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Research Article

# Hyperscanning literature after two decades of neuroscientific research: A scientometric review

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ABSTRACT

Hyperscanning, a neuroimaging approach introduced in 2002 for simultaneously recording the brain activity of multiple participants, has significantly contributed to our understanding of social interactions. Nevertheless, the existing literature requires systematic organization to advance our knowledge. This study, after two decades of hyperscanning research, aims to identify the primary thematic domains and the most influential documents in the field. We conducted a scientometric analysis to examine co-citation patterns quantitatively, using a sample of 548 documents retrieved from Scopus and their 32,022 cited references. Our analysis revealed ten major thematic domains in hyperscanning research, with the most impactful document authored by Czeszumski and colleagues in 2020. Notably, while hyperscanning was initially developed for functional magnetic resonance imaging (fMRI), our findings indicate a substantial influence of research conducted using electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS). The introduction of fNIRS and advancements in EEG methods have enabled the implementation of more ecologically valid experiments for investigating social interactions. The study also highlights the need for more research that combines multi-brain neural stimulation with neuroimaging techniques to understand the causal role played by interpersonal neural synchrony in social interactions.

## Introduction

The term *"hyperscanning"* refers to a neuroimaging approach in which the brain activity of two or more participants is recorded simultaneously. The idea of hyperscanning was first introduced in 2002 by Montague et al. (2002) to investigate the neural dynamics that support people while they actively engage in social exchanges. As argued by Hasson et al. (2012), the introduction of hyperscanning and the second-person neuroscience approach represented a *"Copernican revolution"* in cognitive neuroscience. In fact, while traditional neuroimaging studies captured the complexity of the *"social brain"*, their insights were in most cases obtained by measuring the brain activity of only one participant at a time. Thus, while traditional neuroimaging studies enriched the knowledge on the perception of social stimuli/situations, they did not explore the dyadic or group component of real-life social interactions and its effect on human development (Czeszumski et al., 2020). Conversely, hyperscanning proved useful in investigating the dyadic or group phenomena that emerge from social interactions. Notably, hyperscanning studies revealed that social exchanges are characterized by instances of synchronization in social partners' brain activity (e.g., Dumas et al., 2010). The emergence of interpersonal synchrony at the neural level represents the natural extension of the bio-behavioral synchrony framework (Feldman, 2012), which posits that the behavioral, physiological, and hormonal activities from interacting partners tend to synchronize during social interactions (Carollo et al., 2021).

Methodological and technical advances have and still represent a major boost in hyperscanning research. Notably, hyperscanning was initially introduced for functional magnetic resonance imaging (fMRI). In their seminal article, Montague et al. (2002) presented a feasibility study for conducting a simultaneous fMRI acquisition while nine dyads took part in a game of deception. Yet, subsequent studies have extended the hyperscanning approach to magnetoencephalography (MEG) (Baess et al., 2012), electroencephalography (EEG) (Babiloni et al., 2007b), and, more recently, functional near-infrared spectroscopy (fNIRS) (Funane et al., 2011; Cui et al., 2012). Traditional and novel neuroimaging techniques provide a series of unique strengths and pitfalls when designing a hyperscanning experiment (Carollo et al., 2022; Martin and Huettel, 2022). For instance, fMRI has a higher spatial resolution as compared to fNIRS and EEG, but it requires participants to lie supine in a scanner. This limits the type of social interactions that can be performed in a fMRI scanner.

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Conversely, EEG provides a higher temporal resolution as compared to fMRI and fNIRS, but participants' movements often impair the signal quality. fNIRS seems to represent a good compromise between the strengths and pitfalls of fMRI and EEG. In fact, fNIRS has a good spatial resolution for measuring the activity in the most external cortical layers of the human brain and it is less sensitive to participants' movements. Moreover, fNIRS is highly portable and less costly as compared to fMRI (Carollo et al., 2022). On the downside, fNIRS is much more recent as compared to fMRI and EEG. For this reason, the methodological approaches to treat fNIRS data still require to be standardized and validated to ensure cross-study replicability and comparability (e.g., Bizzego et al., 2022). Thanks to its characteristics, fNIRS allows the implementation of experimental tasks that mirror daily life activities. For instance, Fig. 1 shows an fNIRS hyperscanning setup to measure the brain activity in mother and child during free play (Bizzego et al., 2022b).

In recent times, hyperscanning has evolved beyond brain imaging techniques, with pioneering research employing brain stimulation methods (e.g., transcranical, sensory, optogenetics) to shift from correlation-based to causation-focused approaches (Novembre and Iannetti, 2021). Traditional hyperscanning studies typically measure interpersonal neural synchrony as a dependent variable resulting from social interactions between partners. While this approach yields interesting and valuable results, it alone cannot determine whether interpersonal neural synchrony is merely an epiphenomenon of the fact that participants are being exposed to the same environment and the same stimuli or if it plays a causal role in facilitating social exchanges. A causation approach based on brain stimulation takes the opposite approach by manipulating neural activity and studying its effects on social interaction (for a recent multi-brain stimulation study, see Lu et al. (2023)). Fig. 2 displays an example of how sensory stimulation can be used to entrain participants' brain activity during social interactions.

With their strengths and pitfalls, all the aforementioned techniques were used in the past twenty years for conducting hyperscanning studies. However, experimental tasks have been heterogeneous across studies and a shared theoretical framework to interpret hyperscanning results across research domains is still needed (Hamilton, 2021). In light of this, the current paper aims to identify the main domains of research as well as the most impactful documents in the hyperscanning literature. To do so, we will adopt a scientometric approach to reviews, as done in our previous publications (e.g., Carollo et al., 2021). A scientometric approach was chosen because it merges bibliometric analysis (i.e., application of quantitative techniques to bibliometric data) and scientific mapping (i.e., visualization of the temporal evolution of a research domain) (Carollo et al., 2021). Therefore, the scientometric approach allows the use of a data-driven quantitative method to uncover the main research domains and impactful documents in large samples of data.

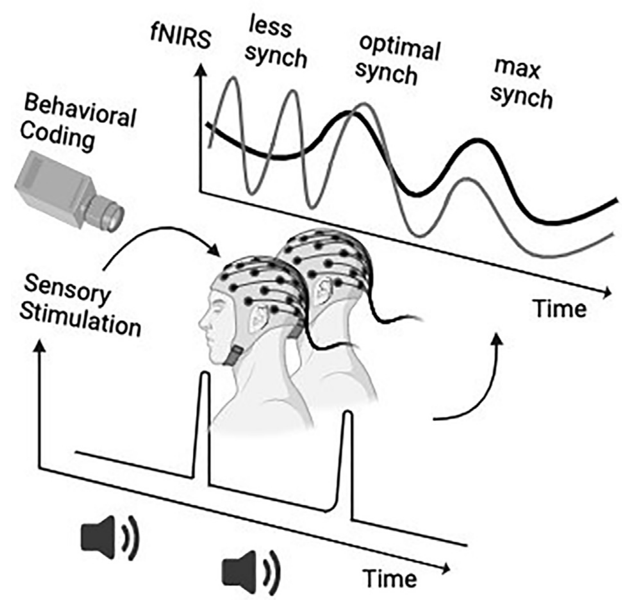


**Fig. 2.** An example of multi-brain stimulation through rhythmic sensory stimulation.

## Experimental procedures

### *Data collection from scopus*

For the current work, all data were collected from Scopus. Scopus was chosen because it has a higher coverage of indexed journals as compared to other platforms (Cataldo et al., 2022). Data were collected on 04 September 2023 with the searching string "TITLE-ABS-KEY(hyperscan*)". A sample of 548 documents published between 1998 and 2023 was retrieved. We qualitatively inspected the documents' abstracts and titles to ensure that the included documents were relevant to the field of hyperscanning. Through this procedure, we excluded an amount of 48 non-relevant documents. Thus, the final sample consisted of 500 documents published between 2002 and 2023.

The dataset consisted of 374 articles, 14 book chapters, 59 conference papers, 1 conference review, 1 data paper, 3 editorials, 6 erratum, 1 letter, 2 notes, 37 reviews, and 2 short surveys.

