Behavioural Brain Research 480 (2025) 115369

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr

Multimodal interpersonal synchrony: Systematic review and meta-analysis

Shay Ohayon [a,1], Ilanit Gordon [a,b,c,*,2]

[a] Department of Psychology, Bar-Ilan University, Ramat Gan, Israel
[b] Gonda Multidisciplinary Brain Research Center, Bar-Ilan University, Ramat Gan, Israel
[c] Yale Child Study Center, Yale School of Medicine, Yale University, CT, USA

ARTICLE INFO

Keywords:
Interpersonal synchrony
Neural synchrony
Physiological synchrony
Behavioral synchrony
Multimodal synchrony

ABSTRACT

This systematic review and meta-analysis examined the interplay among neural, physiological, and behavioral interpersonal synchrony. We included studies written in English, comprising human dyads, and reporting data that could be translated to correlation estimates between at least two modalities of synchrony, sourced from PsycINFO, PubMed, and Google Scholar. The initial meta-analysis, examining associations between neural and behavioral synchrony, assessed 37 samples with 1342 participants, revealed a significant medium effect size (r = 0.32, 95 %CI: [0.23, 0.41]) with higher correlations in studies measured frontocentral regions and used the same epoch size for synchrony calculations. The analysis on associations between physiological and behavioral synchrony included 13 samples (369 participants) and identified small effect size (r = 0.18, 95 %CI: [0.06, 0.30]). Due to the limited sample size of three studies involving 150 participants, we conducted a systematic review rather than a meta-analysis to examine the relationship between neural and physiological synchrony. This review revealed inconsistent results, underscoring the need for further research. Future inquiries address greater multimodal integration in certain brain regions and measures, such as frontal and central regions. A theoretical framework that will explain multimodal integration of synchrony will allow us to ascertain if it is a unique aspect of social experiences, or simply a description of synchrony across levels of organization.

1. Introduction

Interpersonal synchrony is a widespread emergent property of social interactions observed in diverse species [1]. In humans, synchrony spans the lifetime as it is evident from infancy to adulthood [2], with various known prosocial effects, such as cooperation, affiliation, and rapport [3–5]. Interpersonal synchrony is defined as the emerging rhythmic and temporal coordination of actions, emotions, thoughts and bio-physiological processes between two or more individuals [6–8]. As this definition suggests, synchrony occurs across multiple domains or modalities.

In this manuscript we focus on three main domains or modalities in which synchrony occurs. The first and most extensively studied modality is behavioral synchrony, which involves the synchronization of actions between individuals, including activities like walking, shared affect, turn-taking, and mutual gaze [9–12]. In behavioral synchrony, a key aspect is its role as an observable signal, which can also be deliberately communicated. This is crucial for interpreting and understanding the significance of neural and physiological synchronies [13]. Another modality is physiological synchrony, which entails the synchronization of peripheral nervous system activity among individuals. This form of synchrony is typically assessed using measures of sympathetic and parasympathetic activity, such as heart rate, respiratory sinus arrhythmia (RSA), and electrodermal activity (EDA) [8]. Some main interpretations of physiological synchrony in the literature focus on processes of time-dependent coupling of emotional states, attentional engagement processes, emotional transmission, and co-regulation [14]. The third modality is neural synchrony, also referred to as inter-brain synchrony, which involves the coupling of central nervous system activity among individuals. Studies examining neural synchrony utilize hyperscanning, which enables the concurrent recording of brain activity from multiple participants using electrophysiological methods, such as electroencephalography (EEG) and magnetoencephalography (MEG), as well as hemodynamic measures like functional near-infrared spectroscopy (fNIRS) and functional magnetic resonance imaging (fMRI) [15]. The proposed mechanisms of neural synchrony have mainly been the

* Correspondence to: Ilanit Gordon Department of Psychology and Gonda Multidisciplinary Brain Research Center, Bar-Ilan University, Ramat Gan, Israel
E-mail address: ilanit.gordon@biu.ac.il (I. Gordon).
[1] ORCID - https://orcid.org/0000–0001-8417–9121
[2] ORCID – https://orcid.org/0000–0002-4888–1308

https://doi.org/10.1016/j.bbr.2024.115369
Received 5 January 2024; Received in revised form 4 November 2024; Accepted 30 November 2024
Available online 7 December 2024

coupling of attentional states, cognitive alignment, or mutual understanding [14].

In order to assert that the various types of physiological and neural synchrony represent or are related to bonding and social interaction, it is essential to investigate the relationship between physiological and behavioral synchrony. It could not be concluded – based solely on the demonstration of physiological synchrony – that it reflects social alignment. This is because the same physiological response could emerge from different psychological responses. For instance, sympathetic nervous system (SNS) activity can represent both excitement and stress [16]. Therefore, it is possible that the synchronous activity which was demonstrated on a given study actually represents differences between participants rather than alignment. Consequently, is necessary to investigate the relationship between the three modalities of synchrony, or in order words, to evaluate it as a psychophysiological phenomenon. Due to the importance of connecting physiological responses to behavioral ones, Cacioppo et al. [17], conceptualized the psychophysiological relationship in three dimensions by which every psychophysiological phenomenon could be assessed by. The first is generality, or the extent to which the relationship is context dependent. The second is specificity, which is the extent to which a particular psychological process is associated with a specific physiological response. The third dimension is sensitivity, the extent to which the physiological response varies in degree with the psychological process. In line with these dimensions, this study aims to evaluate the specificity of processes related to interpersonal synchrony by examining patterns of neural and physiological activity that correlate with behavioral synchrony. Additionally, the study will explore the sensitivity of interpersonal synchrony by assessing the degree of covariation between behavioral synchrony and both neural and physiological synchrony. Furthermore, the generality of this phenomenon will be evaluated by investigating whether these relationships are context-dependent, considering various aspects of the interaction and the characteristics of the dyads.

Multimodal synchrony is a social phenomenon that manifests at both physiological and behavioral levels. Specifically, the behaviors and physiological activity of one person should flexibly align with those of another. Moreover, Mayo & Gordon [18] emphasized that synchrony itself is flexible, with individuals transitioning in and out of synchrony rather than maintaining continuous synchrony. Therefore, understanding multimodal synchrony requires models that describe the mechanisms of psychophysiological processes and account for flexible activity that adapts to the social environment. The polyvagal theory [19,20] offers such a framework, explaining how the autonomic nervous system's (ANS) neural circuits regulate adaptive behaviors, including social interactions and survival responses. This theory identifies three hierarchical subsystems: the immobilization subsystem (associated with the unmyelinated vagus and linked to behavioral shutdown), the mobilization subsystem (related to the sympathetic nervous system and fight-or-flight responses), and the social engagement system (involving the myelinated vagus, which promotes calm states and social communication). Initially believed to be exclusive to mammals, recent research suggests that the social role of the myelinated vagus extends beyond mammals and that cardiac vagal tone remains stable even when the brainstem's respiratory center connection is inhibited [21,22].

The polyvagal theory underpins the neurovisceral integration model, which connects adaptive behaviors to physiological mechanisms. This model posits that neural networks from the frontal cortex regulate behavior through flexible cardiovascular activity, creating a feedback loop between neural and physiological systems. This dynamic system allows organisms to assess their environments and respond with appropriate physiological and goal-directed behaviors [23]. The model emphasizes non-linear, continuous self-modification via neural feedback. Similarly, Grossman and Taylor [22] highlighted the dynamic nature of neurophysiological responses, suggesting that changes in RSA reflect behavioral and metabolic adaptability across various conditions.

However, when modeling physio-behavioral activity, it is important to consider a fundamental mechanism that has been proposed. This mechanism suggests that the relationship between different modalities may arise from shared metabolic demands through coordinated activity or behavior, implying that physiological synchrony might simply be a byproduct of behavioral synchrony [8]. One such known phenomenon is cardio-locomotor synchronization: A synchronization of repetitive muscle activity and cardiac activity, which is typically observed during rhythmic exercise [24,25]. Although many studies have compared physiological synchrony of real dyads to the physiological synchrony of shuffled or random dyads (e.g., Gordon et al., 2020), it is not clear whether the stimuli or the behavioral activity were matched between random pairs. Similarly, Liu et al. [15] reviewed multiple studies which evaluated the levels of neural synchrony across four different behaviors: joint action, shared attention, interactive decision-making, and affective communication. The finding demonstrated that interpersonal synchrony was present in each behavior type. However, they noted that the psychological requirements for interpersonal synchrony remain unclear, as interpersonal neural synchrony was observed in both cooperative and competitive tasks. Furthermore, the review suggests that some studies have found neural synchrony without any joint action or social interaction between participants. Therefore, is unclear whether neural synchrony represents a unique aspect of social interaction, or it is a representation of similar neural processing of the same task or environment. Similarly, in their comprehensive review, Palumbo et al. [8] highlighted inconsistencies in the existing literature regarding the relationship between physiological and behavioral synchrony. They observed that physiological synchrony was demonstrated across various contexts, different relationship types, and during both shared and independent behaviors. Consequently, they concluded that physiological synchrony possesses unique qualities that are not solely attributed to behavioral synchrony.

In line with Cacioppo's third dimension of psychophysiological phenomena [17] – sensitivity – it is crucial to evaluate the relationship between neural and physiological synchrony and behavioral synchrony to establish the psychological role of physiological and neural synchrony. Additionally, understanding the physiological mechanisms behind these processes requires examining the relationship between neural and physiological synchrony. Furthermore, as no meta-analysis has been conducted, previous reviews [8,15] have reported different results, with some indicating moderation effect of various variables while others suggest the opposite. Therefore, a robust evaluation of the relationship between neural and behavioral synchrony might clarify these discrepancies. By employing meta-analytical techniques, we can investigate the moderating role of shared actions, different contexts, and other relevant factors to determine whether they enhance the relationship between synchrony modalities.

When evaluating potential mechanisms that could explain the inconsistencies in the literature, several factors may contribute to the varying results in the multimodal synchrony research. These factors include dyads characteristics, measurement type or region, task context, and timing parameters.

First, considering dyads characteristics and context, particularly the age of participants, there is substantial literature on the developmental role of multimodal synchrony between young children and adults [27]. However, no studies have directly compared multimodal synchrony between children and adults. This comparison is crucial for investigating multimodal synchrony, as Feldman [9] notes that there are distinct types of parent-child interactions. In some, the parent leads the interaction, and when the parent displays positivity, the child responds by becoming more positive. However, there is also a unique type of social interaction in which the child leads. Indeed, studies involving children and adolescents have shown that parents continue to adapt their behavior based on their child's behaviors and needs, with the child reciprocating accordingly. For example, during competitive interactions, higher levels of in-phase synchrony were observed when children led, compared to when parents led [28]. Additionally, a few studies have demonstrated bidirectional interactions between parents and children. One study found that parents' RSA wat positively correlated with their child's RSA 30 seconds later, while the child's RSA was negatively correlated with the parent's RSA 30 seconds later, suggesting a bidirectional model [29]. Similarly, another study identified a bidirectional pattern where sometimes the parents led the interactions, and at other times, the children did [30]. Therefore, synchrony and multimodal integration of synchrony may manifest differently across age groups.

