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# REAL-TIME NEUROFEEDBACK ON INTER-BRAIN SYNCHRONY: CURRENT STATES AND PERSPECTIVES

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ABSTRACT: During neurofeedback (NFB) user training, participants learn to control the feedback associated with specific components of their brain activity, also called neuromarkers, to improve the cognitive abilities related to these neuromarkers, such as attention and mental workload. The recent development of methods to record the activity of several people's brains simultaneously opens up the study of neuromarkers related to social interactions, computed from inter-brain synchrony (IBS). Here, we review the previous articles that trained participants to control electroencephalographic neuromarkers computed from inter-brain metrics. The topic remains relatively unexplored as we only identified seven articles in the literature. We specifically studied the characteristics of the user's training, i.e., instruction, task and feedback, and the neuromarkers used to provide feedback. The reported results are promising as four studies including subjective measures of interaction report higher interaction and relationship scores with higher IBS during NFB training. Finally, we draw guidelines, identify open challenges, and suggests recommendations for future studies on this topic.

## INTRODUCTION

Neurofeedback (NFB) refers to a paradigm that trains participants to voluntarily modulate specific components of their brain activity, also called neuromarkers. The desired modulation of these neuromarkers is rewarded by sensory stimuli based on the acquired neurophysiological data [1]. The aim is to improve cognitive abilities associated with these neuromarkers as a results of the NFB training. NFB has been widely used for clinical and non-clinical purposes, such as a treatment of social anxiety disorder (SAD) [2] and improving brain-computer interface (BCI) performance [3]. The development of simultaneous multi-brain recording enabled the study of neuromarkers that are specific to social interaction with many new promising applications. In this regard, Saul et al. [2] suggested developing new NFB-based treatments of SAD based on neuromarkers acquired from multi-brain recordings. This suggestion is based on the previous finding of a relationship between inter-brain synchronization and SAD [4]. In addition to self-centered individual NFB, the extended use of NFB aims to integrate individual participants' brain activities in a common framework to detect synchronous brain activities during social interaction paradigms.
However, there is a lack of literature specifically focused on brain-to-brain real-time interactions, as the majority of NFB studies concern individual brain activities [1, 5] rather than inter-brain activities. Also, the majority of hyperscanning studies are investigating offline neuromarkers rather than online synchronization-related neuromarkers [6]. In this regard, the current review aims to provide an overview of the current state of research on inter-brain synchrony-based NFB to identify related challenges, provide recommendation and suggest ideas for future research. We targeted online inter-brain NFB experiments, focusing on feedback scenarios involving more than one participant and online inter-brain neuromarkers. We report on the validation of these neuromarkers, in addition to common essential information in these NFB studies: goals, instructions, sensory stimuli and outcomes. Moreover, we focused this review on electroencephalography (EEG) based on the analysis from Saul et al. that EEG would be the neuroimaging technique of choice for inter-brain NFB studies as EEG provides brain activity measures with high temporal resolution, a requirement for duration-bound experimental stimuli [2]. EEG provides also great portability, which is an advantage for studies in naturalistic environments, as the EEG is not limited to specialized spaces, such as shielded rooms.

## MATERIALS AND METHODS

*Study selection:* This review mainly focuses on both the user training and the neuromarkers characteristics of these NFB protocols. To retrieve all relevant papers, a systematic literature search has been conducted in the Scopus and Web of Science databases as described in Figure 1. The following keywords were used: (*EEG* OR *Electroencephalography*) AND (*Brain-Computer Interface* OR *Brain-Machine Interface* OR *Neural Interface* OR *Neurotherapy* OR *Neurofeedback*) AND (*IBS* OR *Inter-Brain* OR *Hyperscanning* OR *Brain Synchrony* OR *Social interaction*). Papers published until the end of December 2023 were included. Two of the authors (KW and LP) reviewed the titles, abstracts, and KW read



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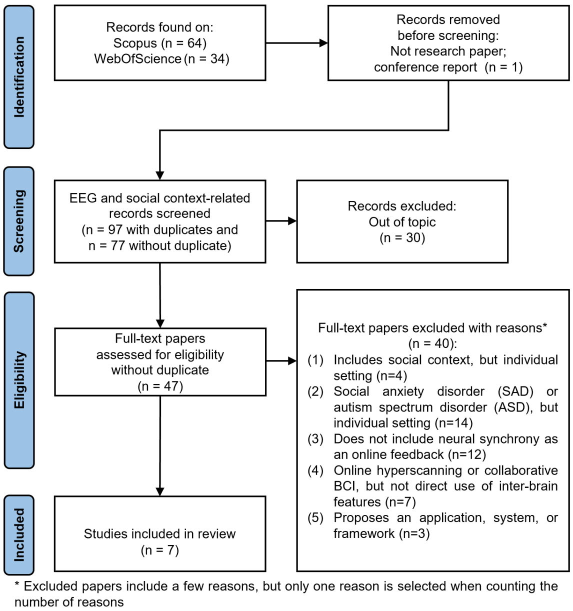