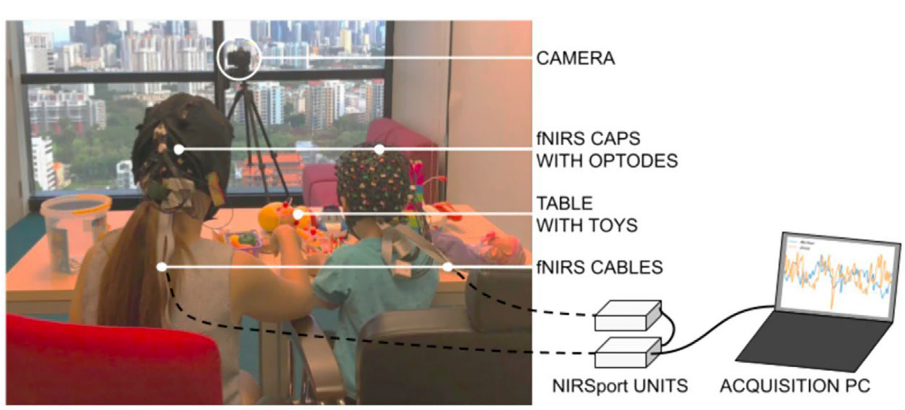


**Fig. 1.** Representation of a functional near-infrared spectroscopy (fNIRS) hyperscanning setup to monitor the brain activity of mother and child during a play session. Image from Bizzego et al. (2022b).

The current scientometric analysis goes beyond the scope of the initial 500 documents obtained from Scopus. These documents serve as the primary layer of data collection, from which additional documents (i.e., all their references) will be gathered and utilized for the comprehensive analysis. This approach is crucial for two key reasons. Firstly, it ensures a substantial sample size, higher than previous reviews on the topic, for a robust analysis. Secondly, it facilitates the collection of literature not necessarily indexed in Scopus but still pertinent to the hyperscanning field. This is because, in principle, cited documents are selected by field experts based on their scientific relevance.

To characterize the structure of knowledge in the hyperscanning literature, we first analyzed the collected data using the *bibliometrix* package for R (Aria and Cuccurullo, 2017). We used *bibliometrix* to detect the most involved countries, scientific journals, authors, documents, and keywords in the hyperscanning literature.

### *Data import on CiteSpace*

To conduct the scientometric analysis, all data were imported into CiteSpace (version 6.1.R6 64-bit Advanced) (Chen, 2006). A total of 32,022 cited references were identified, of which 31,802 (99.31%) were in the valid format to be included in the analysis. The data loss at this stage ($n = 220$ references; 0.69% of the total references) is considered acceptable and it is in line with previous scientometric works (e.g., Carollo et al., 2021).

### *Document co-citation analysis (DCA)*

To identify the main research trends and impactful documents, we conducted a document co-citation analysis (DCA). DCA assesses the frequency with which two or more publications are cited together (i.e., co-cited) by other documents (Trujillo and Long, 2018). The assumption is that two or more documents are frequently co-cited because they belong to the same thematic domain of research. For this reason, co-citation patterns can provide information on the relationships between key concepts, methods, or experiments in the literature (Small, 1973; Small, 1980). In the DCA, single documents are included as the network's nodes, co-citations are included as links, and co-citation frequencies as link weights.

The number of documents that are included in the final graph depends on the node selection criterion and its scaling factor. As done in our previous scientometric analyses (e.g., Carollo et al., 2021), we optimized the parameters to obtain a well-balanced DCA network. Specifically, we compared the networks generated when using g-index, TOP N, or TOP N% as node selection criteria. The g-index is the largest number where the total number of citations received by the top $g$ articles equals at least $g^2$ (Egghe, 2006). The TOP N and TOP% criteria include in the final network the $N$ or the $N$% most cited references for each time slice (i.e., one year in this work). While the node selection criteria specify the rule determining the inclusion of nodes in the final network, their scaling factors set the threshold (Cataldo et al., 2022). For the analysis, we compared the networks generated using g-index with $k$ set at 10, 15, 25, 50; $N$ set at 50; and $N$% set at 10. The metrics for all generated networks were compared and the optimal DCA was obtained with g-index with $k$ set at 25.

The literature search and the generation of the DCA network are summarized in Fig. 3.

### *DCA network evaluation metrics*

Structural and temporal metrics were used to evaluate the results of the scientometric analysis as in previous works (e.g., Carollo et al., 2021). Among structural metrics, we used modularity, silhouette, and betweenness centrality. Modularity is an index of the degree to which the network can be divided into individual clusters (Chen et al., 2010). Modularity values range from 0 to 1. Silhouette is an index of a cluster's inner homogeneity and separation from other clusters (Rousseeuw, 1987). Silhouette values range from $-1$ to 1. Betweenness centrality provides information regarding the extent to which a single document connects two other random documents in the network (Freeman, 1977; Leydesdorff, 2007; Newman, 2005). Among temporal metrics, we used citation burstness and sigma. Citation burstness is computed using Kleinberg's algorithm and detects an abrupt increase in the number of citations received by a document. Documents with high citation burstness values have received significant attention and general recognition in their field (Kleinberg, 2002). Sigma provides information regarding a document's impact on the whole network and its significance in the field. Sigma is computed using the equation $(centrality + 1)^{burstness}$ (Chen et al., 2009).

## Results

### *Bibliometric analysis on the citing documents*

The bibliometric analysis suggests that the hyperscanning literature grew from 2002 to 2023 with a growing rate of 27.6% documents a year. Documents received an average of 25.85 citations, with Dumas et al. (2010) (total citations on Scopus = 532; total citations by year = 38), Montague et al. (2002) (total citations on Scopus = 469; total citations by year = 21.3), Cui et al. (2012) (total citations on Scopus = 440; total citations by year = 36.7) being the most highly cited ones.

In the hyperscanning literature, a total of 1353 single authors were identified. The most productive were Balconi M ($n = 41$ documents), Hu X ($n = 25$ documents), and Li X ($n = 25$ documents).

From the analysis of the corresponding authors' affiliations, most of the publications in the hyperscanning literature were produced in China ($n = 112$ documents; Single Country Publications (SCP) = 84; Multiple Country Publications (MCP) = 28), Italy ($n = 78$ documents; SCP = 50; MCP = 28), and the United States of America ($n = 55$ documents; SCP = 32; MCP = 23).

Documents regarding hyperscanning were mostly published in *NeuroImage* ($n = 44$ documents), *Frontiers in Human Neuroscience* ($n = 39$ documents), and *Social Cognitive and Affective Neuroscience* ($n = 34$ documents).

In the sample of downloaded documents, a total of 1066 keywords were identified. The ten most frequent keywords were *hyperscanning* ($N = 281$ documents), *fNIRS* ($N = 74$ documents), *EEG* ($N = 71$ documents), *social interaction* ($N = 52$ documents), *cooperation* ($N = 44$ documents), *functional near-infrared spectroscopy* ($N = 41$ documents), *social neuroscience* ($N = 31$ documents), *EEG hyperscanning* ($N = 24$ documents), *interpersonal brain synchronization* ($N = 20$ documents), and *fNIRS hyperscanning* ($N = 19$ documents). The main co-occurrence patterns among the keywords are displayed in Fig. 4.

### *Document co-citation analysis*

The optimal DCA network, depicted in Fig. 5, was made of 648 nodes (i.e., documents) and 3065 links (i.e., co-citations). Thus, on average, each document was connected with another 4.73 documents. The network was moderately divisible into separate and highly homogeneous clusters (modularity = 0.6495; average silhouette score = 0.8334).

In the network, ten major thematic clusters of research were identified. The clusters that included the highest number of documents were cluster #0 (size = 88; silhouette = 0.729; mean publication year = 2010), cluster #1 (size = 85; silhouette = 0.820, mean publication year = 2014), and cluster #2 (size = 83, silhouette = 0.781, mean publication year = 2017). Based on their silhouette score, the most homogeneous thematic clusters of research were cluster #9 (size = 30; silhouette = 1.000; mean publication year = 2004),

