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Interpersonal Autonomic Physiology: A Systematic Review of the Literature

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Abstract

Interpersonal autonomic physiology is defined as the relationship between people's physiological dynamics, as indexed by continuous measures of the autonomic nervous system. Findings from this field of study indicate that physiological activity between two or more people can become associated or interdependent, often referred to as physiological synchrony. Physiological synchrony has been found in both new and established relationships across a range of contexts, and it correlates with a number of psychosocial constructs. Given these findings, interpersonal physiological interactions are theorized to be ubiquitous social processes that co-occur with observable behavior. However, this scientific literature is fragmented, making it difficult to evaluate consistency across reports. In an effort to facilitate more standardized scholarly approaches, this systematic review provides a description of existing work in the area and highlights theoretical, methodological, and statistical issues to be addressed in future interpersonal autonomic physiology research.

Keywords

interpersonal physiology, physiological linkage, physiological synchrony, physiological coherence, dyadic interactions, social psychophysiology, interpersonal processes, psychophysiology, autonomic, autonomic nervous system

Interpersonal autonomic physiology (IAP) is defined as the relationship between people's physiological dynamics, as indexed by continuous measures of the autonomic nervous system (ANS). Interpersonal analyses of the ANS have found statistically significant similarities in multiple peoples' physiological activity, including when a couple is engaged in a heated argument (Levenson & Gottman, 1983), a therapist is empathizing with a patient (Marci, Ham, Moran, & Orr, 2007), and a conductor is leading the behaviors of a choir (Müller & Lindenberger, 2011). Whether considering family dynamics or group behaviors, psychotherapy, or team leadership, nearly all research to date indicates that IAP can be informative of social interactions. However, despite a recent increase in the utilization of IAP methods, this body of research is currently fragmented, making it difficult to evaluate consistency and veracity across published reports. The use of idiosyncratic terminologies, data collection methods, and statistical analyses has impeded cross-disciplinary collaboration, and lack of awareness of previous work has led to uninformed conclusions and replications of known procedural issues including inappropriate statistical analyses. In the absence of more standardized empirical approaches, these issues will continue to hinder progress in this promising area of study.

This systematic review is intended to be a reference source wherein we compile extant research and highlight issues deemed critical for future work. Recent advancements in wireless telemetric data collection systems (for a review, see Goodwin, 2012) and dynamic multivariate time-series analysis (Walls & Schafer, 2006) are beginning to enable IAP research in ways not traditionally possible. These methodologies include untethered, continuous, and passive assessment of interpersonal physiological interactions in both laboratory and real-world settings. However, for these novel methods to generate new insights and interventions, increased methodological rigor is needed to better understand and empirically demonstrate the physiological dynamics between two or more people. This is the primary contribution of our systematic review, which is organized in the following way. First, we operationally define basic terminology and detail our methods for search, retrieval, and eligibility criteria. Second, we review key themes and issues identified in the literature and provide a summary of general findings. Last, we discuss strengths and weaknesses

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of methodological and analytical approaches used to date, highlight current limitations, and propose guidelines for future best practices.

Operational Definitions of Key Terms

The general methodology for studying temporal interactions in physiological processes between multiple people is termed herein *interpersonal physiology*. At minimum, these techniques require a bivariate analysis of physiological measures collected from two individuals over time. The focus of this review is on IAP research, which uses continuous measures of the ANS from multiple people concurrently. Other measures have been used to study interpersonal physiological dynamics (e.g., cortisol, electroencephalograph [EEG]); however, they are limited by infrequent data collection (i.e., often only a few data points) and the settings where data are collected (i.e., mostly lab based). Although interpersonal processes measured with other techniques are important, the rapidity of measurable responses, interpretability of data, and potential for mobile, passive collection of continuous data make ANS measures uniquely adaptable to social-psychological research.

A common observation resulting from interpersonal physiological research is interdependence or associations in partners' physiological activities. However, idiosyncratic references and analyses of physiological interdependence or association make cross-study comparisons difficult. For the purposes of the current review, we generalize the term *physiological synchrony* (PS) to refer to any interdependent or associated activity identified in the physiological processes of two or more individuals. PS is therefore conceptualized as a general categorization, under which more specifically defined patterns are included.

Prior to reviewing this body of literature, it is important to highlight several basic principles and interpretive limitations of psychophysiological measurement.

The ANS

The ANS is primarily[1] made up of Sympathetic Nervous System (SNS) and Parasympathetic Nervous System (PNS) branches that together dynamically regulate internal viscera including cardiac, respiratory, and glandular systems. In general, the SNS is a catabolic system associated with physiological activation (i.e., increased arousal or "fight or flight") and the PNS an anabolic system associated with restoration and repair (i.e., decreased arousal or "rest and digest"). Both branches work in tandem, and dynamically change as they regulate the body in preparation for and response to current endogenous and exogenous environmental conditions. The complex interaction between the SNS and PNS can be measured using a variety of techniques, each with its own characteristics. More general measures, such as heart rate (HR), are reflective of overall autonomic state, but cannot distinguish relative contribution of SNS or PNS influence. More specific measures, such as synchrony of breathing rate and HR known as respiratory sinus arrhythmia (RSA), have been shown to be primarily parasympathetic (Camm et al., 1996). Similarly, electrodermal activity (EDA) is an indirect measure of eccrine sweat glands, which are uniquely innervated by the SNS (Boucsein, 1992). Pre-ejection period, a cardiac measure of the time between ventricle depolarization and the beginning of ejection, is also a distinct measure of SNS (N. A. Fox, Schmidt, Henderson, & Marshall, 2007). Specificity of these measures as they relate to SNS and PNS helps determine autonomic activity within an individual. Whereas increasing RSA indicates increasing PNS activity, increasing EDA suggests increasing SNS activity, so PS in these measures may be indicative of different processes. For example, it is possible that interpersonal synchrony in SNS activity is more likely during negative contexts such as stress, whereas synchrony between peoples' PNS activity may be more likely during positive contexts, such as empathy.

The importance of ANS measures to psychological research is difficult to overstate. Psychophysiological findings have contributed to nearly every aspect of psychology, and physiology plays a known role in critical psychosocial processes including cognition, emotion, and behavior (Cacioppo, Tassinary, & Berntson, 2007). Human physiological regulatory systems strive to operate within an optimal range of SNS and PNS influence, constantly adjusting toward an affective state that balances autonomic function with actual demands (S. I. Fox, 1996). Whereas heightened arousal has been shown to associate with enhanced emotion, increased attention, and better memory, over activation can lead to a degradation of these processes (Critchley, 2002; Yerkes & Dodson, 1908).

Although ANS activity is a well-validated measure of physiological arousal, it does not indicate valence (i.e., positive and negative appraisal) or context. Secondary measures are therefore needed to differentiate between physiological activities due to cognitive demands such as mental math, behavioral demands such as running, or emotional states such as anger (cf. Circumplex Model of Emotion, Russell, 1980; Russell & Barrett, 1999).

Intrapersonal Versus Interpersonal

To date, study of the ANS as a measure of human experience has been performed primarily at the intrapersonal level, wherein temporal changes are explored "within-subject." In contrast, the studies included in the current review offer evidence that the ANS is also externally responsive to, and in some instances, dependent on and/or shaped by, the nervous system of others "across-subject." This latter framework suggests that social interactions may be better understood when autonomic processes of all participants are known.

Causal Versus Correlational

It is critical to note that periods of PS do not implicitly denote interpersonal relationships. Extraneous variables including shared environments, matched activities, or long-term processes (e.g., diurnal rhythms) can also lead to PS, giving the false appearance of socially driven physiological interdependence. Similarly, co-occurrences between PS and other variables including conditions (e.g., task assignment) and psychosocial context (e.g., high empathy) do not indicate causal or consistent relationships.

Although many studies are rooted in the assumption of interpersonal causality (i.e., reactivity in one person causes reactivity in another), observations of PS may be informative of social conditions in the absence of causal interdependence. When individuals' physiological processes align over time, it indicates that each person is experiencing similar patterns of physiological activity. Although these physiological responses may not be due to an interaction between individuals, they could reflect matched dependence on another variable. For example, it may be expected that individuals watching a television program in different locations would display synchrony due to matched physiological responses to the show. Their synchrony is then an example of how aligned they were in their responses to this other variable. Furthermore, there is some evidence that viewers' physiologies will synchronize with specific individuals they are watching in a video, suggesting that PS can indicate who viewers associate with (Soto & Levenson, 2009). Similarly, PS between individuals in an audience may be indicative of group engagement, such as synchrony due to crowd members laughing at the same jokes. Such matched responses may also reveal group membership, as likeminded individuals may be more likely to have similar responses to a given condition. Accordingly, studies of interpersonal physiology when causal interdependence is not hypothesized may prove useful in exploring questions about social responses to external variables.

Method

Search and Retrieval

A systematic literature review was conducted according to guidelines presented by Okoli and Schabram (2010). All researchers underwent protocol training to search for and identify relevant articles. The goal was to identify and retrieve all IAP research published in peer-reviewed journals. Several search terms were chosen based on previously identified research. These terms were *physiological synchrony, interpersonal physiology, physiological linkage, physiological coherence*, and *physiological covariation*. Following an initial search, the following four search term combinations were added based on relevant articles that used alternate language: *social psychophysiology, physiology* & *contagion, attunement* & *physiology*, and *attunement* & *physiological*. Keywords were entered into four bibliographic databases: PsycINFO, PsycARTICLES, PubMed, and Science-Direct. Reverse citation was performed on each relevant paper obtained using Google Scholar (i.e., a search for studies that cite the obtained article). Relevant articles referenced in the text of identified studies were also obtained. Searches included all publication dates, and were performed through November 2015.

Eligibility Criteria

Studies selected for the review were based on the following inclusion criteria:

1. Published in English.
2. Published in a peer-reviewed journal.
3. Included human subjects.
4. Continuously collected autonomic measures from two or more proximal individuals simultaneously.
5. Quantitatively assessed temporal relationships in autonomic measures simultaneously collected from two or more people (e.g., bivariate correlations).

Studies not selected for the review were based on the following exclusion criteria:

1. Used only endocrine (e.g., cortisol), neural (e.g., EEG), or behavioral (e.g., daily affect) measures.
2. Only assessed autonomic interactions between individuals who were not simultaneously proximal (e.g., watching a tape of a previous interaction).
3. Only assessed intrapersonal physiological activity, without assessment of interpersonal physiological interactions.
4. Assessed mother–fetal relationships, as physical and metabolic interdependences are known to exist between this particular dyad.
5. Manuscript was not peer-reviewed. Due to the analytical complexities involved in interpersonal physiological research, we did not include manuscripts if they had not passed the rigors of peer review.

Results

Using the keywords mentioned above, a total of 4,236 manuscripts were returned from the search engines. Following the procedures outlined above, 61 studies that met our defined eligibility criteria for interpersonal IAP research were identified. For reference, Tables 1 through 5 summarize each study based on the population studied (e.g., couples, parent–child). The tables also include the purpose of each study, the participant sample, procedures and physiological measures used, and relevant results. Additional information about each study can be found in Appendix A. There, terms each study used to define PS are also listed, as well as statistical analyses used to assess synchrony, methodological approach (i.e., idiographic or nomothetic), and whether a customized null hypothesis was tested.

To help establish a centralized resource synthesizing research in this area to date, as well as identify critical issues to overcome in future work, the following characteristics of included studies are evaluated: terminology, physiological measures, statistical assessment of PS, methodological approach, and study findings.

Terminology

Over a dozen different terms throughout the literature describing research on IAP were identified (see Appendix A for terms used by studies). Most studies used terms based on observed phenomenon such as *synchrony* (e.g., McAssey, Helm, Hsieh, Sbarra, & Ferrer, 2013), whereas others used terms such as *sociophysiology* to describe a general methodological approach (Di Mascio, Boyd, Greenblatt, & Solomon, 1955). Others failed to give a clear definition or term in reference to a method or phenomenon (e.g., Kaplan, Burch, Bloom, & Edelberg, 1963).

Terminology largely varied according to the population under study. For example, approximately 70% of studies using the term *physiological concordance* (n = 9) addressed therapist–client dyads, and 100% using *physiological compliance* (n = 7) examined teammates. However, operational definitions assigned to the same terms were often inconsistent across studies. For example, Henning, Boucsein, and Gil (2001) coined the term *physiological compliance* in reference to spectral coherence and Pearson correlations in concurrent cardiac, respiratory, and EDA measures. More recently, Järvelä, Kivikangas, Kätsyri, and Ravaja (2013) used identical statistical approaches and operational definitions as Henning et al. (2001), but instead used the term *physiological linkage*. Alternatively, Reed, Randall, Post, and Butler (2013) used *physiological linkage* in reference to both concurrent and lagged interdependencies between participants' cardiac and electrodermal measures. Despite the range of terminology, all refer to similarities between signals. Due to this consistency, we generalize the operational definition of PS to include any observed interdependence or association between more than one person's physiology.

PS. PS is typically defined as an interdependence or association between physiological signals from two or more people. However, synchrony is a nonspecific construct, as its identification is dependent on the procedure used to test it. For example, coherence analysis assesses cyclical patterns in the frequency domain (e.g., Henning et al., 2001), whereas bivariate time-series analysis addresses linear relationships in the time domain (e.g., Levenson & Gottman, 1983). As different analyses of synchrony address different components of data, results can differ substantially. It is therefore important for analyses of PS to be well matched to the research question because different approaches can alter interpretations and implications of study results.

In addition to detecting the presence of synchrony, we identified six key parameters that have been used to further define PS: *magnitude, sign, direction, lag, timing*, and *arousal*.

Magnitude refers to the strength of synchrony, such as a regression or correlation coefficient. This typically represents the effect size of a given measure of synchrony, with higher magnitudes indicating signals have greater interdependence or association.

S*ign*, which is typically positive or negative, indicates that peoples' arousal levels synchronously move in the same or opposite directions (e.g., a positive or negative correlation). This has been referred to as concordant and discordant (e.g., Di Mascio et al., 1955), as well as in-phase and anti-phase synchrony (e.g., Reed et al., 2013). Whereas positive synchrony indicates partners' physiologies move in the same direction, negative synchrony can indicate moving toward or away from the state of a partner.

Direction refers to the predictability of one person's physiology from another's. Results from tests of predictability may indicate a unidirectional or multi-directional relationship. In a unidirectional relationship, some magnitude of one person's physiology is predicted by another's, but not vice versa. In a multi-directional relationship, some magnitude of one person's physiology is predicted by another's, and vice versa. For example, Ferrer and Helm (2013) used coupled differential equation models to show that different proportions of male and female partners' respiration were simultaneously predictable from the other's respiration.

Lag refers to a shift in temporal alignment of data and has been used to show that a pattern in one person is followed by a similar pattern in another (e.g., Feldman, Magori-Cohen, Galili, Singer, & Louzoun, 2011; Müller & Lindenberger, 2011). The difference in time alignment from one data set to another is the specific lag, which may indicate millisecond differences, or much longer time offsets. An example of this can be seen in Müller and Lindenberger (2011), who used Granger causality models—a method of testing whether one time series can predict another—to show that respiration rates (RRs) of choir singers could be predicted from the conductor's. These results were interpreted as evidence that the conductor was leading the choir. Although lagged PS implies a unidirectional relationship, there is some evidence that the length of a lag (e.g., 1 s vs. 10 s time offset) can reflect psychosocial properties that are independent of direction and worthy of exploration (e.g., Feldman et al., 2011; Messina et al., 2013). For example, in a study of therapist–client dyads, Messina et al. (2013) found that the lag of significant cross-correlations between empathy and PS differed by therapist training. This was interpreted as evidence that therapists with greater training are better able to maintain empathy with clients.

The *timing* parameter refers to the length of time that a given interaction is assessed or observed. Most extant studies assessed PS for a somewhat arbitrarily defined period of time, such as the length of a condition. Thus, the parameters of synchrony are an aggregate of a given time period. This leads to notable differences in how results can be interpreted across studies, as aggregates of interpersonal interactions over an hour may be substantively different from aggregates of a few minutes. This issue becomes more complex when considering that multiple interpersonal physiological processes can operate at different time scales simultaneously. For instance, synchrony measured in short time scales (e.g., seconds or minutes) may reveal patterns related to momentary interactions, whereas long-term measures (e.g., hours or days) could show interactions that take longer to develop. Both are equally valid approaches, but results could be indicative of different types of processes. An example of this can be seen in Ferrer and Helm (2013), who compared couples' interpersonal patterns of respiration over minutes, with couples' affect over days. They found that in some conditions, couples' patterns of PS in respiration over 3-min trials were the same as those found in daily affect, indicating that, in this case, both short- and long-term interactions were similar. The time scale assessed is therefore a key element of a research question. Another critical issue with timing is choosing an appropriate time scale when the temporal process is unclear. As longer time periods increase potential for relevant changes to be aggregated together, data should be assessed on a time scale that is theorized or known to be consistent with the process of interest. One way to manage this issue is to use time-varying models, which can assess when and how PS changes over time. Although few studies have incorporated time-varying models into IAP research (for exceptions, see Müller & Lindenberger, 2011; Quer, Daftari, & Rao, in press; Waters, West, & Mendes, 2014), this is an important consideration for future work.