Second, the type of measures and brain region. Studies on interpersonal synchrony have employed various neural, physiological, and behavioral measures. For instance, behavioral synchrony has been assessed through specific actions such as drumming together [26], measuring time intervals between button presses [31], or tracking the average number of eye contacts [32]. Other studies have utilized broader measures, including behavioral attunement, shared positive affect, turn-taking behaviors, and shared vocalizations [12,33–35], often coded by research assistants reviewing video recordings. Different measures of physiological synchrony include those assessing the autonomic nervous system such as inter-beat intervals (IBIs), and RSA, or using measures of the SNS like EDA [8,36] and pupil size [37]. While some measurements, such as EDA, have shown mixed results, other have demonstrated consistent findings [8]. Similarly, studies of neural synchrony have utilized various neuroimaging techniques across different brain regions. Some studies have employed hemodynamic measures like fMRI and fNIRS [38,39], while others have used electrophysiological methods such as EEG and transcranial direct current stimulation (tDCS) [40,41]. When considering neural activity, the role of specific brain regions should also be explored. The literature on neural synchrony shows heterogeneity in the brain regions implicated. Some studies have demonstrated neural synchrony in brain areas related to social behavior and movement planning and execution, such as frontocentral regions like the primary motor cortex or the dorsolateral prefrontal cortex (DLPFC) [42,43]. Others have focused on the lateral lobe and the temporoparietal junction (TPJ) [34,41], parietal activity [44], or different regions such as the occipital lobe [45]. Therefore, as part of investigating the specificity of any psychophysiological phenomenon [17], it is crucial to determine whether the relationship between neural synchrony and the other modalities of synchrony is concentrated in a specific brain regions.

Third, another important moderator to consider in addressing the generality of psychophysiological phenomena [17] is the context of the interaction: Mayo and Gordon [18] suggested that adaptive social behavior should adjust according to the interaction context, including the relationship between participants and the nature of the task. Regarding the closeness between individuals during social interactions, studies have produced mixed results. While some research has shown greater correlations between neural and behavioral synchrony among couples compared to strangers, others have found stronger correlations among strangers [46,47]. The context of the task is also crucial in understanding the relationship between different types of synchrony. For example, some studies have found lower levels of neural and physiological synchrony during competitive task compared to cooperative or control conditions [48–51]. In their review, Shemyakina & Nagornova [52] suggest that cooperation in performing creativity tasks is related to higher neural synchronization of the prefrontal, temporal, and temporal-parietal areas, while no neural synchronization has been observed in competitive contexts. Moreover, one study observed a significant correlation between neural and physiological synchrony during competitive task but not during cooperative task [53]. Therefore, the moderating role of the context – both in terms of the dyad's relationship and the task - should be considered a potential moderator in the relationships between different modalities of synchrony.

Finally, timing parameters play a critical role in generating heterogeneity across studies. A review of this topic suggested that different timing parameters could lead to significant variability in results [54], as some physiological measures can be captured in short time periods, while others require longer epochs to capture their full complexity. Consequently, the use of different epoch lengths for analyzing synchrony across studies may contribute to this heterogeneity. Additionally, there is no standardized convention for time lag in synchrony studies. Some studies focus on concurrent synchrony, or synchrony at lag zero [55], while others evaluate synchrony at various time lags, such as 3 seconds or 12 seconds [56,57]. This variation means that studies may capture different aspects of interpersonal synchrony that are not necessarily equivalent. For example, studies measuring concurrent synchrony do not account for anti-phase rhythm (e.g., two people walking together with one person stepping forward with their right foot while the other steps back with their right foot, both moving simultaneously) as a form of synchrony [58]. Similarly, another study found concurrent synchrony only during a puzzle-teaching task, while the time-lagged synchrony was observed only during a problem-solving task [29].

Given the above mentioned gaps in knowledge regarding the associations between the three modalities of synchrony, the inconsistencies in earlier reviews regarding the relationships between neural, physiological, and behavioral synchrony (e.g., [8,15]), and the competing theories regarding these relationships, it is crucial to empirically examine whether significant relationships indeed exist between these modalities. Therefore, this systematic review and meta-analysis aims to investigate the strength of the relationships between behavioral, neural, and physiological synchrony. Additionally, the potential moderators which were mentioned earlier, including age group, familiarity between participants, type of synchrony measurements, and the social context in which synchrony occurs, will be explored to gain a comprehensive understanding of the factors influencing the relationship between modalities of synchrony.

2. Method

This section adheres to the guidelines detailed in the PRISMA Statement [59]. The study was pre-registered after data collection commenced but before the analysis (see https://osf.io/2xpgy).

2.1. Literature search

We conducted comprehensive literature search on PubMed and PsycINFO databases through March 2024 using the following query: ((((behavior*) OR (eye) OR (face*) OR (body)) AND ((physiolog*) OR ("autonomic nervous system") OR ("sympathetic nervous system") OR ("parasympathetic nervous system") OR (fMRI) OR (MEG) OR (fNIRS) OR (EEG))) OR (((physiolog*) OR ("autonomic nervous system") OR ("sympathetic nervous system") OR ("parasympathetic nervous system")) AND ((fMRI) OR (fNIRS) OR (MEG) OR (EEG)))) AND ((alignment) OR (synchron*) OR (coordinat*) OR (coupling) OR (linkage)) AND ((dyad*))". Additional studies were identified by examining reference lists of target articles and using reversed citation searches ("cited by") in Google Scholar.

2.2. Study selection

To comprehensively understand multimodal synchrony. we included heterogeneous participant groups such as romantic couples, groups of strangers, mother-child dyads, and individuals with neural disorders. To ensure robustness, we also re-examined the data without studies involving participants with neural disorders and found that the results remained consistent across both approaches. Therefore, we decided to retain these studies in the final analysis. Additionally, as the critical majority of studies on interpersonal synchrony assesses synchronization from a dyadic approach [14,60,61]. Group synchronization studies require, in our view, a specified meta-analysis as they are not strictly a generalization of the dyadic state. Therefore, it was beyond the scope of our aims to include studies conducted with different group sizes. Studies were considered for inclusion if they (i) were published in English, (ii) involved dyads, (iii) included human participants, (iv) measured at least two modalities of interpersonal synchrony simultaneously, and (v) reported a reliable estimation of the correlation between modalities. Both dissertations and peer-reviewed articles. Four independent reviewers assessed all records for reliability and consistency, resolving discrepancies through discussion until consensus was reached. Ultimately, 49 papers met the inclusion criteria and were included in the final database. The PRISMA diagram in Fig. 1 visually represents the selection process.

2.3. Data extraction

Data extraction was performed by the first author at least three times to ensure accuracy and identify errors. The following information was extracted from each record: percentage of female participants, age groups (adults only, including children), type of behavioral measurement (movement, gaze, and multiple behaviors such as shared affect, vocalizations, and turn-taking), physiological measurements (e.g., interbeat intervals, electrodermal activity), and neural measurements (EEG, fNIRS, MEG, fMRI). Additionally, details on the type of relationship between participants (strangers, familiar), unique sample characteristics (e.g., social anxiety, autistic spectrum disorder), social context of the tasks (positive, neutral, or negative), method used for synchrony calculations (linear, nonlinear) consistency of epoch size between modalities during synchrony calculations, consideration of lagged synchrony, study sample size, and effect size were extracted.

Typically, studies on interpersonal synchrony encompass multiple measures of synchrony under different study conditions. Moreover, in some instances, studies do not report the exact correlation coefficient where the results are not significant. Therefore, we made the following decision: to select randomly the measure for each pair of modalities. We contacted authors who reported non-significant correlations but did not fully disclose, or did not report, comparable effect sizes to request additional data. If we could not achieve the relevant information, these correlations were considered as zero correlations.

The necessary data were extracted and computed as Pearson correlations. In most cases, studies reported Pearson correlations, while in other instances, means or betas were converted to Pearson correlations. For further details, refer to Lakens [62]. Additionally, for studies which reported their finding of sub-samples separately (e.g., men and women). we included the results as different studies. Finally, given the presence of both negative and positive correlations with different substantial meaning (e.g., positive correlation with between physiological synchrony and reaction time – a measurement of behavior which high values represents less synchrony), we standardized the value of correlations with positive meaning where higher values represented greater synchrony.

2.4. Meta-analysis

We planned three meta-analyses: (1) association between behavioral synchrony and physiological synchrony, (2) association between behavioral synchrony and neural synchrony, and (3) association between neural synchrony and physiological synchrony. Due to only three studies reporting on neural and physiological synchrony, we conducted meta-analyses for the first two associations and a systematic review for the third. Each relevant study was selected to the corresponding meta-analysis based on the type of measures employed, namely behavioral, neural, or physiological measures.

Meta analyses were performed using R statistical software [63] using the 'meta' package [64]. Outcome measures for the meta-analyses were Pearson correlation between behavioral synchrony and physiological or neural synchrony. As we expected a non-consistent effect size across all

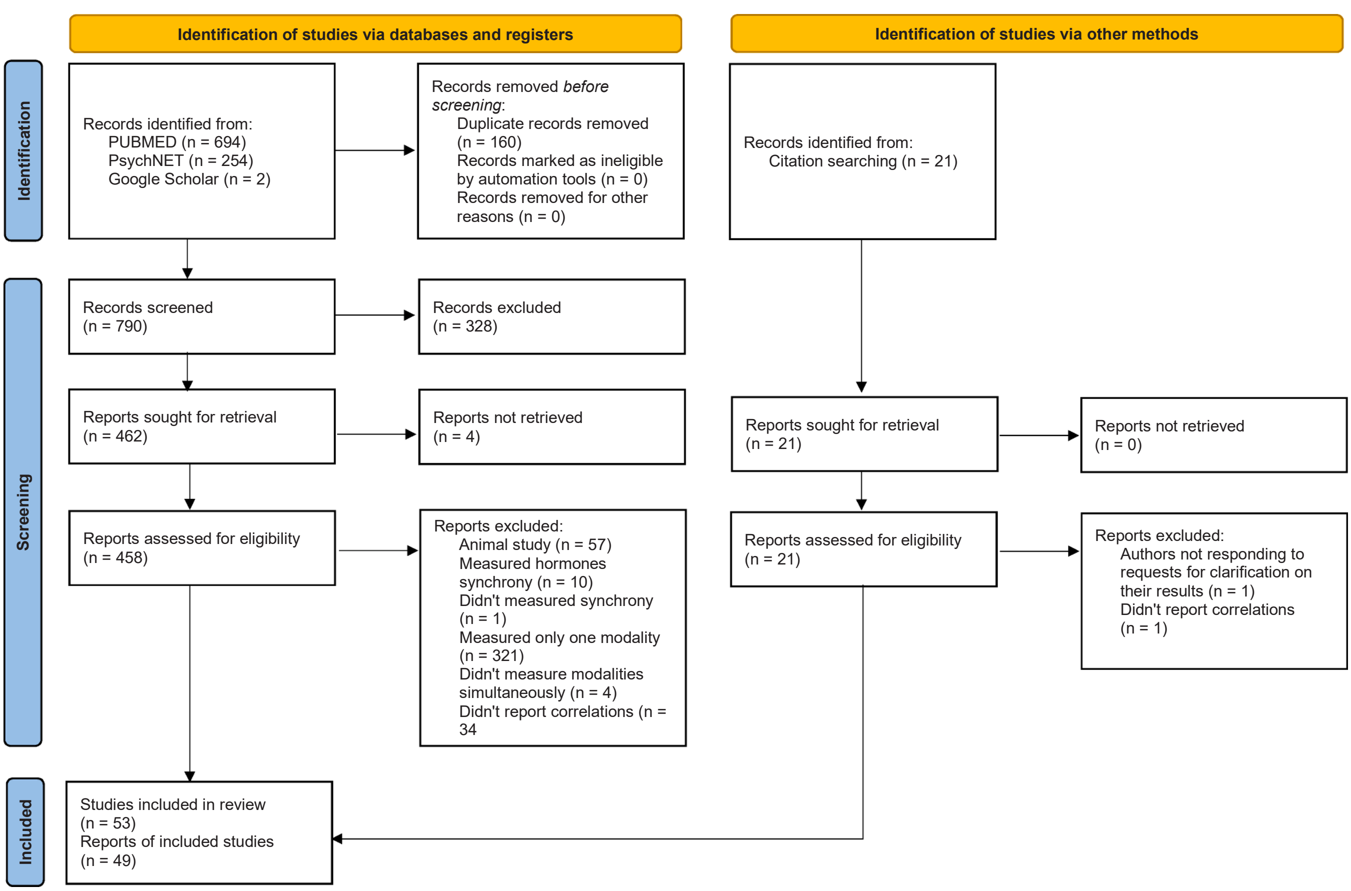

Fig. 1. PRISMA diagram summarizing the literature search and study screening, eligibility, and inclusion process.

of the studies, we used a random-effect model with the Sidik-Jonkman estimator [65] for the between-study heterogeneity, as our primary analysis. Heterogeneity was quantified using Cochran's Q test and I^2 statistics. Subgroup and meta-regression analyses explored sources of heterogeneity. Publication bias was assessed using funnel plots (standard error of correlation estimate versus estimate of effect size for each study) and Egger's test of the intercept [66]. Egger's test assesses the presence of publication bias by examining asymmetry in a funnel plot through a linear regression approach. Specifically, it involves regressing the effect sizes divided by their standard errors against the inverse of the standard errors. The key focus is on the intercept of this regression, which indicates whether the expected value of the standardized effect size is zero when precision is zero (i.e., when the standard error is infinitely large). A non-zero intercept suggests potential asymmetry and, consequently, publication bias.