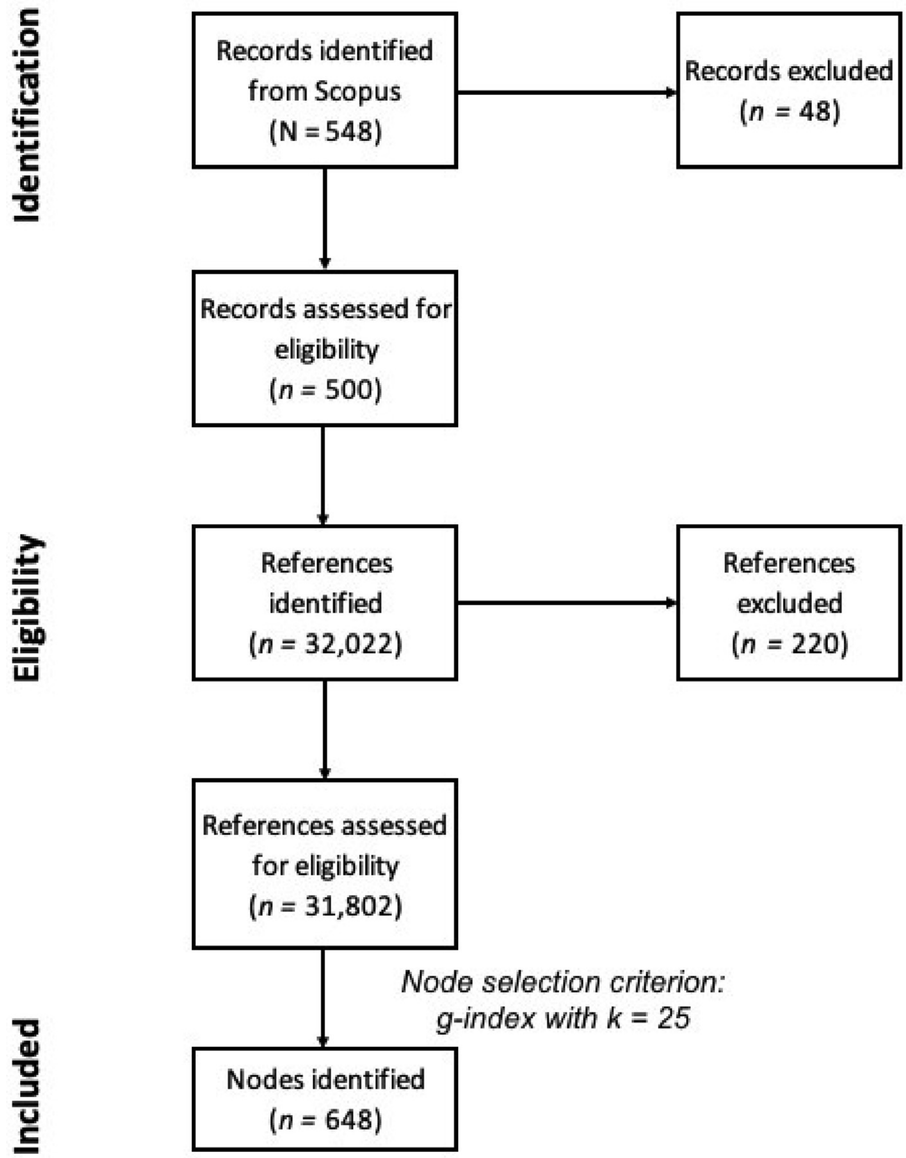


**Fig. 3.** Preferred reporting items for systematic reviews (PRISMA) flowchart for literature search and references eligibility.

cluster #12 (size = 13; silhouette = 0.991; mean publication year = 2007), and cluster #5 (size = 37, silhouette = 0.961, mean publication year = 2008). After inspecting the documents included in the clusters, we manually labeled the clusters to reflect their thematic content as in Carollo et al. (2021). The metrics of all the major thematic clusters of research are presented in Table 1.

### *Impactful documents*

In the network, a total of 46 documents had a sudden burst in their citation history. However, out of the 46 references, 8 were repeated entries that were not recognized as duplicates by CiteSpace. Based on the strength of their citation burstness, the most impactful documents in the network were authored by Czeszumski et al. (2020) (citation burstness = 13.93; duration = 2 years), Lindenberger et al. (2009) (citation burstness = 13.71; duration = 6 years), and Hari and Kujala (2009) (citation burstness = 12.11; duration = 5 years). In particular, Czeszumski et al. (2020) provided a comprehensive review of the state-of-the-art in the hyperscanning literature, focusing the discussion on the main neuroimaging techniques, types of analysis, and research outcomes. A summary of the metrics of the top ten documents with a citation burst is provided in Table 2.

## Discussion

After two decades of hyperscanning research, the aim of the current work was to identify the main thematic domains of research and the most impactful publications in the literature. To do so, we used a scientometric approach and we conducted a DCA on a sample of 548 references. In the literature, we identified ten major thematic clusters of research and the review by Czeszumski et al. (2020) as the most impactful documents in the field. In the following section, we will review the content of the major thematic clusters of research in a qualitative approach. The major thematic clusters will be discussed in chronological order, from the cluster with the oldest mean year of publication to the cluster with the most recent one. When discussing the clusters, we will provide the coverage (i.e., the number of documents in the cluster that were cited by the paper) and the global citation score (GCS; i.e., the total number of citations received by the publication in Scopus).

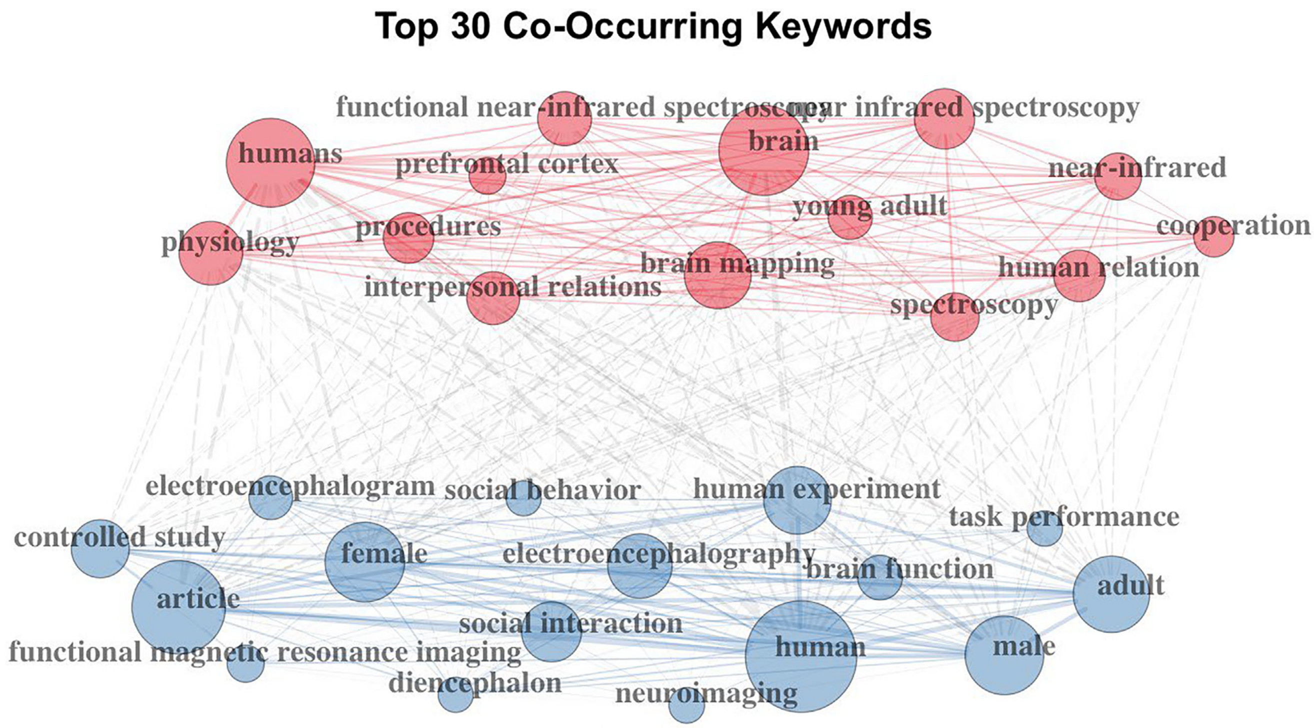


**Fig. 4.** Co-occurrence analysis on the keywords in the hyperscanning literature. In the network, keywords are represented as individual nodes, with their size proportional to their degree. Co-occurrences of keywords are indicated by solid links (for co-occurrences within the same cluster) and dashed links (for co-occurrences across clusters). The width of these links is proportional to the frequency of co-occurrence. Based on the co-occurrence patterns, two clusters of keywords were automatically identified using the *bibliometrix* package for R (Aria and Cuccurullo, 2017) and are depicted in the figure using red and blue colors.

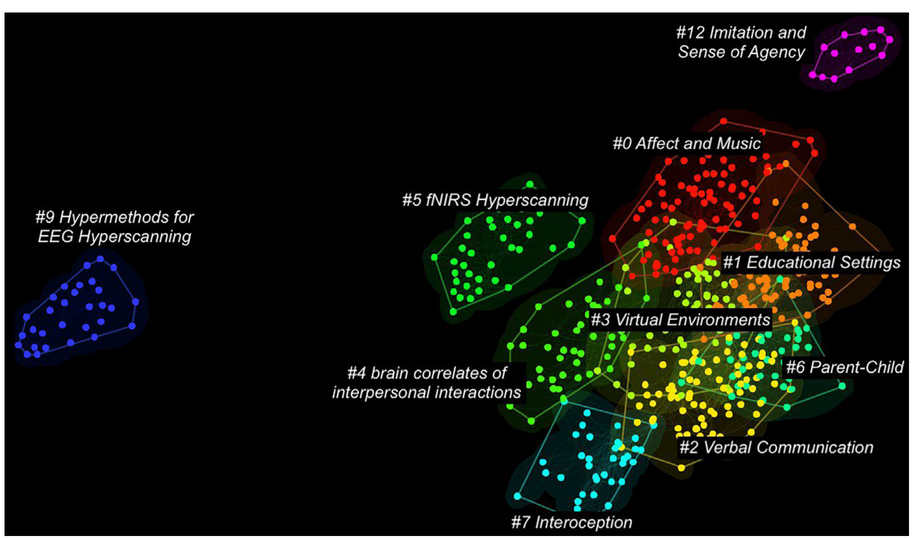


**Fig. 5.** Document co-citation analysis network of the literature on hyperscanning. In the network, documents are represented as single nodes, and co-citations are represented as links. Ten major thematic domains of research were identified. The image was generated with CiteSpace software (Chen, 2006).