Finally, the pattern of *arousal* can be assessed as a covariate of PS. At its simplest, mean arousal level can be used as a covariate of synchrony. This can be seen in Creaven, Skowron, Hughes, Howard, and Loken (2014), who found that higher maternal HR was associated with lower magnitudes of mother–child PS. More complex models of arousal patterns can also be tested as covariates or moderators of PS, such as assessing whether increasing PS correlates with decreasing arousal. Furthermore, arousal patterns themselves may be assessed as an interpersonal moderator. For instance, Butler and Randall (2013) termed one type of moderation *stress buffering*, defined as a period when an individual moderates the stress level of another, but the partners are not necessarily experiencing the same physiology (i.e., *magnitude* may equal zero). Such a pattern may lead to muted arousal responses and faster return to homeostatic states, whether or not PS occurs. For example, the presence of a relaxed partner may lead an individual to maintain a degree of calmness during a stressful event, although the partners' arousal patterns are dissimilar. Whereas *stress buffering* specifically refers to interpersonal moderation of a stress response, a wide range of interpersonal physiological moderators can also be tested. Specific physiological states in one person may contribute to reduced or amplified arousal levels in others, or the likelihood that a given type of PS will develop. In addition, there may be interaction effects that contribute to the potential for moderation, such as someone with very high arousal levels being less likely to experience *stress buffering* or PS than someone with lower arousal. This general approach to IAP research is therefore not dependent on PS, yet has significant potential to reveal other types of interpersonal physiological interactions.

Another construct in the literature is *asynchrony*, used to describe a lack of observable PS (Reed et al., 2013). Although difficult to substantiate without the use of multiple models to test for PS, the concept of *asynchrony* is an important one, as it describes periods of dissimilarity between people (i.e., *magnitude* = 0). *Asynchrony* has been found to be predictive of specific relationship types (e.g., Reed et al., 2013), suggesting that identification of periods that lack PS can also be informative of an interaction. For example, periods of *asynchrony* may occur during an interaction if an individual is ignoring the state of a partner (e.g., Marci & Orr, 2006), or if one member does not correspond with others in a group.

Psychosocial terms. A number of psychosocial constructs identified in the literature refer to specific combinations of PS parameters. However, unique properties as well as inconsistent operational definitions of psychosocial terms can make direct comparisons with measures of PS difficult. Poorly defined terms can blur important distinctions between processes, and inconsistencies can hinder cross-study comparisons. The construct *coregulation* has been identified as a prime example of this issue (Butler & Randall, 2013). It has been defined as a bidirectional emotional relationship leading to emotional and physiological stability around an optimal state for both partners in a close relationship (Butler & Randall, 2013). However, whereas this definition specifically refers to a bidirectional interaction, others have conceptualized *coregulation* as including unidirectional interactions, such as a parent calming a child (e.g., Feldman, 2003). Unidirectional coregulation was observed in Field, Healy, and LeBlanc (1989), who found that infants' HR followed their mothers' at a short (<1 s) lag. Similarly, specifying the state (i.e., optimal) and relationship type (i.e., close) limits the context of *coregulation*, as the same physiological pattern could occur in other relationships or around a suboptimal state, such as coworkers maintaining a bidirectional relationship around a stressful state.

Due to terminological variations, it is important for IAP research to specifically and consistently define and differentiate between psychosocial terms (e.g., coregulation) and physiological measures (e.g., PS parameters) under study. An example of this level of terminological clarity can be seen in Butler (2011), who presents a set of psychosocial terms along with statistical components of synchrony (therein termed *covariation*) they represent. This approach helps clarify and distinguish between the measurable properties of a given physiological interaction and associated psychosocial terms.

Well-defined terms also help make two distinct research approaches possible. The most common is to test whether a given type or magnitude of PS is present. This is typically applied when the primary interest is to determine differences in PS across groups or conditions. For example, Guastello, Pincus, and Gunderson (2006) compared PS between groups engaged in different conversations, and found that competitive, cooperative, and control groups displayed similar magnitudes of PS. Alternatively, when the research question regards the conditions associated with a given type of PS, data can be searched to locate instances of specific parameters of synchrony. For example, using this approach, Helm, Sbarra, and Ferrer (2014) tested couples' RSA for morphostatic coregulation as defined by Butler (2011; i.e., coregulation around a stable level) and found that it was present across different conversation tasks. Similarly, Stratford, Lal, and Meara (2012) searched data from therapy sessions for periods with the highest magnitude of positive PS, then assessed neurological activity during those periods.

Physiological Measures

Measures of PS in the literature we retrieved included cardiovascular (e.g., HR, RSA, heart rate variability [HRV]), respiratory (e.g., respiratory rate; respiration volume time) and EDA (e.g., skin conductance, skin conductance response), and thermal measures (e.g., skin temperature; see Table 1). The majority of studies relied on a single physiological measure to test for synchrony ($n = 38$; 62%), whereas others used multiple concomitant physiological measures ($n = 23$; 38%), typically running separate analyses on each. This practice leads to categories with more results than the number of studies reviewed. For example, Henning et al. (2001) used three techniques to test for PS: cross-correlations in skin conductance, weighted cross-coherence in HR, and weighted cross-coherence in respiratory rates. Levenson and Gottman (1983) used a bivariate time-series analysis to assess PS in a combined index of normalized scores of HR, pulse transmission time, skin conductance level (i.e., the tonic component of skin conductance), and somatic movement.

Results by measure. We assessed results by specific measures of cardiac activity (Appendix B), EDA (Appendix C), respiratory activity (Appendix D), thermal changes (Appendix E), and indexes of multiple measures (Appendix F). Results are summarized in Appendices B to F, including the specific physiological measure used, the context in which synchrony was tested, whether findings were statistically significant, and summaries of relevant results. Each result was further explored according to six categories: general evidence of PS, differences in PS between groups, differences in PS between conditions within groups, moderators of PS (e.g., resting HR moderating PS levels), psychosocial correlates of PS (e.g., PS correlated with empathy), and specific typologies of PS (e.g., significant findings of positive or negative PS). We could not identify any patterns in findings by measure.

An example of the ambiguity of results can be seen in findings of PS through EDA. Whereas studies using most metrics have found significant PS in dyads (e.g., Chanel Kivikangas, & Ravaja, 2012, using skin conductance; Järvelä et al., 2013, using skin conductance response—the phasic component of skin conductance; Marci & Orr, 2006 using skin conductance level), others do not (e.g., Reed et al., 2013, using skin conductance). Cross-study comparisons of between-group differences lead to similar ambiguities, such as one result indicating significant PS in skin conductance between dyads of friends but not strangers (Shearn, Spellman, Straley, Meirick, & Stryker, 1999), whereas another found significant PS in the skin conductance of strangers (Silver & Parente, 2004). Results are also unclear when considering the relationship between psychosocial constructs and PS. For example, most studies comparing PS in EDA with empathy found significant correlations when using skin conductance level (e.g., Marci et al., 2007; Marci & Orr, 2006; Messina et al., 2013; in therapists–clients), although one found no association using skin conductance (Chatel-Goldman, Congedo, Jutten, & Schwartz, 2014, in couples), and another found both significant and non-significant results using multiple novel metrics of skin conductance responses (Robinson, Herman, & Kaplan, 1982, in therapists–clients).

Although no definitive patterns have yet emerged, relatively consistent findings of PS across physiological measures suggest that synchrony is a robust phenomenon identifiable through numerous methods. Studies such as Levenson and Gottman's (1983), which used an index combining multiple physiological measures, may therefore be reasonable approaches for capturing a general autonomic pattern. Still, as different measures reflect distinct autonomic processes, and it is unknown whether different types or outcomes of PS are system-specific, it remains important to test each system independently.

Methodological Approaches

When interpreting IAP research, it is also important to consider the difference between idiographic and nomothetic methods. Idiographic methods focus on an individual unit (e.g., one dyad or team), whereas nomothetic approaches combine data to assess group-level trends (e.g., multiple dyads or teams). Results from the two strategies only correspond when all conditions of the ergodic theorems are met (e.g., multivariate normal data with equal autocorrelation and trends across the data; for more detailed discussion, see

Table 1. Results by Population: Parent–Child.

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Baker et al. (2015)	Tested whether PS developed between parents and their child with autism.	28 parent–child dyads	Participants engaged in 4 min of free play.	EDA	Individual differences in PS were detected in the parent–child dyads. Strength of synchrony was negatively associated with autism severity. More severe diagnosis was associated with lower PS.
Creaven, Skowron, Hughes, Howard, and Loken (2014)	Explored the effect of child maltreatment on PS in mothers with their child.	104 mother–preschool-aged child dyads	Dyads sat closely together, resting quietly while viewing a low-action animated videotape.	HR; RSA	Significant positive PS found in the HRs of non-maltreating mothers and their children. Negative PS between mother and child was observed in the HR and RSA of both maltreating and non-maltreating groups. Mothers' resting HR was found to moderate PS, as higher average resting HR was associated with lower PS.
Ebisch et al. (2012)	Examined empathy and PS in facial skin temperature between mothers and children during distress.	Six mother–child (38-42 months) dyads	Women watched their child participate in a series of play and stress phases through a one-way mirror.	Temp	Significant correlations were found between skin temperatures of mothers and their children.
Feldman, Magori-Cohen, Galili, Singer, and Louzoun (2011)	Examined the effects of face-to-face interactions on PS in HR between mothers and their infants	40 mother–infant (3 months) dyads	Micro assessments of gaze, affect, and vocal synchrony were conducted while mother and infant dyads sat face-to-face and played.	IBI	Statistically significant levels of PS were found during face-to-face interactions. Time periods involving vocal synchrony, affect synchrony, or the co-occurrence of vocal and affect synchrony significantly related to increased positive PS in IBI between mother and infant compared with periods without behavioral synchrony.
Field, Healy, and LeBlanc (1989)	Assessed coherence and cross-coherence between behavioral states, HR, and behavioral states and HR of depressed and non-depressed mother–infant dyads.	16 mother–infant (3 months) dyads	Mothers and infants played in a face-to-face interaction.	HR	Coherence across behaviors for both depressed and non-depressed dyads was found. Positive PS in HRs was found in more than half of the dyads, with no significant differences across depressed and non-depressed dyads.
Ghafar-Tabrizi (2008)	Examined PS in low-conflict and high-conflict mother–adolescent daughter conversations.	63 mother–adolescent dyads	Mother–daughter dyads sat facing one another and were asked to discuss a neutral, a conflictual, and a pleasant topic.	HR; FPA	Levels of felt arousal were associated with the strength of PS during dyadic interaction, suggesting an experiential component was associated with these periods. When daughters led the conversation, their HR predicted the response pattern of mothers better than mothers predicted daughter, and vice versa. Equivalent levels of PS were demonstrated across varied conversation topics. In the high-conflict group when daughters led the conversation, the HR of daughters predicted HR of mothers significantly better than when mothers led the conversation. High-conflict dyads did not demonstrate higher levels of PS than lower level conflict dyads. PS, however, was stronger during conflictual conversation than pleasant conversation for the high-conflict group only.

(continued)

Table 1. (continued)

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Ham and Tronick (2009)	Examined physiological and behavioral synchrony between mother–infant dyads.	18 mother–infant (5 months) dyads	Dyads participated in the face-to-face still-face paradigm, involving three successive 2-min episodes of regular interaction, a perturbation episode where mothers could not respond, and a soothing episode.	SC	Positive PS in SC approached significance during the still-face paradigm when infants displayed negative behaviors. When mothers engaged in subsequent soothing of infants, greater positive PS occurred in relation to behavioral synchrony.
Hill-Soderlund et al. (2008)	Examined physiological differences between insecure-avoidance and securely attached mother–infant dyads.	132 mother–infant dyads	Dyads participated in the Ainsworth SSP, which separates dyads into categories of attachment quality.	RSA	Mothers had significantly greater levels of RSA than infants across all time points; however, there were no significant findings of PS of RSA during the SSP.
Lunkenheimer et al. (2015)	Examined whether PS in RSA between parents and preschoolers varied with child problem behaviors across tasks.	47 mother–child dyads	Dyads completed a baseline, followed by free play, clean-up, and a puzzle task.	RSA	Significant levels of PS in RSA were detected in mother–child dyads. Positive PS was observed in the absence of child behavior problems, and negative PS was observed when problems were present.
Manini et al. (2013)	Compared the PS in thermal signals of mother–child dyads with other woman–child dyads during stress conditions.	18 woman–child (39-45 months) dyads	Women watched their own or another child participating in a series of play and stress phases through a one-way mirror.	Temp	PS was found between women and children regardless of parenting status. Correlations were significantly higher, and cross-correlation lags were shorter between mothers and their own vs. other child dyads.
Moore (2009)	Tested relationships between infants' and mothers' vagal response to anger.	48 mother–infant dyads	Following priming of neutral, anger, or excitement, mother–infant dyads completed the still-face paradigm.	RSA	No correlations were observed between mothers' and infants' RSA change scores within or across conditions.
Moore et al. (2009)	Examined maternal sensitivity to infants as a moderator of physiological regulation during parent–infant interactions.	66 mother–infant dyads	Following baseline, mothers and infants underwent the still-face procedures; due to missing data, only baseline PS was assessed.	HP; RSA	Mother–infant HP, but not RSA, was moderately, significantly correlated during baseline. No other dyadic analyses were conducted due to missing data issues.
Suveg, Shaffer, and Davis (2016)	Explored interactions between behavioral and physiological synchrony between mothers and children, child self-regulation, and family risk during a joint mother–child task.	93 mother–child dyads	Mother–child dyads completed a silent baseline, followed by a joint task that involved drawing a picture on an etch-a-sketch.	IBI	Results indicated PS was present and independent of behavioral synchrony or self-regulation. Interactions between these variables were moderated by family risk. High-risk children had lower self-regulation and behavioral synchrony when PS was higher, suggesting PS within a negative context disrupts self-regulation.

(continued)

Table 1. (continued)

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Van Puyvelde et al. (2015)	Tested the influence of maternal breathing pace on mother–child PS.	11 mother–infant dyads	Mothers breathed at varying paces while holding infants. The procedure was repeated at ages 1, 2, 3, 4, 8, and 12 weeks.	RSA	Mother–infant RSA synchronized across different breathing paces until infants were 2 months, but did not synchronize at 3 months.
Waters, West, and Mendes (2014)	Assessed affect contagion between mothers and infants.	69 mother–child (12-14 months) dyads	Mothers were primed by a stressful-positive, stressful-negative, or a neutral condition, then united with their infants. Physiological interactions between mothers and infants were recorded, and infant's interactions with an interviewer were assessed.	HR; VC	PS was found between infant HR and mother VC. Further analyses revealed that PS was found in the negative and positive conditions, but not the neutral condition. In addition, increasing PS over time was observed in dyads in the negative feedback condition, but not the positive or neutral conditions. Infants whose mothers experienced a stressful-negative event were significantly more avoidant than the other infants. This suggests that mother's stress influences infant physiology and behaviors. The researchers concluded that stressful affect is contagious across mothers and infants.
Woltering, Lishak, Elliott, Ferraro, and Granic (2015)	Investigated interactions between physiological and behavioral synchrony in children with normal and atypical self-regulation during mother–child interactions.	118 mother–child dyads	Dyads discussed a positive (4 min), personally negative (6 min), and another positive (4 min) topic. Mothers completed questionnaires before and after, and observers coded videos of the discussions.	IBI	Higher PS was observed during the positive discussions than negative discussions, with more than twice the magnitude during the last topic than the first topic. Greater PS was associated with significantly better outcomes after the negative interaction. No differences in PS between typical and atypical children groups were found. PS associated with behavioral synchrony only during negative discussion.

Note. PS = physiological synchrony; EDA = electrodermal activity; HR = heart rate; RSA = respiratory sinus arrhythmia; Temp = facial temperature; IBI = interbeat interval; FPA = finger pulse amplitude; SC = skin conductance; SSP = strange situation paradigm; HP = heart period; VC = ventricle contractility.

Molenaar, 2004a; Velicer, Palumbo, & Babbin, 2014). Inappropriately inferring individual processes from group-level results, known as the ecological fallacy, commonly leads to misinterpretations of results (Velicer, Babbin, & Palumbo, 2013). Because nomothetic techniques simultaneously model data from multiple units, results indicate the trend of a group, not necessarily the unique patterns of individuals who make up that group. As a result, nomothetic generalizations should only be interpreted as the tendency of a sample as a whole and used to answer population-level research questions. For example, nomothetic designs are well-suited to determining whether a certain type of video game increases PS between players. As the game will be played by a specified population and is not tailored to an individual gamer, nomothetic results are appropriate. Alternatively, and importantly, if a researcher is interested in processes that lead to PS during gaming for a specific dyad, then detailed temporal results from idiographic methods are needed.

Ferrer and Helm (2013) reviewed this discrepancy when discussing the heterogeneity of results from idiographic models of PS in dyads. They note that if a single model is fit to pooled data from all dyads, it represents an aggregated pattern that does not accurately represent characteristics of individual dyads in the sample. Manini et al. (2013), for instance, observed this issue directly by comparing findings from idiographic and nomothetic analyses completed on the same data. They noted that idiographic results indicated statistically significant levels of PS in dyads at varying lags, but non-significant findings at the nomothetic level. The authors pointed to the heterogeneity of time lags in PS across dyads as a potential source of the discrepancy.

Although some nomothetic techniques (e.g., multilevel modeling) attempt to correct for differences between group and individual patterns, the results from such techniques remain group-level aggregates that are not able to represent idiographic trends unless the sample is relatively homogeneous (Molenaar, 2004b). For example, whereas multilevel modeling allows individual-level parameters to vary, those parameters are assumed to be normally distributed, and models require all individuals to have the same functional form. Therefore, given sufficient data to carry out idiographic analyses, a bottom-up approach (i.e., from individual level to group level) may be more suitable when the aim is to generalize results. For example, detailed analyses of dyads can be used to identify patterns of PS, followed by assessments exploring whether those patterns are recurrent across time, contexts, and relationship types. A simplified example of this approach can be seen in Ghafar-Tabrizi (2008), who assessed PS at the dyadic level, but presented results as the percentage of dyads observed with given characteristics. More quantitative idiographic generalization techniques such as pooled time-series analysis and dynamic cluster analysis are also available (e.g., Aloia et al., 2008; Höppner, Goodwin, & Velicer, 2008).

