillie & Thayer, 2014; Holzmann & Bridgett, 2017). For example, the PNS is implicated in regulating heart rate, whose slowing is linked with increased inhibitory control (Berntson et al., 2007).

Multiple models, such as the *polyvagal theory* and the *neurovisceral integration framework*, support a bidirectional relationship between the central nervous system and functions of the ANS, maintained through the vagus nerve (Beissner et al., 2013; Holzman & Bridget, 2017; Patriquin et al., 2019; Porges, 2009; Stellar & Keltner, 2017; Thayer & Lane 2000, 2009; Smith et al., 2017). Using these conceptual frameworks, researchers have drawn links between particular social behavioral patterns, corresponding psychological states, and patterns of physiological activity (Fig. 1). For example, if an individual were to experience reduced parasympathetic inhibition of the cardiac muscle as a result of some internal or external state change (i.e., a physiological response), through this theoretical lens one could infer that the individual's emotional self-regulation may decrease (i.e., a psychological response), leading them to exhibit a more anxious social behavior (Gillie & Thayer, 2014; Pohl et al., 2019; Porges, 2009; Won & Kim, 2016). This behavioral response could hinder further social engagement by decreasing the psychological benefits of the interaction, as well as providing negative physiological feedback such as the induction of a physiological stress response.

In further support of the utility of such models in interpreting human social contexts, multiple autonomic systems show functional changes in response to failures to satisfy one's social drive. The oxytocin system is significantly affected by the disruption of social relationships, which in turn can impact emotional regulation and reciprocally hinder an individual's future social bonding efforts (Pohl et al., 2019). Additionally, perceived social isolation has been linked long-term to chronic increases in blood pressure, decreased immunity, and overall increased adult mortality (Cacioppo & Cacioppo, 2014; Giuliano et al., 2018; Pantell et al., 2013).

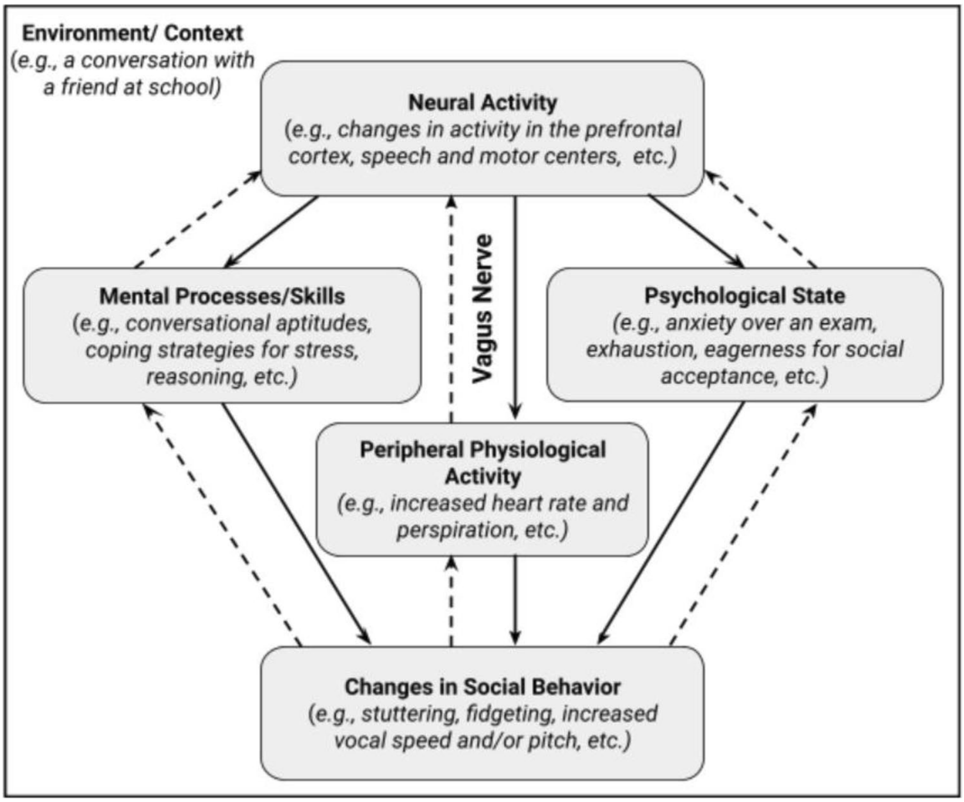

**Fig. 1** Integrating polyvagal theory and neurovisceral integration concepts. The diagram illustrates the relationships that can bedrawn between behavioral, physiological, and psychological phenomena through the conceptual frameworks of*polyvagal theory* and *neurovisceral integration*. A dashed line represents an afferent flow ofinformation while a solid line represents an efferent flow of information. The "Environment/Context" componentcould affect any/all of the other components in the diagram, thus it is depicted outlining the figure

## Defining IPS

Given the evidence for the measurable, negative physiological effects of dysfunction in one's social environment, it follows that the formation of positive social bonds has its own peripheral physical manifestation. Individuals in the context of social interactions have shown a consistent association and/or interdependence between measures of their autonomic nervous system function, which in combination with INS can be referred to broadly as *interpersonal physiological synchrony* (IPS; Butler, 2011; Palumbo et al., 2016; Tscacher & Meier, 2019). Over the course of the human lifespan, the earliest manifestations of IPS arise in the context of parent-infant relationships, thought to be an evolutionary adaptation related to the development of an attachment bond (Feldman, 2006, 2012; Ham & Tronick, 2009; White et al., 2020). Infants are believed to unconsciously mirror bonding behaviors that occur in concert with this initial experience of IPS more acutely in other social contexts across development, moderating their ability to form social bonds throughout their lifetime (Feldman, 2006, 2012; Riess, 2017). Accordingly, IPS has long been considered especially informative as a measure of the characteristics of an individual's social bonds and the psychological processes underlying them in myriad varieties of interpersonal relationships (Feldman, 2012; Ham & Tronick, 2009; Li et al., 2020; Lu & Hao, 2019; Palumbo et al., 2016).