*Cluster #9: Hypermethods for EEG Hyperscanning*

The earliest thematic cluster of research in hyperscanning revolved around the main citing documents by Babiloni et al. (2006) (coverage = 15; GCS = 99), Astolfi et al. (2010) (coverage = 12; GCS = 132), and Babiloni et al. (2007a) (coverage = 7; GCS = 3). This cluster showed the highest silhouette score in the network, indicating high thematic cohesiveness of the included documents and strong thematic separation from other clusters. In fact, this group of works encompassed the early studies showing the feasibility and the value of using high-resolution EEG hyperscanning to characterize the neural dynamics in teams during a cooperative task (e.g., a card game). While doing so, Astolfi et al. (2010) and Babiloni et al. (2006), Babiloni et al. (2007a) presented a series of *"hypermethods"*,

**Table 1**
Metrics for the ten thematic clusters of research identified in the network.

| ID | Size | Silhouette | Mean Year | LLR Label | Suggested Label |
|---|---|---|---|---|---|
| 0 | 88 | 0.729 | 2010 | eeg hyperscanning studies | affect and music |
| 1 | 85 | 0.820 | 2014 | fnirs-based hyperscanning study | educational settings |
| 2 | 83 | 0.781 | 2017 | group creation | verbal communication |
| 3 | 54 | 0.841 | 2015 | interpersonal neural synchronization | virtual environments |
| 4 | 44 | 0.806 | 2012 | functional connectivity | brain correlates of interpersonal interactions |
| 5 | 37 | 0.961 | 2008 | synchronous activity | fNIRS hyperscanning |
| 6 | 37 | 0.829 | 2018 | technologically-assisted communication | parent–child |
| 7 | 37 | 0.938 | 2017 | social framing matter | interoception |
| 9 | 30 | 1.000 | 2004 | neuroelectrical hyperscanning measure | hypermethods for EEG hyperscanning |
| 12 | 13 | 0.991 | 2007 | origin | imitation and sense of agency |

**Table 2**
Summary metrics of the ten with the strongest citation burstness. Citation burstness is defined as an abrupt increase in the number of citations received by a document. In the case of a repeated entry, only the reference with the highest value of citation burstness is presented in the table.

| Reference | Citation Burstness | Publication Year | Burst Begin | Burst End | Duration (years) | Centrality | Sigma |
|---|---|---|---|---|---|---|---|
| Czeszumski et al. (2020) | 13.93 | 2020 | 2021 | 2023 | 2 | 0.00 | 1.07 |
| Lindenberger et al. (2009) | 13.71 | 2009 | 2011 | 2017 | 6 | 0.20 | 11.57 |
| Hari and Kujala (2009) | 12.11 | 2009 | 2012 | 2017 | 5 | 0.02 | 1.22 |
| Cui et al. (2012) | 10.94 | 2012 | 2012 | 2020 | 8 | 0.06 | 1.97 |
| Dumas et al. (2010) | 9.81 | 2010 | 2012 | 2018 | 6 | 0.07 | 1.87 |
| Konvalinka and Roepstorff (2012) | 7.72 | 2012 | 2013 | 2017 | 4 | 0.01 | 1.12 |
| Jiang et al. (2012) | 7.12 | 2012 | 2014 | 2020 | 6 | 0.04 | 1.36 |
| Astolfi et al. (2010) | 7.11 | 2010 | 2011 | 2018 | 7 | 0.04 | 1.29 |
| Nguyen et al. (2020) | 6.77 | 2020 | 2021 | 2023 | 2 | 0.00 | 1.01 |
| Holper et al. (2012) | 6.71 | 2012 | 2016 | 2018 | 2 | 0.03 | 1.22 |

a group of analytical techniques for characterizing the functional connectivity between brains in terms of synchronization and causality relation. In most cases, *"hypermethods"* were derived from single-participant neuroimaging studies (e.g., Astolfi et al., 2005; Babiloni et al., 2005) and were applied to hyperscanning studies.

### *Cluster #12: imitation and sense of agency*

In research cluster #12, the main citing document was authored by Dumas et al. (2012) (coverage = 8; GCS = 50). Building on the growing literature and methodological advances in EEG hyperscanning Astolfi et al. (2010),Tognoli et al. (2007), and Dumas et al. (2012) explored the brain correlates of the sense of agency in a two-body context. In other words, the authors investigated the brain's ability to locate the origin of an action in the self. To do so, participants engaged in the roles of model and imitator. In some cases, these roles were directly elicited by the experiment, while in others, they emerged spontaneously during a live social interaction. The authors observed different patterns of brain oscillation across the two roles in the induced imitation condition. However, no dissociation of roles emerged in the neural activity during the spontaneous imitation condition.

Considering the focus on the neural correlates of imitation and the sense of agency, it is not surprising that some of the cluster's cited documents regarded the mirror-neuron system (Rizzolatti and Craighero, 2004) and mimicry (Ashton-James et al., 2007). In this sense, the initial hyperscanning studies extended the perspective of the mirror-neuron system and mimicry to real interpersonal interactions.

### *Cluster #5: fNIRS Hyperscanning*

The main citing documents in cluster #5 were authored by Funane et al. (2011) (coverage = 12; GCS = 145), Babiloni and Astolfi (2014) (coverage = 11; GCS = 313), and Astolfi et al. (2011b) (coverage = 8; GCS = 78). In the early 2010s, EEG hyperscanning was being consolidated to investigate cooperative and competitive social interactions (e.g., Astolfi et al., 2011a; De Vico Fallani et al., 2010; Dumas et al., 2010). However, researchers aimed to *(i)* use neuroimaging techniques with higher spatial resolution in hyperscanning and *(ii)* use hyperscanning in more ecological experimental paradigms (Astolfi et al., 2011b; Dumas et al., 2011; Funane et al., 2011). While fMRI represented a solution to the first goal, allowing the investigation of the neural substrates of social interactions (e.g., Abe et al., 2019), it still did not allow the design of naturalistic experimental paradigms. The introduction of fNIRS represented the solution for both research goals in hyperscanning. For this reason, in the 2010s, in parallel to its pioneering use in single-participant neuroimaging studies (e.g., Aslin and Mehler, 2005; Atsumori et al., 2007; Atsumori et al., 2009; Atsumori et al., 2010), fNIRS started being employed in an hyperscanning approach. Notably, Funane et al. (2011) conducted the first fNIRS hyperscanning study in 2011. The authors observed that higher spatiotemporal covariance in the brain's prefrontal activity of each participant was associated with higher behavioral coordination when trying to press a button in synchrony. As highlighted by Babiloni and Astolfi (2014),Funane et al. (2011) addressed the issue of synchronizing different devices with similar solutions to the ones that had been adopted in the EEG hyperscanning literature. However, the pioneering study by Cui et al. (2012) showed an alternative solution for fNIRS hyperscanning studies. Unconventionally, Cui et al. (2012) split the same NIRS device in two, using half of the available channels for measuring the brain activity of each participant.

The increased adoption of neuroimaging techniques with higher spatial resolution in hyperscanning stemmed from and aimed to enrich years of neuroscientific research on the neural correlates of social behaviors (e.g., Adolphs, 2003; Carter and Huettel, 2013; Hari and Kujala, 2009).

### *Cluster #0: affect and music*

Cluster #0 was the largest cluster in the network. The major citing documents were authored by Acquadro et al. (2016) (coverage = 20; GCS = 38), Burgess (2013) (coverage = 19; GCS = 127), and Cornejo et al. (2017) (coverage = 17; GCS = 43). After the pioneering studies by Funane et al. (2011) and Cui et al. (2012), fNIRS gained momentum as the elective technique for conducting ecological hyperscanning studies (Scholkmann et al., 2013). However, some solutions to enhance the ecological validity of EEG hyperscanning were proposed too (e.g., Astolfi et al., 2012; Toppi et al., 2016).