Idiographic analyses. Both *idiographic* and *nomothetic* methodologies have been used in IAP research (see Appendix A for the methodology and analysis used in each study). At the idiographic level, one of the most commonly used approaches to measure the relationship between two variables is a Pearson correlation. For example, recent research has used correlations to assess PS between mothers and children (Ebisch et al., 2012), strangers (Silver & Parente, 2004), and teammates (Chanel et al., 2012). However, correlations are not well-suited for continuously measured physiology, because data typically show sequential dependency (i.e., autocorrelations) and non-stationarity over time (i.e., changing mean and variance). An example of issues using correlations to measure PS can be seen in Liu, Zhou, Palumbo, and Wang (in press). There, they show that results from correlations of both simulated data, and electrodermal data from couples, can show spurious results. Similarly, both autocorrelation and non-stationarity violate general linear model (GLM) assumptions of data independence and stationarity, so they need to be accounted for if applying GLM analyses.

Time-series analysis is one way to account for sequential dependency in repeated-measures data, and hence provides a more valid representation of the association between variables than Pearson correlation. It can be carried out in either the time or frequency domain. Time domain models used to capture PS typically come from the autoregressive-moving-average (ARMA) model family. Once dependency in the data is modeled and thus statistically removed, standard analyses based on the GLM can then be performed. Feldman et al. (2011) used these procedures with cross-correlations to assess PS in the interbeat intervals of mothers and children, and found significant levels of PS during face-to-face interactions. Frequency-based techniques (e.g., coherence, phase difference, directed coherence) decompose data into cyclical components, and typically test whether similar frequency bands occur across data sets. These analyses can quantify similarities in the cycles of multiple measures, their lead–lag relations, and directed influences between variables (Liu & Molenaar, in press). Another example of a frequency-based technique can be seen in Henning et al. (2001), who used weighted cross-coherence in skin conductance variability, HR, and respiration and found that PS predicted team errors.

Most time-series models, however, are based on the assumption of stationarity, meaning that statistical properties (i.e., means, covariance matrices) of data are constant over time. This implies that the interpersonal dynamics remain constant during an interaction, which may not be the case. As models aggregate data, if there are multiple processes within a period, results may not accurately represent any of the individual patterns. To model time-varying effects in idiographic data, new methods are emerging, including wavelet analysis, threshold autoregressive models (Hamaker, Zhang, & van der Maas, 2009), and regime-switching models (Yang & Chow, 2010). These methods have rarely been applied to IAP data. In one example, Quer et al. (in press) used wavelet analysis to show that the dynamics of PS between groups of people meditating changed over time. Moving window techniques have also been adapted to detect dynamics in PS, most commonly as part of an analysis known as a "linkage index" (e.g., Marci et al., 2007). Here, an analysis is run on a segment of data, the window is stepped forward in time, and the analysis rerun on the next segment. Continuing this procedure through the data yields a time series of synchrony scores, illustrating how synchrony dynamics change over time. Another example of this can be seen in Stratford et al. (2012), where they calculated "linkage indexes" in windows to determine when synchrony in the skin conductance of therapists and clients peaked during sessions. However, as issues of stationarity and autocorrelation apply to any given window, the potential for Type I error is compounded each time the analysis is calculated on a window.

Another approach that has been used to analyze idiographic data is nonlinear modeling. *Nonlinear modeling* is a broad term that includes analyses that can detect patterns unobservable through linear regression. One example of nonlinear modeling used in interpersonal research is cross-recurrence analysis. This phase space analysis is based on graphing multiple time series, where one axis represents one person and the other axis represents the other person. This plotting method shows periods when both individuals' states are simultaneously the same. Patterns in the plot can then be used to derive measures of the predictability, stability, complexity, and smoothness of the dynamic, bivariate system (Konvalinka et al., 2011). Strang, Funke, Russell, Dukes, and Middendorf (2014) and Konvalinka et al. (2011) used cross-recurrence analysis to detect PS in inter-beat intervals. Konvalinka et al. (2011) found that PS developed between fire walkers and related spectators during ritual fire walking, but not between fire walkers and unrelated spectators. Strang et al. (2014) found that PS between previously unacquainted teammates was no greater than with randomly paired data from different team members. In another nonlinear approach, Guastello et al. (2006) compared results from linear and nonlinear regressions of skin conductance between participants during competitive, cooperative, or neutral discussions. Their results indicated that linear analyses were outperformed by nonlinear tests, which indicated significant PS in all dyads, but no differences across conditions.

Nomothetic analyses. Again, nomothetic analyses involve either aggregating individual data or conducting analyses in a multilevel modeling framework. Aggregation of individual data provides a simple summary of overall trends at the group level, but ignores individual differences. In contrast, multilevel models allow researchers to simultaneously assess group-level tendencies while accounting for individual differences. In addition, multilevel models are very flexible in terms of model specification. In some studies, multilevel growth curve models are used to represent response variables with functions of time (e.g., a linear curve), and PS is represented by covariation in function parameters (e.g., random slopes) between partners. In other studies, PS is represented by covariation between partners in the fluctuations around a deterministic trend (e.g., Reed et al., 2013). In the latter case, an individual-specific index of PS can be estimated, which makes it possible to examine factors or covariates that explain individual differences in strength of synchrony. However, multilevel models typically require a large sample size and normal distributions of parameters. Heterogeneity and small sample sizes common in physiological studies complicate such analyses. A new nomothetic approach applied to PS, dynamical correlation, may be better suited to these data issues (Liu et al., in press). The technique is appropriate for small sample sizes, heterogeneous data, and missing data, and is unaffected by autocorrelation or non-stationarity. In addition, no modeling is required, making it a simpler approach to implement. More importantly, it uses a population-centering step that accounts for group-based similarities, so resulting measures of synchrony are due to dyad-specific relationships. Still, the analysis returns a single descriptive statistic of synchrony for a group, which may not be indicative of mechanisms or processes involved, and does not estimate an individual-specific index of PS.

Dynamic system modeling. A unique approach for studying synchrony is dynamic systems modeling. A dynamic system is often described by a set of equations that expresses how the state of a system changes as a function of its previous state, either in a linear or nonlinear fashion. Dynamic system modeling can be carried out as an idiographic approach by using a set of equations (typically differential equations) to explain variation in each participant's data. Alternatively, it can be carried out at the group level by simply aggregating data across participants or using a multilevel model. Helm, Sbarra, and Ferrer (2012) and Ferrer and Helm (2013) are credited with bringing this approach to the study of PS in their work assessing couples. A significant advantage of this technique is that statistical parameters of synchrony including magnitude (i.e., the strength of synchrony), sign (i.e., positive or negative), direction (i.e., the degree to which each person can be predicted by the other), and lag (i.e., time differences between peoples responses) can be tested simultaneously. This makes dynamic systems models uniquely adaptable to the study of PS.

Null hypothesis testing. Another critical consideration, regardless of the statistical analysis used, is how to validate the detection of PS because synchrony may appear spuriously due to a variety of data conditions (e.g., autocorrelation, linear trends, random chance). For example, due to spurious co-occurrences of unrelated respiratory kinematics, McFarland (2001) observed high correlations in randomly paired RRs from people having conversations. Furthermore, the probability of chance findings can vary across contexts. As data structures can differ by condition (e.g., more or less likely to have a trend over time), the probability of spurious synchrony being detected in one condition may differ from the probability of spurious synchrony detected in another. For example, Codrons, Bernardi, Vandoni, and Bernardi (2014) randomly paired data from participants who completed a baseline and an arm-swinging task in isolation. Using well-suited analyses (Generalized Partial Directed Coherence), they found that PS detected in RRs between random individuals during the arm-swinging task was significantly greater than during baseline. Similarly, McFarland (2001) found different distributions of correlations from randomly paired data collected from dyads engaged in spontaneous versus scripted conversations. Due to the inconsistent probability of chance findings, standard null hypothesis testing may not be sufficient to determine whether findings of PS are statistically significantly different from chance. Therefore, it is important to determine the probability of spurious findings in each context to validate results. A number of studies have dealt with this issue by generating a null hypothesis based on data randomly paired from individuals who participated in the same task with a different partner, then testing whether PS in random dyads is significantly different from actual dyads (e.g., Helm et al., 2012; Marci et al., 2007; Reed et al., 2013). Additional methods used to determine null hypotheses have also been used, including comparing PS from real dyads (or groups) with simulated data, and with data from individuals who participated in the same task while alone (Strang et al., 2014). These customized methods of null hypothesis testing can help determine whether findings of PS are due to data structures, conditional demands, common interpersonal processes, or interpersonal interdependence, although methodological designs are still needed to test causality (see Appendix A for studies that used customized null hypotheses).

A related method designed to isolate interpersonal interdependence uses a baseline condition wherein participants do not interact, and tests whether PS is significantly greater when they do interact (e.g., Helm et al., 2012; Levenson & Gottman, 1983). Significant increases in synchrony from baseline then suggest that interpersonal dynamics, rather than dyadic or context-specific conditions, generated the increase in PS. Still, comparisons with randomized dyads are needed to determine the probability of chance results. Helm et al. (2012) used this approach, comparing periods when participants interacted to periods when they did not, as well as to data from unmatched dyads. They found that couples' baseline PS was significantly greater than in random data, and PS was significantly greater during interaction periods than baseline. Overall, these types of strategies are needed for null hypothesis testing, without which it may be unclear whether findings of PS are significantly different from chance.

Findings by Population

Four distinct populations have been studied to date using IAP methods (see Tables 1-5): therapist–client (n = 8; 13%), couples (n = 10; 16%), parent–child (n = 16; 26%), and teammates (n = 9; 15%). Less intimate relationships have also been studied, including friends, acquaintances, and strangers, referred to here as "other" (n = 18; 30%). Relationship type emerged as a key factor under which other categories were grouped. For example, the terminology and statistical procedures used to define and identify PS were largely restricted to specific populations. Summative findings in each area are reviewed in turn below.

Therapist–client. Research on IAP began more than half a century ago, when a series of studies found significant positive and negative correlations in the EDA and HR of therapists and clients during therapy, interpreted as evidence of therapeutic rapport and empathy (Coleman, Greenblatt, & Solomon, 1956; Di Mascio, Boyd, & Greenblatt, 1957; Di Mascio et al., 1955). These studies found that therapist notes from sessions with high positive correlations in HR had fewer references to being distracted from therapy than sessions with low correlations in HR (Coleman et al., 1956). In addition, the authors noted that all clients showed reduced HR with one particular therapist, potentially an early example of stress buffering. Contemporary research utilizing similar methods supports these results, including significant associations between PS and empathy, as well as attention (e.g., Marci et al., 2007; Marci & Orr, 2006; Robinson et al., 1982).

Couples. Much of the existing interpersonal physiological research has focused on couples (for a review, see Timmons, Margolin, & Saxbe, 2015). In their seminal work in this area, Levenson and Gottman (1983) used a bivariate time-series analysis of multiple physiological measures to show that couples' PS during arguments could account for 60% of variance in marital satisfaction. As they found no statistically significant results when couples were discussing neutral topics, they concluded that PS only developed during negative interactions. They postulated that dissatisfied couples could not disengage from the arousal of a conflict, whereas satisfied couples were able to "step back" and listen. Aspects of Levenson and Gottman's (1983) findings have been supported a number of times, including another early study that found PS in couples' skin conductance and HR during conflict conversations (Thomsen & Gilbert, 1998). Although differences across couples were noted, overall, husbands' physiology was a better predictor of wives' than vice versa, suggesting that husbands tended to lead the interactions. A more recent study found that marital conflict was positively correlated with PS in RSA (Gates, Gatzke-Kopp, Sandsten, & Blandon, 2015). Similarly, using longitudinal multilevel dyadic models, Reed et al. (2013) found that negative interactions between couples (e.g., demand/withdraw behaviors) moderated PS in blood pressure. The presence of negative interactions coincided with positive PS, and their absence with negative PS. The authors concluded that negative PS results from turn taking during dialog and could be a key component in any conversation. Although Reed et al.'s (2013) conclusions may be correct, contradictory findings suggest that positive PS also develops between couples in neutral and positive contexts. For example, Helm et al. (2014) found significantly greater magnitudes of positive PS in couples with higher quality relationships across positive, neutral, and negative conversations, whether partners were listening or talking. However, as Helm et al. (2014) used cross-lagged panel models to test for PS in RSA, differences from Reed et al.'s (2013) findings may be due to the use of different physiological measures and statistical methods.

A recent series of studies assessed PS between couples who were still and quiet, and either blindfolded, gazing at each other, or attempting to silently synchronize with each other (Ferrer & Helm, 2013; Helm et al., 2012, 2014; McAssey et al., 2013). Multiple novel analytical approaches were used in these studies, although the greatest advancements came from dynamic systems analyses capable of detecting multiple parameters of PS within a trial. Results from these studies suggest that sitting next to a partner while blindfolded is sufficient for PS in HR to develop (Ferrer &

Table 2. Results by Population: Therapist–Client.

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Coleman, Greenblatt, and Solomon (1956)	Explored how PS between a therapist and client during psychotherapy correlates with therapist distractions.	One therapist–client dyad	Compared the percentage of disturbance words in therapist's notes from the six interviews with the highest PS with the six interviews with the least PS.	HR	Significant correlations between therapist and client HR reported. Twice the number of disturbance words were used in the low PS sessions, suggesting higher PS was associated with greater focus on the client.
Di Mascio, Boyd, Greenblatt, and Solomon (1955)	Original exploration of PS. Tested whether clinical interactions were reflected in physiology.	Three therapist–client dyads	Assessed PS between therapists and clients during therapeutic interviews.	PR	Reported that positive and negative PS were observed, but statistics only given for one example of each. In addition, reported that one therapist induced lower HR in all patients.
Marci and Orr (2006)	Explored how distraction influenced PS and empathy.	One therapist with 20 participants	Compared PS in SC and empathy scores following brief interviews in which a therapist interviewed clients in a neutral or distracted manner.	SCL	PS was significantly greater during neutral vs. distant conditions. Patient ratings of therapist empathy were significantly higher in the neutral vs. distracted condition.
Marci, Ham, Moran, and Orr (2007)	Assessed PS between clients and therapists during psychotherapy, and how it correlated with social–emotional ratings.	20 established therapist–client dyads	Compared periods of high and low PS in SC with empathy and social–emotional ratings during psychotherapy.	SCL	Patient rating of therapist empathy significantly correlated with peak PS score during the session. Patients and therapists showed significantly more solidarity and positive regard in periods with high vs. low PS.
Messina et al. (2013)	Compared PS and empathy between pseudo-clients and therapists with different levels of training.	39 pseudo-therapist–client dyads	Therapists with different levels of training gave mock-therapy sessions to pseudo-clients, while PS and empathy were tested.	SCL	Differences in PS between the three groups (therapists, psychologists and non-therapists) were found. PS was higher with psychologists compared with therapists at Lag 0, but at Lag 3, PS was lower in psychologists compared with the therapists. PS between pseudo-patients and therapists was significantly correlated with empathy perceived by the pseudo-patients at 3- and 4-s lags.
Robinson, Herman, and Kaplan (1982)	Study designed to assess correlations between empathy and PS during psychotherapy.	21 therapist–client dyads	Assessed PS and empathy scores from therapist–patient dyads during therapy.	SC; FST	Significant correlations found between empathy scores and the level of PS in SC between therapists and clients.
Stratford, Lal, and Meara (2009)	Explored neurological correlates of high PS during psychotherapy.	15 therapist–client dyads	Assessed clients EEG during periods of high PS in SC between therapist and clients during psychotherapy.	SC	Specific sites in the brain found to be active during high PS between therapist and client, such as increased activation of the parietal cortex.
Stratford, Lal, and Meara (2012)	Explored neurological correlates of high PS during psychotherapy.	30 therapist–client dyads	Assessed clients EEG during periods of high PS in SC between therapist and clients during psychotherapy.	SC	Specific sites in the brain found to be active during high PS between therapist and client, and to change over the course of treatment. For example, during high PS, parietal theta activity decreased from the first to the sixth sessions.

Note. PS = physiological synchrony; HR = heart rate; PR = pulse rate; SC = skin conductance; SCL = skin conductance level; FST = finger skin temperature; EEG = electroencephalograph.

Table 3. Results by Population: Couples.

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Chatel-Goldman, Congedo, Jutten, and Schwartz (2014)	Study designed to test whether PS in couples would develop through physical contact during an empathic interaction. They theorized that PS would correlate with social personality traits, and that touching would lead to significant changes in autonomic activity.	14 couples	Participants were seated such that they could hold hands with, but could not see each other. Trials involved the "empathizer" participant receiving a message on a screen stating their partner, the "target," was instructed to recall a given event. In some cases, the "target" was asked to recall the given event, and in others, they were asked to recall a different event. A neutral condition was also included. In half the trials, participants could touch hands with each other. Follow-up questions addressed emotion intensity and perceived coupling.	RVT; PRV; SC	Touch significantly increased PS in SC, beyond what was accounted for in data from random dyads. In addition, partners with higher empathy ratings showed greater PS, whereas touch had a stronger influence on PS between partners who were less empathic. Results were not significant for other physiological measures.
Ferrer and Helm (2013)	Designed to determine whether PS influenced by tasks designed to elicit physiological coordination in romantic dyads. Also assessed whether similar interactions are reflected in daily affect.	32 couples	Participants took relationship satisfaction survey, then physiology was recorded over three tasks: Baseline: Partners sat quietly next to each other blindfolded in the dark; Gazing: Sat quietly next to each other staring into each other's eyes; and Imitation: Sat quietly and instructed to attempt to synch physiologies. Daily reports of emotional experience then collected for 90 days.	HR; Resp	PS in HR and respiration is influenced by intention during passive conditions. Females' physiology adjusted to their male partners' during the imitation task. A similar pattern was identified in daily affect. Males changed their HR to adjust to that of their female partners' during imitation more than other conditions. Individuals were found to adjust their respiration more as a function of their partner's breathing than their own. Respiration was indicated as a driver of PS. Large variation in models for PS indicated that pooling data would be problematic.