Figure 1: PRISMA flowchart for the inclusion of studies.

the whole papers if there was a doubt. Both reviewers agreed on the selection of the studies. The inclusion criteria used were the following ones: (1) presentation of experimental results on NFB training using inter-brain synchrony/similarity for the online feedback (2) electroencephalographic neuromarker used for the NFB training. Studies that did not satisfy both of the inclusion criteria were excluded. The exclusion criteria were the following ones: (1) non-clinical studies including social context, but individual recording and neurofeedback, (2) clinical studies including social context, but individual recordings and neurofeedback, (3) studies not incorporating neural synchrony as online feedback but as offline measures (4) hyperscanning studies not incorporating inter-brain features to limit our focus on feedback training based on direct measure of inter-brain synchrony (voting for decision-making and competition are also interactions, but the performances are often calculated in online scenarios by combining individual features or classification results rather than inter-brain synchrony) (5) studies proposing the development of an algorithm, an application, or a framework instead of a neurophysiological analysis.

*Data extraction:* In this review, we extracted information related to the: (1) objective and results of the NFB study, (2) online neuromarkers used for the NFB, (3) interaction task and feedback, (4) instructions provided to the participants. Additional validation or analyses are described, such as re-calculation of synchrony with statistical validation and correlation analysis with subjective measurements.

## RESULTS

Our search led to the inclusion of seven papers in this review. A summary of experimental scenarios, feedback, online features, and overall characteristics for each selected paper is provided in Tab. 1. Among the selected studies, the two studies [7, 8] from the same group include different numbers of participants and offline data analysis, but they had the same characteristics that we focused on in this review. Eventually, we summarized these two studies in the same row (the fourth row in Tab. 1).

*Neurofeedback outcomes:* To investigate neurofeedback outcomes, five studies out of the selected studies conducted subsequent offline analyses to validate synchrony and investigate correlations to subjective measurements through more sophisticated artifact reduction and complex synchrony metrics with statistical validation [7–11]. For example, Susnoschi Luca et al. [9] re-calculated synchrony using phase-locking value (PLV) instead of their online measure (relative alpha) and validated it through a permutation test. As a result, they found that the PLV obtained during the baseline period did not pass the permutation test, meaning that participants did not exhibit synchrony during this phase. In contrast, the PLV during the task showed significant synchrony in theta, alpha, and beta bands, showing that the synchrony-based NFB could also affect different bands other than the target bands. Müller et al. found a significant positive correlation between the synchrony in theta band and the self-reported partner's likeability [10], and Salminen et al. found higher self-reported empathy toward partners with synchrony-based feedback blocks compared to no-feedback blocks [7, 8]. Lastly, Dikker et al. re-calculated synchrony with two different measures, imagery part of coherence (iCOH) and projected power correlation (PPC), and found significant correlations between PPC (7-8 Hz) and relationship duration, iCOH (21-22 Hz) and social closeness, and PPC (14-15 Hz) and personal distress.

*Neurofeedback scenario and stimuli:* Among the selected papers, five studies provided visual feedback [7–11], and two studies involved auditory feedback [12, 13]. As visual feedback, Dikker et al. [11] used a mutual wave machine in a dome-like environment during public exhibitions where two participants were seated face-to-face. The participants were engaged in a 10-minute face-to-face interaction, and the light pattern of the mutual wave machine was rendered so that higher synchrony between partners corresponded to brighter lighting projected onto each surface. Salminen et al. [7, 8] designed a shared virtual environment of meditation called DYNECOM, where multiple avatars representing participants were sitting in a ring on a small shrine-like platform with natural wind sounds. A bridge connected the two facing avatars, and the participants were instructed to concentrate on empathetic feelings toward their partner. The synchrony between the two participants modulated the intensity and color of the light shining on both sides of the bridge between the two avatars. Susnoschi Luca et al. [9] designed a GUI that consists of two gauge bars on the left and right-sides representing the relative alpha for each participant and a seesaw in the middle indicating the balance between their relative alpha. During the collaborative task,



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the participants were instructed to maintain their relative alpha levels within 5% to keep the balance of the seesaw without speaking and body movements. Likewise, Müller et al. [10] designed an NFB task that consists of two balls. During the task, the balls got closer or further away from each other depending on the neural synchrony between the two participants. The participants were instructed to move the balls towards each other by controlling their brain activity accordingly, relying on various mental strategies such as relaxation, mental calculation, thoughts generation, etc.