3. Results

3.1. Descriptive analysis

The 53 studies included in our analysis are summarized in Table 1, Table 2, and Table 3. Regarding the association between behavioral and neural interpersonal synchrony, 19 studies (51.35 %) used fNIRS to measure neural synchrony, 15 studied (40.54 %) utilized EEG, two studies (5.41 %) employed tDCS, and one study (2.70 %) used fMRI. Most studies (28, 75.68 %) recorded neural data from frontal or central brain regions. Additionally, the majority (34, 91.90 %) assessed behavioral synchrony by measuring objective body movement (e.g., finger tapping, button pressing, eye contact), while three studies (8.11 %) employed subjective coding by research assistants who evaluated various interaction characteristics (e.g., shared affect, mutual responsiveness, turn-taking).

Concerning dyad characteristics, 72.97 % of the studies (27) involved adult dyads, and 27.03 % (10) involved adult-child dyads. Most studies (15, 40.54 %) involved stranger dyads, eight studies (21.62 %) included parent-child dyads, three studies (8.11 %) involved friends or romantic couples, one study (2.70 %) involved a client-therapist dyad, and ten studies (27.03 %) did not specify the relationship type or included participants with various relationship types. In addition, one study [67] was conducted in children diagnosed with autistic spectrum disorder and their parents. Additionally, four studies (10.81 %) used a negative context, thirteen studies (35.14 %) used a positive task context, and twenty studies (54.05 %) used a neutral context.

In terms of synchrony calculation methods, only 43.24 % of the studies (16) used the same duration of epochs for both neural and behavioral data during synchrony calculations, while 56.76 % of the studies (21) did not use the same epoch durations for the two modalities. Additionally, among studies analyzed, fourteen (37.84 %) employed wavelet-transform coherence (WTC) to calculate neural synchrony, seven studies (18.92 %) used phase-locking value, eight (21.62 %) used correlation, four (10.81 %) used coherence, one (2.70 %) used cross-correlation function (CCF) one (2.70 %) used circular correlation, and two studies (5.40 %) employed other methods. In contrast, for behavioral synchrony calculations, fourteen studies (37.84 %) used the delta between response time of participants, seven studies (18.92 %) manipulated behavioral synchrony or compared neural synchrony between times of behavioral synchrony (for instance, eye contact, shared affect etcetera) to times of not. Four studies (10.81 %) employed correlation, and another four (10.81 %) coded the entire interaction as a synchronized or not using a manual. Six studies (16.22 %) measured number or time proportion of synchronized behaviors, and two studies (5.40 %) utilized other methods. Furthermore, 3 studies (8.11 %) considered lagged synchrony in both neural and behavioral measures, 13 studies (35.14 %) considered lagged synchrony in one modality only, and 21 studies (56.76 %) did not consider lagged synchrony at all. Finally, one study (2.70 %) was a dissertation, and 36 studies (97.30 %) were published in peer-reviewed articles.

Regarding the association between behavioral and physiological synchrony, seven studies (53.85 %) measured physiological synchrony using IBI, three studies (23.07 %) used EDA, one study (7.69 %) used pupil size, one study (7.69 %) used impedance, and one study (7.69 %) used a combined measure of IBI, EDA, transmission time to the finger, and general somatic activity. Additionally, the majority of the studies (9, 69.23 %) assessed behavioral synchrony by measuring objective body movement (e.g., head sway, smiling, eye contact etc.), while three studies (23.08 %) employed a ranking system involving subjective coding by research assistants (e.g. shared affect, vocalizations, gaze direction etc.), and one study (7.69 %) asked the participants to rank their affect while watching the video recordings of their interaction.

As for the characteristics of the dyads, 61.54 % of the studies (8) involved adult dyads, and 38.46 % (5) involved adult-child dyads. Four studies (30.77 %) involved parent-child dyads, three studies (23.08 %) involved stranger dyads, three studies (23.08 %) involved romantic couples, and another three studies (23.08 %) did not specify the relationship between participants. In addition, one study [68] was conducted among children, some of whom were diagnosed with autistic spectrum disorder. Additionally, eight studies (61.54 %) implemented a positive task context, three studies (23.08 %) used a neutral context, and two studies (15.38 %) used a negative context. Lastly, one study (7.69 %) was a dissertation, and twelve studies (92.31 %) were peer-reviewed articles.

As for the methods of quantifying synchrony, most studies (84.62 %, 11) used linear measures of synchrony, while 2 studies (15.38 %) used nonlinear measures. Additionally, among studies analyzed, eight (61.54 %) employed CCF for calculating physiological synchrony, three studies (23.08 %) used correlation, and two studies (15.38 %) utilized other methods for quantifying physiological synchrony. In contrast, for behavioral synchrony calculations, three studies (23.08 %) used CCF, one study (7.69 %) employed correlation, five studies (38.45 %) measured number or time proportion of synchronized behaviors, and four studies (30.77 %) utilized other methods. Additionally, 30.77 % of the studies (4) considered lagged synchrony, 38.46 % (5) considered concurrent synchrony only, and 30.77 % (4) considered concurrent synchrony for one modality and lagged synchrony for the other. Furthermore, most studies (69.23 %, 9) used different epoch durations for synchrony calculations between modalities.

Regarding the association between neural synchrony and physiological synchrony, as shown in Table 3, all three studies measured neural synchrony using fNIRS. One study measured multiple brain regions, while two studies focused on the prefrontal cortex (PFC). These three studies consisted of dyads familiar with each other: two studies involved parent-child dyads and one study involved romantic couples. The studies differed in their choice of physiological measures, with one study measuring IBI, one measuring RSA, and one measuring EDA. Additionally, the studies varied in the of context task used: one study used a positive context, one used a neutral task context, and one used negative task context. As for their findings, only one study reported significant positive correlation between neural and physiological activity, specifically EDA ($r = 0.68$), and two studies reported non-significant results.

In terms of the method for quantifying synchrony, one study used a linear method, and two studies used a linear method for one modality, and a nonlinear method for the other modality. All studies used WTC for neural synchrony calculations. For behavioral synchrony quantification, one study used CCF, another used correlation, and a third used Cross-Recurrence Quantification Analyses. All studies used one epoch duration for synchrony calculations across modalities. However, one study measured concurrent synchrony, while the other two measured concurrent synchrony for one modality and lagged synchrony for the other.

Table 1
Correlations, sample sizes, and potential moderator values for studies in the meta-analysis of the relationship between behavioral and neural synchrony.

Study	Context	Neural measure	Brain region	Behavior type	Age group	Familiarity	Lag considerations	Epochs size consistency	Method of quantifying synchrony	Sample size	Correlation
[38]	Neutral	fNIRS	Frontal & Lateral lobes	Movement	Adults only	Strangers	Both	No	Linear	111	0.60
[55]	Neutral	fNIRS	Right DLPFC	Movement	Adults only	Strangers	No	No	Linear	11	0.37
[69]	Neutral	EEG	Parietal lobe	Movement	Adults only	Strangers	No	No	Linear	12	0.00
[32] (1)	Negative	fNIRS	Frontal lobe	Gaze	Adults only	Strangers	No	No	Linear	26	0.57
[32] (2)	Negative	fNIRS	Right TPJ	Gaze	Adults only	Strangers	No	No	Linear	23	0.04
[57]	Neutral	fNIRS	Right TPJ	Movement	Adults only	Strangers	Both	No	Linear	33	0.02
[70]	Neutral	EEG	Parietal-occipital cortex	Movement	Adults only	Strangers	Yes	No	Mixed	41	−0.11[a]
[71]	Positive	EEG	Whole brain	Gaze	Adults only	Both	Both	Yes	Linear	53	0.35
[42]	Neutral	fNIRS	DLPFC	Movement	Adults only	Strangers	Both	No	Linear	30	0.44
[72]	Neutral	fNIRS	Frontal lobe	Movement	Adults only	Strangers	Both	Yes	Linear	43	0.35
[73]	Neutral	fNIRS	Temporal lobe	Gaze	Adults only	Both	No	Yes	Linear	19	0.67
[74] (1)	Neutral	fNIRS	Frontal lobe	Movement	Adults only	Strangers	No	No	Linear	20	0.46
[74] (2)	Neutral	fNIRS	Frontal lobe	Movement	Adults only	Strangers	No	No	Linear	16	−0.26
[75]	Neutral	fNIRS	Frontal lobe	Movement	Adults only	Strangers	Yes	Yes	Linear	40	0.66
[76]	Positive	fNIRS	IFG	Movement	Adults only	Strangers	No	Yes	Linear	21	0.63
[47] (1)	Positive	EEG	Temporal and parietal cortices	Gaze	Adults only	Familiar	Both	No	Nonlinear	24	0.39
[47] (2)	Positive	EEG	Temporal and parietal cortices	Gaze	Adults only	Strangers	Both	No	Mixed	25	0.43
[39]	Neutral	fMRI	Right IFG	Gaze	Adults only	Strangers	No	Yes	Linear	14	0.38[a]
[77]	Neutral	EEG	Frontoparietal cortex	Gaze	Children	Strangers	No	Yes	Linear	29	0.55
[78]	Neutral	EEG	Whole brain	Gaze	Adults only	Both	No	Yes	Nonlinear	56	0.50
[45]	Positive	EEG	Occipital lobe	Gaze	Children	Familiar	No	Yes	Nonlinear	55	0.00
[33]	Positive	EEG	Whole brain	Multiple behaviors	Children	Familiar	Yes	No	Mixed	27	−0.01
[79]	Neutral	EEG	Central, parietal, and occipital cortices	Other	Adults only	Strangers	No	Yes	Nonlinear	33	0.47
[80]	Neutral	EEG	Not specified	Movement	Adults only	Strangers	No	Yes	Mixed	45	0.37
[43]	Neutral	tACS	Primary motor cortex	Movement	Adults only	Strangers	No	Yes	Nonlinear	30	0.50
[31] (1)	Neutral	fNIRS	Frontoparietal cortex	Movement	Adults only	Familiar	No	No	Linear	17	0.50
[31] (2)	Neutral	fNIRS	Frontoparietal cortex	Movement	Adults only	Both	No	No	Linear	32	0.00
[40]	Positive	tDCS stimulation	IFC	Movement	Adults only	Strangers	Both	Yes	Linear	24	0.68
[81]	Positive	fNIRS	Frontal lobe	Gaze	Children	Strangers	Both	Yes	Linear	18	0.38
[12]	Positive	fNIRS	Frontal lobe	Multiple behaviors	Children	Familiar	Both	No	Linear	98	0.21
[53]	Negative	fNIRS	Frontal lobe	Movement	Children	Familiar	No	No	Linear	33	−0.22
[34]	Positive	fNIRS	Right TPJ	Multiple behaviors	Children	Familiar	Both	Yes	Mixed	88	−0.11
[41]	Positive	EEG	Frontal lobe	Gaze	Children	Familiar	Both	No	Mixed	62	0.23
[44]	Positive	EEG	Frontal lobe	Movement	Adults only	Familiar	No	No	Linear	41	0.00
[67]	Neutral	fNIRS	Frontal lobe	Movement	Children	Familiar	No	No	Linear	16	0.19
[82]	Negative	EEG	Frontal lobe	Movement	Adults only	Strangers	Both	Yes	Mixed	52	0.30
[83]	Positive	EEG	Not specified	Gaze	Children	Familiar	No	No	Mixed	24	0.52

Note: DLPFC – Dorsolateral Prefrontal Cortex; TPJ - Temporoparietal Junction; IFG – Inferior Frontal Gyrus; IFC – Inferior Frontal Cortex.
[a] Correlation was calculated by the authors based on data provided by the study investigators.