(continued)

Table 3. (continued)

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Gates, Gatzke-Kopp, Sandsten, and Blandon (2015)	Tested whether PS in RSA was correlated with marital conflict.	49 couples	Cardiac data were collected during 10 min of natural play between couples and their children.	RSA	PS in RSA was significantly and positively correlated with self-reported marital conflict.
Helm, Sbarra, and Ferrer (2012)	Tested whether PS was present during tasks designed to elicit physiological coordination between romantic couples.	32 couples	Couples completed a relationship satisfaction questionnaire followed by three tasks. Baseline: Partners sat quietly next to each other blindfolded in the dark; Gazing: Sat quietly next to each other staring into each other's eyes; and Imitation: Sat quietly and instructed to attempt to synch physiologies.	HR; Resp	During all three tasks, females' HR changed from increasing to decreasing when the males' HR increased. Males' HR changed from a decreasing to an increasing rate when their female partners' HR increased during the baseline and gazing, but changed from decreasing to increasing when their female partners' HR decreased (opposite the other conditions) during imitation. During the gazing and imitation tasks, RR for both females and males shifted from exhalation to inhalation when their partners inhaled. No significant findings were found with data from random dyads.
Helm, Sbarra, and Ferrer (2014)	Study designed to evaluate covariation of RSA in romantic couples to determine whether coregulatory patters are present in physiology, and whether they are moderated by relationship satisfaction.	32 couples	Participants completed a questionnaire on relationship satisfaction, followed by four conditions during which physiology was monitored. A 5-min baseline involved participants sitting quiet and still in the dark with masks over their eyes. Next, conversation conditions involved 3-min discussion of a neutral, a positive, and a negative topic.	RSA	Results indicated a significant increase in between-partner correlation of RSA from baseline to the conversation tasks. This suggests that high RSA in one partner led to higher RSA in the other partner. In addition, this pattern was significantly stronger in couples with higher quality relationships. Results were not dependent on the type of conversation.

(continued)

Table 3. (continued)

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Levenson and Gottman (1983)	Study to determine whether PS could be detected in couples during high- and low-conflict conversations, and whether that was predictive of marital satisfaction.	30 couples	Couples participated in the following while physiology and video were recorded: 1. Low-conflict session: 5-min baseline then 15 min of conversation about the events of the day. 2. Completed questionnaires. 3. High-conflict session: 5-min baseline, then 15 min discussing the problem area. 4. Video-recall: Each spouse watched a video of their sessions and used a dial to continuously rate their affect during the original trials.	ACT[a]; IBI; PTT; SCL; Physiological index (HR; PTT; SCL; ACT[a])	A significant correlation was only found between PS and marital satisfaction during high-conflict interactions. No significant correlations were found between PS and affect, suggesting the constructs are independent. The index of PS accounted for 60% of the variance in marital satisfaction during the high-conflict segment. Greater PS was associated with lower marital satisfaction. PS was significantly stronger during high-conflict than low-conflict segments. PS, affect, and intra-individual physiology measures were found to be independent (non-redundant).
Liu, Zhou, Palumbo, and Wang (in press)	Tested whether greater PS was detected between couples when seated face to face compared with back to back.	16 couples	Participants were instructed to sit still and quietly for 30 min. They were positioned back to back for the first half of the trial, then face to face for the second half.	SC	Results indicated significant PS during the face to face, but not during the back to back period. The authors concluded that PS was due to interpersonal influences, rather than matched activity or environment.
McAssey, Helm, Hsieh, Sbarra, and Ferrer (2013)	A methodological paper showcasing two methods used to assess PS. Data used were from tasks designed to elicit physiological coordination in romantic dyads.	Four couples	Couples completed a relationship satisfaction questionnaire followed by three tasks. Baseline: Partners sat quietly next to each other blindfolded in the dark; Gazing: Sat quietly next to each other staring into each other's eyes; and Imitation: Sat quietly and instructed to attempt to synch physiologies.	HR; RR; TI	PS in all measures tended to be greater during the gazing and in-sync tasks relative to the baseline, but there was a high degree of heterogeneity across dyads. Cross-validation analyses provided no evidence for synchrony with data paired from random participants.

(continued)

Table 3. (continued)

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Reed, Randall, Post, and Butler (2013)	Tested whether PS was predicted by the presence of negative influence or demand/withdraw behaviors between partners.	44 couples	Partners completed self-report questionnaires separately at home prior to the trial. At the lab, couples engaged in a video recorded 20 min conversation with their partner about health behaviors. Autonomic measures assessed continuously. Following the conversation, each partner privately watched the videotape of their own interaction and used a dial to rate their own affect.	BP; IBI; SC	A number of conditions were found to predict PS in BP, but not using other measures. Partner's patterns of PS in BP shifted from negative to positive during periods when demand behaviors were present. Results also indicated that as negative partner influence increased, negative PS in BP became asynchronous. Partner's PS in BP shifted from negative to positive during withdraw behaviors. No significant interactions were found using data from random participants.
Thomsen and Gilbert (1998)	Tested how self-reports, observations, and physiology interacted to predict couples' marital satisfaction.	32 married couples	Following a baseline, couples discussed a conflict topic. They then completed questionnaires, and rated their own states while watching video of their interaction.	HR; SC	PS was detected in both HR and SC during the conflict discussion, but with notable individual differences. Husbands' SC was a significantly better predictor of wives' SC than vice versa.

Note. PS = physiological synchrony; RVT = respiration volume time; PRV = pulse rate variability; SC = skin conductance; HR = heart rate; Resp = respiration; RSA = respiratory sinus arrhythmia; RR = respiration rate; ACT = somatic movement; IBI = interbeat interval; PTT = pulse transmission time; SCL = skin conductance level; TI = thoracic impedance; BP = blood pressure.
[a]ACT is a behavioral measure, but was used as part of an index of physiology.

Helm, 2013), and that instructions can influence patterns of PS to change when behaviors remain constant. Using similar procedures, Liu et al. (in press) used dynamical correlations, a well-suited nomothetic analysis, to show that PS did not develop between couples seated back-to-back, but did when they turned and sat quietly face-to-face. Results were interpreted as indicating that PS resulted from interpersonal processes, as during the back-to-back phase, couples were exposed to the same metabolic demands and environmental conditions, but displayed significantly less PS than when they turned and faced each other.

Taken together, findings from couples research suggest that PS is not dependent on environmental or metabolic demands, that PS may be influenced by intention, and that dynamic interpersonal physiological patterns change according to context. Results from other populations largely support findings from couples, although more work is needed before generalizations can be made.

Parent–child. Parent–child dyads have received the most research attention to date, and relatively consistent findings of PS have been documented (see Hill-Soderlund et al., 2008; Moore, 2009, for exceptions). Although there is some evidence that PS between parents and children is dependent on behavioral synchrony (Feldman et al., 2011), other results indicate that PS can occur in the absence of behavioral synchrony (Suveg, Shaffer, & Davis, 2016; Woltering, Lishak, Elliott, Ferraro, & Granic, 2015). Such discrepancies

Table 4. Results by Population: Teammates.

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Chanel, Kivikangas, and Ravaja (2012)	Study designed to test whether the quality of team performance during video game play was influenced by PS.	21 two-person teams of friends	Physiological measures were continuously recorded while two-person teams of friends played a video game. Games were set to either cooperative or competitive mode, and replayed in the lab and the home, followed by a questionnaire on gaming experience.	Resp-Amp; IBI; HF-HRV; HF-Resp-Amp; VLF-HRV; SC	PS increased with players' self-reported involvement in the social interaction, suggesting it could be used as an objective measure of social presence. For most measures, PS was higher for competitive vs. cooperative play.
Elkins et al. (2009)	A proof of concept study to test whether PS could predict team performance in real-world military training. Multiple statistical analyses of PS were tested.	10 four-person teams (only one dyad analyzed from each team)	Teams participated in a military training task clearing houses of enemy combatants using both computer simulation and real-world trials. No distinction was made between real and simulated trials. Multiple statistical methods were tested.	IBI; RSA	Visual inspection of the data suggested PS could be used to differentiate between high and low team performance. Validation results suggested that multiple combinations of statistical tests and physiological measures reached the same conclusions.
Henning, Boucsein, and Gil (2001)	Study tested whether PS was predictive of team performance.	16 two-person teams	Following a passive baseline in which participants could not see each other, teams played a jointly controlled video game in silence. Three trials ran in counterbalanced orders altering whether or not participants had visual contact with their partner.	HRV; RR; SC	Multiple measures of team performance were significantly predicted by PS in RR, SC, and HRV. Social-visual contact was not a significant predictor of PS, team performance, or team coordination suggesting that changes in visual cues did not disrupt the teammate's interaction. Team coordination was not predictive of PS, suggesting that matched behaviors were not necessary for physiological relationships.
Henning and Korbelak (2005)	Study tested whether PS was predictive of future team performance.	32 two-person teams	Teams engaged in a series of trials playing the same virtual jointly controlled task as in Henning et al. (2001), but joystick controls were switched (i.e., Left/Right became Up/Down; Right became Left) at random points. Participants were seated adjacent but could not see each other's joystick movements. Analyses tested whether PS predicted team performance following control changes.	IBI	There was a small significant effect indicating that PS predicts team performance in the immediate future, suggesting that increased PS was associated with lower team error in the immediate future.

(continued)

Table 4. (continued)

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Henning, Armstead, and Ferris (2009)	Explored whether PS was predictive of perceived teamwork in a research group.	One team of four (a student research group)	HRV was monitored in a preexisting graduate research group during meetings over 6 months (n = 18 meetings). Following meetings, each team member completed a questionnaire on teamwork.	HRV	PS during periods of sequential speech activity between team members negatively predicted ratings of teamwork. Higher magnitudes of positive PS were associated with lower ratings for team productivity, quality of communication, and ability to work together.
Järvelä, Kivikangas, Kätsyri, and Ravaja (2013)	Tested whether PS developed between teammates playing video games, how it related to team cohesion, and how VT influenced the interactions.	41 dyads	Volunteer friend dyads played a turn-based artillery game. A 5-min resting period was followed by four competitive and cooperative conditions, with and without a VT. Self-report questionnaires were completed before and after each condition.	IBI; HF-HRV; SCR; SCL	Results indicated that changes in each physiological measure tended to co-occur within the dyads. Increased reports of empathy and understanding between players were associated with increased PS in cardiac measures. PS in SCL and SCR was not associated with condition, suggesting that PS in SC is not related to contextual changes in gaming. When players felt their actions influenced other player's action, PS in HF-HRV was lower. The presence of a VT in the game was associated with decreased PS, suggesting that it kept the players from focusing on each other.
Montague, Xu, and Chiou (2014)	Aimed to test PS during joint activity and performance in technologically complex environments.	24 dyads	Teams performed virtual tasks across three levels of difficulty. One participant had control and the other was a passive adviser.	IBI; HF-HRV; LF-HRV; SC	Under varied task difficulty conditions with reliable and unreliable technology, different measures of PS were significantly related to teammates performance and trust in technology.
Strang, Funke, Russell, Dukes, and Middendorf (2014)	To compare PS between teammates playing a video game with simulated dyadic data, data paired from individuals, and data from random team members.	80 adults participated (40 men and 40 women). Forty were paired into two-person teams, 40 played as individuals.	Individuals and two-person teams of strangers played three 20-min sessions of a video game (two practice and one trial).	IBI	Teammates PS was not significantly greater than data from random team members, suggesting that PS was due to conditional similarities, rather than interpersonal dynamics.
Walker, Muth, Switzer, and Rosopa (2013)	Investigated the relationship between PS and joint team performance in a simulated task.	34 teams of two	Teammates tasked with maintaining safe levels of operation in a simulated chemical plant. Conditions involved altered levels of individual task difficulty (low and high), and team task difficulty (low and high).	RSA; PEP; LVET; Physiological index (RSA; PEP; LVET)	An index of PS accounted for approximately 10% of the variance in team performance scores.

Note. PS = physiological synchrony; Resp-Amp = respiration amplitude; IBI = interbeat interval; HF-HRV = high-frequency heart rate variability; HF-Resp-Amp = high-frequency respiration amplitude; VLF-HRV = very-low-frequency heart rate variability; SC = skin conductance; RSA = respiratory sinus arrhythmia; HRV = heart rate variability; RR = respiration rate; VT = virtual teammates; SCR = skin conductance response; SCL = skin conductance level; LF-HRV = low-frequency heart rate variability; PEP = pre-ejection period; LVET = left ventricular ejection time.

Table 5. Results by Population: Other.

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Bachrach, Fontbonne, Joufflineau, and Ulloa (2015)	Tested whether RR of dancers and audience members synchronized during a live performance.	10 dancers, two audience groups (*n* = 5; *n* = 7)	Audience members attended a live, music-free, slow-paced dance performance. They completed questionnaires before and after the dance. Participants' RR was monitored.	RR	PS in RR was significant between audience members and dancers. PS was significantly associated with audience members self-reported attention to their own and the dancers breathing, but not with their appreciation of the dance.
Codrons, Bernardi, Vandoni, and Bernardi (2014)	Tested whether group's arm movements would synchronize along with heart rhythms and RR.	Three groups of 10, and 30 individuals	Participants were either alone or in a group of 10. They were asked to move their arms vertically. Music, a metronome, or silent conditions were compared with pre and post still/silent baselines.	RR; HP	Significant PS in RR, but not HP, was found in groups during the baseline and music conditions. Synchronized arm movement and PS did not coincide, suggesting they are independent.
Field et al. (1992)	Compared PS of sixth-grade friend and acquaintance dyads.	28 sixth-grade child friend dyads; 27 sixth-grade child acquaintance dyads	Dyads were seated in a face-to-face position across a small table and instructed to have a conversation about a topic of their choice	HR	No statistically significant difference was found between friend and acquaintance dyads on measures of PS (HR coherence).
Goldstein, Field, and Healy (1989)	Compare PS between preschool-aged friends and acquaintances during play	34 nursery school toddlers and preschoolers ranging in age from 21 to 64 months	Each child took part in two dyadic play interactions; once with a friend, and once with an acquaintance.	HR	Greater PS on baseline HR was found for friend vs. acquaintance dyads
Guastello, Pincus, and Gunderson (2006)	Evaluate PS in dyads engaging in a 20-min discussion.	37 pairs of college students	Dyads engaged in a 20-min discussion about a prescribed topic while seated. Participants were randomly assigned to one of three groups: Competition (instructed to try to convince their partner of their view point), shared understanding (instructed to listen and understand their partner's reasoning), and a control group who were just told to get to know one another.	SC	PS was found for all dyads using nonlinear regression analysis; however, no statistically significant difference in PS was found between groups.

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Table 5. (continued)

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Kaplan, Burch, Bloom, and Edelberg (1963)	Compared PS between dyads who self-reported liking, disliking, or feeling neutral about one another.	Three 4-person groups of medical students	Groups met for five 45-min sessions, during which they discussed topics of general interest.	SCR	Correlation between pairs in group who liked or disliked each other (as opposed to neutral rating) was more likely to co-vary (tested using chi-square for number of positive and significant correlations)
Konvalinka et al. (2011)	Evaluated PS between performers and spectators during a fire-walking ritual	12 fire walkers, nine spectators who were friends or relatives of the fire walkers, and 17 spectators with no relationship to the fire walkers	HR was recorded from all participants while performers took part in a 30-min fire-walking ritual	HR	PS found between fire walkers and related spectators, but not between fire walkers and unrelated spectators
Kraus and Mendes (2014)	Assessed PS between partners when social status was manipulated.	64 previously unacquainted male dyads	Dyads were randomly assigned to social status condition through clothing: Wearing a suit (high status), their own clothes (neutral status), or sweatpants (low status) during mock negotiations.	PEP	Lagged correlations indicated high-status partners led low-status partners PEP during the mock negotiations.
Marci (2006)	Tested whether PS and arousal level predicted viewers engagement in advertisements.	27 male viewers assigned to two groups	Multiple measures taken to test PS and arousal level to test "engagement" of groups of viewers watching commercials during high- and low-rated shows.	Physiological index (SC; HR; RR; ACT[a])	Patterns of PS and arousal between audience members during commercials were influenced by the contexts in some conditions.
McFarland (2001)	Evaluated respiratory coordination during conversational turn taking	10 pairs of adult friends	Respiratory movements were recorded for each dyad during quiet breathing, reading a passage aloud, a spontaneous monologue, scripted dialogue, and spontaneous conversation.	RR	Cross-correlation between true partners differed significantly in comparison with randomly selected simulated dyads.
Mitkidis, McGraw, Roepstorff, and Wallot (2015)	Investigated whether PS predicted outcome of a trust building game.	37 randomly paired student dyads	Students participated in a joint cooperative activity. In one group, an economic game (public goods game), in which they contributed to a mock fund and received a portion of the money, was played between joint activities.	HR	PS was significantly greater in the group that played the economic trust game. In the public goods game, PS was positively associated with expectations of returns but not of investments. The authors concluded that PS could be viewed as a proxy measure of trust.

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Table 5. (continued)

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Morgan, Gunes, and Bryan-Kinns (2015)	Tested whether PS developed between drummers.	Five pairs of drummers	Drummers played together with and without visual contact.	HR	No PS was detected between changes in drummers' HR. Comparisons of PS were not made between conditions.
Müller and Lindenberger (2011)	Explored leader–follower relationships in PS in Resp and HRV of choir members during choral singing. Used advanced data acquisition and analysis methods to explore oscillatory couplings during interpersonal interactions.	An 11-person choir with one conductor	The choir participated in 12 conditions, including singing in unison, in parts, with eyes open and closed, both with and without the conductor.	HRV; Resp	PS was significantly greater when singing than at rest. Network analysis was able to detect subgroups singing in parts, which were not detected when singing in unison. In addition, results showed directed positive PS where physiological changes in the conductor were followed by choir members. Results were consistent across multiple measures of PS.
Noy, Levit-Binun, and Golland (2015)	Examined associations between joint movement, subjective togetherness, and PS.	Nine pairs of experts in joint movement	Participants engaged in the "mirror game," where they put their hands together and moved in synchrony, with or without a defined leader.	HR	PS in HR was significantly correlated with synchronized movement, subjectively reported togetherness, and high HR. The authors cautioned that results may be due to matched movement rather than social interactions.
Quer, Daftari, and Rao (in press)	Assessed PS between group members engaged in meditation activities.	Groups of four to seven adults	Groups participated in group breathing, chanting, and mediation tasks.	HF-HRV; LF-HRV; VLF-HRV; RR	Varying magnitudes of group-level PS was detected across mediation activities, in multiple HRV frequency bands and in RR. Magnitude of PS between individuals varied within and across tasks.
Shearn, Spellman, Straley, Meirick, and Stryker (1999)	Evaluated PS in friend and stranger dyads in relation to empathic blushing and SC during mild embarrassment.	72 undergraduates	Groups of three participants (two friends and one stranger) watched a previously recorded video of one of them (the performer) singing a song.	SC; Blush	Significant PS between performers and friends, but not between friends and strangers or strangers and performers.