The interest in ecologically valid experiments directed the research focus to a core and largely neglected side of daily life social interactions: the affective component (Balconi and Vanutelli, 2017; Cornejo et al., 2017). Affect and emotions influence people's daily lives in multiple ways. For instance, they are crucial in creating social cohesion as well as determining the willingness to undertake joint actions or prosocial behaviors (Czeszumski et al., 2020; Konvalinka et al., 2011; Lopes et al., 2005; Twenge et al., 2007). Despite the importance of emotions in daily life, they had been scarcely investigated in hyperscanning studies due to the complexity of the setups (Czeszumski et al., 2020). Acquadro et al. (2016) proposed that using hyperscanning in musical settings represents one possible solution to investigate the affective component of social interactions. For the authors, the use of musical settings guarantees high ecological validity, the emotional component (which is a catalyst for social interactions), and an enactive view of human social interactions. Moreover, musical performances combine both intrapersonal action coordination and interpersonal action synchronization (Czeszumski et al., 2020). For these reasons, several citing and cited documents in the clusters used musical settings to show that interpersonal brain synchrony supports interpersonal behavioral coordination (e.g., Babiloni et al., 2011; Babiloni et al., 2012; Sänger et al., 2012; Sänger et al., 2013). Notably, Lindenberger et al. (2009), in one of the documents with the highest citation burst, used EEG hyperscanning to investigate brain synchrony in eight pairs of guitarists playing a melody together. In this pioneering work, the authors showed that interbrain synchrony regularly anticipates interpersonally coordinated actions.

### *Cluster #4: brain correlates of interpersonal interactions*

In cluster #4, the major citing documents were authored by Koike et al. (2015) (coverage = 13; GCS = 90), Balconi et al. (2018a) (coverage = 11; GCS = 9), Balconi et al. (2018c) (coverage = 9; GCS = 12), and Balconi et al. (2018b) (coverage = 9; GCS = 7). In this cluster of research, initial studies helped identifying some regions of interest from which patterns of interpersonal neural synchrony frequently emerge (e.g., Astolfi et al., 2015; Balconi et al., 2018c). For instance, Nozawa et al. (2016) showed enhanced interpersonal neural synchrony in frontopolar brain regions during natural verbal exchanges between people. Interestingly, the same brain regions are typically involved in social communication. Similarly, Hirsch et al. (2017) found an increased interpersonal neural synchrony in the left superior temporal gyrus, middle temporal gyrus, supramarginal gyrus, pre-motor cortex, and supplementary motor cortex during mutual gaze. In light of the increased interest in the neural basis of real-life social interactions, Koike et al. (2015) suggested employing EEG-fMRI hyperscanning to combine the high temporal resolution of EEG with the high spatial resolution of fMRI. As argued by the authors, such an approach would allow the use of inter-brain dynamics as a neuro-marker of real-life social interactions.

### *Cluster #1: educational settings*

The major citing documents in cluster #1 were authored by Nam et al. (2020) (coverage = 41; GCS = 21), Czeszumski et al. (2020) (coverage = 40; GCS = 153), and Balters et al. (2020) (coverage = 31; GCS = 9). Particularly, both Nam et al. (2020) and Czeszumski et al. (2020) systematically reviewed the hyperscanning literature. According to Nam et al. (2020), most hyperscanning studies are conducted using MEG/EEG and the most covered fields are cognition and educational applications. The field of hyperscanning in education seems to be well-reflected in the cluster (e.g., Lu et al., 2019; Pan et al., 2021). For instance, Nozawa et al. (2019) observed that the behavioral synchrony between teacher and learner enhanced both the perceived quality of the interaction and the interpersonal brain synchrony in the lateral prefrontal cortex. Considering the association between interactional quality, behavioral, and neural synchrony, Balters et al. (2020) suggested that a hyperscanning approach would be ideal to assess the differences between in-person and virtual social interactions, which were largely used in educational settings during the COVID-19 pandemic.

### *Cluster #3: virtual environments*

In cluster #3, the major citing documents were authored by Nam et al. (2020) (coverage = 27; GCS = 21), Czeszumski et al. (2020) (coverage = 23; GCS = 153), and Schwartz et al. (2022) (coverage = 19; GCS = 5). In line with Balters et al. (2020), the focus of cluster #3 appears to be the investigation of interpersonal neural synchrony in virtual environments (e.g., Barde et al. (2020)). With the increase in the use of virtual environments for collaboration and social interactions (Barde et al., 2020), several documents in the cluster examined whether in-person and virtual social interactions share the same neural underpinnings. The preliminary studies by Gumilar et al. (2021) and by Wikström et al. (2022) showed that interpersonal brain synchrony in virtual interactions mimics the one observed in in-person interactions. However, contrasting results were reported by Schwartz et al. (2022), who observed lower interpersonal neural synchrony in technologically-assisted interactions as compared to in-person interactions between mother and child.

### *Cluster #2: verbal communication*

The major citing documents in cluster #2 were authored by Nam et al. (2020) (coverage = 35; GCS = 21) and Kelsen et al. (2022) (coverage = 22; GCS = 26). The common thematic interest of research in this cluster regards the use of hyperscanning to investigate the neural mechanisms of verbal communication (e.g., Jiang et al., 2021; Wang et al., 2022). Particularly, Kelsen et al. (2022) observed that patterns of interpersonal brain synchrony among communicators predominantly emerge from frontal and temporo-parietal brain regions. As for the authors, synchronization in these regions might reflect the activity of the mirror and mentalizing system.

### *Cluster #7: interoception*

In cluster #7, the major citing documents were written by Balconi and Angioletti (2023c) (coverage = 20; GCS = 3), Balconi and Angioletti (2023b) (coverage = 16; GCS = 0), and Balconi and Angioletti (2023a) (coverage = 15; GCS = 2). This cluster of research includes scientific works in which hyperscanning was used to investigate how interoceptive attentiveness modulates interpersonal brain synchrony. Interoception is the mechanism through which the brain perceives and integrates information derived from the body (Balconi and Angioletti, 2023a; Khalsa et al., 2018). Single-participant studies have suggested that interoception plays a role in social processes (e.g., self-other distinction, social cognition, social isolation, and connectedness Balconi and Angioletti (2023a). Moving from this scientific literature, several works in cluster #7 assessed the effect of interoceptive attentiveness on the physiological and neural mechanisms in dyadic settings. Results from Balconi and Angioletti (2023a), Balconi and Angioletti (2023b), Balconi and Angioletti (2023c) and Balconi et al. (2023) seem to corroborate the hypothesis for which interoceptive attentiveness modulates social connectedness by acting on both the physiological and neural levels.

*Cluster #6: parent–child*

The major citing documents in cluster #6 were authored by Schwartz et al. (2022) (coverage = 13; GCS = 5), Holroyd (2022) (coverage = 12; GCS = 12), and Nguyen et al. (2021) (coverage = 12; GCS = 16). The focus of the cluster was twofold. On the one side, several documents explored the methodological approaches and challenges in hyperscanning studies (e.g., Bizzego et al., 2021; Bizzego et al., 2022a; Holroyd, 2022). From this effort, several methodological guidelines for conducting fNIRS and EEG hyperscanning studies were derived and made available for the scientific community (e.g., Kayhan et al., 2022; Nguyen et al., 2021; Turk et al., 2022). On the other side, many works in the cluster used hyperscanning to investigate the neural mechanisms underlying mother–child interactions (e.g., Azhari et al., 2022; Nguyen et al., 2020). Particularly, Endevelt-Shapira and Feldman (2023) showed that profiles of interpersonal neural synchrony differentiate between caregiving behaviors in terms of intrusiveness and sensitivity. Similar works on mother–child also suggest adopting a multimodal approach to investigate instances of synchrony in behavior, physiology, and neural data during real-life social interactions (e.g., Horowitz-Kraus and Gashri, 2023). The integration of behavioral, physiological, and neural data unifies the literature on bio-behavioral synchrony to obtain a holistic perspective of real-life social interactions (Carollo et al., 2021; Feldman, 2012; Hamilton, 2021).

*Overall temporal evolution of the clusters*

The network of documents developed starting from 2002 with Montague et al. (2002)'s seminal paper on hyperscanning. After the introduction of this new paradigm in neuroscience, initial works focused on the feasibility of using EEG to conduct experiments with two participants. These works also developed a set of methods to characterize synchrony between brains. The initial experiments in hyperscanning were designed using controlled tasks, such as cooperative games, and mainly focused on the domains of cooperation and imitation, taking inspiration from the findings and the tasks related to the mirror-neuron system theory.

Subsequently, around 2008, some scholars sought to gain more insight into the brain regions supporting individuals involved in naturalistic interactions. fNIRS emerged as the elective tool to do so, as it has higher spatial resolution and is less sensitive to movements than EEG (Carollo et al., 2022). The interest in ecologically valid experiments led to considering more complex and previously neglected components of social interactions, such as affect and communication patterns.

More recently, hyperscanning research has shown translational potential in educational settings and in investigating the underlying mechanisms supporting interactions in virtual environments. The most recent cluster focuses on the use of hyperscanning to investigate parent–child interactions using real-life tasks, often employing a multimodal approach and integrating behavioral, physiological, and neural data.