INS and autonomic synchrony have most often been studied in isolation; however, more recent work has sought to examine their interaction and characterize their interrelationship (Nguyen et al., 2021; Palumbo et al., 2016; Stuldreher et al., 2019; Vanutelli et al., 2017). To this end, the same strategies used to compare multiple types of peripheral physiological readings or multiple channels of neural activity have been applied to create and analyze neural-physiological composite measures (Montague, 2002; Stratford et al., 2012; Stuldreher et al., 2019; Tscacher & Meier, 2019). For example, some researchers have resampled recordings of different physiological systems to the same frequency and then segmented these recordings into epochs of equal length that can be compared amongst themselves and/or correlated across time between dyad-members (Kinreich et al., 2017; Levenson & Gottman, 1983; Nguyen et al., 2021; Stuldreher et al., 2019). The shift toward multimodal studies of IPS provides greater flexibility in the social contexts researchers are able to examine and has allowed them to produce more evidence linking psychological states to physiological response patterns. However, this added level of complexity in IPS studies also means that more emphasis must be placed on experimental design in order to draw meaningful conclusions from differing biological measurements (Butler, 2011; Helm et al., 2018; Thorson et al., 2018).

The following review describes some of the methodological considerations that researchers should take into account when designing studies characterizing IPS. As synchrony inherently includes a temporal component, we focus on the logistics of choosing timing parameters for the physiological measurement. In addition, we outline some of the most frequently utilized physiological measures in the IPS literature, including electrodermal and cardiovascular activity, respiration, and neural oscillatory recordings, and describe trends in the experimental design choices made for each.

## Timing considerations

In studies of manifestations of IPS during interpersonal interactions, multiple biological systems have been measured both independently and in combination, and within various dyadic and group contexts. Each physiological measure (e.g., electrocardiogram [ECG]) requires a different length of recording time to capture a single observation (*sampling rate*; Helm et al., 2018). Researchers must coordinate this value with the length of time needed to translate this measure into a meaningful physiological variable (e.g., heart rate variability [HRV]) that can then be related to the psychological process being studied (Helm et al., 2018; Palumbo et al., 2016; Thorson et al., 2018; Tschacher & Meier, 2019). Sampling rate must be fast enough to record minute changes in physiological systems to capture enough events for dyadic comparison. As a general rule, faster sampling rates are better, so a rate of 500-1000 Hz (the default on most physiological recording tools) is sufficient for most IPS studies (Helm et al., 2018; Palumbo et al., 2016; Thorson et al., 2018).

### Timing of the physiological system

When determining the length of time (i.e., the *epoch*) over which to analyze IPS, it is essential to know the timing of the physiological process being observed. Many researchers have chosen to record and average dynamic physiological measures over a somewhat arbitrary interval, such as the length of an experimental trial (Bacharach et al., 2015; Kinreich et al., 2017; McFarland, 2001; Mu et al., 2016; Thorson et al., 2019; Vanutelli et al., 2017). However, autonomic responses are temporally dynamic (e.g., heart rate, skin response), changing frequently over the course of an experiment (Jennings & Gianaros, 2012; Palumbo et al., 2016; Tschacher & Meier, 2019). Thus, comparing dynamic responses over a longer time period increases the probability that relevant data trends will be averaged together and eliminated (Boker & Nesselroade, 2002; Helm et al., 2012,2018). It is important if possible to use a data-driven approach to choose shorter time intervals for analysis, as opposed to evaluating the entire length of an experiment (Ahonen et al., 2018; Ekman et al., 2011; Palumbo et al., 2016; Thorson et al., 2018).

For example, in EEG recordings, responses occur within milliseconds post-stimulus, resulting from the almost immediate transmission of neural electrical signals via the opening and closing of ion channels (Critchley, 2005; Kinreich et al., 2017; Pizzagalli, 2007). Slower physiological processes such as electrodermal skin activity (EDA) or heart rate (HR) instead produce responses within seconds, as they rely on more widespread bodily processes (i.e., sweat gland secretions or coordinated endocrine activity, respectively; Boucsein, 2012; Kinreich et al., 2017; Lorig, 2007; Shaffer & Ginsberg, 2017). Hypothalamic-pituitary-adrenal (HPA) activation, an endocrine function relying on the diffusion of hormones through the bloodstream, can take 15 to 20 minutes to produce a measurable response (Helm et al., 2018; Palumbo et al., 2016; Pohl et al., 2019; Thorson et al., 2018). Thus, while shorter epochs would allow for precise examination of fluctuations and their patterns in an EEG, that same time window might be insufficient to capture the full scope of slower physiological responses, such as EDA, HR, or HPA activity (Boucsein, 2012; Helm et al., 2018; Sherwood et al., 1986, 1990; Thorson et al., 2018).

When in doubt, graphing the physiological responses for individual participants can help to determine an appropriate epoch length for a particular measure (for details, see supplemental material from Thorson et al., 2018). Relatively consistent values for a given measure within a specified time window indicate that a physiological response has reached its maximal intensity and/or a stable pattern within that period (Feldman, 2012; Jennings & Gianaros, 2012; Thorson et al., 2018). Provided the sampling rate is considered fast enough to record the physiological process of interest, this suggests that other, relevant fluctuations are unlikely to be captured within the dataset should this time window be shortened (Boker & Nesselroade, 2002; Feldman, 2012; Thorson et al., 2018). For future experimental designs, it should be noted that artificial intelligence and machine-learning techniques for signal processing currently in development may provide simpler methods for evaluating relevant changes in physiological response patterns with unknown dynamics (Debnath et al., 2021; Lin et al., 2020; Wiens & Shenoy, 2017).