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Table 5. (continued)

Reference	Purpose	Sample	Procedure	Physiological measures	Results
Silver and Parente (2004)	Tested whether PS developed between strangers meeting for the first time.	20 strangers	Pairs of unacquainted participants engaged in a 5-min unstructured conversation.	SC	Large significant correlations between the SC of the pairs.
Vickhoff et al. (2013)	Compared PS between choir members during different singing conditions.	11-person choir	Choir members completed a silent baseline, then sang a hum, a hymn, and a mantra.	HRV	PS in HRV was detected during the hymn and mantra singing.

Note. RR = respiration rate; PS = physiological synchrony; HP = heart period; HR = heart rate; SC = skin conductance; SCR = skin conductance response; PEP = pre-ejection period; ACT = somatic movement; HRV = heart rate variability; HF-HRV = high-frequency heart rate variability; LF-HRV = low-frequency heart rate variability; VLF-HRV = very-low-frequency heart rate variability.
[a]ACT is a behavioral measure, but was used as part of an index of physiology.

between behavioral synchrony and PS may be due to context, as one study found that when PS was higher between mothers and children, behavioral synchrony and self-regulation were lower in high-risk children (Suveg et al., 2016). These results suggest that PS between parents and children in a negative context may disrupt behavioral synchrony, as well as the child's self-regulation.

Overall, PS between mothers and children has been found to develop across groups and conditions using a variety of measures and analyses. Significant magnitudes of PS appear equally across many categorizations of mother–child dyads, including depressed and non-depressed mothers (Field et al., 1989), child maltreating and non-maltreating mothers (Creaven et al., 2014), mothers and their child with typical and atypical self-regulation (Woltering et al., 2015), and both high- and low-conflict mother–daughter relationships (Manini et al., 2013) and high- and low-risk families (Suveg et al., 2016). However, there is some evidence that PS is affected in children with autism, as magnitudes of PS between parents and their children with autism were negatively correlated with severity of the child's diagnosis (Baker et al., 2015). This groundbreaking finding suggests that PS could be a useful diagnostic and clinical tool when supporting individuals with autism spectrum disorders, although systematic research is still needed.

Evidence from multiple studies suggests that PS magnitudes increase when mothers are under stress, such that individual physiological profiles moderate the development of PS (Ebisch et al., 2012; Ghafar-Tabrizi, 2008; Manini et al., 2013; Waters et al., 2014). In addition, children have been found to be more likely to avoid others when mothers undergo a stressful-negative event, suggesting that infant behavior is influenced by mothers' psychophysiological state (Waters et al., 2014). Mothers' influence on infants was further supported in a study by Van Puyvelde et al. (2015), which showed that by intentionally adjusting themselves, mothers could change their infants' physiology. In this study, mothers paced their breathing while holding their infants at different ages. While controlling for motor and respiratory confounds, results indicated that mother–infant RSA synchronized across different breathing paces and infant ages until infants were 2 months old, but RSA did not synchronize when infants reached 3 months of age. This is the first study to investigate a potential mother–infant physiological relationship independent of a social interaction, and suggests that early infants rely on their mother for self-regulation. Findings by Ham and Tronick (2009) suggest that mothers capitalize on this autonomic contagion to regulate the arousal levels of their children, as they found that mothers calm themselves in an effort to calm their infants.

Although emphasis has been placed on directed PS from mother to child, synchrony has also been shown to be influenced by the child's actions. One recent study found that positive PS occurred in the absence of child behavior problems, and negative PS occurred when behavior problems were present (Lunkenheimer et al., 2015). Similarly, Manini et al. (2013) found that the direction of influence between mothers and their daughters switched across discussions. These results suggest that during parent–child interactions, the type and direction of PS are contextually dependent.

Teammates. Assessment of PS in teams has gained significant interest in recent years (for a focused review, see Ekman et al., 2012). Henning et al. (2001) were the first to explore PS between team members through a series of studies examining teamwork during video games. Using cross-coherence and cross-correlations in respiration, HRV, and skin conductance, they found that PS was a significant predictor of team performance. Although their findings have not been supported consistently (e.g., Walker, Muth, Switzer, & Rosopa, 2013), recent work has also shown a significant correlation between team performance and PS (Montague, Xu, & Chiou, 2014). Henning et al.'s (2001) results also indicated that PS was not associated with team coordination, suggesting that

PS is not dependent on coordinated behaviors. In a follow-up study, Henning and Korbelak (2005) used cross-correlations of teammates' HRV to show that PS is predictive of future team performance during video game play.

Synchrony has also been found to correlate with psychosocial aspects of teamwork. Using a variety of measures and analyses, teammates' social interactions (Chanel et al., 2012), as well as empathy and understanding between players (Järvelä et al., 2013), were found to be significantly associated with the magnitude of PS. Interestingly, one study found coherence in high-frequency HRV to be significantly higher during competitive versus cooperative games, as well as evidence that multiple metrics of PS correlated with empathy and positive affect (Chanel et al., 2012). The authors concluded that PS is most likely due to the intensity of an interaction rather than the context under which it occurs (Chanel et al., 2012).

In-vivo teamwork has also been assessed, although results have been inconsistent. Henning et al.'s (2009) study of teamwork between members of a research group observed that cross-correlations in HRV negatively predicted team ratings of their ability to work together. Conversely, Elkins et al. (2009), using correlations between teammates' RSAs, found that better team performance was associated with significantly higher positive PS during military training tasks.

Strang et al. (2014) assessed PS in interbeat intervals of teammates playing a video game using analyses including cross-correlation and cross-recurrence quantification. In addition, they tested whether PS was significantly greater than simulated data, data paired from individuals who played alone, and data randomly paired from other teams. Results indicated that teammates' PS was not significantly greater than data randomly paired from other teams, suggesting that PS was due to conditional similarities, rather than interpersonal dynamics.

Other relationships. This subgroup domain is a general categorization of participant relationships that do not fall under the aforementioned group types. The first such study assessed PS in casual relationships (Kaplan et al., 1963). They analyzed conversations of medical students in a group setting, and found significantly greater magnitudes of PS in skin conductance responses when dyads reported strong affective ties (i.e., liked or disliked each other), than when they reported a neutral relationship. Recent work found that when status is manipulated in dyads of strangers, high-status partners lead low-status partners' pre-ejection period (a measure of SNS) during mock negotiations (Kraus & Mendes, 2014). PS may therefore be more dependent on social context rather than the type of relationship or the given affect. This could explain why studies comparing specific relationship types have been contradictory. Whereas some indicate PS only occurs between friends (McFarland, 2001, using respiration; Shearn et al., 1999, using skin conductance and facial blushing) or family members (Konvalinka et al., 2011, using HR), others found PS between strangers (Silver & Parente, 2004, using skin conductance), and still others found no difference in PS between friends and acquaintances (Field, 1992, using HR).

In a study comparing friends during different conversations, Guastello and colleagues (2006) compared linear and nonlinear regression models capable of detecting PS in skin conductance. PS was detected during high-conflict and neutral conversation topics, with no statistically significant difference between conditions observed. Nonlinear regressions detected significantly greater magnitudes of PS between partners than the linear regressions, prompting the authors to conclude that physiological interdependencies are multilevel processes with both linear and nonlinear characteristics. Mitkidis, McGraw, Roepstorff, and Wallot (2015) used cross-recurrence quantification analysis, but tested whether PS in dyads' HR during an economic trust game (the public goods game) contributed to the outcome. They found that PS was positively associated with expectations for financial returns from partners, leading the authors to conclude that PS held potential as a proxy measure of trust.

Müller and Lindenberger (2011) applied a series of advanced statistical procedures to assess group interactions in a conductor-led choir, including wavelet analysis, multivariate autoregressive (MVAR) models, network analysis, and Granger causality. Results showed that the magnitude of PS in HRV and RRs was greater when singing in unison compared with singing in parts or rest periods. When the choir was singing in parts, network analyses detected subgroups with greater PS that corresponded to the musical parts subgroups sang. In addition, Granger causality models indicated that changes in the conductor's HRV and RR predicated similar changes in choir members. These general findings were supported in later work that found PS in singers' HRV when they sang, but not when they hummed or during a baseline (Vickhoff et al., 2013). Conversely, a study on musicians was unable to detect synchrony in the HR of dyads drumming together, although their analysis was more descriptive than quantitative (Morgan, Gunes, & Bryan-Kinns, 2015).

Expanding on Müller and Lindenberger's (2011) approach, Quer et al. (in press) used a novel time-varying wavelet analyses to assess group-level PS in people meditating. They found that PS could be detected across measures of HRV and respiration, and that the magnitude of the groups' synchrony changed over time. Their analysis offers a time-frequency strategy to test changes in the magnitude of synchrony in a group across a range of frequencies, which may prove to be an important advancement.

Two extant studies have directly assessed the interaction between synchronized behavior and PS. Codrons et al. (2014) had participants swing their arms while listening to music, a metronome, or in silence. Half the participants completed the exercise in isolation, and the other half completed the procedures in groups of 10. Results indicated significant PS in RR, but not heart period, occurred in groups during the baseline and music conditions. Interestingly, synchrony in arm movement did not coincide with PS, suggesting that behavioral synchrony and PS are independent processes. Noy, Levit-Binun, and Golland (2015) failed to find differences between behavioral synchrony and PS. They explored whether joint movement was associated with PS by having participants play the “mirror game.” Experienced participants put their hands together and moved in synchrony. Results indicated that PS in HR was significantly correlated with synchronized movement and subjectively reported togetherness. However, as PS was also correlated with high HR, the authors cautioned that PS could be due to metabolic demands of movements, rather than interpersonal processes.

Two studies have also used PS to test the influence of a third variable, rather than an interpersonal interaction. Marci (2006) assessed PS in groups watching television commercials to determine whether context influenced group response to advertisements. He used an index of physiological measures similar to Levenson and Gottman’s (1983) to test for PS, and incorporated arousal level in an attempt to capture “emotional engagement.” Using this strategy, he tested whether commercials would produce different results in different contexts (i.e., during shows with high and low ratings). Although their results are difficult to evaluate due to an undisclosed proprietary analysis, this appears to be the first study that aimed to use PS to test group engagement, rather than an interpersonal interaction. More recently, Bachrach, Fontbonne, Joufflineau, and Ulloa (2015) found that audience members’ breathing rates synchronized with dancers during a recital. Synchrony was positively correlated with audience members’ self-reported attention to their own and the dancers’ breathing, but not with their appreciation for the performance. Together, these two studies exemplify the potential to use PS to explore variables beyond interpersonal relationships.

Theoretical Explanations

A number of researchers and theorists have considered potential mechanisms and implications of IAP relationships. Multiple mechanisms have been implicated as the source of synchrony, including shared metabolic demands through matched activity or behavior (e.g., Field et al., 2011), conditional and environmental influences (e.g., Strang et al., 2014), and synchronized breathing (e.g., Ferrer & Helm, 2013). However, PS has also been found in the absence of each of these mechanisms. Multiple studies tested a null hypothesis by randomly pairing data from individuals undergoing the same conditions at different times (e.g., Marci et al., 2007; Reed et al., 2013), nearly all of which found significantly greater PS when participants are together (for an exception, see Strang et al., 2014). Synchrony has been found to differ across conditions, indicating that participants who are in the same environment display PS in some contexts but not others (e.g., Ghafar-Tabrizi et al., 2008; Liu et al., in press). Comparisons of behavioral synchrony and PS suggest that these processes are independent, as they do not consistently co-occur (Codrons et al., 2014; Henning et al., 2001). Furthermore, as observable behaviors are only marginally correlated with physiology (Mauss, Levenson, McCarter, Wilhelm, & Gross, 2005), behavioral cues may not be sufficient to generate PS. In addition, studies in which physical demands differed for participants have found that PS was still present (e.g., Elkins et al., 2009; Montague et al., 2014). Although some findings suggest that matched breathing patterns are the root cause of PS (e.g., Ferrer et al., 2013), others have found that cardiac measures of synchrony were statistically significant when measures of respiration were not (Henning et al., 2001). Combined, these results suggest that PS goes beyond metabolic demands, and can be influenced by psychosocial processes.

The presence of PS has been considered evidence of a number of psychosocial constructs, including empathy (Adler, 2002, 2007), attachment (Diamond, 2008), conflict (e.g., Levenson & Gottman, 1983), and emotional coregulation (Field, 2012; Sbarra & Hazan, 2008), although conflicting results suggest it is not specific to any of these. Empathy is the most commonly considered psychosocial explanation of PS. From the original studies (Di Mascio et al., 1955) through recent reports (Stratford et al., 2012), researchers (Chatel-Goldman et al., 2014; Marci & Orr, 2006; Messina et al., 2013) and theorists (Adler, 2007; Sbarra & Hazan, 2008) have considered the possibility that experiential connections that define emotional empathy (Hatfield, Cacioppo, & Rapson, 1994; Preston & de Waal, 2002) are mirrored in physiology. These ideas suggest that the ANS reflects a component of shared experience, so PS may be an objective measure of internal processes accompanying an empathic interaction. Adler (2007) made recommendations for doctors to recognize the state of their patients to increase understanding, and to consciously control their own physiological responses to improve interactions with patients. Grove (2007) made similar recommendations, proposing an exploration of the therapeutic utility of PS through group biofeedback. Although repeated findings show an association between PS and empathy, other results indicate these constructs are independent. Whereas PS may correlate with emotional empathy, physiological interactions in other contexts suggest it is not specific to that construct. Future research is needed to help disentangle this association, such as exploring whether a subtype of PS is specific to empathy.

Feldman (2012) has considered PS to be a component of a multi-systemic bio-behavioral synchronization that begins in gestation and continues throughout life. In a recent review incorporating her extensive work assessing biological, psychological, and behavioral synchrony, mainly between mother and infants, she considered any synchrony as a regulatory process. This research indicates that interpersonal bio-behavioral synchronization is required for healthy interaction, and is an integral component of coregulation, empathy, and attachment

(Feldman, 2012). Furthermore, Feldman (2012) concluded that PS results from facial cues, and that if such behavioral synchronizations do not develop between mothers and infants, children will have lasting issues with attachment and self-regulation. Although a number of studies have contradicted the assertion that PS is dependent on facial cues (e.g., Chatel-Goldman et al., 2014; Ferrer & Helm, 2013; Helm et al., 2012), the importance of synchronistic relationships remains.

Sbarra and Hazan (2008) gave a parallel explanation, as they consider positive PS to be a coregulatory process unique to attachment relationships. They argue that each individual is the primary physiological regulator for his or her partner, resulting in interpersonal maintenance of emotional homeostasis. They cite evidence from a series of animal studies by Hofer (e.g., Hofer, 1995; Polan & Hofer, 1999), wherein removal of an attachment figure creates dysregulation in physiology and behavior. Because this implies that autonomic functioning is synergetic rather than independent, they recommend modeling physiology as a bivariate system in which physiological processes are dependent on previous physiological measures of a partner. The authors further recommend experimental procedures that systematically remove certain components of an attachment relationship during stress-inducing tasks, such as controlling visual or olfactory cues. The presumption is that dysregulation and asynchrony are most likely to occur during stress, and that systematically interrupting channels through which synchrony may be based could elucidate mechanisms underlying this process. Similarly, Field (2012) considered synchronization a regulatory process that develops during attachment relationships, and recommends assessing what is missing when attachment figures are removed and synchronization is no longer evident. Although presumptions that PS will only occur in attachment relationships and is disrupted during stress have been contradicted, recommendations for systematic explorations of interpersonal physiology are well founded.

Discussion

A number of important findings can be extracted from this systematic review. First, the development of PS between two or more people does not appear to be dependent on (a) shared conditions such as behavior or environment, (b) a specific sensory mode of communication, or (c) psychosocial conditions such as valence or relationship type. Multiple methods have been used to show that PS is not dependent on individuals being in the same conditions (e.g., Marci et al., 2007) or environments (e.g., McAssey et al., 2013), and that engaging in the same behaviors does not reliably lead to synchrony (e.g., Henning et al., 2001). In addition, PS has been observed in studies that eliminate sensory modalities including visual (e.g., Ferrer & Helm, 2013) and physical (Guastello et al., 2006) cues. Mounting evidence indicates that physiological interactions can be observed across contexts, including individuals meeting for the first time (e.g., Marci & Orr, 2006; Silver & Parente, 2004), as well as in dyads or groups with established relationships (e.g., Ham & Tronick, 2009; Müller & Lindenberger, 2011). It has also been observed in positive (e.g., empathy; Marci et al., 2007) and negative (e.g., conflicting relationships; Levenson & Gottman, 1983) conditions, as well as relatively neutral settings (e.g., couples sitting together quietly; Ferrer & Helm, 2013). Collectively, these findings suggest that psychosocial processes are operating at the physiological level; however, systematic work is needed to determine the variables and conditions that contribute to these interactions.

