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Boosting Prefrontal Brain Responsiveness by Interoceptive Attentiveness during Synchronized Breathing, Motor, and Cognitive Task

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Abstract: Background: this study explored the prefrontal cortex (PFC) hemodynamic variations produced by the association of an Interoceptive Attentiveness (IA) condition with a simple breath, motor, and cognitive synchronization task. Methods: 18 healthy individuals performed different synchronization activities (breath, motor, and cognitive) under both IA and control conditions, while levels of oxygenated (O2Hb) and deoxygenated hemoglobin were measured using functional Near-Infrared Spectroscopy (fNIRS). Results: findings revealed higher O2Hb levels in the prefrontal brain region during the experimental condition (IA) in contrast to the control condition. Notably, this difference was particularly evident during the cognitive task as opposed to the other tasks (breath and motor). In contrast, no significant differences were found for the PFC lateralization effect. Conclusions: This evidence holds potential for rehabilitation professionals suggesting that the combination of deliberate attention to the breath and a cognitive synchronization task (such as a vocal exercise executed simultaneously) could boost PFC responsiveness.

Keywords: interoception 1; fNIRS 2; prefrontal cortex 3; breath synchronization 4; motor task 5; cognitive task 6

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1. Introduction

Among the various dimensions included in the interoception construct, the "Interoceptive Attentiveness (IA)" [1,2] defined as the focused attention to a particular interoceptive signal (e.g., heart rate or breath) for a specified time interval has received less attention so far.

One of the reasons why this dimension has been less studied in the literature concerns the inherent challenges associated with accurately measuring (i) the capability of individuals to detect and pay attention to subtle bodily signals, such as the heart rate, and (ii) the neural correlates of this ability [3,4]. To overcome the barriers related to the accurate measurement of IA and its neural correlates, Wang and colleagues [4] proposed using a visceral channel that is more easily perceived and autonomously controlled, such as breathing, which allows for studying IA as a deliberate attentional focus on the breath.

IA, understood as the deliberate attention to the breath, stands at the basis of structured and popular protocols integrating the mind and body practices, such as short relaxation practices, brief sessions of controlled breathing, breath counting practices, and focused breathing, which, in turn, demonstrated a positive impact on individuals' neurocognitive functioning [5,6].

At the cognitive level, previous research demonstrated that exercises involving IA could have an empowering effect on a variety of cognitive and emotional functions, including prolonged attentional concentration, cognitive control, and awareness [6,7], regulation of negative emotions [8–11], and the capacity to manage distress and recover from this condition [12]. Of interest to rehabilitation professionals and physiotherapists, it should be noted that even motor processes (such as motor planning, formulating predictions of a partner's movements, and motor coordination with a partner) can be improved by interoceptive training [13]. Furthermore, previous research has proposed a relationship between controlled breathing and motor synchronization, claiming that the former plays a key role in establishing respiration-entrained brain synchrony, which improves motor performance [14] and motor cortex alignment [15].

While the literature previously explored the effects of breath-control exercises on cognition [16] or motor performance [17], less is known about the relation between the attention to breath and cognitive and motor synchronization.

Interpersonal synchronization, which encompasses various social communicative behaviors like collaborative attention, mimicry, turn-taking, and nonverbal social-communication interactions [18], implies temporal and content synchronization between two or more individuals, and deserves special attention [19]. Cognitive and motor synchronization are subtypes of interpersonal synchrony that involve the synchronization of two people engaged in a social engagement and focus on verbal versus nonverbal socio-communicative interactions [20]. The combination of IA practices and cognitive and motor synchronization tasks should be better explored.

Given that exercises and practices involving IA produce benefits at the cognitive, emotional, and motor levels and these effects are supported by specific neural correlates, which "conditions" could be considered optimal for obtaining an empowering cortical effect? Is it possible to obtain greater benefits and higher cortical responsiveness if the "interoceptive exercises" are proposed during resting conditions or when performing a specific cognitive task?

Due to this main aim, preliminary evidence was found about the effect of IA on both behavioral and brain responsiveness level.