Table 2
Correlations, sample sizes, and potential moderator values for studies in the meta-analysis of the relationship between behavioral and physiological synchrony.

Study	Context	Physiological measure	Behavior type	Age group	Familiarity	Lag considerations	Epochs size consistency	Method of quantifying synchrony	Sample size	Correlation
[84]	Positive	IBI	Multiple behaviors	Children	Familiar	No	No	Linear	42	0.00
[35]	Positive	IBI	Movement	Children	Familiar	Both	No	Nonlinear	40	0.08
[56]	Neutral	IBI	Movement	Adults only	Strangers	Yes	Yes	Linear	25	0.45
[85]	Negative	EDA	Multiple behaviors	Children	Familiar	No	No	Linear	10	0.43
[11]	Neutral	IBI & EDA & PTT to the finger & somatic muscle activity	Shared affect	Adults only	Familiar	Yes	Yes	Linear	30	0.00
[86]	Positive	Impedance	Gaze	Adults only	Familiar	Yes	Yes	Linear	4	0.65
[87]	Positive	IBI	Movement	Adults only	Strangers	Both	Yes	Linear	9	−0.48
[88]	Positive	IBI	Movement	Adults only	Strangers	Both	No	Linear	47	0.41[a]
[53]	Positive	IBI	Movement	Children	Familiar	No	No	Linear	31	−0.02
[89]	Positive	IBI	Movement	Adults only	Strangers	No	No	Linear	20	0.22
[68]	Positive	EDA	Multiple behaviors	Children	Familiar	No	No	Linear	16	0.25
[37]	Positive	pupil size	Gaze	Adults only	Strangers	Both	No	Nonlinear	47	0.25
[90]	Neutral	EDA	Movement	Adults only	Strangers	Yes	No	Linear	41	0.18

Note: IBI – Inter-Beat interval; EDA - Electrodermal Activity; PTT - Pulse Transit Time.
[a] Correlation was calculated by the authors based on data provided by the study investigators.

Table 3
Correlations, sample sizes, and potential moderator values for studies in the review of the relationship between physiological and neural synchrony.

Study	Context	Physiological measure	Neural measure	Brain region	Age group	Familiarity	Lag considerations	Epochs size consistency	Method of quantifying synchrony	Sample size	Correlation
[91]	Negative	EDA	fNIRS	Frontal, temporal, and parietal cortices	Adults only	Familiar	Both	Yes	Linear	44	0.68
[92]	Positive	RSA	fNIRS	PFC	Including children	Familiar	Both	Yes	Mixed	72	0
[53]	Neutral	IBI	fNIRS	PFC	Including children	Familiar	No	Yes	Mixed	34	−0.18

Note: EDA - Electrodermal Activity; RSA - Respiratory Sinus Arrhythmia; IBI – Inter-Beat Interval.

3.2. Quantitative analysis

Two meta-analyses were conducted to examine the associations between neural synchrony and behavioral synchrony, and between physiological synchrony and behavioral synchrony.

3.2.1. The associations between interpersonal behavioral synchrony and interpersonal neural synchrony

Thirty-three articles and 37 results met criteria for this meta-analysis. A random-effect model showed an overall significant correlation (correlation estimate = 0.32, 95 %CI = [0.23, 0.41], $p < 0.001$; see Fig. 2) across all studies. However, a considerable heterogeneity was found (I^2 = 72.9 %, Q(36) = 132.74, $p < 0.001$). A meta-regression analysis using a mixed-effect model with brain regions represented by three dummy variables for each lobe (frontal, parietal, and lateral) as moderators, revealed a significant moderation effect (QM(3) = 8.70, p = 0.034). Specifically, studies that included measures of frontal activity showed a significantly greater effect size compared to others (B = 0.25, SE = 0.11, p = 0.017). No significant differences were found for studies including measures of lateral activity (B = 0.17, SE = 0.10, p = 0.087) or parietal activity (B = −0.13, SE = 0.09, p = 0.153). The model accounted for 23.68 % (R2) of the heterogeneity.

Additionally, sub-group analysis with a random effect model, comparing effects between age groups revealed a significant difference between those groups (Q(1) = 4.69, p = 0.030). The estimated correlation between behavioral and neural synchrony in studies including children was 0.17 (N = 10, p = 0.040), while the estimate for studies not including children was 0.38 (N = 27, $p < 0.001$). Meta-regression analysis with a mixed-effect model using age group as a moderator, revealed a significant effect (QM(1) = 5.01, p = 0.025; B = 0.21, SE = 0.09, p = 0.025). The model accounted for 19.37 % (R2) of the heterogeneity. Another sub-group analysis with a random effect model, comparing effects between familiarity levels, revealed a significant difference between studies with familiar dyads only and those with stranger dyads as well (Q(1) = 8.76, p = 0.003). The estimated correlation between behavioral and neural synchrony in the studies with familiar duads was 0.15 (N = 11, p = 0.002), while the estimate for studies with stranger dyads was 0.40 (N = 26, $p < 0.001$). Meta-regression analysis with a mixed-effect model, using familiarity level as a moderator, revealed a significant effect (QM(1) = 8.94, p = 0.003; B = 0.26, SE = 0.09, p = 0.003). The model accounted for 33.24 % (R^2) of the heterogeneity.

Another sub-group analysis with a random effect model comparing effects between types of behavioral measures revealed a significant

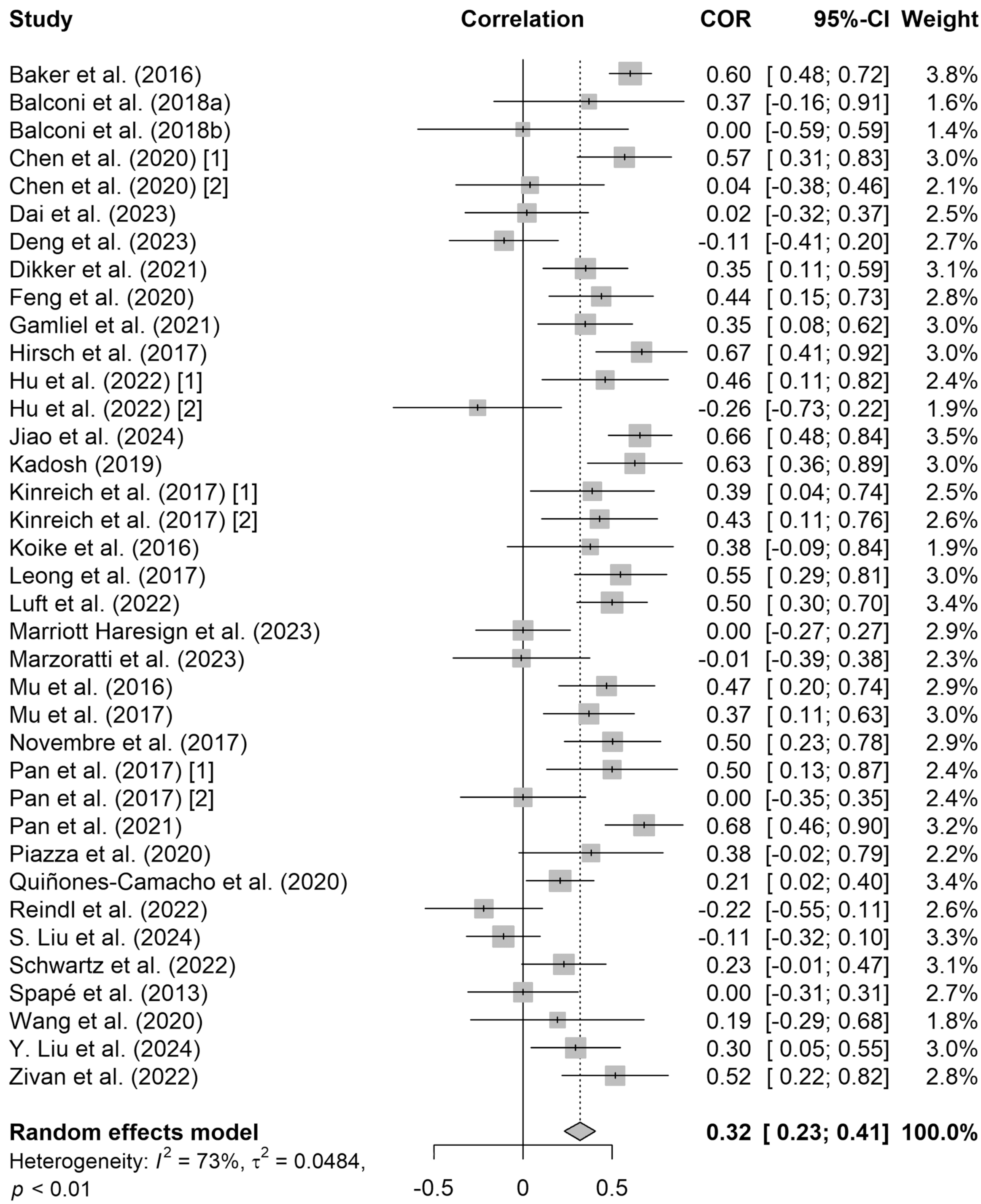

Fig. 2. Forest plot of meta-analysis of the association between behavioral synchrony and neural synchrony.

difference ($Q(1) = 6.57$, $p = 0.010$). The estimated correlation between behavioral and neural synchrony in the studies using objective measures was 0.35 ($N = 34$, $p < 0.001$), while the estimate for studies using subjective measures was 0.04 ($N = 3$, $p = 0.460$). Meta regression analysis with a mixed-effect model, using type of behavioral measurement yielded a significant moderation effect ($QM(1) = 4.66$, $p = 0.031$, $B = 0.31$, $SE = 0.15$, $p = 0.031$). The model accounted for 16.21 % (R^2) of the heterogeneity.

Another sub-group analysis with a random effect model, comparing effects between studies that calculated synchrony using the same epochs size for both for neural and behavioral data versus those that did not, revealed a significant difference ($Q(1) = 4.81$, $p = 0.028$). The estimated correlation between behavioral and neural synchrony in studies using the same epoch sizes was 0.42 ($N = 16$, $p < 0.001$), while the estimate for studies not using the same epochs size was 0.23 ($N = 21$, $p < 0.001$). Meta-regression analysis with a mixed-effect model, using epochs size consistency as a moderator, revealed a significant effect ($QM(1) = 4.71$, $p = 0.030$; $B = 0.19$, $SE = 0.09$, $p = 0.030$). The model accounted for 10.00 % (R2) of the heterogeneity.