Second, the extant literature suggests that PS is a transient state. Studies showing differences in PS across contexts and conditions indicate that physiological relationships change over time. This is evident in studies such as Müller and Lindenberger's (2011) and Ghafar-Tabrizi et al.'s (2008), which show that during a given time period, parameters of PS are not static. This is an important consideration, as attempts to apply statistical models that assume a constant state may be problematic. For example, if a dyad shifts between periods of positive and negative PS during a trial, but the entire interaction is assessed using a single linear model, then results will be an aggregate of two heterogeneous processes and will misrepresent the patterns of both. Guastello et al. (2006) and Helm et al. (2014) addressed this issue well, highlighting the need for flexible statistical models capable of identifying multiple types of physiological relationships occurring during a single interaction.

A third primary finding in this review is that autonomic activation may moderate PS. Results indicate that magnitudes of PS differ as arousal levels change (Creaven et al., 2014; Ebisch et al., 2012; Ghafar-Tabrizi, 2008; Manini et al., 2013; Reed et al., 2013; Waters et al., 2014). For example, multiple studies suggest that average resting HR moderates PS magnitude (Creaven et al., 2014; Ghafar-Tabrizi et al., 2008). Future studies should be designed to explore whether combinations of partners' physiological states, such as arousal levels or variability, influence PS.

Finally, and perhaps most importantly, PS has been found to be predictive of other variables. However, results appear to be dependent on the context in which a specific type of PS occurs. For example, high magnitudes of positive PS during conflict were found to be predictive of dissatisfaction in marriages (Levenson & Gottman, 1983, using an index of measures), whereas during psychotherapy (Marci et al., 2007, using skin conductance) and gaming (Henning et al., 2001, using HRV, skin conductance, and respiration), high positive PS was found to correspond to greater empathy and improved team performance. This type of synchrony has been interpreted as both a feeling of being "locked into" negative conflict (Levenson & Gottman, 1983) and connected and understood during positive interactions (Marci et al., 2007). In another context, negative PS in blood pressure was associated with positive interactions during partner conflict, which was interpreted as coordinated turn taking leading to more balanced communication (Reed et al., 2013). PS can therefore be predictive of an outcome, although more research is needed to explore interactions between PS parameters and variables including context, valence, and arousal.

Important Questions

Beyond these findings, a number of important questions became apparent in the existing IAP literature. A primary question relates to the mechanism of interpersonal physiological interactions (e.g., PS; stress buffering). How do physiological interactions develop and what affects them? Although there is evidence that these processes are not fully dependent on environment or behavior, it is unclear how one individual's autonomic activity responds to or mimics another's. One likely possibility is that these complex interactions can develop through a number of different mechanisms, including shared environment, coordinated behaviors, and matched responses to a third variable, as well as through interpersonal processes. Future research may be directed at experimentally determining the degree to which given variables are driving interpersonal physiological interactions during a given condition, as multiple modalities may be simultaneously involved.

A second question relates to the awareness of interpersonal physiological interactions. Can individuals recognize and report when some aspect of PS is occurring? A number of studies have linked PS with self-reports of co-occurring psychosocial constructs, suggesting a reportable component to PS. For example, Marci et al. (2007) found that clients' reports of therapist empathy were positively correlated with the magnitude of PS. Clients therefore had a reportable experience of feeling more understood when PS was higher. Similarly, Chatel-Goldman et al. (2014) found that couples reported greater empathy when their PS was higher. Although such findings suggest that individuals have the potential to recognize and report when their own physiological patterns are matching with others, this has not been directly explored.

A third question considers whether interpersonal understanding improves through self-awareness. If two people are experiencing the same physiological patterns, does recognition of one's own arousal patterns (i.e., interoception) improve interpersonal understanding? Levenson and Ruef (1992) offered some support for this possibility, as they found that higher PS with a person they watched on video was associated with accurately recognizing that person's negative emotion. However, no other works have directly addressed this question. Still, this line of inquiry could be used to explore whether a component of interpersonal understanding depends on a combination of physiological-level interactions and interoceptive awareness of those processes.

Relatedly, it is unclear whether individuals have some control over PS. Marci and Orr (2006) touched on this concept by having an interviewer intentionally redirect attention from an interviewee. They found that this type of disengagement from a partner significantly reduced PS. Ferrer and colleagues addressed this question more directly by asking participants to "mirror each other's physiology" (Ferrer & Helm, 2013; Helm et al., 2012; McAssey et al., 2013). They found evidence that when dyads were given this instruction, the magnitude of their PS was significantly greater than in other conditions (Ferrer et al., 2013; McAssey, Helm, Hsieh, Sbarra, & Ferrer, 2012). More directly, Van Puyvelde et al. (2015) found that mothers who changed the pace of their breathing were able to alter their own and their infants' RSA. This practice influenced the dyad's PS, as well as the infant's physiological state. Despite these indications, more systematic work is needed to determine whether PS can be consciously controlled. Perhaps more importantly, there is currently no evidence to indicate whether such changes in PS would cause or correlate with changes in other variables. For example, if partners' intentionally increased their PS, would affective empathy or interpersonal understanding also increase?

As an extension of the concept of control, the extent to which people use physiological processes in social interactions is unknown. Do people adjust their physiology as a technique to engage, influence, or ignore others? Ham and Tronick (2009) discussed this question in relation to findings that mothers calm themselves prior to calming their children. If this hypothesis is more generally accurate, in that individuals strategically adjust their own physiology in an effort to influence (or be influenced by) others, then interpersonal physiological processes may be an important factor in the social regulation of emotion. The general concept of social-emotional regulation has been discussed in recent literature, where it is suggested that interpersonal regulatory processes play a substantial role in the ways in which people interact (Reeck, Ames, & Ochsner, 2016). However, these theories are largely limited to intentional social regulation (e.g., trying to calm an angry partner), with little attention to physiological components. Methodologies designed to observe and define physiological interactions as components of communication are needed to determine the role PS plays in social encounters.

Critical Issues for Future Research

A number of issues critical to future work in IAP are identified in this systematic review. The following sections highlight some of these issues, including terminology, physiological variables measured, idiographic versus nomothetic methods, laboratory versus in-vivo designs, and statistical analyses.

Terminology. Our systematic review of the IAP literature identified terminological variation across the field, including inconsistent operational definitions. This issue is more than mere semantics, as the methodological and statistical approaches used in a study are dependent on the definition of the phenomenon to be identified. A number of authors have highlighted this issue and made attempts to resolve terminological ambiguities by operationally defining specific types of physiological relationships and their inherent statistical properties, as well as their relationships with psychophysiological constructs (e.g., Butler, 2011; Butler & Randall, 2013; Field, 2012; Helm et al., 2014). Quantitatively assessable operational definitions are needed for valid cross-study comparisons.

In line with the need for more specific terminology, as well as growing research interest in interpersonal processes, we propose the use of the term *physiological entanglement* to specify a measureable interdependence between peoples' physiological activities. The term, adopted from physics, denotes periods when particles are best understood as a system, rather than a collection of individual units (Horodecki, Horodecki, Horodecki, & Horodecki, 2009). This definition is directly transferable to psychology, meaning that the processes of each individual are better understood when the processes of all individuals are considered together.

To test for *physiological entanglement*, analyses are needed to isolate PS due to interpersonal interactions. This has been done through methodological checks and statistical modeling (e.g., dynamic systems analysis, Granger causality). The proportion of a dyad's PS due to entanglement has been methodologically tested by comparing a dyad's PS when they are interacting with each other to their PS under the same conditions when they are not interacting with each other. For example, Ferrer and Helm (2013) compared the PS in dyads who were quietly seated together while blindfolded with their PS in the same condition without blindfolds. If a dyad's PS when they were interacting is significantly greater than when they were not interacting, the difference can be considered evidence of entanglement. In addition to these procedures, the authors used dynamic systems analyses designed to determine the degree to which a dyad is interdependent. For instance, their dynamic systems model tests the degree to which changes in each partner are predictable from the other (see Ferrer & Helm, 2013, for details). More complex models can also be used to test for entanglement, such as Muller and Lindenberger's (2011) use of wavelet analysis paired with network analysis and Granger causality models, although methodological checks are still necessary.

Physiological variables. Although no clear patterns of results by ANS measure were identified in this review, different physiological measures have led to differential findings. For example, positive PS was found to occur in both RR and HR under some conditions, whereas in another condition, HR, but not RR, was synchronized (Ferrer & Helm, 2013; Helm et al., 2012). Such findings suggest that each measure reflects unique processes. Collecting multiple autonomic measures can lead to greater specificity of processes related to each physiological system. Furthermore, cross-measure analyses may be indicative of interactions between systems, such as one individual's PNS contributing to variance in another's SNS. An example of successful use of multiple measures can be seen in Creaven et al. (2014). They found significant magnitudes of PS between mothers' HR and their children's RSA that differed by group assignment. In addition to specific autonomic measures used, the collection, analysis, and interpretation of physiological data require a substantial knowledge base. The interested reader is referred to other resources (e.g., Cacioppo et al., 2007; Goodwin, 2012) for more details.

Methodological approach

Controlled laboratory designs. The current lack of experimental research assessing the mechanisms and processes involved in interpersonal physiological interactions is problematic. Most studies to date compare PS across groups or conditions, with the aim of observing variations in interpersonal characteristics due to population or context. However, this approach does little to explain *why* PS differs, leading to significant interpretation issues. For example, Messina et al. (2013) tested whether different levels of therapeutic training were associated with different levels of PS between therapists and clients. Although differences were found, conclusions as to why those differences exist are speculative. Systematic, experimentally manipulated, research is needed to isolate the basic components that contribute to PS for interpretations of group and conditional differences to be meaningful. Until controlled, systematic research addresses the basic components and outcomes of PS, interpretations of results will be limited (Sbarra & Hazan, 2008).

In-vivo studies. In addition to laboratory experiments, in-vivo designs that incorporate ambulatory assessments of participants in daily life are needed to reveal patterns that can only be assessed over longer periods of time and across contexts. Longitudinal assessments may reveal ecologically valid processes that would not be obtainable through laboratory-based research alone. Tracking individual and interpersonal patterns over time may be the only way to establish the ecological validity of conclusions about processes such as coregulation, and may reveal a more complete picture of the emergence and consequences of interpersonal physiological interactions. Although a few studies have collected longitudinal data in-vivo (e.g., Marci et al., 2007), none to date have analyzed longitudinal trends.

Statistical analyses. Another critical issue for IAP research is the type of statistical analysis used. The analysis of multivariate, non-stationary, intensive time series of physiology is wrought with complexities, as these data violate a number of assumptions of parametric statistics (e.g., stationarity, independence of measures). Still, the number of viable statistical procedures applicable to IAP research is rapidly increasing, and many studies have developed strategies tailored to these data. Some example methods include dynamic systems models (Ferrer et al., 2013), cross-lagged panel models (Helm et al., 2014), multilevel models (Reed et al., 2013), wavelet analysis (Müller, & Lindenberger, 2011; Quer et al., in press), and functional data analysis (Liu et al., in press). Despite their promise, it is important that researchers adequately match these statistical approaches to appropriate research questions, as interpretation of results can differ substantially depending on the method used.

Another important consideration when running any analysis of IAP is the length of time being assessed. As of now, the temporal dynamics of PS are largely unknown, yet the length of time PS is measured and analyzed is typically arbitrary. If analyses are run on segments that are too short for PS to develop, they may falsely suggest no relationship. Alternatively, if the time span is too long, the dynamics of physiological interactions may vary, and model results could be inappropriate aggregates of multiple processes. In addition, co-occurring physiological interactions may exist at multiple time scales, so explorations of timing are critical to uncovering long- and short-term processes. Future work is needed to both assess the time range in which interpersonal physiological interactions occurs and to develop and adapt analyses capable of detecting when and how they change over time.

Finally, regardless of statistical procedures used, determining a valid null hypothesis is a necessary component for testing PS. Spurious synchrony can be detected in randomly paired data, and the probability of chance findings can vary due to contextually dependent data structures. To validate findings, a null hypothesis determining the potential for chance findings of PS in contextually matched, randomized data is often necessary. Otherwise, it may be unclear whether results are valid, or due to chance.

Conclusion

Results from this systematic review of the IAP literature indicate that social processes operate at the physiological level. The published research to date has shown that the presence or absence of PS can be informative of the state of a relationship, whereas synchrony due to external variables may be informative of shared levels of involvement. Group and conditional differences have been shown to influence parameters of PS, but additional work is needed to determine why these differences exist. Controlled experiments are required to explore mechanisms that generate PS, as well as to determine interactions with different variables. In addition, in-vivo designs are needed to explore PS under natural conditions, and to add external validity to lab-based research. The application of an inductive strategy is recommended to identify and define a typology of PS, followed by systematic replication of studies across contexts and time, both within and across people. Although converging evidence suggests that PS is robust enough to be detected using correlational analyses and nomothetic methods, results from these strategies may be too broad to identify complex, time-varying components of PS. Combining idiographic designs with time-varying analyses offers the greatest potential to explore various processes involved in PS.

In summary, interpersonal physiological relationships have far-reaching implications concerning the nature of human interactions. This systematic review, however, indicates that IAP is currently an underexplored area, and extensive, well-designed research is required for these interactions to be understood and leveraged for developmental, therapeutic, and performance gains in human behavior.

Appendix A

Systematic Literature Review Results.

Reference	Population	Term for physiological synchrony	Statistic of physiological synchrony	Methodology (idiographic or nomothetic)	Null hypothesis tested	Physiological measures
Bachrach, Fontbonne, Joufflineau, and Ulloa (2015)	Other: Dancers and audience	Entrainment	Regression	Both	No	RR
Baker et al. (2015)	Mother–child	Biobehavioral synchrony	Correlation	Nomothetic	No	EDA
Chanel, Kivikangas, and Ravaja (2012)	Teammates	Compliance	Correlation; Weighted coherence	Nomothetic	No	HF-HRV; HF-Resp-Amp; IBI; Resp-Amp; SC; VLF-HRV
Chatel-Goldman, Congedo, Jutten, and Schwartz (2014)	Couples	Physiological coupling	Cross-correlations	Nomothetic	Yes	RVT; PRV; SC
Codrons, Bernardi, Vandoni, and Bernardi (2014)	Other: Student group	Entrainment	Generalized Partial directed coherence	Nomothetic	Yes	RR; HP
Coleman, Greenblatt, and Solomon (1956)	Therapist–client	Physiological relationship	Correlation	Idiographic	No	HR
Creaven, Skowron, Hughes, Howard, and Loken (2014)	Mother–child	Concordance	Multilevel model	Nomothetic	No	HR; RSA
Di Mascio, Boyd, Greenblatt, and Solomon (1955)	Therapist–client	Sociophysiology	Correlation	Idiographic	No	PR
Ebisch et al. (2012)	Mother–child	Synchrony	Correlation	Nomothetic	No	Temp
Elkins et al. (2009)	Teammates	Compliance	Signal matching; Instantaneous derivative matching; Directional agreement; Correlation	Nomothetic	No	IBI; RSA

(continued)

Appendix A (continued)

Reference	Population	Term for physiological synchrony	Statistic of physiological synchrony	Methodology (idiographic or nomothetic)	Null hypothesis tested	Physiological measures
Feldman, Magori-Cohen, Galili, Singer, and Louzoun (2011)	Mother–child	Biological synchrony	ARIMA model with cross-correlation function	Nomothetic	Yes	IBI
Ferrer and Helm (2013)	Couples	Covariation	Differential equation models	Both	Yes	HR; Resp
Field, Healy, and LeBlanc (1989)	Mother–child	Synchrony	Coherence and cross-coherence	Nomothetic	No	HR
Field et al. (1992)	Other: Friends–acquaintances	Coherence	Coherence	Nomothetic	No	HR
Gates, Gatzke-Kopp, Sandsten, and Blandon (2015)	Couples	Linkage	Cross-correlation	Nomothetic	No	RSA
Ghafar-Tabrizi (2008)	Mother–child	Linkage	Bivariate time-series analysis	Both	No	HR; FPA
Goldstein, Field, and Healy (1989)	Other: Friends–acquaintances	Concordance	Repeated-measures ANOVA	Nomothetic	No	HR
Guastello, Pincus, and Gunderson (2006)	Other: Classmates	Linkage	Linear regression; Nonlinear regression	Both	No	SC
Ham and Tronick (2009)	Mother–child	Concordance	Windowed correlation of slope	Nomothetic	No	SC
Helm, Sbarra, and Ferrer (2012)	Couples	Covariation	Coupled oscillator models	Nomothetic	Yes	HR; Resp
Helm, Sbarra, and Ferrer (2014)	Couples	Synchrony	Cross-lagged panel models	Both	No	RSA
Henning, Armstead, and Ferris (2009)	Teammates	Compliance	Cross-correlation	Nomothetic	No	HRV
Henning, Boucsein, and Gil (2001)	Teammates	Compliance	Cross-correlation; Weighted cross-coherence	Nomothetic	No	HRV; RR; SC
Henning and Korbelak (2005)	Teammates	Compliance	Cross-correlation	Nomothetic	No	IBI
Hill-Soderlund et al. (2008)	Mother–child	Physiological Attunement	General linear model with repeated-measures and time-varying covariates	Nomothetic	No	RSA
Järvelä, Kivikangas, Kätsyri, and Ravaja (2013)	Teammates	Linkage	Cross-correlation; Weighted cross-coherence	Nomothetic	No	IBI; HF-HRV; SCR; SCL
Kaplan, Burch, Bloom, and Edelberg (1963)	Other: Classmates	Covariation	Correlation	Nomothetic	No	SCR
Konvalinka et al. (2011)	Other: Familial vs. non-familial	Synchronized arousal	Cross-recurrence quantification analysis	Both	No	HR
Kraus and Mendes (2014)	Other: Mock businessmen	Affect contagion	Lagged correlation	Nomothetic	No	PEP
Levenson and Gottman (1983)	Couples	Linkage	Bivariate time-series analysis	Nomothetic	No	HR; PTT; SCL; ACT[a]; Physiological index (HR; PTT; SCL; ACT[a])
Liu, Zhou, Palumbo, and Wang (in press)	Couples	Linkage	Dynamic correlation	Nomothetic	Yes	SC
Lunkenheimer et al. (2015)	Mother–child	Synchrony	Multilevel coupled autoregressive model	Both	No	RSA
Manini et al. (2013)	Mother–child	Attunement	Correlations; Cross-correlations	Both	No	Temp
Marci (2006)	Other: Audience members	Emotional engagement	Proprietary analysis not divulged	Unspecified	No	Physiological index (SC; HR; RR; ACT[a])