At the behavioral level, previous studies explored the effect of brief focused breathing exercises on cognitive tasks measuring sustained attention, memory, and other cognitive functions and found this practice helpful for reducing mind wandering [21] and augmenting memory performance [22]. Concerning the motor system, practices such as yoga teach to bring attention to the breath while performing synchronized motor tasks together with the teacher. Studies have shown that this practice has a beneficial impact on learning speed, task accuracy, and overall performance of a motor task by enhancing attention and reducing stress via an improved control of sensorimotor rhythms [23]. However, the difference between IA manipulation (intended as a simple focus on the breath) and yoga is that this last type of practice gradually requires breath volitional control while performing motor movements. Moreover, in these studies, the cognitive tasks were not conducted simultaneously with the IA exercises.

At the neural level, during the execution of IA tasks, previous neuroscientific studies showed the activation of a right-lateralized neural network involving both subcortical areas and different regions of the cortex, such as the supra-marginal gyrus [24–28], the insular cortex, the prefrontal cortex (PFC) [29], the dorsolateral prefrontal cortex (DLPFC) [30], and the frontopolar cortex [31]. Also, works using scalp electroencephalogram reveal that frontal regions are involved in breath tracking [32].

It should be noted that, in addition to interoceptive processing, such regions are involved in several other cognitive and emotional processing. For instance, the DLPFC plays a relevant role in directing and maintaining focused attention on a goal when balancing inner and external distractions [33]. It also aids in maintaining the attention on breathing by becoming more conscious of instances of mind wandering, letting the person refocus the attention on respiration [26]. Furthermore, social functions have been connected to this brain region, such as being fully aware of movement control and flexibility in response to a shifting rhythmic pattern [34], or interpersonal coordination, and cooperative relationships with others [35,36]. In contrast, there is yet no proof of the impact on the PFC of combining

IA manipulation during a cognitive or motor synchronization task, compared to a breath synchronization task.

In a prior pilot work, we sought to investigate how explicit IA modulation affected the PFC hemodynamic correlates when two easy synchronization tasks—a cognitive and a motor task—were performed [37].

Greater activity was seen in the neuroanatomical regions (right PFC) that support synchronization mechanisms, prolonged attention, and attention reorientation, particularly under specific circumstances, such as when the joint task is performed concurrently with the subject's attention to their physiological responses. More precisely, these findings showed that the advantages of deliberate focus on neurophysiological interoception markers have been detected precisely while the participants were executing the task demanding synchronization (in particular, linguistic synchronization) in combination with the attentional focus on his/her interoceptive experience [37].

Thus, in this study, we intend to focus on a possible boosting effect due to the motor or cognitive synchronization task compared to the simple breath synchronization task in association with IA, specifically, we aim to explore the neurophysiological effect produced by these associations.

To find an answer to this question, we designed a study to investigate the differences in PFC responsiveness due to the explicit IA manipulation while participants were performing a simple breath synchronization task compared to two cognitive synchronization tasks. The PFC responsiveness was explored in terms of hemodynamic variations (deoxy- and oxygenated hemoglobin) measured through functional Near-Infrared Spectroscopy (fNIRS). fNIRS demonstrated its suitability for studying IA during cognitive synchronization tasks [37], by proving to be a non-invasive good solution to ensure freedom of movement and measurement accuracy of the PFC hemodynamic variations.

In line with a previous study [37] and evidence on the effect of IA manipulation on the cognitive and emotional processes [6], we, firstly, hypothesized a higher PFC activation and augmented oxyhemoglobin in the explicit IA manipulation compared to the control condition. Secondly, considering the empowering outcome of combining multiple training, this effect is especially expected during the motor and cognitive synchronization tasks compared to the simple breath synchronization task. Thirdly, it is supposed that this effect could be more evident for one of the two tasks (especially the linguistic one) since the cognitive nature of the task could be more efficient in inducing a real synchronization and thus a boosting effect on brain PFC responsiveness in comparison to simple breathing or a motor task.

2. Materials and Methods

2.1. Sample of Participants

For this purpose, pilot research was conducted involving 18 university students [14 females; mean age (M) = 27; standard deviation (SD) = 3], recruited from a convenience non-probabilistic sampling process.

To determine the minimum required sample size, we conducted an a priori power analysis for repeated measures ANOVA, revealing that a total sample size of 15, with an alpha error probability of 0.05 and a power of 0.80 (number of groups = 1; effect size f = 0.4), was necessary to detect a significant within effect or interaction between factors (G*Power 3.1 software, Heinrich-Heine, Germany) [38]. By estimating a subject attrition of 10%, we added two more subjects reaching the minimum sample size of 17 participants.