## Timing of the psychological construct

To leverage INS effectively as a neural metric of psychological activity, accounting for physiological timing constraints alone is insufficient. Considering the timescale of a psychological construct of interest when choosing timing parameters for identifying IPS increases the likelihood that observed patterns in neural activity can be directly attributed to that psychological state (Butler, 2011; Critchley, 2005, 2009; Kinreich et al., 2017). For example, in a study measuring changes in cardiac activity among adolescents resulting from the psychological states associated with solving increasingly difficult math problems, the researchers coordinated the length of their epochs for analysis with the amount of time the participants were given to complete the math problem (Thorson et al., 2019). These researchers knew the timing of their phenomena of interest (i.e., the mental processes associated with mathematical problem-solving), because they could directly initiate these processes via the timing of mathematical problem presentation. Thus, the researcher could justifiably argue a causal relationship between a participant's underlying psychological state and their observed physiological responses (Boker & Nesselroade, 2002; Helm et al., 2012; Wilson et al., 2018).

However, this degree of control may not always be possible. Even without constraint by data-driven timing parameters, continuous recordings of physiological responses during longer time periods can still be informative of individual moments of IPS, and their relationship to psychological processes. For example, in a study examining the cardiovascular responses of married partners during a conflictual discussion, in the absence of discrete timing parameters for the experience of the negative emotional states associated with this context, researchers evaluated the degree of synchrony in sliding 1-s epochs throughout the length of the conflict (Wilson et al., 2018). Strategies involving such fine-grained analysis require more data points, and are thus better suited to physiological measures recorded at a faster sampling rate, such as EEG or (ECG).

With longer time windows for a physiological recording, researchers also can evaluate response fluctuations acutely clustered around a single relevant time point, such as the presentation of a stimulus or a particular behavioral response (Boker & Nesselroade, 2002; Helm et al., 2012, 2018). In doing so, they retain the ability to correlate these fluctuations to an individual's underlying psychological state. However, such extended measures are more likely to lead to false conclusions of constant trends (e.g., linear, quadratic), especially if response patterns are rapidly cyclic, and may leave more complex patterns of dyadic synchrony unidentified (Boker & Nesselroade, 2002; Helm et al., 2012, 2018; Thorson et al., 2018). This analytic strategy is thus most suited for measures with slower sampling rates, because it may take more time to capture a single functional cycle, meaning longer time windows are needed to identify trends (Jennings & Gianaros, 2012; Shaffer & Ginsberg, 2017).

In summary, when choosing the time window over which to record and analyze physiological responses in studies of IPS, a balance must be struck between the temporal dynamics of both the physiological process and the mental phenomenon presumed to be moderating it (Jennings & Gianaros, 2012; Thorson et al., 2018). Autonomic measures can differ widely in their timing, and physiological timing is often distinct from the timing of a psychological state of interest (Butler, 2011; Helm et al., 2018; Thorson et al., 2018). Using shorter epochs during analysis centered around measurable outcomes or stimuli that are linked to a particular psychological construct, creates a stronger argument that this construct underlies any observed patterns of IPS (Boker & Nesselroade, 2002; Thorson et al., 2018; Wilson et al., 2018). However, certain physiological measures may require a slower sampling rate, in which case the epoch for analysis may need to be lengthened to capture the full complexity of a relevant pattern (Jennings & Gianaros, 2012; Shaffer & Ginsberg, 2017). By completing these methodological valuations early in the process of study design, researchers may require fewer steps during processing to produce informative dyadic physiological data for analysis.

## Specific autonomic measures and their experimental use

The vast literature of existing IPS studies serves as a vital resource that can inform design considerations for future experiment. The dynamic physiological processes underlying some of the commonly used measures of IPS are outlined below, along with how researchers have approached choosing timing parameters with which to record them. The studies discussed in the following section and details of their experimental design are summarized in Table 1.

### Electrodermal activity

EDA refers to a measurable increase in the electrical conductivity of the skin when secretions from eccrine sweat glands fill the pores (Boucsein, 2012; Dawson et al., 2017). It is one of the best characterized measures of ANS activation and is commonly sampled at 20 Hz using electrodes placed on the fingers or hand (Boucsein, 2012; Hernandez et al., 2014; Vanutelli et al., 2017). EDA is thought to be triggered