(continued)

Appendix A (continued)

Reference	Population	Term for physiological synchrony	Statistic of physiological synchrony	Methodology (idiographic or nomothetic)	Null hypothesis tested	Physiological measures
Marci, Ham, Moran, and Orr (2007)	Therapist–client	Concordance	Windowed correlation of slope	Nomothetic	Yes	SCL
Marci and Orr (2006)	Therapist–client	Concordance	Windowed correlation of slope	Nomothetic	No	SCL
McAssey, Helm, Hsieh, Sbarra, and Ferrer (2013)	Couples	Synchrony	Structural heteroscedastic measurement-error model; Empirical mode decomposition	Both	Yes	HR; RR; TI
McFarland (2001)	Other: Friends	Synchrony	Cross-correlation	Nomothetic	Yes	RR
Messina et al. (2013)	Therapist–client	Concordance	Windowed correlation of slope	Both	No	SCL
Mitkidis, McGraw, Roepstorff, and Wallot (2015)	Other: randomly paired students	Synchrony	Cross-recurrence quantification analysis	Both	No	HR
Montague, Xu, and Chiou (2014)	Teams	Compliance	Signal matching; Instantaneous derivative matching; Directional agreement; Cross-correlation; Weighted coherence	Nomothetic	Yes	IBI; HF-HRV; LF-HRV; SC
Moore (2009)	Mother–child	None	Correlation	Nomothetic	No	RSA
Moore et al. (2009)	Mother–child	Synchrony	Correlation	Nomothetic	No	HP; RSA
Morgan, Gunes, and Bryan-Kinns (2015)	Other: Musicians	Physiological linkage	Percentage of matched slope	Nomothetic	No	HR
Muller and Lindenberger (2011)	Other: Choir members	Synchrony	Wavelet coherence; Granger causality (multivariate autoregressive model)	Both	No	HRV; Resp
Noy, Levit-Binun, and Golland (2015)	Other: Experts at joint improvisation	Synchrony	Correlation	Nomothetic	No	HR
Quer, Daftari, and Rao (in press)	Other: Groups meditating	Entrainment	Wavelet coherence	Idiographic	No	HF-HRV; LF-HRV; VLF-HR; RR
Reed, Randall, Post, and Butler (2013)	Couples	Linkage	Longitudinal multilevel dyadic model	Nomothetic	Yes	BP; IBI; SC
Robinson, Herman, and Kaplan (1982)	Therapist–client	Concordance	Correlation; Discrete categorizations of SCR	Nomothetic	No	SCR; FST
Shearn, Spellman, Straley, Meirick, and Stryker (1999)	Other: Friends–strangers	Shared physiology	Correlations	Nomothetic	No	SC; Blush
Silver and Parente (2004)	Other: Strangers	Shared physiological reaction	Correlation	Nomothetic	No	SC
Strang, Funke, Russell, Dukes, and Middendorf (2014)	Teammates	Physio-behavioral coupling	cross-correlation, cross-recurrence quantification analysis, and cross-fuzzy entropy	Both	Yes	IBI
Stratford, Lal, and Meara (2009)	Therapist–client	Concordance	Windowed correlation of slope	Nomothetic	No	SC

(continued)

Appendix A (continued)

Reference	Population	Term for physiological synchrony	Statistic of physiological synchrony	Methodology (idiographic or nomothetic)	Null hypothesis tested	Physiological measures
Stratford, Lal, and Meara (2012)	Therapist–client	Concordance	Windowed correlation of slope	Nomothetic	No	SC
Suveg, Shaffer, and Davis (2016)	Mother–child	Synchrony	Cross-correlation	Nomothetic	No	IBI
Thomsen and Gilbert (1998)	Couples	Linkage	Bivariate time-series analysis	Nomothetic	No	HR; SC
Van Puyvelde et al. (2015)	Mother–child	Synchrony	Difference score	Nomothetic	No	RSA
Vickhoff et al. (2013)	Other: Choir singers	Inter-individual synchronization	Cross-coherence	Both	No	HRV
Walker, Muth, Switzer, and Rosopa (2013)	Teammates	Compliance	Regressions and correlations	Nomothetic	No	Physiological index (RSA; PEP; LVET)
Waters, West, and Mendes (2014)	Mother–child	Covariation	Growth curve model	Nomothetic	No	HR; VC
Woltering, Lishak, Elliott, Ferraro, and Granic (2015)	Mother–child	Synchrony	Structural heteroscedastic measurement-error model	Nomothetic	No	HR

Note. RR = respiration rate; EDA = electrodermal activity; HF-HRV = high-frequency heart rate variability; HF-Resp-Amp = high-frequency respiration amplitude; IBI = interbeat interval; Resp-Amp = respiration amplitude; SC = skin conductance; VLF-HRV = very-low-frequency heart rate variability; RVT = respiration volume time; PRV = pulse rate variability; HP = heart period; HR = heart rate; RSA = respiratory sinus arrhythmia; PR = pulse rate; Temp = facial temperature; ARIMA = autoregressive integrated moving average model; Resp = respiration; FPA = finger pulse amplitude; ANOVA = analysis of variance; HRV = heart rate variability; SCR = skin conductance response; SCL = skin conductance level; PEP = pre-ejection period; PTT = pulse transmission time; ACT = somatic movement; TI = thoracic impedance; LF-HRV = low-frequency heart rate variability; BP = blood pressure; FST = finger skin temperature; Blush = facial blushing; LVET = left ventricular ejection time; VC = ventricle contractility.
[a]ACT is a behavioral measure, but was used as part of an index of physiology.

Appendix B

Results by Physiological Measure: Cardiac Activity.

Source	Measure	Context	Finding	Results
Coleman, Greenblatt, and Solomon (1956)	HR	General	S	Significant correlations found between client and therapist HR.
Creaven, Skowron, Hughes, Howard, and Loken (2014)	HR	General	S	Positive concurrent PS between mother and child HR was observed during the resting condition.
		Between	S	Magnitudes of PS in HR significantly greater in the maltreating group. When a child maltreating mother displayed lower relative HR, her child displayed lower HR. Conversely, higher maternal HR was associated with higher child HR in non-maltreating dyads.
		Moderator	S	Mother–child PS in HR was moderated by mothers' average HR, such that mothers with greater HR elevations had lower PS, and those with lower average HR had greater PS.
Ferrer and Helm (2013)	HR	Within	S	Change across tasks (baseline, gazing, and imitation) was significant for some participants, although on average it was not.
		Typology	S	Negative PS was found, such that when parameters for one partner decreased, the other partner's increased. Positive PS in HR was found in more than half of the dyads.
		PsychoSoc		Females' PS in HR during the imitation task was related to daily affect, suggesting that females' physiology adjusted to their male partners' in this task similarly to adjustments in response to their partners' daily affect.
Field et al. (1992)	HR	Between	NS	No statistically significant difference in PS between friend and acquaintance dyads.
Field, Healy, and LeBlanc (1989)	HR	Between	NS	No significant differences in PS magnitudes across depressed and non-depressed dyads.

(continued)

Appendix B (continued)

Source	Measure	Context	Finding	Results
Ghafar-Tabrizi (2008)	HR	Between	S	In the high-conflict group when daughters led the conversation, daughter's HR predicted mother's HR significantly better than when mothers led the conversation.
		Within	NS	Equivalent levels of PS demonstrated across varied conversation topics.
			S	When daughters led the conversation, their HR predicted the mother's HR better than mother's HR predicted daughter's, and vice versa.
		PsychoSoc	S	Levels of felt and preferred arousal were associated with the magnitude of PS during dyadic interaction.
Goldstein, Field, and Healy (1989)	HR	Between	S	Greater PS for friends vs. acquaintance dyads. During pre-play baseline, friends showed significantly greater PS than acquaintances.
Helm, Sbarra, and Ferrer (2012)			NS	No significant differences in PS between friend and acquaintance dyads during play period.
	HR	Within	S	Different patterns of PS were found in couples across baseline, gazing, and imitation tasks.
		Typology	S	Patterns suggesting both positive and negative PS present in couples during baseline and gazing tasks, but only negative PS was observed during imitation task.
		PsychoSoc	S	Higher anxiety and avoidance were associated with greater magnitudes of PS in couples during the imitation task, but not during the baseline or gazing tasks.
			NS	Neither relationship length or satisfaction was related to couples' PS in HR.
Konvalinka et al. (2011)	HR	Between	S	PS was found between fire walkers and familial spectators during ritual fire walking, but not between fire walkers and non-familial spectators.
Levenson and Gottman (1983)	HR	Within	NS	PS in HR was not detected when couples were discussing neutral or conflict topics.
		PsychoSoc	NS	PS in HR was not predictive of marital satisfaction, affect, or affect reciprocity.
McAssey, Helm, Hsieh, Sbarra, and Ferrer (2013)	HR	Within	S	No PS during baseline, and significant PS for some couples during gazing and imitation task. No significant results were seen in randomly paired participant data.
Mitkidis, McGraw, Roepstorff, and Wallot (2015)	HR	Between	S	PS was significantly greater in student dyad groups that played an economic trust game (public goods game) following a joint cooperative task, compared with groups who did not play the trust game.
		Within	S	In the group that played the public goods game, PS was positively associated with expectations of returns but not of investments (i.e., mock money they thought they would get back, vs. mock money they would invest). The authors concluded that PS could be viewed as a proxy measure of trust.
Morgan, Gunes, and Bryan-Kinns (2015)	HR	General	NS	No PS was detected between drummers' HR.
Noy, Levit-Binun, and Golland (2015)	HR	General	S	Significant PS in HR was found between dyads mirroring each other's movements. PS was significantly, positively correlated with behavioral synchrony, and heart rate.
		PsychoSoc	S	Significant positive correlation found between PS in HR and dyads' self-reported experiences of togetherness.
Stratford, Lal, and Meara (2009)	HR	Within	S	Patterns of EEG during high PS differed across therapy sessions.
Stratford, Lal, and Meara (2012)	HR	Within	S	Patterns of EEG during high PS differed across therapy sessions.
Thomsen and Gilbert (1998)	HR	General	S	PS was detected in couples' HR when discussing a conflict topic, but results varied across dyads

(continued)

Appendix B (continued)

Source	Measure	Context	Finding	Results
Woltering, Lishak, Elliott, Ferraro, and Granic (2015)	HR	Within	S	PS in HR observed between mother–child dyads during positive and negative discussions. More than twice the magnitude of PS observed during the last vs. first topic, suggesting increased attempts at repair.
			NS	PS in HR between mother–child dyads associated with behavioral synchrony during negative, but not positive, discussion.
		Group	NS	No difference in mother–child PS in HR between children with typical and atypical self-regulation during discussions.
		PsychoSoc	S	Increased PS significantly predicted the degree of "repair" in mother–child relationship following a negative discussion, for both children with and without self-regulation issues.
Creaven, Skowron, Hughes, Howard, and Loken (2014)	HR/RSA	General	S	PS was observed in mother HR and child RSA over time.
		Moderator	S	Higher resting maternal HR was associated with significantly lower PS in mother HR and child RSA.
Waters, West, and Mendes (2014)	HR/VC	General	S	Significant PS was found between infant HR and mother VC.
		Within	S	PS between infant HR and mother VC was found in the negative and positive stress conditions, but not the neutral condition. PS increased over time in negative stress condition, but not positive or neutral conditions.
Di Mascio, Boyd, Greenblatt, and Solomon (1955)	PR	General	S	PS of pulse rate fluctuations found between patient and doctor during a psychiatric interview.
		Typology	S	Pulse rates observed to vary together or inversely, labeled *concordance* and *discordance* (i.e., positive and negative PS).
Chatel-Goldman, Congedo, Jutten, and Schwartz (2014)	PRV	General	NA	Significance of PS between couples' pulse rate variability was not tested.
		Within	NS	No significant differences in PS of pulse rate variability when couples could or could not touch each other.
		PsychoSoc	NS	No significant correlations between empathy scores and PS in pulse rate variability found.
Levenson and Gottman (1983)	PTT	Within	NS	PS in PTT was not detected when couples were discussing neutral or conflict topics.
		PsychoSoc	NS	PS in PTT was not predictive of marital satisfaction, affect, or affect reciprocity.
Ghafar-Tabrizi (2008)	FPA	Between	S	PS was stronger during conflict than pleasant conversation for the high-conflict group only.
		PsychoSoc	S	Levels of preferred, but not felt, arousal were associated with the strength of PS in finger pulse amplitude during dyadic interaction.
Reed, Randall, Post, and Butler (2013)	BP	PsychoSoc	S	At low levels of negative influence, PS in BP was significantly negative, but at high levels of negative influence, BP was unsynchronized. When demand behaviors were not present, PS in BP was significantly negative, while during demand behaviors, PS was positive. When withdraw behaviors were not present, PS in BP was negative. When withdraw behaviors were present, PS was significantly positive.
McAssey, Helm, Hsieh, Sbarra, and Ferrer (2013)	TI	Within	S	Significant increase in PS in thoracic impedance from baseline to the gazing and in-sync tasks for some couples.
Chanel, Kivikangas, and Ravaja (2012)	IBI	General	S	Teammates' PS in IBI positive and significantly different from zero.
		Within	S	Teammates' PS in IBI higher during competitive vs. cooperative play.
		PsychoSoc	NS	No self-report gaming experience constructs were significantly related to PS in IBI.
Elkins et al. (2009)	IBI	Between	NS	Trend-level differences in mean PS in IBI found between teams with high and low performance, but did not reach significance.
Feldman, Magori-Cohen, Galili, Singer, and Louzoun (2011)	IBI	General	S	Statistically significant levels of PS in IBI were found during face-to-face interactions between mothers and infants.
		Moderator	S	Time periods involving vocal synchrony, affect synchrony, or the co-occurrence of vocal and affect synchrony between mothers and infants were significantly related to increased PS in IBI.

(continued)

Appendix B (continued)

Source	Measure	Context	Finding	Results
Henning and Korbelak (2005)	IBI	General	S	There was a small significant effect indicating that PS in IBI predicted some measures of team performance.
Järvelä, Kivikangas, Kätsyri, and Ravaja (2013)	IBI	General	S	PS present among team members.
		Within	S	PS highest during competitive conditions without a computerized opponent.
		Moderator	S	Previous experience with the game minimized conditional differences in PS.
		PsychoSoc	S	Increased empathy and understanding between players associated with increased PS in IBI.
Montague, Xu, and Chiou (2014)	IBI	Within	S	PS in teammates' IBI was higher during team trials than during baseline.
			NS	A number of metrics of team performance and experience were not correlated with PS in IBI.
Reed, Randall, Post, and Butler (2013)	IBI	General	NS	PS in IBI was not observed during couples' conversations.
		PsychoSoc	NS	PS in IBI was not observed and not significantly different across contexts of couples' conversations.
Strang, Funke, Russell, Dukes, and Middendorf (2014)	IBI	General	NS	PS in IBI was not significantly greater than PS from randomly paired dyads.
Suveg, Shaffer, and Davis (2016)	IBI	General	S	PS was detected between mothers' and their children during a joint task.
			NS	PS was not detected between mothers and their children during a silent baseline.
		Moderator	S	Family risk moderated the relationship between physiological and behavioral synchrony between mothers and their children. Higher risk families showed a negative association between behavioral and physiological synchrony.
				Family risk moderated the relation between PS and child self-regulation. High-risk children had a negative relation between self-regulation and PS.
			NS	There were no moderating effects between behavioral and physiological synchrony or child-self-regulation in low-risk families.
		Within	S	PS in IBI was equal during high and low arousal, in both high- and low-risk dyads.
		Between	S	PS was negatively correlated with behavioral synchrony in high-risk families.
Henning, Armstead, and Ferris (2009)	HRV	Within	S	Teammates' PS in HRV negatively associated with ratings for team productivity.
			NS	Teammates' PS in HRV not significantly associated with ratings of individual participation, workload, or effort for decisions.
		PsychoSoc	S	Teammates' PS in HRV negatively associated with ratings for quality of communication, and ability to work together.
Henning, Boucsein, and Gil (2001)	HRV	Within	S	PS in HRV a significant predictor of some measures of team performance.
			NS	Teammates' PS in HRV not significantly correlated with team behavioral coordination.
Muller and Lindenberger (2011)	HRV	Within	S	PS in HRV was significantly stronger during singing than during rest. Directed positive PS where physiological changes in the conductor were followed by choir members.
Vickhoff et al. (2013)	HRV	Within	S	PS in choir members' HRV was detected during the hymn and mantra singing.
			NS	PS in choir members' HRV was not detected during silent baselines, or when members were humming.
Chanel, Kivikangas, and Ravaja (2012)	HF-HRV	Within	NS	Teammates' PS in HF-HRV at the home and at the lab not significantly different.
			S	Teammates' PS in HF-HRV significantly higher for cooperative play as compared with competitive play.
		PsychoSoc	S	Teammates' PS in HF-HRV was positively associated with social negative feelings.