Experimental subjects were right-handed, with normal or corrected vision. Criteria for excluding participants comprised physiological disorders like chronic pain conditions, severe medical illnesses, epilepsy, traumatic brain injury, any mental or neurological deficits, prior experience with meditation practices, and previous or ongoing psychoterapy treatment. All participants provided written informed consent and were informed that no compensation would be provided for participation in this pilot study. The Ethics Committee of the Department of Psychology at the Catholic University of the Sacred Heart of Milan, Italy, approved the study, which adhered to the principles outlined in the Declaration of Helsinki (2013), and to the GDPR - Reg. UE 2016/679 and its ethical guidelines.

2.2. Procedure

The subjects were seated facing an experimenter who provided instructions and conducted tasks during the experiment, which took place in a darkened room. While fNIRS hemodynamic data were being recorded, participants were instructed to perform basic synchronization tasks involving breathing, movements, and language synchronization, following the lead of the experimenter.

Regarding the experimental manipulation of IA, all participants executed the three synchronization tasks under two different conditions, the explicit IA and the control condition, in relation to the experimental manipulation of IA [37]. The following were the instructions for the explicit IA condition:

> *"During this task, we ask you to focus your attention on your breath. Try to observe how you feel and if there are any variations in your breath as you perform the task".*

The sample in the control condition was given generic guidelines to complete the activities without being specifically asked to pay attention to the interoceptive correlates.

To avoid potential biases related to sequence effects, both the experimental conditions and the task execution order was a priori randomized and counterbalanced. At the start of the trial, a resting baseline of 120 s was recorded. Upon completion of each task, experimental subjects were required to fill in the manipulation checks. The entire experiment took less than 40 min (for the procedure, see Figure 1).

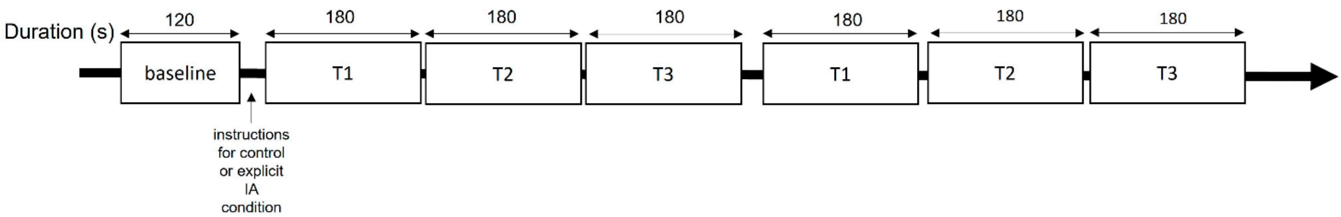

Figure 1. Experimental procedure. The protocol and task arrangement T1 = breath synchronization task; T2 = motor synchronization task; and T3 = cognitive synchronization task.

2.3. Breath, Motor, and Cognitive Synchronization Tasks

For the breath synchronization task, participants were required to observe the experimenter and align their breath to his/her breath rhythm in the two different experimental conditions. The breath synchronization task lasted three minutes.

For the synchronization tasks, two simple tasks, one motor and one cognitive were adopted [37]. The motor synchronization task consists of a finger movement task to be performed in sync with another partner. Participants were asked to synchronize with the movement performed by the experimenter seated in front of them; they were not asked to perform the movement at a specific speed or to raise their fingers in a specific manner. The motor synchronization task lasted three minutes.

In the cognitive synchronization task, the participants had to spell a sequence of syllables alternating with the experimenter. The rhythms of the speech were not established a priori. Each session of the language synchronization activity lasted three minutes, with no intervals. The average number of syllable repetitions was not less than 45 for the three minutes. The cognitive synchronization task lasted three minutes.

2.4. Manipulation Checks

Upon completion of each task, subjects were required to fill in the following manipulation checks on a Numeric Rating Scale (NRS) ranging from 0 to 10. These items evaluated how much attention participants have paid to the situation, the self, or others. This way, fluctuations of attention and perceived self-synchronization were checked over the different tasks (Table 1).