Regarding auditory feedback, two studies controlled music, such as volume and beats, using neural synchrony. Winters and Koziej [12] mapped neural synchrony to control the volume of an ambient music stream (higher synchrony was mapped to increased volume) played through speakers during natural face-to-face interactions in public exhibitions. Ceccato et al. [13] developed a Brain-Computer Musical Interface (BCMI) that changed music through the neural synchrony estimation by increasing or decreasing the interval between musical notes, yielding more pleasant music in case of high synchrony between two participants.

*Task instructions:* We investigated whether the task instructions provided in the studies were explicit, i.e., participants were told that the synchrony in their brain activity modulated the perceived stimuli. Salminen et al. [7, 8] implicitly instructed participants to utilize the information provided by the environment and concentrate on empathetic feelings toward their pair, whereas Winters and Koziej explicitly informed participants that they would hear the music when their brain activities were synchronized [12]. Dikker et al. compared implicit vs explicit instructions, and found that explicit instructions increased synchrony significantly over time, whereas implicit instructions induced no significant changes [11].

Additionally, we divided the studies into goal-oriented and not goal-oriented instructions depending on whether the participants had a goal to achieve. For example, Susnoschi Luca et al. and Müller et al. [9, 10] gave their participants the goal to keep the balance of the seesaw and to move balls towards each other by modulating their brain activity. The participants focused on the balls and seesaw controlled by their synchrony during the NFB. On the other hand, the rest of the studies places participants in a natural face-to-face interaction and did not specify any goal. Even though synchrony between participants modulated the environment (light patterns, music, etc.), there was no direct instruction on whether they should modulate their environment to desired states, such as maintaining specific light patterns or volume or beat of the music. In these face-to-face experiments, the participants just focused on their partner.

*Online neuromarkers:* To calculate inter-brain synchrony as a neurofeedback feature during online scenarios, amplitude or phase coupling measures between two participants were assessed. Amplitude coupling was obtained by comparing band power and filtered EEG amplitudes. For example, Susnoschi Luca et al. [9] compared the relative alpha power (RA) at Pz electrode for each participant and instructed them to maintain their RA within 5% of each other to maintain a collaborative state within pairs. Likewise, Winters and Koziej [12] compared the average alpha band power of two participants at AF7, AF8, TP9, and TP10 electrodes. Dikker et al. [11] assessed the similarity by calculating average and highest Pearson correlation coefficients from all electrode pairs between two participants (AF3, AF4, F3, F4, F7, F8, FC5, FC6, P7, P8, T7, T8, O1, and O2) in delta (1-4 Hz), theta (4-7 Hz), alpha (7-12 Hz), and beta (12-30 Hz) frequency bands. Salminen et al. [7, 8] compared frontal alpha asymmetry between F3 and F4 electrodes between two participants.

Phase coupling was obtained by extracting the instantaneous phase from EEG data and calculating the phase difference or consistency of the difference. Müller et al. [10] calculated the coupling strength as a sum of all possible electrode pairs within and between the two participants through frontocentral (F3, Fz, F4, C3, Cz, and C4) Absolute Coupling Index (ACI) in four frequency bins (2.5, 5, 10, and 20 Hz). The ACI counts the number of samples achieving phase differences ranging between $-\pi/4$ and $\pi/4$. Ceccato et al. [13] calculated phase locking value (PLV) between two participants (Fz, F3, F4, C3, Cz, C4, Pz, and Oz electrodes). The PLV calculates instantaneous phase difference between two signals for each trial and measures variability of the difference across trials, assuming the difference between phase-coupled signals varies little, which is called phase-locking.