## Limitations of the study

Although the scientometric approach offers valuable insights into the main thematic domains of research in the scientific literature, it has several limitations to consider. Among all, the scientometric approach strongly relies on quantitative bibliometric information among documents, which does not necessarily convey any information regarding the quality of the science or the nature of citations. For instance, certain studies might receive less attention from the academic community despite having high scientific standards and quality in their designs (Callaham et al., 2002). This is particularly true for documents published by less prestigious institutions or by disadvantaged groups (e.g., researchers who cannot afford to publish their documents in high-impact journals). The current manuscript does not aim to perpetuate a system where quantitative measures are prioritized over qualitative ones. Therefore, in the Discussion section, we included a qualitative review of the clusters (Hicks et al., 2015). Additionally, when discussing the clusters, we not only reviewed the content of the cited documents but also focused more on the citing documents. This approach helps mitigate biases resulting from the quantitative properties of documents since citing documents are included in the thematic clusters based on the citations they make, rather than the citations they receive.

The literature on hyperscanning has been strongly influenced by ten key research trends. Over time, the field has evolved from discussions about methods for EEG hyperscanning studies to the exploration of more ecologically valid paradigms that simulate everyday life. The introduction of fNIRS has enabled the implementation of hyperscanning designs in more naturalistic settings (e.g., musical settings, educational settings, parent–child interactions) while providing spatial information about the brain activity under investigation. According to scientometric analysis, the use of neuroimaging techniques in hyperscanning is well-established, while the use of brain stimulation has not yet emerged, likely due to its recent introduction as an approach. This finding suggests the need for further studies that combine multi-brain stimulation with neuroimaging techniques to begin interpreting interbrain neural synchrony in a causal manner.

## Data and code availability statement

All data were retrieved from Scopus using the string "TITLE-ABS-KEY(hyperscan*)". CiteSpace software (Chen, 2006) was used for the scientometric analysis and *bibliometrix* package (Aria and Cuccurullo, 2017) was used for the bibliometric analysis.

## Authors contribution

Conceptualization: AC, GE; Methodology: AC; Formal Analysis: AC; Investigation: AC; Writing–original draft preparation: AC; Writing–review and editing: AC, GE; Supervision: GE. All authors have read and agreed to the published version of the manuscript.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

Abe, M.O., Koike, T., Okazaki, S., Sugawara, S.K., Takahashi, K., Watanabe, K., Sadato, N., 2019. Neural correlates of online cooperation during joint force production. NeuroImage 191, 150–161.
Acquadro, M.A., Congedo, M., De Riddeer, D., 2016. Music performance as an experimental approach to hyperscanning studies. Front. Human Neurosci. 10, 242.
Adolphs, R., 2003. Cognitive neuroscience of human social behaviour. Nat. Rev. Neurosci. 4 (3), 165–178.
Aria, M., Cuccurullo, C., 2017. bibliometrix: An r-tool for comprehensive science mapping analysis. J. Inform. 11 (4), 959–975.
Ashton-James, C., Van Baaren, R.B., Chartrand, T.L., Decety, J., Karremans, J., 2007. Mimicry and me: The impact of mimicry on self–construal. Soc. Cognit. 25 (4), 518–535.
Aslin, R.N., Mehler, J., 2005. Near-infrared spectroscopy for functional studies of brain activity in human infants: promise, prospects, and challenges. J. Biomed. Opt. 10 (1). 011009–011009.
Astolfi, L., Cincotti, F., Mattia, D., Babiloni, C., Carducci, F., Basilisco, A., Rossini, P., Salinari, S., Ding, L., Ni, Y., et al, 2005. Assessing cortical functional connectivity by linear inverse estimation and directed transfer function: simulations and application to real data. Clin. Neurophysiol. 116 (4), 920–932.
Astolfi, L., Toppi, J., Borghini, G., Vecchiato, G., He, E.J., Roy, A., Cincotti, F., Salinari, S., Mattia, D., He, B., et al, 2012. Cortical activity and functional hyperconnectivity