Table 1. The table shows the items administered at the end of each synchronization task performed in the two experimental conditions. Participants could respond on a Numeric Rating Scale (NRS) ranging from 0 to 10.

Manipulation Checks	
1.	how much attention did you pay to the task?
2.	how much attention did you pay to yourself?
3.	how much attention did you pay to the other person?
4.	how complex did you find the task?
5.	how engaged did you feel while carrying out the task?
6.	how complex did you find to focus on your breath?
7.	how much do you think you have been synchronized with the experimenter?
8.	how much you felt emotionally synchronized with the experimenter?
9.	how much you felt synchronized on a body level with the experimenter?
10.	how much do you think the experimenter was able to synchronize with you?
11.	how much you felt your breath synchronized with that of the experimenter?
12.	how much you felt the experimenter's breath synchronized with yours?
13.	how much did you perceive the experimenter most favourable/close to you?
14.	how much do you think you were able to perceive your body and guide it?
15.	how much do you think the experimenter was able to perceive his body and guide him?
16.	how much time do you estimate has passed? ________ (in seconds)

2.5. Measurement of Brain Activity by fNIRS

A total of 8 optodes belonging to a NIRScout system (NIRx Medical Technologies, LLC, Los Angeles, CA, USA) were employed to capture hemodynamic signals, specifically variations in oxygenated hemoglobin (O2Hb) and deoxygenated hemoglobin (HHb) concentrations. These optodes consisted of four light sources and four detectors, positioned on the scalp using an fNIRS cap following the international standard system 10/5 [39]. The emitter–detector distance was standardized at 30mm for consecutive optodes, and a near-infrared light with wavelengths of 760 and 850 nm was utilized. A six channels matrix was arranged to cover the left, and right PFC as reported in Figure 2 [30,40].

To attribute hemodynamic variations during the task to specific brain regions, a probabilistic atlas integrated into the fOLD toolbox version 2.2. [fNIRS Optodes' Location Decider [41]] was employed. This utilized the automated anatomical labeling atlas Brodmann [42]. Various sources and atlases were used to determine the most appropriate functional region and the locations of the sources and detectors, as well as the space between them, and were associated with the most suited Brodmann area [43,44].

We focused only on frontal sites since we were specifically interested in observing the PFC responsiveness to IA and synchronization tasks.

The fluctuations in concentrations of O2Hb and HHb were continuously measured during tasks using the NIRStar Acquisition Software (version 15.2; NIRx Medical Technologies LLC, 15Cherry Lane, Glen Head, NY, USA). The measurement began with a 120 s resting baseline. The data from 6 channels were collected at a sample rate of 6.25 Hz, then processed and analyzed using the nirsLAB software (v2014.05; NIRx Medical Technologies LLC, 15Cherry Lane, Glen Head, NY, USA). The mmol*mm values corresponding to O2Hb and HHb concentration fluctuations per channel were derived, accounting for their wavelengths and locations. Raw O2Hb and HHb signals from each channel underwent digital band-pass filtering within the range of 0.01–0.3 Hz.

A thorough visual inspection was conducted on the raw time-series data on a subject-by-subject basis during both the experimental phase and signal analysis to identify noisy channels caused by motion artifacts or amplitude changes. Channels with weak optical coupling and absence of ~1 Hz heartbeat oscillations were excluded based on this visual assessment [45]. Additionally, a linear-phase FIR filter was applied to the data to extract symmetric impulse responses related to breathing (0.3 Hz) [46,47].