## DISCUSSION

*Neurofeedback outcomes:* The selected studies reported neural synchrony during the feedback blocks and correlations between the neural synchrony and self-reported questionnaires, such as social relationship duration and likeability. These results show the presence of neural synchrony during the NFB and its relationship with subjective measures of interaction. However, it is difficult to investigate the progress of these outcomes over time since all the selected studies designed single-session experiments, unlike classical NFB studies, which often includes multi-session [5]. This is mostly likely related to the significant additional time and efforts for installing EEG headsets on multiple people. The selected studies observed significant neural synchrony between participants during the feedback period. However, without comparing before and after the feedback, it is unclear how the NFB modulates neural synchrony over time compared to the pre-feedback period. Furthermore, self-reported questionnaires were collected once either at the beginning or at the end of the experiment with a single condition, so it is difficult to investigate whether the synchrony-based NFB changed the subjective experience and feeling of partners along the experiment, even though the correlation between the synchrony and self-reported



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questionnaires post NFB were obtained. A few selected studies designed control condition, such as a no-feedback condition in addition to a feedback condition [7, 8, 10]. Salminen et al. designed the NFB with various feedback conditions and observed higher self-reported empathy after EEG-based feedback compared to no-feedback condition [7, 8]. Interestingly, Müller et al. designed conditions with normal, fake, and negative feedback (rewarded on weaker synchrony). They found that negative feedback achieved the highest neurofeedback performance, and normal neurofeedback performance achieved the lowest performance in the ball task, meaning that the participants could achieve their best performance when their synchrony was negatively mapped to the balls [10]. Taken together, more evidence is still needed to test the feasibility of the inter-brain NFB, such as how long the feedback effects could last, how many sessions are required to train the synchrony, and how much inter-brain NFB improves social interaction. Therefore, it seems necessary to design a multi-session experiment including pre/post-baseline analysis and various control conditions to confirm whether the neural synchrony could be trained by an inter-brain NFB and investigate the progresses over time.

*NFB scenarios and stimuli:* The selected studies designed NFB scenarios, including 2D object control [9, 10], natural face-to-face interaction [11–13], and meditation [7, 8]. During the NFB condition, feedback was delivered via visual and auditory stimuli. Visual stimuli are effective sensory stimuli for a single task as they are intuitive, and the two studies that used it used objects visually moving according to the neural synchrony [9, 10]. On the other hand, for multitasking situations, using only visual stimuli may not be the ideal stimuli because participants should separate their visual attention on each task. During the NFB tasks designed by Dikker et al. and Salminen et al., participants had to look at the same time at their partner and at the visual feedback (light) controlled by the neural synchrony. The switch of their gaze back and forth between their partner and the visual feedback could have decreased their attention. Attention to their partner and to the feedback stimuli was probably more easily shared in the two studies delivering auditory feedback (music control) during face-to-face interactions [12, 13]. Participants were able to look at their partner while listening to the music controlled by the neural synchrony. Among unused sensory stimuli in the selected studies, tactile stimulation could be used as feedback for the multitasking paradigm. Jeunet et al. incorporated tactile feedback in a multitasking environment consisting of motor imagery BCI and counting visual distracters task [14], showing a better performance than in a condition with visual feedback only. In this regard, the tactile stimulation could be applied within natural face-to-face interactions while maintaining visual attention to partners. However, the effects of those multi-sensory stimuli on neural synchrony and workload should be investigated.

*Task instructions:* Among the selected studies, we investigated task instructions in terms of explicitness and goal-orientation. Regarding goal-orientation instructions, Susnoschi Luca et al. and Müller et al. [9, 10] provided specific goals to achieve to their participants, such as moving balls towards each other and keeping the balance of a seesaw. On the other hand, the rest of the selected studies used indirect instructions in the feedback scenarios. Even though the participants were informed that their synchrony would change their environments, their main task was to interact face-to-face with their partner or to concentrate on empathetic feelings. Those instructions can relate to active and passive NFB, as Saul et al. discussed that their difference is whether the NFB platform responds to a participant who is trying to modulate brain activity to reach or maintain a certain pattern, or to a participant who does not consciously attempt to modulate their brain activity but rather interacts naturally with the setup [2]. Even though it is unclear whether the participants who received non goal-oriented instructions tried to modulate their brain activity, the fact that they did not have a specific goal may have led to differences from the participants who received goal-oriented instructions.

Comparing directly explicit and implicit instructions, Dikker et al. found that a group who was explicitly told that their neural synchrony would be reflected in light patterns showed significantly increased neural synchrony over time, whereas a group with implicit instructions did not show significant changes [11]. They hypothesized that the explicit instruction would function as an incentive for participants to remain focused on the interaction. It shows that instructions can increase or decrease the effectiveness of the NFB on neural synchrony by influencing participants' comprehension of the task and environment. It remains unclear which instructions and scenarios effectively enhance neural synchrony through feedback, so future research should further investigate the effect of different instructions.