**Table 1** Empirical studies examining interpersonal physiological synchrony

| Article | Recording Context | Mental Construct(s) | Synchrony Measure | Sampling Rate | Epoch Length for Analysis | Primary Basis for Epoch Length |
|---|---|---|---|---|---|---|
| Ahonen et al., 2018 | Pairs of adolescents during a cooperative programming task. | Cooperativity, Social cohesion | EDA (SCR, SCL) | 51.2 Hz | 20 s | Task length |
| Bacharach et al., 2015 | Performers and spectators during a dance performance. | Subjective engagement, Joint attention | Respiration | 1 Hz | 420 s | Task length |
| Dikker et al., 2017 | High school students in a naturalistic classroom context. | Classroom engagement, Social closeness | EEG | 43 Hz | 1 s | Synchrony analysis |
| Fu et al., 2021 | Patients with dementia and healthy controls during a free-flow movement activity. | Interpersonal connection (e.g., emotion, attention) | EDA | 150 Hz | 60 s | Synchrony analysis |
| Gates et al., 2015 | Married couples during a conflictual discussion. | Interpersonal connection (e.g., emotion, attention) | RSA | 500 Hz | 32 s | Synchrony analysis |
| Ham & Tronick, 2009 | Mothers and infants during naturalistic interaction and still-face perturbation. | Transference of emotional affect | EDA | Not Provided | 1 s | Synchrony analysis |
| Helm et al., 2012 | Romantic couples during cooperative tasks | Transference of emotional affect, interpersonal connection | HRV (IBI)<br>Respiration | 1000 Hz | 180–300 s | Task length |
| Helm et al., 2018 | Mothers and children completing cooperative tasks of increasing challenge. | Emotional reaulation | HR<br>PEP<br>RSA | 500 Hz | 2 s<br>30 s<br>30 s | Synchrony analysis |
| Hernandez et al., 2014 | Parents and children during naturalistic, structured play. | Social engagement, Interaction quality | EDA | 32 Hz | 12–300 s | Task length |
| Kinreich et al., 2017 | Naturalistic social interactions between male and female strangers and romantic couples. | Interpersonal connection (emotion, attention) | EEG | Not Provided | 300 s | Task length |
| Levenson & Gottman, 1983 | Romantic couples during a conflictual discussion. | Transference of emotional affect | EDA (SC)<br>HRV (IBI) | 1000 Hz<br>Not Provided | 10 s | Synchrony analysis |
| Li et al., 2020 | Two parents and their adolescent child during a triadic conflictual discussion. | Interpersonal connection (e.g., emotion, attention) | RSA | 300 Hz | 60 s | Biological dynamics |
| Lindenberger et al., 2009 | Pairs of guitarists playing a melody together. | Interpersonal connection (i.e.., action coordination) | EEG | 5000 Hz | 3 s | Psychological construct dynamics |
| Liu et al., 2016 | Pairs of strangers playing cooperative or competitive Jenga games. | Cooperativity, Social cohesion | fNIRS | 10 Hz | 120 s | Task length |
| Lu & Hao, 2019 | Three-person groups (two participants and one confederate) during a cooperative task. | Cooperativity, Social cohesion | fNIRS | 10 Hz | 80 s | Synchrony analysis |

**Table 1** (continued)

| Article | Recording Context | Mental Construct(s) | Synchrony Measure | Sampling Rate | Epoch Length for Analysis | Primary Basis for Epoch Length |
|---|---|---|---|---|---|---|
| McFarland, 2001 | Dyads of adult female friends during, spontaneous and scripted verbal interactions. | Interpersonal connection (e.g., emotion, attention) | Respiration | Not Provided | 5 s | Biological dynamics |
| Marci et al., 2007 | Pairs of therapists and their clients during a therapy session. | Interpersonal connection (i.e., therapeutic alliance) | EDA (SCL) | Not Provided | 5 s | Synchrony analysis |
| Mønster et al., 2016 | Groups of three college students collaborating to build an origami boat. | Cooperativity, Social cohesion | EDA (SCL)<br>HR | 125 Hz<br>1000 Hz | 240 s | Task length |
| Montague, 2002 | Pairs of individuals competing in a simple game involving deception. | Cooperativity, Social cohesion | fMRI | Not Provided | 25 s | Task length |
| Mu et al., 2016 | Pairs of male subjects or a subject and a computer playing a game requiring interpersonal coordination. | Cooperativity, Social cohesion | EEG | 250 Hz | 6 s | Task length |
| Müller & Lindenberger, 2011 | A conductor and choir performing songs in separate voice parts or in unison. | Interpersonal connection (i.e.., coordinated action) | HRV<br>Respiration | 5000 Hz | 300 s | Task length |
| Murata et al., 2021 | Pairs of friends playing a cooperative Jenga game. | Transference of emotional affect | HRV (IBI) | 1000 Hz | 25 s | Synchrony analysis |
| Nguyen et al., 2020 | Pairs of mothers and children during free verbal conversation. | Social engagement,<br>Interaction quality | fNIRS | 7.81 Hz | 30 s | Synchrony analysis |
| Nguyen et al., 2021 | Infants and caregivers during interactive free play and while watching a video . | Maternal responsivity, Attachment bond | fNIRS HRV (IBI) RSA | 7.81 Hz<br>500 Hz<br>500 Hz | 90 s | Task length |
| Reed et al., 2013 | Pairs of romantic partners discussing their influences on each other's health behaviors. | Transference of emotional affect | HRV (IBI)<br>EDA (SC) | Not Provided | 10s | Psychological construct dynamics |
| Stratford et al., 2012 | Pairs of psychotherapists and their clients clinically diagnosed with anxiety during a therapeutic session. | Interpersonal connection (i.e., therapeutic alliance) | EEG | 1000 Hz | 180 s | Synchrony analysis |
| Tschacher & Meier, 2019 | Pairs of therapists and their clients during a therapy session. | Interpersonal connection (i.e., therapeutic alliance) | HRV Respiration | 80 Hz<br>16 Hz | 10 s | Synchrony analysis |
| Vanutelli et al., 2017 | Pairs of individuals of the same sex completing a cooperative attention task with trial-by-trial feedback. | Cooperativity, Social cohesion | EDA (SCL, SCR) | 20 Hz | 15 s | Task Length |