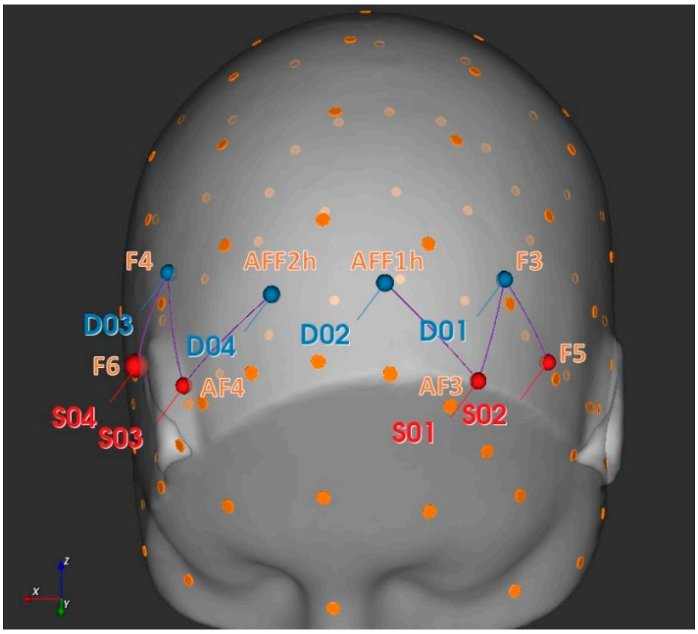

Figure 2. Arrangement of the six channels on a topographic layout. The fNIRS montage included four sources (in red) positioned in AF3-AF4, F5-F6, and four detectors (in blue) located in AFF1h-AFF2h, F3-F4. The following six channels (in violet): Ch1 (AF3-F3), Ch2 (AF3-AFF1h), Ch3 (F5-F3), corresponding to the left PFC, and Ch4 (AF4-F4), Ch5 (AF4-AFF2h), and Ch6 (F6-F4) consistent with the right PFC were acquired. This rendering has been generated with NIRSite software version 2.0 (NIRx Medical Technologies LLC).

The effect size for each condition was calculated using the means in the time series for each channel and subject. The formula for calculating Cohen's d effect sizes is D = (m1 − m2)/s, where m1 and m2 stand for the mean concentration levels for the baseline and trial, respectively, and s is the baseline standard deviation. This formula is derived by dividing the difference between the baseline and trial means by the baseline standard deviation. The effect sizes from the six channels were averaged in order to improve the signal-to-noise ratio. Although raw fNIRS data initially comprised relative values that could not be directly averaged across participants or channels, normalized effect size data were averaged regardless of the unit, as effect size remains unaffected by the differential pathlength factor (DPF).

2.6. Statistical Analysis

A set of repeated measures ANOVAs with independent within factors Condition (2: Explicit IA, Control) × Lateralization (2: Left, Right) × Type of Task (3: Breath, Motor, Linguistic) was applied to D dependent fNIRS data (O2Hb and HHb concentration values). The lateralization was calculated by considering the homologous channels of the frontal left (Ch1-Ch2-Ch3) and right (Ch4-Ch5-Ch6) areas, corresponding to left and right PFC.

If significant effects were observed, pairwise comparisons were conducted on the data to examine simple effects for significant interactions. Bonferroni correction was applied to mitigate potential biases arising from multiple comparisons. Degrees of freedom were adjusted using Greenhouse–Geisser epsilon when appropriate for all ANOVA tests. Furthermore, the normality of the data distribution was assessed using kurtosis and asymmetry indices. Partial eta squared (η^2) indices were utilized to gauge the magnitude of statistically significant effects.

3. Results

3.1. Manipulation Checks

The results of the descriptive statistics were reported in the table below for each task and condition (Table 2).

Table 2. The table shows the descriptive data of the items administered at the end of each synchronization task performed in the two experimental conditions. Participants could respond on a Numeric Rating Scale (NRS) ranging from 0 to 10.

	Breath				Motor				Cognitive			
	Control		IA		Control		IA		Control		IA	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
item 1	9.00	1.14	8.56	1.41	9.17	0.90	8.44	1.34	8.89	1.10	8.39	1.77
item 2	7.13	1.87	7.81	1.76	7.89	1.63	8.11	1.37	8.22	1.08	7.72	1.66
item 3	8.63	1.37	8.56	1.41	9.00	1.00	8.72	1.19	8.39	1.42	8.22	1.65
item 4	6.18	2.67	7.00	2.44	8.09	1.44	7.91	1.92	7.91	2.54	8.00	2.04
item 5	7.63	1.94	7.56	2.06	8.06	1.61	7.72	1.76	7.61	2.29	7.61	2.43
item 6	5.69	2.92	6.31	2.78	6.17	2.65	6.33	2.69	6.72	2.70	6.28	2.45
item 7	8.31	1.01	7.63	1.53	8.72	1.15	8.39	1.34	7.94	1.35	7.89	1.05
item 8	6.19	1.92	6.63	1.81	6.61	1.77	6.78	2.10	6.89	1.82	6.83	1.74
item 9	8.19	1.20	7.69	1.52	8.50	1.12	8.22	1.18	8.11	1.52	7.72	1.24
item 10	8.31	1.12	7.75	1.63	8.72	1.04	8.39	1.38	8.39	1.01	8.56	1.07
item 11	8.44	0.97	7.94	1.51	5.78	1.96	6.00	1.56	5.78	2.02	5.61	2.26
item 12	8.31	1.07	7.81	1.76	5.56	1.83	5.78	1.47	5.35	1.68	5.39	2.21
item 13	7.75	1.73	7.38	1.71	7.89	1.20	7.00	2.03	7.44	1.54	7.44	1.83
item 14	8.56	1.03	8.06	1.30	8.67	0.88	8.28	1.45	8.06	1.31	7.11	1.59
item 15	8.38	0.76	8.25	1.06	8.72	0.93	8.39	1.06	8.06	1.47	7.28	1.33
item 16	144.38	63.89	163.75	57.38	187.78	65.03	198.89	70.39	198.33	78.05	208.33	83.95