by simultaneous eeg recordings from interacting couples of professional pilots. In: 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, pp. 4752–4755.
Astolfi, L., Toppi, J., Borghini, G., Vecchiato, G., Isabella, R., Fallani, F.D.V., Cincotti, F., Salinari, S., Mattia, D., He, B., et al, 2011a. Study of the functional hyperconnectivity between couples of pilots during flight simulation: an eeg hyperscanning study. In: 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, pp. 2338–2341.
Astolfi, L., Toppi, J., Casper, C., Freitag, C., Mattia, D., Babiloni, F., Ciaramidaro, A., Siniatchkin, M., 2015. Investigating the neural basis of empathy by eeg hyperscanning during a third party punishment. In: 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, pp. 5384–5387.
Astolfi, L., Toppi, J., De Vico Fallani, F., Vecchiato, G., Salinari, S., Mattia, D., Cincotti, F., Babiloni, F., 2010. Neuroelectrical hyperscanning measures simultaneous brain activity in humans. Brain Topogr. 23, 243–256.
Astolfi, L., Toppi, J., Fallani, F.D.V., Vecchiato, G., Cincotti, F., Wilke, C.T., Yuan, H., Mattia, D., Salinari, S., He, B., et al, 2011b. Imaging the social brain by simultaneous hyperscanning during subject interaction. IEEE Intell. Syst. 26 (5), 38.
Atsumori, H., Kiguchi, M., Katura, T., Funane, T., Obata, A., Sato, H., Manaka, T., Iwamoto, M., Maki, A., Koizumi, H., et al, 2010. Noninvasive imaging of prefrontal activation during attention-demanding tasks performed while walking using a wearable optical topography system. J. Biomed. Opt. 15 (4). 046002–046002.
Atsumori, H., Kiguchi, M., Obata, A., Sato, H., Katura, T., Funane, T., Maki, A., 2009. Development of wearable optical topography system for mapping the prefrontal cortex activation. Rev. Sci. Instrum. 80 (4).
Atsumori, H., Kiguchi, M., Obata, A., Sato, H., Katura, T., Utsugi, K., Funane, T., Maki, A., 2007. Development of a multi-channel, portable optical topography system. In: 2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, pp. 3362–3364.
Azhari, A., Bizzego, A., Balagtas, J.P.M., Leng, K.S.H., Esposito, G., 2022. Asymmetric prefrontal cortex activation associated with mutual gaze of mothers and children during shared play. Symmetry 14 (5), 998.
Babiloni, C., Buffo, P., Vecchio, F., Marzano, N., Del Percio, C., Spada, D., Rossi, S., Bruni, I., Rossini, P.M., Perani, D., 2012. Brains "in concert": frontal oscillatory alpha rhythms and empathy in professional musicians. Neuroimage 60 (1), 105–116.
Babiloni, C., Vecchio, F., Infarinato, F., Buffo, P., Marzano, N., Spada, D., Rossi, S., Bruni, I., Rossini, P.M., Perani, D., 2011. Simultaneous recording of electroencephalographic data in musicians playing in ensemble. Cortex 47 (9), 1082–1090.
Babiloni, F., Astolfi, L., 2014. Social neuroscience and hyperscanning techniques: past, present and future. Neurosci. Biobehav. Rev. 44, 76–93.
Babiloni, F., Cincotti, F., Babiloni, C., Carducci, F., Mattia, D., Astolfi, L., Basilisco, A., Rossini, P.M., Ding, L., Ni, Y., et al, 2005. Estimation of the cortical functional connectivity with the multimodal integration of high-resolution eeg and fmri data by directed transfer function. Neuroimage 24 (1), 118–131.
Babiloni, F., Cincotti, F., Mattia, D., de Vico Fallani, F., Tocci, A., Bianchi, L., Salinari, S., Marciani, M., Colosimo, A., Astolfi, L., 2007a. Simultaneous tracking of multiple brains activity with high resolution eeg hyperscannings. In: 2007 Joint Meeting of the 6th International Symposium on Noninvasive Functional Source Imaging of the Brain and Heart and the International Conference on Functional Biomedical Imaging. IEEE, pp. 196–199.
Babiloni, F., Cincotti, F., Mattia, D., Fallani, F.D.V., Tocci, A., Bianchi, L., Salinari, S., Marciani, M., Colosimo, A., Astolfi, L., 2007b. High resolution eeg hyperscanning during a card game. In: 2007 29th annual international conference of the IEEE engineering in medicine and biology society. IEEE, pp. 4957–4960.
Babiloni, F., Cincotti, F., Mattia, D., Mattiocco, M., Fallani, F.D.V., Tocci, A., Bianchi, L., Marciani, M.G., Astolfi, L., 2006. Hypermethods for eeg hyperscanning. In: 2006 International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, pp. 3666–3669.
Baess, P., Zhdanov, A., Mandel, A., Parkkonen, L., Hirvenkari, L., Mäkelä, J.P., Jousmäki, V., Hari, R., 2012. Meg dual scanning: a procedure to study real-time auditory interaction between two persons. Front. Human Neurosci. 6, 83.
Balconi, M., Allegretta, R.A., Angioletti, L., 2023. Autonomic synchrony induced by hyperscanning interoception during interpersonal synchronization tasks. Front. Human Neurosci. 17.
Balconi, M., Angioletti, L., 2023a. Dyadic inter-brain eeg coherence induced by interoceptive hyperscanning. Scient. Rep. 13 (1), 4344.
Balconi, M., Angioletti, L., 2023b. Hemodynamic and electrophysiological biomarkers of interpersonal tuning during interoceptive synchronization. Information 14 (5), 289.
Balconi, M., Angioletti, L., 2023c. Inter-brain hemodynamic coherence applied to interoceptive attentiveness in hyperscanning: Why social framing matters. Information 14 (2), 58.
Balconi, M., Gatti, L., Vanutelli, M.E., 2018a. Eeg functional connectivity and brain-to-brain coupling in failing cognitive strategies. Conscious. Cogn. 60, 86–97.
Balconi, M., Vanutelli, M.E., 2017. Cooperation and competition with hyperscanning methods: review and future application to emotion domain. Front. Comput. Neurosci. 11, 86.
Balconi, M., Vanutelli, M.E., et al, 2018b. Eeg hyperscanning and behavioral synchronization during a joint actions. Neuropsychol. Trends 2018 (24), 23–47.
Balconi, M., Vanutelli, M.E., Gatti, L., 2018c. Functional brain connectivity when cooperation fails. Brain Cognit. 123, 65–73.
Balters, S., Baker, J.M., Hawthorne, G., Reiss, A.L., 2020. Capturing human interaction in the virtual age: a perspective on the future of fnirs hyperscanning. Front. Human Neurosci. 14, 588494.
Barde, A., Gumilar, I., Hayati, A.F., Dey, A., Lee, G., Billinghurst, M., 2020. A review of hyperscanning and its use in virtual environments. Informatics 7 (4), 55.
Bizzego, A., Azhari, A., Esposito, G., 2021. Assessing computational methods to quantify mother-child brain synchrony in naturalistic settings based on fnirs signals. Neuroinformatics, 1–10.
Bizzego, A., Azhari, A., Gianluca, E., 2022a. Reproducible inter-personal brain coupling measurements in hyperscanning settings with functional near infra-red spectroscopy. Neuroinformatics 20 (3), 665–675.
Bizzego, A., Gabrieli, G., Azhari, A., Lim, M., Esposito, G., 2022b. Dataset of parent-child hyperscanning functional near-infrared spectroscopy recordings. Scient. Data 9 (1), 625.
Bizzego, A., Neoh, M., Gabrieli, G., Esposito, G., 2022. A machine learning perspective on fnirs signal quality control approaches. IEEE Trans. Neural Syst. Rehabil. Eng. 30, 2292–2300.
Burgess, A.P., 2013. On the interpretation of synchronization in eeg hyperscanning studies: a cautionary note. Front. Human Neurosci. 7, 881.
Callaham, M., Wears, R.L., Weber, E., 2002. Journal prestige, publication bias, and other characteristics associated with citation of published studies in peer-reviewed journals. Jama 287 (21), 2847–2850.
Carollo, A., Cataldo, I., Fong, S., Corazza, O., Esposito, G., 2022. Unfolding the real-time neural mechanisms in addiction: Functional near-infrared spectroscopy (fnirs) as a resourceful tool for research and clinical practice. Addict. Neurosci. 4, 100048.
Carollo, A., Lim, M., Aryadoust, V., Esposito, G., 2021. Interpersonal synchrony in the context of caregiver-child interactions: A document co-citation analysis. Front. Psychol. 12, 701824.
Carter, R.M., Huettel, S.A., 2013. A nexus model of the temporal–parietal junction. Trends Cognit. Sci. 17 (7), 328–336.
Cataldo, I., Lieu, A.A., Carollo, A., Bornstein, M.H., Gabrieli, G., Lee, A., Esposito, G., et al., 2022. From the cradle to the web: The growth of "sharenting"—a scientometric perspective. Human Behav. Emerg. Technol., 2022.
Chen, C., 2006. Citespace ii: Detecting and visualizing emerging trends and transient patterns in scientific literature. J. Am. Soc. Inform. Sci. Technol. 57 (3), 359–377.
Chen, C., Chen, Y., Horowitz, M., Hou, H., Liu, Z., Pellegrino, D., 2009. Towards an explanatory and computational theory of scientific discovery. J. Inform. 3 (3), 191–209.
Chen, C., Ibekwe-SanJuan, F., Hou, J., 2010. The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis. J. Am. Soc. Inform. Sci. Technol. 61 (7), 1386–1409.
Cornejo, C., Cuadros, Z., Morales, R., Paredes, J., 2017. Interpersonal coordination: methods, achievements, and challenges. Front. Psychol. 8, 1685.
Cui, X., Bryant, D.M., Reiss, A.L., 2012. Nirs-based hyperscanning reveals increased interpersonal coherence in superior frontal cortex during cooperation. Neuroimage 59 (3), 2430–2437.
Czeszumski, A., Eustergerling, S., Lang, A., Menrath, D., Gerstenberger, M., Schuberth, S., Schreiber, F., Rendon, Z.Z., König, P., 2020. Hyperscanning: a valid method to study neural inter-brain underpinnings of social interaction. Front. Human Neurosci. 14, 39.
De Vico Fallani, F., Nicosia, V., Sinatra, R., Astolfi, L., Cincotti, F., Mattia, D., Wilke, C., Doud, A., Latora, V., He, B., et al, 2010. Defecting or not defecting: how to "read" human behavior during cooperative games by eeg measurements. PloS one 5 (12), e14187.
Dumas, G., Lachat, F., Martinerie, J., Nadel, J., George, N., 2011. From social behaviour to brain synchronization: review and perspectives in hyperscanning. Irbm 32 (1), 48–53.
Dumas, G., Martinerie, J., Soussignan, R., Nadel, J., 2012. Does the brain know who is at the origin of what in an imitative interaction? Front. Human Neurosci. 6, 128.
Dumas, G., Nadel, J., Soussignan, R., Martinerie, J., Garnero, L., 2010. Inter-brain synchronization during social interaction. PloS One 5 (8), e12166.
Egghe, L., 2006. Theory and practise of the g-index. Scientometrics 69 (1), 131–152.
Endevelt-Shapira, Y., Feldman, R., 2023. Mother–infant brain-to-brain synchrony patterns reflect caregiving profiles. Biology 12 (2), 284.
Feldman, R., 2012. Bio-behavioral synchrony: A model for integrating biological and microsocial behavioral processes in the study of parenting. Parenting 12 (2–3), 154–164.
Freeman, L.C., 1977. A set of measures of centrality based on betweenness. Sociometry, 35–41.
Funane, T., Kiguchi, M., Atsumori, H., Sato, H., Kubota, K., Koizumi, H., 2011. Synchronous activity of two people's prefrontal cortices during a cooperative task measured by simultaneous near-infrared spectroscopy. J. Biomed. Opt. 16 (7). 077011–077011.
Gumilar, I., Barde, A., Hayati, A.F., Billinghurst, M., Lee, G., Momin, A., Averill, C., Dey, A., 2021. Connecting the brains via virtual eyes: eye-gaze directions and inter-brain synchrony in vr. In Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems, pages 1–7.
Hamilton, A.F.d.C., 2021. Hyperscanning: beyond the hype. Neuron 109 (3), 404–407.
Hari, R., Kujala, M.V., 2009. Brain basis of human social interaction: from concepts to brain imaging. Physiol. Rev. 89 (2), 453–479.
Hasson, U., Ghazanfar, A.A., Galantucci, B., Garrod, S., Keysers, C., 2012. Brain-to-brain coupling: a mechanism for creating and sharing a social world. Trends Cognit. Sci. 16 (2), 114–121.
Hicks, D., Wouters, P., Waltman, L., De Rijcke, S., Rafols, I., 2015. Bibliometrics: the leiden manifesto for research metrics. Nature 520 (7548), 429–431.
Hirsch, J., Zhang, X., Noah, J.A., Ono, Y., 2017. Frontal temporal and parietal systems synchronize within and across brains during live eye-to-eye contact. NeuroImage 157, 314–330.