Furthermore, sub-group analysis with a random effect model, comparing effects between types of neural measures (hemodynamic measures, EEG and brain stimulation) revealed a significant difference ($Q(2) = 10.39$, $p = 0.006$). The estimated correlation between behavioral and neural synchrony in studies using hemodynamic measures was

0.31 (N = 20, $p < 0.001$), in studies using EEG was 0.29 (N = 15, $p < 0.001$), and in stimulation studies was 0.61 (N = 2, p = 0.002). However, further meta-regression analysis with a mixed-effect model using neural measure type as a moderator, yielded a non-significant effect (QM(2) = 2.74, p = 0.254; Hemodynamic measures: B = 0.03, SE = 0.09, p = 0.706; Stimulation studies: B = 0.31, SE = 0.19, p = 0.098). The model accounted for 2.94 % (R^2) of the heterogeneity. Sub-group analyses of the moderating role of task context (Q(2) = 1.73, p = 0.421), and consideration of lagged synchrony (Q(2) = 0.27, p = 0.875) were not significant.

Next, we conducted a multivariate meta-regression using the significant moderators as predictors. Due to a strong correlation with age group (Cramer's V = 0.67, $p < 0.001$), which might indicate of multicollinearity [93], we chose to include age group rather than levels of familiarity levels in the multivariate model. Results indicated a significant moderation effect (Q(4) = 17.74, p = 0.001), with significant effects for brain region (B = 0.20, SE = 0.09, p = 0.030), and epochs size consistency (B = 0.15, SE = 0.07, p = 0.042). There were no significant effects for age group (B = −0.15, SE = 0.10, p = 0.138), or behavioral coding method (B = −0.15, SE = 0.15, p = 0.323). This model accounted for 41.86 % (R^2) of the heterogeneity between studies.

Finally, we assessed a possible publication bias. As shown in Fig. 3, the funnel plot appeared asymmetric. Egger's test of the intercept was significant (intercept = −2.56, SE = 0.87, p = 0.006), confirming asymmetry. The negative intercept suggests that the overall effect size biased towards lower values, indicating that the missing studies have high effect sizes [94].

3.2.2. *The associations between interpersonal behavioral synchrony and interpersonal physiological synchrony*

Thirteen articles met criteria for this meta-analysis. The random-effect model revealed a non-significant overall correlation effect (correlation estimate = 0.18, 95 %CI = [0.06, 0.30], p = 0.004; see Fig. 4) across all studies. Additionally, non-significant amount of heterogeneity was observed (I^2 = 39.3 %, Q(12) = 19.32, p = 0.081). Therefore, no further sub-group analysis or meta-regression were conducted. We assessed possible publication bias. As Fig. 5 suggest, the plot was relatively symmetric. Egger's test of the intercept was not significant (intercept = −0.90, SE = 1.37, p = 0.523), providing support for the claim that there is no evidence for publication bias.

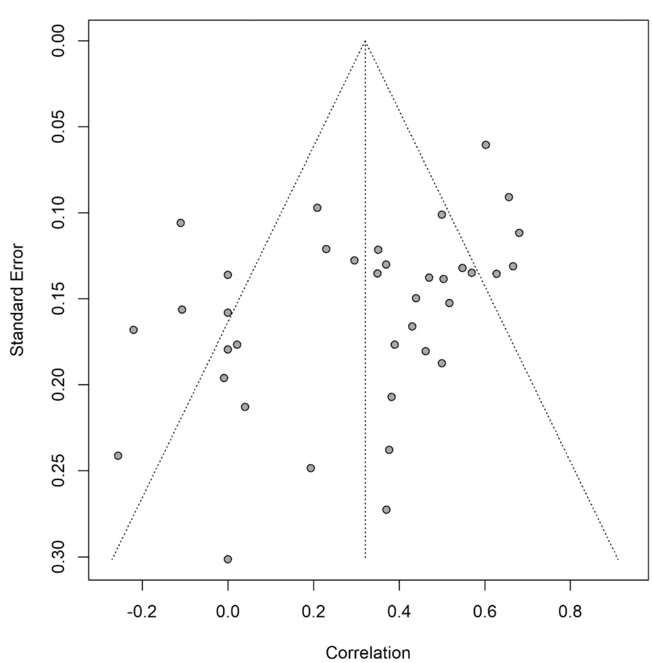

Fig. 3. Funnel plot of the association between behavioral and neural synchrony. Standard error of the correlation estimates versus estimates of effect size for each study is presented on the vertical axis.

4. Discussion

This review and meta-analysis aimed to explore the relationships between three modalities of interpersonal synchrony: neural, physiological, and behavioral. The results are summarized in Fig. 6. In the first meta-analysis, which investigated the correlation between behavioral and neural synchrony, we found a significant medium effect size (ES = 0.32). To further explore this relationship, we conducted a multivariate meta-regression that included significant moderators identified from sub-group analyses and meta-regressions. These moderators included brain region, type of behavioral measure, age group, and epoch size consistency. Notably, significant effects were observed only for brain region and epoch size consistency. The subgroup analysis revealed that studies measuring frontal and central brain activity showed a greater effect size (ES = 0.38) compared to those focusing on other brain regions (ES = 0.15). This finding may suggest that the neural mechanisms underlying interpersonal synchrony are more pronounced in these regions. Shamay-Tsoory et al. [95] have proposed that three neural systems, located in the frontal cortex and parietal lobe, are involved in social alignment: The misalignment detection system, which detects deviations from social norms and is activated during gap-monitoring; the observer-execution system, which is involved in motor understanding and high-level decoding of emotions and cognition; and the alignment reward circuit, which is associated with the satisfaction experienced during connectedness.

This finding is consistent with another sub-group analysis which demonstrated a greater effect size in stimulation studies (ES = 0.61) compared to those that measured neural activity using EEG (ES = 0.29) or hemodynamic measures (ES = 0.31). Although this effect was not significant in further meta-regression, it may still underscore the role of synchronized interpersonal neural activity in behavioral synchrony. While the higher correlation between neural and behavioral synchrony in frontocentral regions and stimulation studies might reflect similarities in movement planning and execution between participants – given that these regions are crucial for motor movement [96,97] – our multivariate meta-regression model the type of behavioral measure, indicating that the effect of brain region remained significant beyond the potential influence of the behavioral measure.

Another subgroup analysis indicated that studies using the same epoch size for calculating synchrony in both neural and behavioral modalities demonstrated a greater effect size (ES = 0.42) compared to studies that used different epoch sizes (ES = 0.23). This finding emphasizes the importance of consistency in synchrony calculations across different measures and may partially explain the heterogeneity in effect sizes observed between studies. This result aligns with earlier research suggesting that timing parameters can generate notable heterogeneity across studies [54]. However, contrary to previous claims [8], our study did not find a significant effect of lag considerations on the relationship between neural and behavioral synchrony. This null effect suggests that, although previous studies identified concurrent synchrony in one context and lagged synchrony in another [29], leader-follower synchrony may not differ fundamentally from concurrent synchrony in its relationship to synchrony across different modalities. Indeed, one study that evaluated neural synchrony across different time lags [81] demonstrated significant neural synchrony between participants in both concurrent synchrony and up to a 3-second lag when they interacted together.

Interestingly, a significant moderation effect was found for age group, with dyads consisting of adult-child pairs demonstrating a lower effect size compared to adult-only dyads. Additionally, a significant effect was observed for type of behavioral measurement, where studies utilizing objective behavioral measures shoed a greater effect size than those using video-codded multifaceted measures. However, these

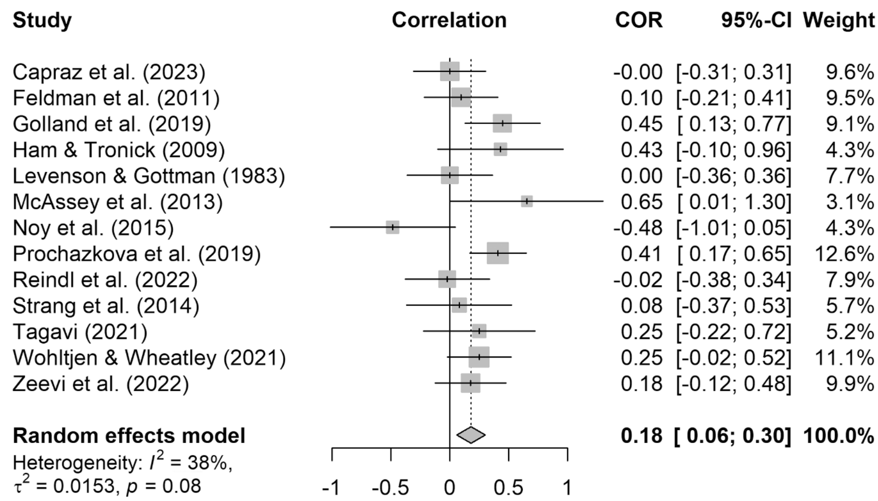

Fig. 4. Forest plot of meta-analysis of the association between behavioral synchrony and physiological synchrony.

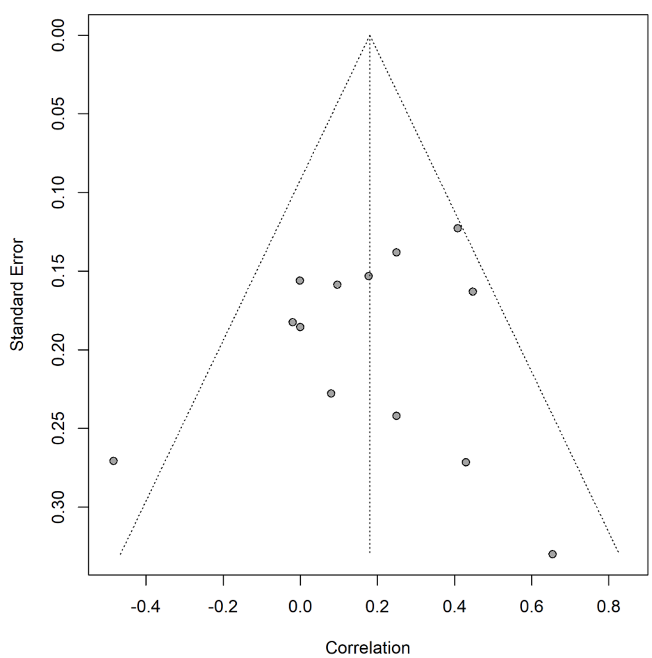

Fig. 5. Funnel plot of the association between behavioral and physiological synchrony. standard error of the correlation estimates versus estimates of effect size for each study is presented on the vertical axis.

variables did not show significant effects in the multivariate meta-regression model, suggesting they do not have a unique impact on the relationship between neural and behavioral synchrony beyond the other predictors. Taking together, the results from the first meta-analysis can be conceptualized using Cacioppo et al.'s [17] framework for psycho-physiological relationships as follow: In terms of generality, the results suggest that the relationship between neural and behavioral synchrony is not context-dependent – at least not with regard to the variables tested. There were no significant effects for age group, task context, or familiarity between participants beyond the significant effects of brain region and epoch size consistency. Second, in terms of specificity, the results indicated that frontocentral neural synchrony is related to behavioral synchrony, implying a specific neural region associated with the behavioral response. Lastly, in terms of sensitivity, the medium effect size observed suggests a considerable covariation between psychological and neural activity.

In the second meta-analysis, a significant overall effect size was found for the relationship between physiological and behavioral synchrony (ES = 0.18). This finding suggesting might supports Palumbo et al.'s [8] claim that physiological synchrony might represent different aspects of interpersonal synchrony, due to the small effect size. This small effect size might reflect an interesting finding from a study conducted in triads, which evaluated the relationship between IBI synchrony and motion energy synchrony [98]. The study revealed dynamic changes in the correlation between these two modalities of synchrony throughout the interaction, with correlations shifting from significant to non-significant repeatedly during the interaction. Furthermore, it was found that autonomic activity moderates the levels of physiological synchrony [8] indicating that the magnitudes of physiological synchrony varies as arousal levels change. These findings, along with previous results showing that HRV decreases under high arousal [99], support the neurovisceral integration theory, which posits that the ANS plays a crucial role in regulating behaviors through feedback loops. As such, while the ANS may successfully synchronize with others at times, high arousal and other factors can lead to a decrease in HRV and other adaptive physiological processes, reducing the flexibility required to align others' physiological systems, and necessitating the renewal of synchrony. Only thirteen studies were included in this meta-analysis. As the screening process described earlier suggests, a large portion of the literature is not included because most studies do not integrate several modalities of synchrony and correlate these different measures of synchrony to each other. Most studies choose one modality of synchrony and correlate it with an outcome (social-oriented, goal-oriented or self-oriented).