Table legend: The reported data corresponds to mean (M) and standard seviation (SD).

3.2. fNIRS Results

The subsequent findings pertain to the statistical analyses conducted on the dependent measures for O2Hb and HHb concentration values.

Concerning the O2Hb, it was detected as a significant main effect for the Condition (F[1,17] = 7.09, p = 0.001, η^2 = 0.452), with higher response for explicit IA than the control condition (Figure 3A,B). Secondly, the following interaction effect Condition × Task was found to be significant (F[1,17] = 6.90, p = 0.001, η^2 = 0.411) and, according to pairwise comparisons, greater mean values were found for explicit IA than the control condition in the cognitive task (p = 0.001) (Figure 4A,B).

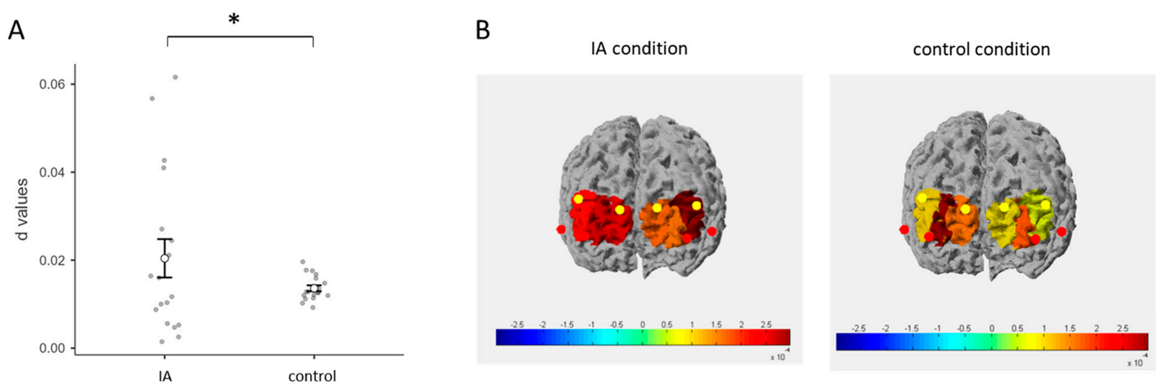

Figure 3. Hemodynamic O2Hb results for conditions. (**A**) The plot shows significantly higher O2Hb values in the IA confronted with the control (non-IA) condition. (**B**) Graphical head representation of the O2Hb activation in the IA confronted with the control (non-IA) condition. In the plot, asterisk marks statistically significant differences with $p \leq 0.05$.