Holper, L., Scholkmann, F., Wolf, M., 2012. Between-brain connectivity during imitation measured by fnirs. Neuroimage 63 (1), 212–222.
Holroyd, C.B., 2022. Interbrain synchrony: on wavy ground. Trends Neurosci. 45 (5), 346–357.
Horowitz-Kraus, T., Gashri, C., 2023. Multimodal approach for characterizing the quality of parent–child interaction: A single synchronization source may not tell the whole story. Biology 12 (2), 241.
Jiang, J., Dai, B., Peng, D., Zhu, C., Liu, L., Lu, C., 2012. Neural synchronization during face-to-face communication. J. Neurosci. 32 (45), 16064–16069.
Jiang, J., Zheng, L., Lu, C., 2021. A hierarchical model for interpersonal verbal communication. Soc. Cognit. Affect. Neurosci. 16 (1–2), 246–255.
Kayhan, E., Matthes, D., Haresign, I.M., Bánki, A., Michel, C., Langeloh, M., Wass, S., Hoehl, S., 2022. Deep: A dual eeg pipeline for developmental hyperscanning studies. Develop. Cognit. Neurosci. 54, 101104.
Kelsen, B.A., Sumich, A., Kasabov, N., Liang, S.H., Wang, G.Y., 2022. What has social neuroscience learned from hyperscanning studies of spoken communication? a systematic review. Neurosci. Biobehav. Rev. 132, 1249–1262.
Khalsa, S.S., Adolphs, R., Cameron, O.G., Critchley, H.D., Davenport, P.W., Feinstein, J. S., Feusner, J.D., Garfinkel, S.N., Lane, R.D., Mehling, W.E., et al, 2018. Interoception and mental health: a roadmap. Biol. Psychiatry: Cognit. Neurosci. Neuroimag. 3 (6), 501–513.
Kleinberg, J. (2002). Bursty and hierarchical structure in streams. In: Proceedings of the eighth ACM SIGKDD international conference on Knowledge discovery and data mining, pages 91–101.
Koike, T., Tanabe, H.C., Sadato, N., 2015. Hyperscanning neuroimaging technique to reveal the "two-in-one" system in social interactions. Neurosci. Res. 90, 25–32.
Konvalinka, I., Roepstorff, A., 2012. The two-brain approach: how can mutually interacting brains teach us something about social interaction? Front. Human Neurosci. 6, 215.
Konvalinka, I., Xygalatas, D., Bulbulia, J., Schjødt, U., Jegindø, E.-M., Wallot, S., Van Orden, G., Roepstorff, A., 2011. Synchronized arousal between performers and related spectators in a fire-walking ritual. Proc. Nat. Acad. Sci. 108 (20), 8514–8519.
Leydesdorff, L., 2007. Betweenness centrality as an indicator of the interdisciplinarity of scientific journals. J. Am. Soc. Inform. Sci. Technol. 58 (9), 1303–1319.
Lindenberger, U., Li, S.-C., Gruber, W., Müller, V., 2009. Brains swinging in concert: cortical phase synchronization while playing guitar. BMC Neurosci. 10 (1), 1–12.
Lopes, P.N., Salovey, P., Côté, S., Beers, M., Petty, R.E., 2005. Emotion regulation abilities and the quality of social interaction. Emotion 5 (1), 113.
Lu, H., Wang, X., Zhang, Y., Huang, P., Xing, C., Zhang, M., Zhu, X., 2023. Increased interbrain synchronization and neural efficiency of the frontal cortex to enhance human coordinative behavior: A combined hyper-tes and fnirs study. NeuroImage, 120385.
Lu, K., Qiao, X., Hao, N., 2019. Praising or keeping silent on partner's ideas: Leading brainstorming in particular ways. Neuropsychologia 124, 19–30.
Martin, R.S., Huettel, S.A., 2022. Cognitive functions as revealed by imaging of the human brain. In: Neuroscience in the 21st century: From basic to clinical. Springer, pp. 3087–3113.
Montague, P.R., Berns, G.S., Cohen, J.D., McClure, S.M., Pagnoni, G., Dhamala, M., Wiest, M.C., Karpov, I., King, R.D., Apple, N., et al, 2002. Hyperscanning: simultaneous fmri during linked social interactions. Neuroimage 16 (4), 1159–1164.
Nam, C.S., Choo, S., Huang, J., Park, J., 2020. Brain-to-brain neural synchrony during social interactions: a systematic review on hyperscanning studies. Appl. Sci. 10 (19), 6669.
Newman, M.E., 2005. A measure of betweenness centrality based on random walks. Social networks 27 (1), 39–54.
Nguyen, T., Banki, A., Markova, G., Hoehl, S., 2020. Studying parent-child interaction with hyperscanning. Prog. Brain Res. 254, 1–24.
Nguyen, T., Hoehl, S., Vrtička, P., 2021. A guide to parent-child fnirs hyperscanning data processing and analysis. Sensors 21 (12), 4075.
Nguyen, T., Schleihauf, H., Kayhan, E., Matthes, D., Vrtička, P., Hoehl, S., 2020. The effects of interaction quality on neural synchrony during mother-child problem solving. cortex 124, 235–249.
Novembre, G., Iannetti, G.D., 2021. Hyperscanning alone cannot prove causality. multibrain stimulation can. Trends Cognit. Sci. 25 (2), 96–99.
Nozawa, T., Sakaki, K., Ikeda, S., Jeong, H., Yamazaki, S., Kawata, K.H.d.S., Kawata, N. Y.d.S., Sasaki, Y., Kulason, K., Hirano, K., et al, 2019. Prior physical synchrony enhances rapport and inter-brain synchronization during subsequent educational communication. Scient. Rep. 9 (1), 12747.
Nozawa, T., Sasaki, Y., Sakaki, K., Yokoyama, R., Kawashima, R., 2016. Interpersonal frontopolar neural synchronization in group communication: an exploration toward fnirs hyperscanning of natural interactions. Neuroimage 133, 484–497.
Pan, Y., Guyon, C., Borragán, G., Hu, Y., Peigneux, P., 2021. Interpersonal brain synchronization with instructor compensates for learner's sleep deprivation in interactive learning. Biochem. Pharmacol. 191, 114111.
Rizzolatti, G., Craighero, L., 2004. The mirror-neuron system. Annu. Rev. Neurosci. 27, 169–192.
Rousseeuw, P.J., 1987. Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. J. Comput. Appl. Math. 20, 53–65.
Sänger, J., Müller, V., Lindenberger, U., 2012. Intra-and interbrain synchronization and network properties when playing guitar in duets. Front. Human Neurosci. 6, 312.
Sänger, J., Müller, V., Lindenberger, U., 2013. Directionality in hyperbrain networks discriminates between leaders and followers in guitar duets. Front. Human Neurosci. 7, 234.
Scholkmann, F., Holper, L., Wolf, U., Wolf, M., 2013. A new methodical approach in neuroscience: assessing inter-personal brain coupling using functional near-infrared imaging (fniri) hyperscanning. Front. Human Neurosci. 7, 813.
Schwartz, L., Levy, J., Endevelt-Shapira, Y., Djalovski, A., Hayut, O., Dumas, G., Feldman, R., 2022. Technologically-assisted communication attenuates inter-brain synchrony. Neuroimage 264, 119677.
Small, H., 1973. Co-citation in the scientific literature: a new measure of the relationship between two documents. J. Am. Soc. Inform. Sci. 24 (4), 265–269.
Small, H., 1980. Co-citation context analysis and the structure of paradigms. J. Document..
Tognoli, E., Lagarde, J., DeGuzman, G.C., Kelso, J.S., 2007. The phi complex as a neuromarker of human social coordination. Proc. Nat. Acad. Sci. 104 (19), 8190–8195.
Toppi, J., Borghini, G., Petti, M., He, E.J., De Giusti, V., He, B., Astolfi, L., Babiloni, F., 2016. Investigating cooperative behavior in ecological settings: an eeg hyperscanning study. PloS one 11 (4), e0154236.
Trujillo, C.M., Long, T.M., 2018. Document co-citation analysis to enhance transdisciplinary research. Sci. Adv. 4 (1), e1701130.
Turk, E., Endevelt-Shapira, Y., Feldman, R., van den Heuvel, M.I., Levy, J., 2022. Brains in sync: Practical guideline for parent–infant eeg during natural interaction. Front. Psychol. 13, 833112.
Twenge, J.M., Baumeister, R.F., DeWall, C.N., Ciarocco, N.J., Bartels, J.M., 2007. Social exclusion decreases prosocial behavior. J. Personal. Soc. Psychol. 92 (1), 56.
Wang, X., Lu, K., He, Y., Gao, Z., Hao, N., 2022. Close spatial distance and direct gaze bring better communication outcomes and more intertwined neural networks. NeuroImage 261, 119515.
Wikström, V., Saarikivi, K., Falcon, M., Makkonen, T., Martikainen, S., Putkinen, V., Cowley, B.U., Tervaniemi, M., 2022. Inter-brain synchronization occurs without physical co-presence during cooperative online gaming. Neuropsychologia 174, 108316.