Taken together, the results from the second meta-analysis can be conceptualized using Cacioppo et al.'s [17] framework for psycho-physiological relationships as follows: In terms of generality, the results suggest that the relationship between physiological and behavioral synchrony is not context-dependent – at least with respect to the variables tested. There were no significant effects observed for age group, task context, or familiarity between participants. Second, in terms of specificity, the results did not suggested a specific physiological structure that is more related to behavioral synchrony than others, suggesting that physiological synchrony of different types is associated with the behavioral response. Finally, in terms of sensitivity, we observed a small nut significant effect size, indicating that there is indeed a covariation between psychological and physiological activity.

Concerning the relationship between neural and physiological synchrony, there were only three studies, therefore we conducted only a systematic review. All reviewed studies involved acquaintances, and employed fNIRS to measure brain activity, yielding mixed results. Two studies reported no significant correlations, while one study found

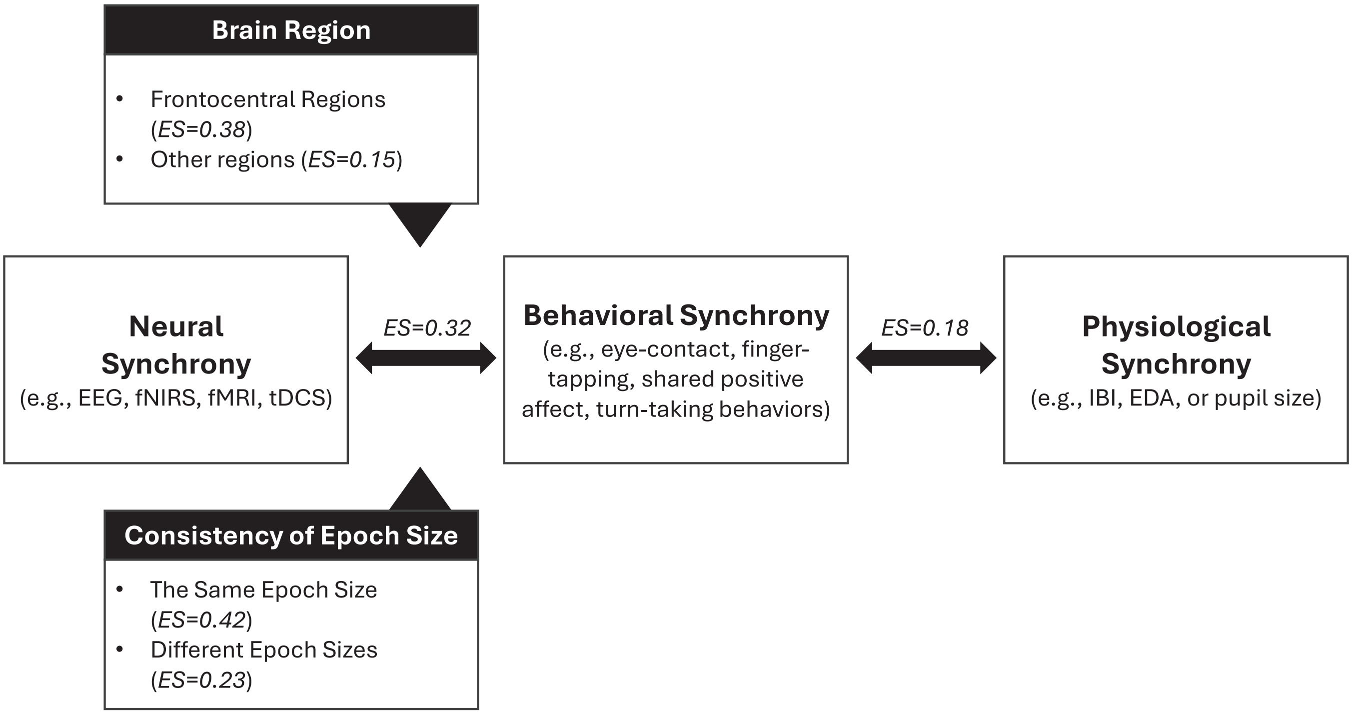

Fig. 6. Synthesis of neural, behavioral, and physiological synchrony: summary of results from the meta-analyses performed on the relationships between behavioral synchrony and both neural and physiological synchrony, with brain region and consistency of epoch size as significant moderators. Effect Size (ES) values are shown for each significant relationship. Abbreviations: EEG – electroencephalogram, fNIRS – functional near-infrared spectroscopy, fMRI – functional magnetic resonance imaging, tDCS – transcranial direct current stimulation, IBI – inter-beat intervals, EDA – electrodermal activity.

significant positive correlations between physiological and neural synchrony. This divergence underscores the need for additional research to elucidate the nature of this relationship, and ascertain whether interpersonal synchrony truly reflects the anticipated relationship between neural and physiological activity as postulated by certain theories [19,23].

Taken together, the results of the current systematic review and meta-analysis emphasized the critical need for a robust evidence-based theory to elucidate multimodal synchrony. Such a theory should encompass several fundamental aspects. Firstly, it should clearly define the relationship between modalities, determining more clearly its bidirectional nature: A pivotal step for understanding the functionality of all three modalities and their sub-components to enable connection and thus support the emergence of synchronization. Furthermore, the theory should also address the low effect size of the correlation between physiological and behavioral synchrony. This theoretical framework will enhance our understanding of multimodal interpersonal synchrony, delineating the particular circumstances under which it occurs and if it explains a unique aspect of the social experience, or if it simply describes synchronization as it occurs in different levels of organization.

It is important to acknowledge the limitations of our systematic review and meta-analyses. First, the inclusion criteria focused specifically on studies conducted in dyads, limiting the generalizability of our conclusions to dyadic interactions only. Second, there was a large level of heterogeneity in the studies' participant: The examined populations varied greatly in terms of individual differences and relationship type, and included participants with neural disorders, neurotypicals, romantic couples, groups of strangers and mother-child dyads. Third, the sample size of the second meta-analysis was small. However, it was deemed sufficient for conducting a robust meta-analysis, consistent with other meta-analyses in the field of interpersonal synchrony [3,36]. This might explain why the subgroup analyses did not converge between the two meta-analyses.

5. Conclusions

The findings of the present study lay the groundwork for future explorations into the realm of multimodal synchrony. Validation of these results can be pursued by analyzing the relationships between different synchrony modalities across different brain regions and physiological measures. Additionally, this study emphasizes the differences in effect sizes between different epoch sizes. Echoing the suggestions of prior research [36,54], forthcoming studies should adopt an a-priori, clearer definition of synchrony and its calculation metrics using consistent measures across different modalities. This approach will enhance the interpretative accuracy for synchrony in specific studies and elucidate its potential effects. While this meta-analysis pioneers in addressing the critical issue of multimodal integration in synchrony, it also illuminates the need for further exploration to comprehend the intricacies of the relationships between neural and physiological synchrony. Notwithstanding, this is a first meta-analysis to address the important issue of multimodal integration in synchrony which is a key remaining question in synchrony research. Understanding this issue is important to establish a crystalized understanding of multimodal integration and dynamics of synchrony for social interactions. The results of this study demonstrate that both physiological and neural synchrony are relate to synchronous behaviors, and that factors such as brain region, and epoch size consistency influence the strength of correlations between modalities. The evidence-based understanding of the current state-of-the-art regarding multimodal synchrony, which we provide here, is an essential step in paving the way for a more comprehensive, nuanced, and integrated understanding of the multifaceted world of multimodal synchrony.

Research data for this article

The data extracted from included studies is available in Open Science Framework, at https://dx.doi.org/10.17605/OSF.IO/WY9Q7.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors have no specific issue to disclose.

CRediT authorship contribution statement

Shay Ohayon: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Ilanit Gordon:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of Competing Interest

None.