**Table 1** (continued)

| Article | Recording Context | Mental Construct(s) | Synchrony Measure | Sampling Rate | Epoch Length for Analysis | Primary Basis for Epoch Length |
|---|---|---|---|---|---|---|
| Wilson et al., 2018 | Romantic couples during a conflictual discussion. | Transference of emotional affect | HRV (IBI) | 1000 Hz | 1 s | Synchrony analysis |
| Xue et al., 2018 | Pairs of individuals with high- and low-creativity levels completing a cooperative production task. | Social facilitation, Cooperativity | fNIRS | 10 Hz | 300 s | Task Length |
| Zhang et al., 2018 | Pairs of therapists and their clients during a therapy session and during casual conversation. | Interpersonal connection (i.e., therapeutic alliance) | fNIRS | 10 Hz | 90 s | Synchrony analysis |

This table lists the empirical studies of IPS mentioned in this review. It differentiates the experimental construct in which IPS was investigated from the class of psychological construct that this context was designed to elicit. The measures used to evaluate IPS are noted, as well as the sampling rate, and the length of the epochs that were analyzed for synchrony. The final column describes the logical justification provided by the authors for the epoch length chosen (e.g., based on the task length, for ease of analysis, etc.).

by premotor-basal ganglia impulses during preparation for certain motor programs, and by hypothalamic-limbic structures as a response to more emotionally based psychological processes (Boucsein, 2012; Dawson et al., 2017; Wei et al., 2016). There also is a theorized connection between activity within the reticular activating system and EDA fluctuations in response to general arousal (Bach & Friston, 2012; Dawson et al., 2017; Mønster et al., 2016).

EDA is exclusively triggered by sympathetic arousal, a fact often leveraged in experimental design (Ahonen et al., 2018; Boucsein, 2012; Dawson et al., 2017; Fu et al., 2021; Ham & Tronick, 2009; Hernandez et al., 2014; Mønster et al., 2016; Palumbo et al., 2016; Reed et al., 2013; Marci et al., 2007). Activity in the SNS is believed to underlie the immediate patterns of arousal that occur in response to novel stimuli; many of these patterns can be uniquely associated with different valences of emotional affect (Bradley & Lang, 2007; Picard, 2001; Thayer & Lane, 2000). In fact, promising work has emerged in the development of algorithms leveraging EDA data to automatically detect affective states based on specific patterns of sympathetic arousal (Lamichhane et al., 2016; Picard et al., 2001; Wei et al., 2016). EDA can thus be useful in the context of interpersonal interactions, as understanding the valence of one's physiological response can be as informative about the nature of an interaction as the response's magnitude. Levenson and Gottman (1983) studied EDA among romantic couples and found that responses were more strongly correlated during conflicts, when negative affect was shown behaviorally to transfer between partners. Other studies have found increased degrees of synchrony during high stress interactions between dyad-members, such as opponents playing video games or therapists treating clients during moments of anxiety, further supporting an association between EDA synchrony and emotional transfer (Ekman et al., 2011; Stratford et al., 2012).

An additional benefit of EDA as a measure of IPS is its high level of timing precision. Phasic skin conductance response (SCR) occurs 1 to 3 seconds post-stimulus, on average (Boucsein, 2012; Dawson et al., 2017). However, SCR must be differentiated during analysis from baseline skin conductance level (SCL), which also undergoes slight variations over time (Boucsein, 2012; Dawson et al., 2017; Hernandez et al., 2014; Marci et al., 2007). Causal models of SCR typically account for the possible mediating effects of SCL on the relationship between SCR and acute psychological states (Bach & Friston, 2012; Dawson et al., 2017). In practice, the epochs most frequently used to record and analyze phasic SCR responses can vary provided they capture the time window one to four seconds poststimulus, as responses within this range are assumed to be elicited by the stimulus (Ahonen et al., 2018; Bach & Friston, 2012; Fu et al., 2021; Marci et al., 2007). The closer the recording is to the stimulus onset, the less likely it is to be contaminated by SCL, and the more robust the evidence for a causal relationship between psychology and physiology in that context (Bach & Friston, 2012; Boucsein, 2012; Dawson et al., 2017).

## Cardiovascular measures

The ANS affects HR in multiple ways. Heart rate variability (HRV) is one of the most commonly measured metrics of cardiac function. It is derived from a continuous ECG recording by calculating the average change in time between heartbeats, the average of the interbeat interval (IBI; Helm et al., 2012; Shaffer & Ginsberg, 2017; Thorson et al., 2018). Often in combination with other measures like EDA, HRV has been used as a simple metric for autonomic synchrony in dyadic contexts, including arguments between romantic couples, laboratory interactions, and psychotherapy sessions (Helm et al., 2012; Murata et al., 2021; Reed et al., 2013; Tschacher & Meier, 2019; Vanutelli et al., 2017; Wilson et al., 2018). However, HRV only reflects general autonomic activation and cannot differentiate between sympathetic and parasympathetic effects (Cacioppo et al., 1994; Tschacher & Meier, 2019). Thus, more specific metrics of heart activity are often calculated to provide some indication of the specific mechanisms for stress-induced changes in cardiac activity.

Respiratory sinus arrhythmia (RSA) is a component of HRV that refers to fluctuations in the natural change in cardiac rhythm that accompanies respiration, reflecting PNS activation of the heart via the vagus nerve (Cacioppo et al., 1994; Palumbo et al., 2016). RSA is quantified by calculating the power of IBI measures within the respiratory frequency (e.g., 0.12-0.40 Hz; Cacioppo et al., 1994). Epochs of 60-120 s are considered sufficient to produce enough IBI data points to evaluate all frequency ranges in the ECG (Gates et al., 2015; Malik et al., 1996). However, shorter epoch lengths have been used in cases where researchers are interested in quantifying power in only the frequency band associated with respiration, and to maximize the visibility of changes in the measure over time, including in studies of interpersonal dynamics (Gates et al., 2015; Malik et al., 1996). RSA is especially implicated in regulatory physiological functions associated with facilitative social behaviors, which are marked by a greater prevalence of contingent responses (Gates et al., 2015; Li et al., 2020; Nguyen et al., 2021; Porges, 2009). For example, compared with control mother-infant dyads, mothers with histories of documented child neglect showed *decreased* RSA responsivity to their infant's behavior over the course of their interaction (Giuliano et al., 2015). Similarly, Gates et al. (2015) found that RSA synchrony increased between couples during an argument, reflecting increased contingent reactivity and reduced ability to moderate arousal in response to one's partner's behaviors.