(continued)

Appendix B (continued)

Source	Measure	Context	Finding	Results
Järvelä, Kivikangas, Kätsyri, and Ravaja (2013)	HF-HRV	General	S	PS in HF-HRV was present among team members.
		PsychoSoc	S	PS in HF-HRV was positively associated with self-report ratings of perceived comprehension and negatively with behavioral involvement.
Montague, Xu, and Chiou (2014)	HF-HRV	Within	S	PS in teammates' HF-HRV during difficult team virtual tasks and when technology was unreliable was significantly higher than in other conditions. Also, PS in HF-HRV was negatively correlated with teams' trust in the technology.
			NS	A number of measures of team performance were not significantly correlated with teams' PS in HF-HRV.
Quer, Daftari, and Rao (in press)	HF-HRV	Within	S	Group-level PS in HF-HRV was detected in groups meditating, chanting, and performing breathing exercises.
Montague, Xu, and Chiou (2014)	LF-HRV	Within	NS	A number of measures of team performance and experience were not significantly correlated with teams' PS in LF-HRV.
Quer, Daftari, and Rao (in press)	LF-HRV	Within	S	Group-level PS in LF-HRV was detected in groups meditating, chanting, and performing breathing exercises.
Chanel, Kivikangas, and Ravaja (2012)	VLF-HRV	Within	S	Teammates' PS in VLF-HRV significantly higher at home than in the lab.
Quer, Daftari, and Rao (in press)	VLF-HRV	Within	S	Group-level PS in VLF-HRV was detected in groups meditating, chanting, and performing breathing exercises.
Creaven, Skowron, Hughes, Howard, and Loken (2014)	RSA	General	NS	No significant PS in mother and child RSA.
		Moderator	NS	Maltreatment status not a significant moderator of mother–child PS in RSA.
Elkins et al. (2009)	RSA	Between	S	Teammates in high- and low-performance groups had significantly different levels of PS in RSA.
Gates, Gatzke-Kopp, Sandsten, and Blandon (2015)	RSA	PsychoSoc	S	PS in RSA was significantly and positively correlated with self-reported marital conflict.
Helm, Sbarra, and Ferrer (2014)	RSA	General	S	Results indicated that PS in RSA was significantly different from zero.
		Within	S	PS in RSA significantly increased from the baseline to the conversation tasks, and that high RSA in one partner led to higher RSA in the other partner.
			NS	Couples' PS in RSA did not significantly differ by conversation type.
		Typology	S	Results indicated that PS followed a morphostatic pattern (i.e., bidirectional interdependence around a stable arousal level).
		PsychoSoc	S	PS was significantly stronger in couples with higher quality relationships.
Hill-Soderlund et al. (2008)	RSA	General	NS	No significant findings of PS in RSA between mothers and infants during the strange situation paradigm.
		PsychoSoc	NS	No significant findings of PS in RSA between mothers and infants during the strange situation paradigm with attachment status as an interaction term.
Lunkenheimer et al. (2015)	RSA	General	S	Models of PS explained over 30% of variance in mothers' and children's RSA across lab-based tasks.
		Moderator	S	PS between mother and child RSA was negative when children's problem behaviors were high, but positive when low.
Moore (2009)	RSA	General	NS	Correlations between mothers' and their infants' RSA change scores during the still-face paradigm were not statistically significant.
Moore et al. (2009)	RSA	General	NS	PS in RSA was not detected between mother–infant dyads during a quiet, still 2-min baseline.
Walker, Muth, Switzer, and Rosopa (2013)	RSA	Within	NS	PS in teammates' RSA not a significant predictor of team errors.
Codrons, Bernardi, Vandoni, and Bernardi (2014)	HP	Within	NS	PS in HP was not observed between groups of 10 people sitting still and quiet, or swinging their arms while in silence, listening to music, or listening to a metronome.
Moore et al. (2009)	HP	General	S	A moderate, significant correlation between mother–infant's HP was detected during a quiet, still 2-min baseline.

(continued)

Appendix B (continued)

Source	Measure	Context	Finding	Results
Kraus and Mendes (2014)	PEP	Between	S	Results indicated low-status partners' PEP was positively synchronized with high-status partners' PEP at a 30-s lag during mock negotiations, suggesting high-status partners led the interaction.
Van Puyvelde et al. (2015)	RSA	Within	S	Mother–infant RSA synchronized during different maternal breathing paces until infants were 2 months.
			NS	Mother–infant RSA did not synchronize during different maternal breathing paces when infants were 3 months.
Walker, Muth, Switzer, and Rosopa (2013)	PEP	Within	NS	PS in teammates' PEP not a significant predictor of team errors.
Walker, Muth, Switzer, and Rosopa (2013)	LVET	Within	NS	PS in teammates' LVET not a significant predictor of team errors.

Note. HR = heart rate; General = tested for presence of PS; S = statistically significant; PS = physiological synchrony; Between = tested for differences in PS across groups; Moderator = tested whether a variable moderated PS; Within = tested difference of PS across conditions within groups; Typology = tested for a specific type of PS; PsychoSoc = tested whether PS was associated with a psychosocial construct; NS = statistically non-significant; RSA = respiratory sinus arrhythmia; VC = ventricle contractility; PTT = pulse transmission time; FPA = finger pulse amplitude; BP = blood pressure; TI = thoracic impedance; IBI = interbeat interval; HRV = heart rate variability; HF-HRV = high-frequency heart rate variability; LF-HRV = low-frequency heart rate variability; VLF-HRV = very-low-frequency heart rate variability; HP = heart period; PEP = pre-ejection period; LVET = left ventricular ejection time.

Appendix C

Results by Physiological Measure: Electrodermal Activity.

Source	Measure	Context	Finding	Results
Baker et al. (2015)	SC	Moderator	S	Strength of PS in SC was negatively associated with autism severity. More severe diagnosis was associated with lower PS.
Chanel, Kivikangas, and Ravaja (2012)	SC	General	S	PS in SC significantly different from zero.
		PsychoSoc	S	Positive affect during gaming experience positively associated with PS in SC.
			NS	Other psychosocial results non-significant.
Chatel-Goldman, Congedo, Jutten, and Schwartz (2014)	SC	General	S	PS in SC of couples beyond what was accounted for in data from random dyads.
		Within	S	Touch significantly increased couples' PS in SC.
		PsychoSoc	NS	No main effects of empathy state on PS in SC.
			S	Negative correlation between "splitting emotions" and PS, as well as empathy and PS with touch, indicating touch had a stronger influence on PS between partners who were less empathic.
Guastello, Pincus, and Gunderson (2006)	SC	General	S	Significant levels of PS in SC between dyads during all conversation types.
		Between	S	No statistically significant difference in PS between groups having different conversations.
Ham and Tronick (2009)	SC	Within	NS	Positive PS in SC between mothers and infants approached significance during the still-face paradigm when infants displayed negative behaviors. PS in SC not significantly related to engagement behaviors between mother and infant during normal interaction.
			S	When mothers engaged in soothing of infants during reengagement, greater positive PS occurred in relation to behavioral synchrony.
Henning, Boucsein, and Gil (2001)	SC	Within	S	PS in SC was a significant predictor for some measures of team performance.
			NS	PS in SC not predictive of team coordination.
Liu, Zhou, Palumbo, and Wang (in press)	SC	Within	S	Significant PS was detected in couples' SC when participants were quietly seated face-to-face. PS during this condition was significantly greater than when couples were seated back-to-back.
			NS	PS was not detected in couples' SC when participants were quietly seated back-to-back.
Reed, Randall, Post, and Butler (2013)	SC	General	NS	PS in SC not observed during couples' conversations.
		PsychoSoc	NS	PS in SC not observed and not significantly different across contexts of couples' conversations.

(continued)

Appendix C (continued)

Source	Measure	Context	Finding	Results
Shearn, Spellman, Straley, Meirick, and Stryker (1999)	SC	Between	S	Significant PS in SC between performers and friends, but not between friends and strangers or strangers and performers.
Silver and Parente (2004)	SC	General	S	Significant PS in SC between pairs of strangers conversing for the first time.
Stratford, Lal, and Meara (2009)	SC	Within	S	PS in SC increased from Therapy Sessions 1 to 4. Highest PS in SC between therapists and clients recorded during Session 4. Patterns of EEG accompanying peak PS in SC differed across therapy sessions.
Stratford, Lal, and Meara (2012)	SC	Within	S	During peak PS in SC between therapists and clients, frontal site showed significantly lower EEG beta activity during Therapy Session 6 compared with 3.
Thomsen and Gilbert (1998)	SC	General	S	PS was detected in couples' SC when discussing a conflict topic, but results were varied across dyads. Husbands' SC was a significantly better predictor of wives' SC than vice versa.
Järvelä, Kivikangas, Kätsyri, and Ravaja (2013)	SCL	General	S	PS in SCL significantly higher than zero among team members.
		Within	NS	PS in SCL not significantly different in cooperative/competitive conditions or including computer/non-computer players.
		PsychoSoc	NS	PS in SCL not significantly related to teammates' emotional or behavioral self-report items.
Levenson and Gottman (1983)	SCL	Within	NS	PS in SCL not detected when couples discussing neutral or conflict topics.
		PsychoSoc	NS	PS in SCL not predictive of marital satisfaction, affect, or affect reciprocity.
Marci, Ham, Moran, and Orr (2007)	SCL	PsychoSoc	S	PS in SCL significantly and positively correlated with patient ratings of therapist empathy. Patients and therapists showed significantly more solidarity and positive regard when PS in SCL was high.
Marci and Orr (2006)	SCL	Within	S	PS in SCL significantly higher between interviewer and patient during neutral than during emotionally distant condition.
		PsychoSoc	S	Patient ratings of interviewer empathy significantly higher in neutral than in emotionally distant condition.
Messina et al. (2013)	SCL	Between	S	Significant differences in PS between the three groups (therapists, psychologists, and non-therapists) at Lag 0. PS in SCL with pseudo-patients was significantly higher with psychologists compared with therapists. At Lag 3, psychologists showed lower PS than therapists.
		PsychoSoc	S	PS in SCL between pseudo-patients and therapists was significantly correlated with empathy perceived by the pseudo-patients at 3- and 4-s lags.
Järvelä, Kivikangas, Kätsyri, and Ravaja (2013)	SCR	General	S	PS in SCR significantly higher than zero among team members.
		Within	NS	PS in SCR not significantly different in cooperative/competitive conditions or with computer/non-computer players.
		PsychoSoc	NS	PS in SCR not significantly related to teammates' emotional or behavioral self-report items.
Kaplan, Burch, Bloom, and Edelberg (1963)	SCR	Between	S	PS in SCRs significantly more likely to occur in dyads who liked or disliked each other (as opposed to neutral rating).
Robinson, Herman, and Kaplan (1982)	SCR	PsychoSoc	S	Therapist–client PS using SCR 1 (small but rapid skin conductance responses) and SCR 3 (large amplitude and short latency responses) significantly correlated with empathy.
			NS	Therapist–client PS using SCR 2 (responses of fairly large amplitude and long latency) and the composite measure (SCR 1, 2, and 3) of SCR types not significantly correlated with empathy.

Note. SC = skin conductance; Moderator = tested whether a variable moderated PS; S = statistically significant; PS = physiological synchrony; General = tested for presence of PS; PsychoSoc = tested whether PS was associated with a psychosocial construct; Within = tested difference of PS across conditions within groups; NS = statistically non-significant; Between = tested for differences in PS across groups; EEG = electroencephalograph; SCL = skin conductance level; SCR = skin conductance response.

Appendix D

Results by Physiological Measure: Respiration.

Source	Measure	Context	Finding	Results
Ferrer and Helm (2013)	Resp	General	S	PS observed between couples across all conditions, but substantial differences in synchrony parameters across couples.
		Within	NS	Coregulation not significantly different from zero at baseline. PS parameters did not differ by gender.
			S	PS parameters changed across conditions, but differed substantially across couples.
				PS increased from baseline through imitation task, indicating individuals adjusted their respiration more as a function of their partners' breathing than their own.
		PsychoSoc	S	Females' PS in respiration during imitation task related to daily affect, suggesting females' physiology adjusted to their male partners' in this task similar to adjustments in response to their partners' daily affect.
Helm, Sbarra, and Ferrer (2012)	Resp	PsychoSoc	NS	Anxiety did not effect PS in respiration in any task. Length in the relationship not related to any cross-partner associations.
			S	Higher avoidance associated with reduced PS in respiration during resting and gazing tasks, but associated with increased PS for males during imitation task. Relationship satisfaction associated with different patterns of PS in respiration across tasks and genders.
Muller and Lindenberger (2011)	Resp	Within	S	Magnitudes of PS in respiration were higher during singing than during rest. Directed positive PS where physiological changes in the conductor were followed by choir members.
Chanel, Kivikangas, and Ravaja (2012)	Resp-Amp	General	S	PS in respiration amplitude significantly different from zero.
		Within	NS	No significant differences between cooperative and competitive play in respiration amplitude.
		Typology	S	PS positive for most participants, but negative for others.
		PsychoSoc	NS	No gaming experience self-report constructs significant covariates with PS in respiration amplitude.
Chanel, Kivikangas, and Ravaja (2012)	HF-Resp-Amp	Within	S	PS in high-frequency respiration amplitude higher for competitive than for cooperative play.
		PsychoSoc	S	PS in high-frequency respiration amplitude positively correlated with social empathy self-evaluations.
Bachrach, Fontbonne, Joufflineau, and Ulloa (2015)	RR	General	S	PS found between RR of audience members and dancers during a music-free, slow-paced, live dance performance.
		PsychoSoc	S	PS between RR of audience members and dancers was positively and significantly associated with audience members' self-reported attention to their own and the dancers' breathing.
			NS	PS between RR of audience members and dancers was not significantly associated with audience members' appreciation for the performance.
Codrons, Bernardi, Vandoni, and Bernardi (2014)	RR	Within	S	PS in 10-person groups was found during a still, silent baseline, and when swinging their arms while listening to music.
			NS	PS was not significant in 10-person groups when swinging their arms in silence or while listening to a metronome.
Henning, Boucsein, and Gil (2001)	RR	Within	S	Teammates' PS in RR a significant predictor of some performance measures.
			NS	Teammates' PS in RR not a significant predictor of team behavioral coordination.
McAssey, Helm, Hsieh, Sbarra, and Ferrer (2013)	RR	Within	S	PS in RR significantly increased from baseline to in-sync task for all four couples, but only for one couple during the gazing task.
McFarland (2001)	RR	General	S	Friends' PS in RR differed significantly in comparison with randomly selected simulated dyads.
Chatel-Goldman, Congedo, Jutten, and Schwartz (2014)	RVT	General	NA	Significance of PS between couples' respiration volume time was not tested.
		Within	NS	No significant differences in PS of respiration volume time when couples could or could not touch each other.
		PsychoSoc	NS	No significant correlations found between empathy scores and PS in respiration volume time.

Note. Resp = respiration; General = tested for presence of PS; S = statistically significant; PS = physiological synchrony; Within = tested difference of PS across conditions within groups; NS = statistically non-significant; PsychoSoc = tested whether PS was associated with a psychosocial construct; Resp-Amp = respiration amplitude; Typology = tested for a specific type of PS; HF-Resp-Amp = high-frequency respiration amplitude; RR = respiration rate; RVT = respiration volume time.

Appendix E

Results by Physiological Measure: Thermal Measures.

Source	Measure	Context	Finding	Results
Ebisch et al. (2012)	Temp	General	S	Significant correlations between facial temperature of mothers and their children.
Manini et al. (2013)	Temp	General	S	Significant PS in facial temperature between women and children.
		Between	S	PS in mother–child group significantly higher during experiential condition than mother–other-child group.
				PS significantly higher and cross-correlation lags shorter between mothers and their own vs. other child dyads.
		Within	S	Significant differences in PS between mother–child dyads during neutral vs. experimental conditions.
			NS	No significant differences in PS across conditions in the mother–other-child group.
Shearn, Spellman, Straley, Meirick, and Stryker (1999)	Blush	Between	S	PS in blushing between performers and friends, but not between friends and strangers or strangers and performers.
Robinson, Herman, and Kaplan (1982)	FST	PsychoSoc	NS	PS in finger skin temperature of the counselor–client dyads not significantly correlated with empathy.

Note. Temp = facial temperature; General = tested for presence of PS; S = statistically significant; PS = physiological synchrony; Between = tested for differences in PS across groups; Within = tested difference of PS across conditions within groups; NS = statistically non-significant; FST = finger skin temperature; PsychoSoc = tested whether PS was associated with a psychosocial construct.

Appendix F

Results by Physiological Measure: Indexes of Measures.

Source	Measures	Context	Finding	Results
Levenson and Gottman (1983)	HR; PTT; SCL; ACT[a]	Within	S	PS detected when couples discussing conflict topics.
			NS	PS not detected when couples discussing neutral topics.
		PsychoSoc		Couples' PS during arguments accounted for 60% of variance in marital satisfaction.
Marci (2006)	SC; HR; RR; ACT[a]	Within	S	Arousal levels significantly different when commercials viewed in positive (i.e., during a highly rated show) and neutral (i.e., shown alone) contexts; both PS and arousal patterns changed when viewed during less positive context (i.e., a poorly rated show).
			NS	Patterns of PS not significantly different when commercials viewed in positive (i.e., during a highly rated show) and neutral (i.e., shown alone) contexts.
Walker, Muth, Switzer, and Rosopa (2013)	LVET; PEP; RSA	Within	S	An index of PS significantly predicted team errors, but only accounted for a small proportion of variance in team error.

Note. HR = heart rate; PTT = pulse transmission time; SCL = skin conductance level; ACT = somatic movement; Within = tested difference of PS across conditions within groups; S = statistically significant; PS = physiological synchrony; NS = statistically non-significant; PsychoSoc = tested whether PS was associated with a psychosocial construct; SC = skin conductance; RR = respiration rate; LVET = left ventricular ejection time; PEP = pre-ejection period; RSA = respiratory sinus arrhythmia.
[a]ACT is a measure of somatic movement, but was used as part of an index of physiology.

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Note

1. The Enteric Nervous System is also involved in the autonomic nervous system (ANS), but to our knowledge, its measures

have not been used in interpersonal autonomic physiology (IAP) research; therefore, we include no further discussion of it in this review.

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