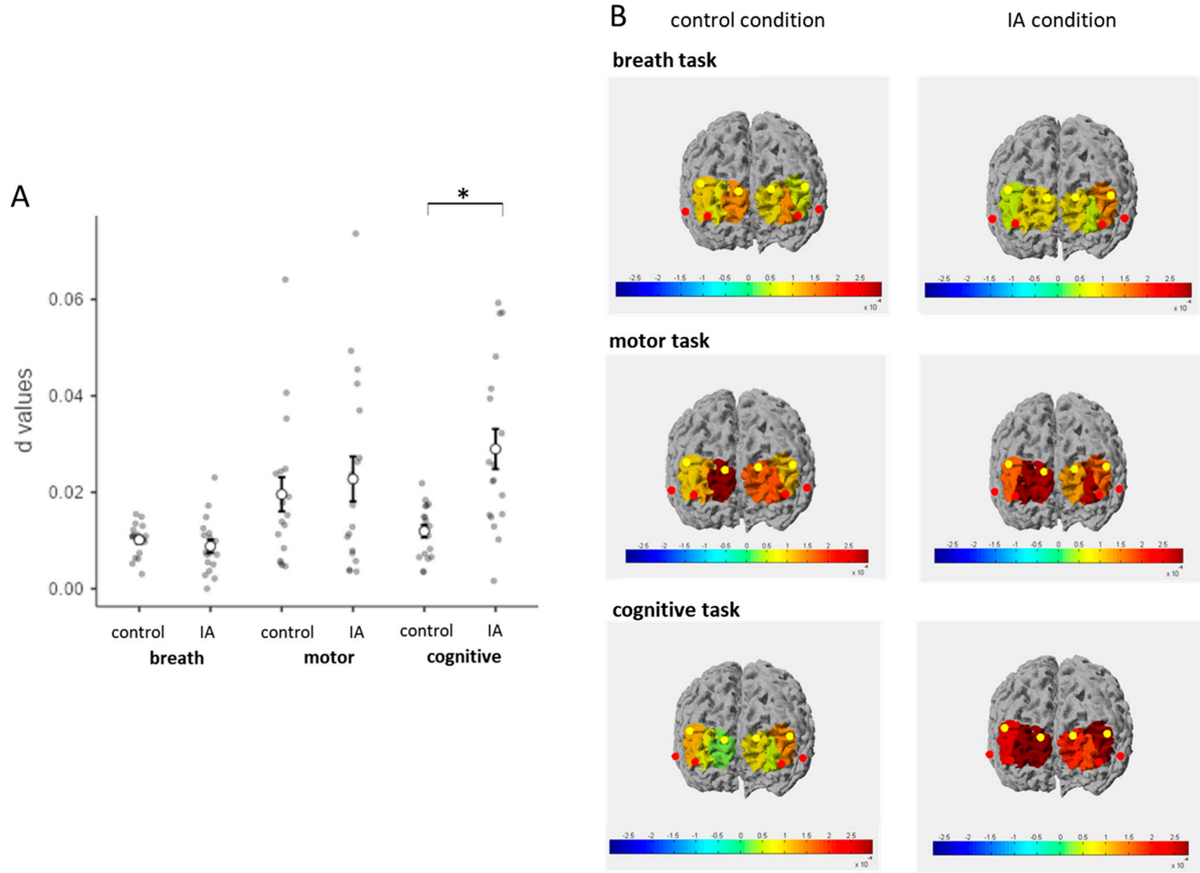

Figure 4. Hemodynamic O2Hb results for Condition × Task. (**A**) The plot shows the significant interaction effect Condition × Task detected for the O2Hb values. (**B**) In the head renderings, the red color corresponds to the increase in O2Hb values for the control (left heads) versus the IA condition (right heads) for the breath, motor and cognitive synchronization tasks. In the plot, asterisk marks statistically significant differences with $p \leq 0.05$.

No other significant differences were observed for the O2Hb and HHb components.

4. Discussion

The current work investigated the differences in PFC responsiveness due to the explicit IA manipulation while participants were performing a simple breath synchronization task compared to the motor and cognitive synchronization tasks. The PFC responsiveness was explored in terms of hemodynamic variations measured through fNIRS. In line with our hypotheses, the following results were found first, a greater level of O2Hb in the PFC sites in the explicit IA manipulation compared to the control condition was observed. In addition, this effect was found in the cognitive task compared to the simple breath and motor synchronization tasks. In contrast, no significant differences were found for the PFC lateralization effect. Furthermore, in contrast to the breathing and motor synchronization tasks, the same effect was observed in the cognitive task. Finally, no PFC hemispheric lateralization effects were found.