Pre-ejection period (PEP) is a measure of the time during which the cardiac ventricle generates force between its depolarization and the start of the *systole,* its ejection upon the opening of the aortic valve (Cacioppo et al., 1994; Shaffer & Ginsberg, 2017; Sherwood et al., 1990). In order to derive PEP, impedance cardiograph devices are used to induce a constant current through the thorax and measure changes in voltage that accompany heartbeats, allowing one to calculate changes in electrical impedance (i.e., the *impedance signal* or *dZ/dt waveform*), which can be associated with activity of the aortic valve (Berntson et al., 2007; Sherwood et al., 1990). In addition to impedance cardiograph measures, simultaneous ECG recordings are used to identify the onset of the systole and deduce the systolic time interval. Alternatively, PEP has been derived through simultaneous ECG, phonocardiogram, and pulse measurements (Berntson et al., 2007).

Smaller PEP values indicate increased cardiac activity and blood flow, suggesting a heightened state of arousal and increased sympathetic activation (Berntson et al., 2007; Cacioppo et al., 1994; Helm et al., 2018; Sherwood et al., 1990). Like EDA, PEP is most often associated with arousal via activity of the SNS (Helm et al., 2018; Palumbo et al., 2016). Students delivering timed speeches exhibited increased HR and decreased PEP in response to the stress associated with that experience (Cacioppo et al., 1994). PEP was found to shorten during a task in which individuals were instructed to progressively reduce their reaction time under threat of electric shock, suggested by the authors to be a stress response (Sherwood et al., 1986). Follow-up analyses revealed that this PEP response was eliminated with the administration of beta-adrenergic blockers before the task, supporting this interpretation.

HRV, RSA, and PEP collectively can be used to index both sympathetic and parasympathetic activation, making the cardiovascular system one of the more consolidated sources of metrics for evaluating total autonomic activity (Shaffer & Ginsberg, 2017; Stellar & Keltner, 2017). It is not uncommon to extract all three measures from a single experimental task or session, as they all at least partially rely on ECG. For example, a study by Helm et al. (2018) examined IPS in both RSA and PEP measures among mother-infant dyads by recording ECG during the five minute experimental task. HR was measured in consecutive 2-s epochs as a comparison measure of baseline cardiac activity, and both RSA and PEP were analyzed as measures of SNS and PNS activity in 30-s epochs. The conventional minimum length of ECG recording for extracting HRV and other HR measures is 5 minutes (Shaffer & Ginsberg, 2017; Sherwood et al., 1986, 1990; Thorson et al., 2018). Epoch lengths of 10-30 s are sufficient to accurately characterize multiple HR measures during analysis, provided these intervals are consecutive and nonoverlapping (Malik et al., 1996; Sherwood et al., 1990). While sampling rates typically fall within 500-1,000 Hz, some studies have used lower sampling rates (e.g., 80 Hz) to monitor less variable behaviors (Helm et al., 2018; Tschacher & Meier, 2019).

### Respiration

The patterns of pulmonary inhalations and exhalations known as respiration make up one of multiple automatic functions governed by the central nervous system; however, they are also under the control of the ANS, and thought to be influenced by psychological states (Butler, 2011; Palumbo et al., 2016; Stellar & Keltner, 2017). SNS activation tends to increase respiratory rate, promoting oxygenation in response to arousing stimuli and creating an energetic affective state (Lorig, 2007). Like RSA, PNS activation is negatively correlated with respiratory rate, and corresponds to a relaxed-subdued state (Lorig, 2007; Palumbo et al., 2016). Respiration is also under voluntary control (e.g., for speech, conscious exhalation, etc.) and can thus be used to represent both conscious and unconscious psychologically motivated responses (Butler, 2011; Stellar & Keltner, 2017).

Research involving the use of respiration as a metric for IPS overlaps a great deal with work investigating HRV, as both are dually innervated by the SNS and PNS and are indicators of general autonomic arousal (Muller & Lindenberger, 2011; Palumbo et al., 2016; Thorson et al., 2018). Respiration often is used to examine interactions characterized by positive interpersonal connection (McFarland, 2001; Palumbo et al., 2016; Stellar & Keltner, 2017). As such, it has been used in studies evaluating social bonds between dyads during extended periods of direct eye contact, amongst choir members while singing, and during secondary experiences of emotional connection, such as between audience members at an artistic performance (Bachrach et al., 2015; Helm et al., 2012; Muller & Lindenberger, 2011). However, as the process for respiratory measurement can be more physically constraining compared with other biological measurements, it also can interfere with naturalistic observations of more spontaneous emotional experiences, somewhat limiting its utility (Helm et al., 2012; Lorig, 2007).