*Online neuromarkers:* In general, inter-brain synchronization measures, such as phase synchronization, could be obtained after dedicated pre-processing, excluding bad channels and trials, and reducing noise components, such as motion artifacts and eye blinking. Afterwards, instantaneous phase is obtained for each channel and compared to different channels (intra and inter-brain), yielding adjacency matrices. Each connectivity is then compared to surrogate data to validate that the connectivity is statistically significant. However, feedback must be delivered nearly in real time, which limits the processing time to calculate common synchrony metrics with statistical validation. As a result, we found that the selected studies frequently used band power comparisons and correlation of EEG amplitudes to calculate synchrony as online features instead of complex synchrony metrics used in previous hyperscanning studies, as summarized in the following reviews [15, 16]. A few selected studies conducted the subsequent analysis offline to validate the effects of the NFB [7–11]. Besides band power-based features, one selected study utilized phase-locking value (PLV) from



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eight electrode channels as neural synchrony, but it needs to be further validated, as they only included one pair, and the PLV was not investigated in-depth with statistical validation [13]. Another selected study calculated phase coupling measures online from six electrode channels [10], showing that some measures could be obtained online. In this regard, it would be interesting to investigate the relationship between the online and offline neuromarkers, as the selected studies that conducted further offline analysis and obtained different synchrony measures did not compare those online and offline measures [9, 11].

*Future direction:* We discussed the characteristics of the current inter-brain NFB studies and suggested a few recommendations for future research regarding training features, instructions, and feedback scenarios to address the current concerns. In summary, inter-brain NFB should consider comparing online features to complex synchrony features, use explicit instructions, and investigate the training effects over time. With proper validation of neural synchrony enhancement between two individuals, it seems to have the potential to address difficulties with daily social interactions, as the selected studies found correlations in the neural synchrony between partners during NFB tasks with pairs' likability [10], empathy [7, 8], and social closeness [11].

## CONCLUSION

This review provided a comprehensive overview of the current state of inter-brain synchrony-based NFB. Online synchrony features in amplitude and phase coupling and subsequent offline analyses were identified. Regarding the feedback scenarios and outcomes, we observed the importance of instruction and the necessity of a multi-session experimental design. We hope this review contributes to the groundwork of future investigations into inter-brain NFB based on inter-brain synchrony.

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| Ref. | Dyad | EEG (nb elec.) | Objective | Online feature | Feedback Scenario | Instructions | Outcomes |
|---|---|---|---|---|---|---|---|
| **[9]** | 10 | g.USBamp (16) | To investigate how indirect, non-muscular social interaction during neurofeedback affects players' oscillatory brain activity | Difference of relative alpha | Visual (Screen, 2D seesaw) | Keep the balance of the seesaw | Inter-brain synchrony existed only during the task. |
| **[10]** | 25 | Brain Products (6) | To explore whether inter-brain synchronization (IBS) is amenable to neurofeedback (NFB) | Absolute coupling index (ACI) | Visual (Screen, 2D ball and pendulum) | Move balls towards each other | NFB showed stronger IBS in delta, theta, and beta, and weaker IBS in alpha than rest. |
| **[11]** | 360 | Emotiv (14) | To test the hypothesis that real-time reflection of synchrony would motivate participants to remain socially engaged with each other for the duration of the interaction | Correlation between EEG | Visual (FtF, light pattern) | Explicit group were told that the light patterns reflected the IBS.<br>Non-explicit group: no instruction | Low alpha and beta IBS were correlated to relationship duration and social closeness. Explicit groups showed stronger IBS at beta. |
| **[7]**, **[8]** | 21, 36 | Brain Products (6) | To examine how the different neurofeedback types affected physiological synchrony between the users of the shared space and their self-reported empathy | Difference of alpha asymmetry | Visual (VR-FtF meditation) | Concentrate on empathetic feelings and direct them at partners | NFB induced higher empathy and synchrony of alpha asymmetry compared to non-feedback. |
| **[12]** | NI* | Muse (4) | To design the neurofeedback instrument to be easy to understand and related and pleasant for members of the general public in an exhibition context | Similarity of alpha power | Auditory (FtF, music control) | "When your brainwaves are similar, you will hear the music." | - |
| **[13]** | 1 | Modified g.tec Unicorn (8) | To apply inter-brain synchronization metrics for the development of a multi-user passive brain-computer musical interfaces (BCMI) | Phase locking value (PLV) | Auditory (FtF, music generation) | - | - |

Table 1: Summary of the information extracted from our selected papers. * 4 exhibitions without any number of participants specified. Screen means that participants looked at the screen, and FtF means that participants were seated Face-to-Face during the task.



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