Data availability

This paper analyzed previously reported data in meta analysis

References

[1] L.J. Trainor, L. Cirelli, Rhythm and interpersonal synchrony in early social development, Ann. N. Y. Acad. Sci. 1337 (2015) 45–52, https://doi.org/10.1111/nyas.12649.
[2] R. Feldman, The neurobiology of human attachments, Trends Cogn. Sci. 21 (2017) 80–99, https://doi.org/10.1016/j.tics.2016.11.007.
[3] R. Mogan, R. Fischer, J.A. Bulbulia, To be in synchrony or not? A meta-analysis of synchrony's effects on behavior, perception, cognition and affect, J. Exp. Soc. Psychol. 72 (2017) 13–20, https://doi.org/10.1016/j.jesp.2017.03.009.
[4] M. Rennung, A.S. Göritz, Prosocial consequences of interpersonal synchrony, Z. F. üR. Psychol. 224 (2016) 168–189, https://doi.org/10.1027/2151-2604/a000252.
[5] L.K. Miles, L.K. Nind, C.N. Macrae, The rhythm of rapport: interpersonal synchrony and social perception, J. Exp. Soc. Psychol. 45 (2009) 585–589, https://doi.org/10.1016/j.jesp.2009.02.002.
[6] J.M. Ackerman, J.A. Bargh, Two to Tango: Automatic Social Coordination and the Role of Felt Effort. in: Effortless Atten, The MIT Press, 2010, https://doi.org/10.7551/mitpress/9780262013840.003.0015.
[7] F.J. Bernieri, R. Rosenthal, Interpersonal coordination: Behavior matching and interactional synchrony, in: R.S. Feldman, B. Rime (Eds.), Fundam. Nonverbal Behav., Cambridge University Press, Cambridge, UK, 1991, pp. 401–432.
[8] R.V. Palumbo, M.E. Marraccini, L.L. Weyandt, O. Wilder-Smith, H.A. McGee, S. Liu, M.S. Goodwin, Interpersonal autonomic physiology: a systematic review of the literature, Personal. Soc. Psychol. Rev. 21 (2017) 99–141, https://doi.org/10.1177/1088868316628405.
[9] R. Feldman, Parent–infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions, J. Child Psychol. Psychiatr. 48 (2007) 329–354, https://doi.org/10.1111/j.1469-7610.2006.01701.x.
[10] S.S. Wiltermuth, C. Heath, Synchrony and cooperation, Psychol. Sci. 20 (2009) 1–5, https://doi.org/10.1111/j.1467-9280.2008.02253.x.
[11] R.W. Levenson, J.M. Gottman, Marital interaction: physiological linkage and affective exchange, J. Pers. Soc. Psychol. 45 (1983) 587–597, https://doi.org/10.1037/0022-3514.45.3.587.
[12] L.E. Quiñones-Camacho, F.A. Fishburn, M.C. Camacho, C.O. Hlutkowsky, T. J. Huppert, L.S. Wakschlag, S.B. Perlman, Parent–child neural synchrony: a novel approach to elucidating dyadic correlates of preschool irritability, J. Child Psychol. Psychiatr. 61 (2020) 1213–1223, https://doi.org/10.1111/jcpp.13165.
[13] A.F. de, C. Hamilton, Hyperscanning: beyond the hype, Neuron 109 (2021) 404–407, https://doi.org/10.1016/j.neuron.2020.11.008.
[14] I. Gordon, A. Tomashin, O. Mayo, A Theory Flex. Multimodal Synchrony (2023), https://doi.org/10.31234/osf.io/9u7q8.
[15] D. Liu, S. Liu, X. Liu, C. Zhang, A. Li, C. Jin, Y. Chen, H. Wang, X. Zhang, Interactive brain activity: review and progress on EEG-based hyperscanning in social interactions, Front. Psychol. 9 (2018) 1862, https://doi.org/10.3389/fpsyg.2018.01862.
[16] K.R. Thorson, Measuring physiological influence in dyads: a guide to designing, implementing, and analyzing dyadic physiological studies, Psychol. Methods 23 (2017) 595, https://doi.org/10.1037/met0000166.
[17] J.T. Cacioppo, L.G. Tassinary, G.G. Berntson, Psychophysiological science: Interdisciplinary approaches to classic questions about the mind. Handb. Psychophysiol., Cambridge University Press, New York, NY, US, 2007, pp. 1–16, https://doi.org/10.1017/CBO9780511546396.001.
[18] O. Mayo, I. Gordon, In and out of synchrony—Behavioral and physiological dynamics of dyadic interpersonal coordination, Psychophysiology 57 (2020), https://doi.org/10.1111/psyp.13574.
[19] S.W. Porges, The polyvagal theory: New insights into adaptive reactions of the autonomic nervous system, Cleve. Clin. J. Med. 76 (2009) S86–S90, https://doi.org/10.3949/ccjm.76.s2.17.
[20] S.W. Porges, The polyvagal theory: phylogenetic substrates of a social nervous system, Int. J. Psychophysiol. 42 (2001) 123–146, https://doi.org/10.1016/S0167-8760(01)00162-3.
[21] P. Grossman, Fundamental challenges and likely refutations of the five basic premises of the polyvagal theory, Biol. Psychol. 180 (2023) 108589, https://doi.org/10.1016/j.biopsycho.2023.108589.
[22] P. Grossman, E.W. Taylor, Toward understanding respiratory sinus arrhythmia: Relations to cardiac vagal tone, evolution and biobehavioral functions, Biol. Psychol. 74 (2007) 263–285, https://doi.org/10.1016/j.biopsycho.2005.11.014.
[23] J.F. Thayer, R.D. Lane, A model of neurovisceral integration in emotion regulation and dysregulation, J. Affect. Disord. 61 (2000) 201–216, https://doi.org/10.1016/S0165-0327(00)00338-4.
[24] K. Nomura, Y. Takei, Y. Yanagida, Comparison of cardio-locomotor synchronization during running and cycling, Eur. J. Appl. Physiol. 89 (2003) 221–229, https://doi.org/10.1007/s00421-002-0784-0.
[25] K. Nomura, Y. Takei, M. Yoshida, Y. Yanagida, Phase-dependent chronotropic response of the heart during running in humans, Eur. J. Appl. Physiol. 97 (2006) 240–247, https://doi.org/10.1007/s00421-005-0103-7.
[26] I. Gordon, A. Gilboa, S. Cohen, N. Milstein, N. Haimovich, S. Pinhasi, S. Siegman, Physiological and behavioral synchrony predict group cohesion and performance, Sci. Rep. 10 (2020) 8484, https://doi.org/10.1038/s41598-020-65670-1.
[27] C. Leclère, S. Viaux, M. Avril, C. Achard, M. Chetouani, S. Missonnier, D. Cohen, Why synchrony matters during mother-child interactions: a systematic review, PLOS ONE 9 (2014) e113571, https://doi.org/10.1371/journal.pone.0113571.
[28] J. Yarmolovsky, R. Geva, Follow the leader: parent- and child-led synchrony in competitive and cooperative play, J. Nonverbal Behav. 48 (2024) 235–251, https://doi.org/10.1007/s10919-023-00445-6.
[29] E. Armstrong-Carter, J.G. Miller, J. Obradović, Parent–child physiological synchrony: Concurrent and lagged effects during dyadic laboratory interaction, Dev. Psychobiol. 63 (2021) e22196, https://doi.org/10.1002/dev.22196.
[30] Z. Cuadros, E. Hurtado, C. Cornejo, Infant-adult synchrony in spontaneous and nonspontaneous interactions, PLOS ONE 15 (2020) e0244138, https://doi.org/10.1371/journal.pone.0244138.
[31] Y. Pan, X. Cheng, Z. Zhang, X. Li, Y. Hu, Cooperation in lovers: an fNIRS-based hyperscanning study, Hum. Brain Mapp. 38 (2017) 831–841, https://doi.org/10.1002/hbm.23421.
[32] M. Chen, T. Zhang, R. Zhang, N. Wang, Q. Yin, Y. Li, J. Liu, T. Liu, X. Li, Neural alignment during face-to-face spontaneous deception: does gender make a difference? Hum. Brain Mapp. 41 (2020) 4964–4981, https://doi.org/10.1002/hbm.25173.
[33] A. Marzoratti, M.E. Liu, K.M. Krol, G.R. Sjobeck, D.J. Lipscomb, T.L. Hofkens, S. M. Boker, K.A. Pelphrey, J.J. Connelly, T.M. Evans, Epigenetic modification of the oxytocin receptor gene is associated with child-parent neural synchrony during competition, Dev. Cogn. Neurosci. 63 (2023) 101302, https://doi.org/10.1016/j.dcn.2023.101302.
[34] S. Liu, Z.R. Han, J. Xu, Q. Wang, M. (Miranda) Gao, X. Weng, S. Qin, K.H. Rubin, Parenting links to parent–child interbrain synchrony: a real-time fNIRS hyperscanning study, Cereb. Cortex 34 (2024) bhad533, https://doi.org/10.1093/cercor/bhad533.
[35] R. Feldman, R. Magori-Cohen, G. Galili, M. Singer, Y. Louzoun, Mother and infant coordinate heart rhythms through episodes of interaction synchrony, Infant Behav. Dev. 34 (2011) 569–577, https://doi.org/10.1016/j.infbeh.2011.06.008.
[36] O. Mayo, M. Lavidor, I. Gordon, Interpersonal autonomic nervous system synchrony and its association to relationship and performance – a systematic review and meta-analysis, Physiol. Behav. 235 (2021) 113391, https://doi.org/10.1016/j.physbeh.2021.113391.
[37] S. Wohltjen, T. Wheatley, Eye contact marks the rise and fall of shared attention in conversation, Proc. Natl. Acad. Sci. 118 (2021), https://doi.org/10.1073/pnas.2106645118.
[38] J.M. Baker, N. Liu, X. Cui, P. Vrticka, M. Saggar, S.M.H. Hosseini, A.L. Reiss, Sex differences in neural and behavioral signatures of cooperation revealed by fNIRS hyperscanning, Sci. Rep. 6 (2016) 26492, https://doi.org/10.1038/srep26492.
[39] T. Koike, H.C. Tanabe, S. Okazaki, E. Nakagawa, A.T. Sasaki, K. Shimada, S. K. Sugawara, H.K. Takahashi, K. Yoshihara, J. Bosch-Bayard, N. Sadato, Neural substrates of shared attention as social memory: a hyperscanning functional magnetic resonance imaging study, NeuroImage 125 (2016) 401–412, https://doi.org/10.1016/j.neuroimage.2015.09.076.
[40] Y. Pan, G. Novembre, B. Song, Y. Zhu, Y. Hu, Dual brain stimulation enhances interpersonal learning through spontaneous movement synchrony, Soc. Cogn. Affect. Neurosci. 16 (2021) 210–221, https://doi.org/10.1093/scan/nsaa080.
[41] L. Schwartz, J. Levy, Y. Endevelt-Shapira, A. Djalovski, O. Hayut, G. Dumas, R. Feldman, Technologically-assisted communication attenuates inter-brain synchrony, NeuroImage 264 (2022) 119677, https://doi.org/10.1016/j.neuroimage.2022.119677.
[42] X. Feng, B. Sun, C. Chen, W. Li, Y. Wang, W. Zhang, W. Xiao, Y. Shao, Self–other overlap and interpersonal neural synchronization serially mediate the effect of behavioral synchronization on prosociality, Soc. Cogn. Affect. Neurosci. 15 (2020) 203–214, https://doi.org/10.1093/scan/nsaa017.
[43] G. Novembre, G. Knoblich, L. Dunne, P.E. Keller, Interpersonal synchrony enhanced through 20 Hz phase-coupled dual brain stimulation, Soc. Cogn. Affect. Neurosci. 12 (2017) 662–670, https://doi.org/10.1093/scan/nsw172.
[44] M.M. Spapé, J.M. Kivikangas, S. Järvelä, I. Kosunen, G. Jacucci, N. Ravaja, Keep your opponents close: social context affects EEG and fEMG linkage in a turn-based