For the purposes of observing IPS, respiratory activity today is most often recorded using a piezoelectric belt placed around a participant's waist or chest to measure diaphragm and rib extension (Bachrach et al., 2015; Ham & Tronick, 2009; Lorig, 2007). Breathing cycles, which take around 5-s to complete, are a common respiratory measure quantified for IPS analysis by identifying cycle "peaks" and calculating the length of time between them, constructing an inter-breath interval time series that can be compared between dyad members (Helm et al., 2012; Lorig, 2007; Palumbo et al., 2016). A sampling rate of 2 Hz or greater is typically considered sufficient to capture the variability within a breathing cycle during analysis (Lorig, 2007; Muller & Lindenberger, 2011). Recording epochs can vary in length, provided they are divided into shorter intervals for analysis that are more reflective of the length of the breathing cycle (Helm et al., 2012). For example, in a study of patient-psychotherapist interactions, respiration was recorded in 30-s intervals and IPS was analyzed over consecutive 5-s epochs (Tschacher & Meier, 2019).

### Neural synchrony

Underlying all other measures of IPS are the neural signals that trigger these physiological changes. IPS has frequently been identified in the temporo-parietal junction, which has been linked to perspective-taking and other mental capacities related to social functioning (Bitsch et al., 2018; Kinreich et al., 2017; Nguyen et al., 2021). Activity reflective of IPS has similarly been shown in the dorsolateral prefrontal cortex, a region associated with top-down emotional regulation, which is key for facilitating socially appropriate responses (Balconi and Pagani, 2014; Lu & Hao, 2019; Nguyen et al., 2021). The neural manifestations of IPS tend to occur in gamma band frequencies (30-90 Hz), which are associated with mental processes underlying interpersonal interaction such as attention, arousal, and top-down modulation of sensory perception (Cohen et al., 2009; Kinreich et al., 2017; Pizzagalli, 2007). Accordingly, a study by Kang et al. (2012) found that emotional pictures elicited greater increases in gamma band activity compared with neutral pictures, supporting the role of this frequency in modulating emotional responses.

EEG measures neural electrical oscillations, which are reflective of the power and spectral qualities of electrical energy released when large groups of neurons are firing (Dick et al., 2014). While EEG characterizes neural functional activity, other neural recording techniques are more informative as to regional localization of neural activity. For example, blood-oxygen level dependent functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIRS) measure changes in the volume of oxygenated hemoglobin, which increases in response to the metabolic demand of neuronal firing (i.e., hemodynamic response; Anders et al., 2011; Liu et al., 2016). In order to draw direct links between neural manifestations of IPS and behaviors, it is more critical that measures of neural activity have high temporal resolution (Cook & Kenny, 2005; Stuldreher et al., 2019). EEG and fNIRS are thus favored for studies of IPS, as they are among the most temporally precise neural recording devices that are also portable and suited for naturalistic environments (Dick et al., 2014; Lindenberger et al., 2009; Tschacher & Meier, 2019).

### Identification using EEG

EEG signals are acquired using electrodes placed on the scalp, and consist of the difference in electrical potential between each electrode and a reference signal (Dick et al., 2014; Pizzagalli, 2007). While electrodes are placed according to a standardized scheme (e.g., the 10-20 international system), activity captured via EEG at a particular spatial location cannot be used to identify its source due to the tendency of electrical signals to diffuse to multiple locations in biological tissue (Dick et al., 2014). The source chosen for the reference signal, often an electrode placed on some region with minimal electrical activity, such as the mastoid or an earlobe, completely determines the shape of the EEG recording output, making this a critical consideration in designing EEG studies (Dick et al., 2014; Pizzagalli, 2007).

EEG studies of IPS tend to center on evaluating its correlations with different types and qualities of interpersonal bonds and rely on behavioral observations of the participants to indicate the valence of their interactions and/or the psychological states reflected by the IPS (Cook & Kenny, 2005; Dikker et al., 2017; Kang et al., 2012; Lindenberger et al., 2009; Stuldreher et al., 2019). For example, a study by Kinreich et al. (2017) found that compared with dyads made up of strangers, romantic couples demonstrated more frequently synchronized gamma oscillations as well as greater increases in behavioral measures, such as interpersonal gaze and positive affect. In another study, psychotherapist-client dyads exhibited greater IPS during sessions of explicit therapy compared with periods in which the dyads engaged in casual conversation, providing evidence for physiological effects of a strong therapeutic alliance (Zhang et al., 2018). In both studies, researchers compared physiological and behavioral measures to provide evidence for the association between EEG synchrony and positive social behavior.

### Identification using fNIRS

Recordings using fNIRS take advantage of the ability of near-infrared light to penetrate biological tissue, utilizing optodes placed on the scalp that emit light several inches into the skull and detect the light that is reflected back (Dick et al., 2014; Chen et al., 2020; Ferrari & Quaresima, 2012). Differences between the emitted and detected light can be used to evaluate relative concentrations of oxygenated and deoxygenated hemoglobin due to their differential light-absorption properties (Dick et al., 2014; Chen et al., 2020; Ferrari & Quaresima, 2012). This allows researchers to calculate a participant's hemodynamic response in different cortical regions over time, their *hemodynamic response function* (*HRF).*

Similarly to EEG, fNIRS often is used experimentally to identify IPS and evaluate its correlations with different qualities of interpersonal relationships (Liu et al., 2016; Lu & Hao, 2019; Nguyen et al., 2020, 2021; Xue et al., 2018; Zhang et al., 2018). While the accuracy of fNIRS measurement has consistently been validated using fMRI, its spatial resolution is comparatively lower, in part due to the lack of precedent in the field for co-registering optode placement using previously acquired structural images (Chen et al., 2020; Ferrari & Quaresima, 2012). Yet as advances in the technology make recording fNIRS increasingly precise and portable, it is more frequently being used for studies focused on localizing neural activity in settings in which fMRI is not possible (Ferrari & Quaresima, 2012). For example, in a study of fNIRS recorded over a naturalistic mother-child conversation, researchers found that positive social behaviors, such as turn-taking predicted neural synchronization, and were able to localize instances of IPS to the tempoparietal junction and the prefrontal cortex (Nguyen et al., 2020).