computer game, PLOS ONE 8 (2013) e78795, https://doi.org/10.1371/journal.pone.0078795.
[45] I. Marriott Haresign, E. a M. Phillips, M. Whitehorn, F. Lamagna, M. Eliano, L. Goupil, E.J.H. Jones, S.V. Wass, Gaze onsets during naturalistic infant-caregiver interaction associate with 'sender' but not 'receiver' neural responses, and do not lead to changes in inter-brain synchrony, Sci. Rep. 13 (2023) 3555, https://doi.org/10.1038/s41598-023-28988-0.
[46] A. Djalovski, G. Dumas, S. Kinreich, R. Feldman, Human attachments shape interbrain synchrony toward efficient performance of social goals, NeuroImage 226 (2021) 117600, https://doi.org/10.1016/j.neuroimage.2020.117600.
[47] S. Kinreich, A. Djalovski, L. Kraus, Y. Louzoun, R. Feldman, Brain-to-brain synchrony during naturalistic social interactions, Sci. Rep. 7 (2017) 17060, https://doi.org/10.1038/s41598-017-17339-5.
[48] P. Léné, A.J. Karran, E. Labonté-Lemoyne, S. Sénécal, M. Fredette, K.J. Johnson, P.-M. Léger, Is there collaboration specific neurophysiological activation during collaborative task activity? An analysis of brain responses using electroencephalography and hyperscanning, Brain Behav. N./a (2021) e2270, https://doi.org/10.1002/brb3.2270.
[49] M. Balconi, M.E. Vanutelli, Functional EEG connectivity during competition, BMC Neurosci. 19 (2018) 63, https://doi.org/10.1186/s12868-018-0464-6.
[50] Á. Romero-Martínez, A. Rodríguez, L. Moya-Albiol, Is it easy to synchronize our minds when we are forced to cooperate? Brain Sci. 9 (2019) 282, https://doi.org/10.3390/brainsci9100282.
[51] N. Sinha, T. Maszczyk, Z. Wanxuan, J. Tan, J. Dauwels, EEG hyperscanning study of inter-brain synchrony during cooperative and competitive interaction, 2016 IEEE Int. Conf. Syst. Man Cybern. SMC (2016) 004813–004818, https://doi.org/10.1109/SMC.2016.7844990.
[52] N.V. Shemyakina, Zh.V. Nagornova, Neurophysiological characteristics of competition in skills and cooperation in creativity task performance: a review of hyperscanning research, Hum. Physiol. 47 (2021) 87–103, https://doi.org/10.1134/S0362119721010126.
[53] V. Reindl, S. Wass, V. Leong, W. Scharke, S. Wistuba, C.L. Wirth, K. Konrad, C. Gerloff, Multimodal hyperscanning reveals that synchrony of body and mind are distinct in mother-child dyads, NeuroImage 251 (2022) 118982, https://doi.org/10.1016/j.neuroimage.2022.118982.
[54] A. Marzoratti, T.M. Evans, Measurement of interpersonal physiological synchrony in dyads: a review of timing parameters used in the literature, Cogn. Affect. Behav. Neurosci. 22 (2022) 1215–1230, https://doi.org/10.3758/s13415-022-01011-1.
[55] M. Balconi, L. Gatti, M.E. Vanutelli, When cooperation goes wrong: brain and behavioural correlates of ineffective joint strategies in dyads, Int. J. Neurosci. 128 (2018) 155–166, https://doi.org/10.1080/00207454.2017.1379519.
[56] Y. Golland, D. Mevorach, N. Levit-Binnun, Affiliative zygomatic synchrony in co-present strangers, Sci. Rep. 9 (2019) 3120, https://doi.org/10.1038/s41598-019-40060-4.
[57] X. Dai, X. Li, N. Xia, J. Xi, Y. Zhang, Client-counselor behavioral and inter-brain synchronization among dismissing and secure clients and its association with alliance quality and outcome, Psychother. Res. 0 (2023) 1–14, https://doi.org/10.1080/10503307.2023.2249587.
[58] Y. Hu, X. Cheng, Y. Pan, Y. Hu, The intrapersonal and interpersonal consequences of interpersonal synchrony, Acta Psychol. 224 (2022) 103513, https://doi.org/10.1016/j.actpsy.2022.103513.
[59] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-Wilson, S. McDonald, L.A. McGuinness, L.A. Stewart, J. Thomas, A.C. Tricco, V.A. Welch, P. Whiting, D. Moher, The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, Int. J. Surg. 88 (2021) 105906, https://doi.org/10.1016/j.ijsu.2021.105906.
[60] I. Gordon, S. Wallot, Y. Berson, Group-level physiological synchrony and individual-level anxiety predict positive affective behaviors during a group decision-making task, Psychophysiology 58 (2021) e13857, https://doi.org/10.1111/psyp.13857.
[61] A. Tomashin, I. Gordon, S. Wallot, Interpersonal physiological synchrony predicts group cohesion, Front. Hum. Neurosci. 16 (2022). ⟨https://www.frontiersin.org/articles/10.3389/fnhum.2022.903407⟩ (accessed January 10, 2024).
[62] D. Lakens, Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs, Front. Psychol. 4 (2013). ⟨https://www.frontiersin.org/articles/10.3389/fpsyg.2013.00863⟩.
[63] R Core Team, R: A Language and Environment for Statistical Computing, (2021). https://www.R-project.org/.
[64] S. Balduzzi, G. Rücker, G. Schwarzer, How to perform a meta-analysis with R: a practical tutorial, BMJ Ment. Health 22 (2019) 153–160, https://doi.org/10.1136/ebmental-2019-300117.
[65] K. Sidik, J.N. Jonkman, A comparison of heterogeneity variance estimators in combining results of studies, Stat. Med. 26 (2007) 1964–1981, https://doi.org/10.1002/sim.2688.
[66] M. Egger, G.D. Smith, M. Schneider, C. Minder, Bias in meta-analysis detected by a simple, graphical test, BMJ 315 (1997) 629–634, https://doi.org/10.1136/bmj.315.7109.629.
[67] Q. Wang, Z. Han, X. Hu, S. Feng, H. Wang, T. Liu, L. Yi, Autism symptoms modulate interpersonal neural synchronization in children with autism spectrum disorder in cooperative interactions, Brain Topogr. 33 (2020) 112–122, https://doi.org/10.1007/s10548-019-00731-x.
[68] D. Tagavi, Parent-Child Psychophysiological Synchrony in Early Autism Intervention: A Pilot Investigation, University of California, 2021.
[69] M. Balconi, L. Gatti, M.E. Vanutelli, EEG functional connectivity and brain-to-brain coupling in failing cognitive strategies, Conscious. Cogn. 60 (2018) 86–97, https://doi.org/10.1016/j.concog.2018.03.001.
[70] X. Deng, M. Yang, X. Chen, Y. Zhan, The role of mindfulness on theta inter-brain synchrony during cooperation feedback processing: an EEG-based hyperscanning study, Int. J. Clin. Health Psychol. 23 (2023) 100396, https://doi.org/10.1016/j.ijchp.2023.100396.
[71] S. Dikker, G. Michalareas, M. Oostrik, A. Serafimaki, H.M. Kahraman, M. E. Struiksma, D. Poeppel, Crowdsourcing neuroscience: inter-brain coupling during face-to-face interactions outside the laboratory, NeuroImage 227 (2021) 117436, https://doi.org/10.1016/j.neuroimage.2020.117436.
[72] H.N. Gamliel, M. Nevat, H.Z.G. Probolovski, M. Karklinsky, S. Han, S.G. Shamay-Tsoory, Inter-group conflict affects inter-brain synchrony during synchronized movements, NeuroImage (2021) 118661, https://doi.org/10.1016/j.neuroimage.2021.118661.
[73] J. Hirsch, X. Zhang, J.A. Noah, Y. Ono, Frontal temporal and parietal systems synchronize within and across brains during live eye-to-eye contact, NeuroImage 157 (2017) 314–330, https://doi.org/10.1016/j.neuroimage.2017.06.018.
[74] Y. Hu, M. Zhu, Y. Liu, Z. Wang, X. Cheng, Y. Pan, Y. Hu, Musical meter Induces interbrain synchronization during interpersonal coordination, eNeuro 9 (2022), https://doi.org/10.1523/ENEURO.0504-21.2022.
[75] Z. Jiao, J. Song, X. Yang, Y. Chen, G. Han, Social pain sharing boosts interpersonal brain synchronization in female cooperation, Acta Psychol. 243 (2024) 104138, https://doi.org/10.1016/j.actpsy.2024.104138.
[76] N. Kadosh, Brains that Fire Together Wire Together: Inter-Brain Plasticity Underlies Learning to Synchronize, Master's, University of Haifa (Israel), 2019. ⟨https://www.proquest.com/docview/2585931089/abstract/801F9B269C3D4F19PQ/1⟩ (accessed July 27, 2024).
[77] V. Leong, E. Byrne, K. Clackson, S. Georgieva, S. Lam, S. Wass, Speaker gaze increases information coupling between infant and adult brains, Proc. Natl. Acad. Sci. 114 (2017) 13290, https://doi.org/10.1073/pnas.1702493114.
[78] C.D.B. Luft, I. Zioga, A. Giannopoulos, G. Di Bona, N. Binetti, A. Civilini, V. Latora, I. Mareschal, Social synchronization of brain activity increases during eye-contact, Commun. Biol. 5 (2022) 1–15, https://doi.org/10.1038/s42003-022-03352-6.
[79] Y. Mu, C. Guo, S. Han, Oxytocin enhances inter-brain synchrony during social coordination in male adults, Soc. Cogn. Affect. Neurosci. 11 (2016) 1882–1893, https://doi.org/10.1093/scan/nsw106.
[80] Y. Mu, S. Han, M.J. Gelfand, The role of gamma interbrain synchrony in social coordination when humans face territorial threats, Soc. Cogn. Affect. Neurosci. 12 (2017) 1614–1623, https://doi.org/10.1093/scan/nsx093.
[81] E.A. Piazza, L. Hasenfratz, U. Hasson, C. Lew-Williams, Infant and adult brains are coupled to the dynamics of natural communication, Psychol. Sci. 31 (2020) 6–17, https://doi.org/10.1177/0956797619878698.
[82] Y. Liu, Y. Zhang, Y. Zhong, J. Liu, C. Zhang, Y. Meng, N. Pang, X. Cheng, H. Wang, Favoritism or bias? Cooperation and competition under different intergroup relationships: evidence from EEG hyperscanning, Cereb. Cortex 34 (2024).
[83] M. Zivan, C. Gashri, N. Habuba, T. Horowitz-Kraus, Reduced mother-child brain-to-brain synchrony during joint storytelling interaction interrupted by a media usage, Child Neuropsychol. 28 (2022) 918–937, https://doi.org/10.1080/09297049.2022.2034774.
[84] Y.Z. Capraz, K. Konrad, V. Reindl, Concurrent and lagged physiological synchrony during mother–child interaction and their relationship to positive affect in 8- to 10-year-old children, Sci. Rep. 13 (2023) 17744, https://doi.org/10.1038/s41598-023-43847-8.
[85] J. Ham, E. Tronick, Relational psychophysiology: Lessons from mother–infant physiology research on dyadically expanded states of consciousness, Psychother. Res. 19 (2009) 619–632, https://doi.org/10.1080/10503300802609672.
[86] M.P. McAssey, J. Helm, F. Hsieh, D.A. Sbarra, E. Ferrer, Methodological advances for detecting physiological synchrony during dyadic interactions, Methodology 9 (2013) 41–53, https://doi.org/10.1027/1614-2241/a000053.
[87] L. Noy, N. Levit-Binun, Y. Golland, Being in the zone: physiological markers of togetherness in joint improvisation, Front. Hum. Neurosci. 9 (2015), https://doi.org/10.3389/fnhum.2015.00187.
[88] E. Prochazkova, E.E. Sjak-Shie, F. Behrens, D. Lindh, M.E. KretThe choreography of human attraction: physiological synchrony in a blind date setting, (2019) 748707. https://doi.org/10.1101/748707..
[89] A.J. Strang, G.J. Funke, S.M. Russell, A.W. Dukes, M.S. Middendorf, Physio-behavioral coupling in a cooperative team task:contributors and relations, J. Exp. Psychol. Hum. Percept. Perform. 40 (2014) 145–158, https://doi.org/10.1037/a0033125.
[90] L. Zeevi, N. klein Selle, E.L. Kellmann, G. Boiman, Y. Hart, S. Atzil, Bio-behavioral synchrony is a potential mechanism for mate selection in humans, Sci. Rep. 12 (2022) 4786, https://doi.org/10.1038/s41598-022-08582-6.
[91] Y. Long, C. Chen, K. Wu, S. Zhou, F. Zhou, L. Zheng, H. Zhao, Y. Zhai, C. Lu, Interpersonal conflict increases interpersonal neural synchronization in romantic couples, Cereb. Cortex 32 (2022) 3254–3268, https://doi.org/10.1093/cercor/bhab413.
[92] T. Nguyen, D.H. Abney, D. Salamander, B.I. Bertenthal, S. Hoehl, Proximity and touch are associated with neural but not physiological synchrony in naturalistic mother-infant interactions, NeuroImage 244 (2021) 118599, https://doi.org/10.1016/j.neuroimage.2021.118599.
[93] M. Harrer, P. Cuijpers, T. Furukawa, D. Ebert, Doing Meta-Analysis with R: A Hands-On Guide, Chapman and Hall/CRC, New York, 2021, https://doi.org/10.1201/9781003107347.

[94] L. Shi, L. Lin, The trim-and-fill method for publication bias: practical guidelines and recommendations based on a large database of meta-analyses, Medicine 98 (2019) e15987, https://doi.org/10.1097/MD.0000000000015987.
[95] S.G. Shamay-Tsoory, N. Saporta, I.Z. Marton-Alper, H.Z. Gvirts, Herding brains: a core neural mechanism for social alignment, Trends Cogn. Sci. 23 (2019) 174–186, https://doi.org/10.1016/j.tics.2019.01.002.
[96] R.P. Dum, P.L. Strick, Motor areas in the frontal lobe of the primate, Physiol. Behav. 77 (2002) 677–682, https://doi.org/10.1016/S0031-9384(02)00929-0.
[97] C. Gerloff, J. Richard, J. Hadley, A.E. Schulman, M. Honda, M. Hallett, Functional coupling and regional activation of human cortical motor areas during simple, internally paced and externally paced finger movements, Brain 121 (1998) 1513–1531, https://doi.org/10.1093/brain/121.8.1513.
[98] I. Gordon, A. Gilboa, S. Cohen, T. Kleinfeld, The relationship between physiological synchrony and motion energy synchrony during a joint group drumming task, Physiol. Behav. 224 (2020) 113074, https://doi.org/10.1016/j.physbeh.2020.113074.
[99] T. Pham, Z.J. Lau, S.H.A. Chen, D. Makowski, Heart rate variability in psychology: a review of HRV indices and an analysis tutorial, Sensors 21 (2021) 3998, https://doi.org/10.3390/s21123998.