Hyperscanning algorithms, such as the one originated by Montague, (2002), enable researchers to identify IPS and regional activation patterns during an interactive task by using EEG and fNIRS signals recorded simultaneously from multiple participants (Lindenberger et al., 2009; Liu et al., 2016; Lu & Hao, 2019; Mu et al., 2016). IPS can be quantified in neural data, either over the length of the recording or within bins locked to certain events (Kinreich et al., 2017; Montague, 2002; Mu et al., 2016). For example, in an EEG study of naturalistic interactions between adults, the time window analyzed extended from 200 ms before the stimulus to the cutoff time for the experimental condition, 6,000 ms poststimulus onset (Mu et al., 2016). In another EEG study in a similar experimental context, this window was 300 s, the length of the conversation task (Kinreich et al., 2017). Because the sampling rates for EEG recordings tend to be relatively fast, ranging from 256-1,024 Hz, it is possible to identify meaningful patterns within longer epochs, such as the length of an experimental task, by using short analytic epochs (Chen et al., 2020; Kinreich et al., 2017). While sampling rates used for fNIRS tend to be lower, averaging 10 Hz, they are still high enough that researchers have used longer epochs for analysis with similarly precise results (Liu et al., 2016; Nguyen et al., 2021; Xue et al., 2018). For both measures, sliding analytical windows of equal length (e.g., 1 to 5 seconds) can be used to identify synchrony in recordings of variable lengths, while providing for simple comparison between dyad members (Dikker et al., 2017; Nguyen et al., 2021).

## Other measurement considerations

It is important to note that the structural and functional characteristics of human biological systems change across development to varying degrees. Compared with adults, children tend to exhibit higher baseline HR and HRV measures, as well as cardiac and EDA responses of higher magnitude, all of which approach more adult-like levels over the course of development (Shields, 1983). Other autonomic responses, such as SCL, the tonic component of EDA, reach adult-like levels during early infancy (Shields, 1983; Thorson et al., 2018). Beyond typical developmental changes, other individual-level characteristics can lead to differences in baseline autonomic activity between individuals. For example, infants born prematurely often exhibit significantly more disorganized cardiac rhythms and altered neurodevelopment compared with infants carried to term (Feldman, 2006). Additionally, individuals diagnosed with anxiety disorders show significantly reduced HRV relative to controls, even accounting for covariates, such as traumatic brain injury (Gillie & Thayer, 2014).

In addition to variations in peripheral autonomic function, the brain also undergoes significant longitudinal changes. Alongside the age-related development of various cognitive skills and exposure to different environmental stressors, humans experience shifts in gray matter volume, cortical thickness, functional connectivity, spectral power, and most other measures of neural structure and function over time (Hedman et al., 2011; Giedd et al., 1999; Soto-Icaza et al., 2015). These neuroplastic changes also can affect autonomic responses. For example, differences observed in HRV responses among those diagnosed with anxiety disorders have been linked to differences in neuroendocrine activity related to cognitive self-regulation processes (Gillie & Thayer, 2014). Resting HRV and PEP measures have been shown to differ significantly based on measures of selective attention, which could affect studies of individuals with attention disorders (Giuliano et al., 2018). Thus, differences among dyad-members in developmental stage and other background characteristics can play a role in observed patterns of physiological responses in studies of IPS and should be taken into account in experimental design and data analyses.

Operationally defining IPS is another critical methodological choice that must be made in studies of synchrony. Across the literature, there are multiple statistical procedures to quantify synchrony in raw physiological recordings; however, an in-depth comparison of different forms of IPS and the methods used to calculate them is beyond the scope of this article. For discussion of specific analytical strategies for identifying IPS, see Butler (2011), Cook and Kenny (2005), Ekman et al. (2011), Helm et al. (2018), Kenny (1996), Stuldreher et al. (2019), and Thorson et al. (2018). Regardless of the analytic model, tailoring decisions made during experimental design to the dynamics of the physiological and psychological processes being examined as we have described can increase the probability of identifying relevant patterns.

## Conclusions

This review outlined some of the existing studies of interpersonal physiological synchrony (IPS)—a term used to encompass synchronization between individuals in both neural and autonomic physiological measures. Timing was a major point of focus due to the inherent temporal component of evaluating IPS. We described particular considerations to be made in choosing recording parameters for different physiological measures using prior IPS studies examining these systems as bases. These measures included electrodermal activity (EDA), cardiac activity, respiration, and neural activation, and we discussed some of the constructs and experimental contexts most often associated with each.

Across the literature, identifying moments of IPS requires that researchers use the known dynamics of the physiological processes being recorded to ensure that observed responses are direct results of the experimental context and the psychological processes associated with it. Biological processes operate on different time scales, so experimental time windows must take these dynamics into account. Therefore, choosing an appropriate length for the epochs within a physiological recording used for analysis is especially important in studies of IPS. Too long of an epoch risks wrongfully correlating a physiological fluctuation to the interaction, and too small of an epoch may not capture a relevant change (Boker & Nesselroade, 2002; Jennings & Gianaros, 2012; Palumbo et al., 2016; Thorson et al., 2018). In addition, the timing of an analytic epoch in relation to the psychological construct being studied can affect the ability to draw causal links between this construct and instances of IPS that are identified. Regardless of the analytic approach used to identify IPS, it is essential that researchers capture the full scope of the physiological fluctuations associated with the psychological process being reflected. Despite the complexities of recording it, IPS can be an informative measure of the qualities of relationships between individuals and can serve as a crucial window into the human brain as it fulfills the basic human drive for interpersonal connection.

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