First, a significant PFC increase in O2Hb was found in the IA confronted with the control condition, regardless of the lateralization and type of task executed by the participants. Previous research has demonstrated that the PFC [29] contributes to interoceptive attention activities, implying that this region aids in sustaining concentration on the breath and improving awareness when a person's mind wanders and then returns the focus to the breath [26]. In this case, given the nature of the tasks requiring synchronization, another plausible explanation of this activation concerns the role of this site in social processes including cooperation [48], social cognition [49], reciprocal cooperative interactions and interpersonal coordination [35,36]. Taken together, this evidence may suggest that there is a general effect of the IA on the PFC regions. This was consistent with prior research that found IA and brief relaxation methods to support a range of cognitive processes, such as meta-awareness, cognitive monitoring, and sustained attention [6], as well as demanding arithmetic tasks [31]. This finding could be interpreted as the effect of paying attention to breathe, which enhances cortical activity and mental performance.

Secondly, an increase in oxygenated hemoglobin was found during the combination of explicit IA condition and the cognitive confronted with the motor and breath synchronization task. It should be underlined that there was no significant difference between the three tasks in the control condition, that is, in the condition in which individuals were not explicitly asked to pay attention to their breathing. This data is interesting as it confirms that the significant effect is given by the boosting of the association of IA with a cognitive (linguistic) task. In fact, since in the simple control condition no significant differences were detected, an interpretation based on the need for additional cognitive resources or task load, which have determined the increased O2Hb concentration in the PFC, is not plausible. Therefore, we may conclude that this boosting effect can be attributable to a combination of these two specific tasks: IA manipulation combined with the cognitive task.

In addition, we must point out that the effect of synchronization might be also relevant: indeed, mentalizing ability and verbal cooperation were required by the cognitive task and hyperscanning studies suggested neural alignment predominantly occurred in the frontal and temporo-parietal areas during verbal communication [50]. It is important to underline at this point that it is not a simple cognitive or motor or breath task but that each of these tasks was performed by asking the participant to synchronize temporally with the experimenter. We may thus suggest that a cognitive synch task may have produced the best effect on PFC responsiveness, in association with an explicit IA condition.

This note is relevant as it fully simulates the condition of work with a rehabilitation professional, such as speech therapists, physiotherapists but also experts of embodied awareness practices (such as yoga or Feldenkrais method teachers; [51]). In particular, these findings suggest that if a professional performs a task together with the patient or client (for example, a speech therapy exercise to be performed simultaneously) and asks them to pay attention to their own breathing, it can generate an increase in PFC responsiveness, and this can have positive repercussions in terms of performance. Whether this boosting effect can also be observed when performing a motor synchronization task still needs to be better examined. Former studies in the sports field also suggested that when attention is directed inside into the execution of the movement rather than outward toward the results of the movement itself, accuracy scores decrease [52,53]. However, to our best knowledge, this field of research still needs to be expanded since there are no works exploring the effect of the focus on breathing during synchronized movement execution at the behavioral and neural level.

In the future, we will have to further investigate and discuss this effect by also comparing cognitive and motor tasks without the synchronization instruction, in order to effectively estimate how relevant the synchronization is. This is a proposal that can be explored in prospective works.

Thirdly, it is worth noticing that in our results there is a lack of lateralization effect. Interestingly, despite previous studies that underlined a special contribution of the right hemisphere for these types of processes [6,54], in this case, we did not find any differences in the lateralization, but a massive effect on the PFC, not localized in specific portions of the PFC. In this study, a merge of the fNIRS single channels into two main ROIs—left and right PFC—has been performed, and given the reduced number of channels, making a comparison with the free channels would have provided little useful information. We are aware that this could also be considered a possible limitation of our study. In any case, in the analyses, we had made a preliminary comparison of the six channels and no significant differences were observed, thus confirming the usefulness of the exploration of only two ROIs.

5. Conclusions

The results of this study could be interesting for rehabilitation practices that integrate breathing exercises with cognitive tasks. For instance, the specific significant effect observed for the cognitive linguistic task, compared to the other tasks, could open interesting avenues for logopedics suggesting vocal exercises could be carried out in synchrony and combined with the focused attention on the breath to boost the PFC activation. More evidence is needed to understand how such a combination of exercises may inform treatment outcomes.

Although current research strives to fill a gap currently present in the literature, it is not free from limitations. In fact, to assess the impact of the intentional IA manipulation on the PFC, the current study used the simplest tasks as an example. Second, given the fNIRS was only applied to PFC and not to other brain regions, including somatosensory cortical areas, the insula cortex, and subcortical structures, the role of these areas should be investigated further in future research. To extend the current results to the widest population, the sample size can be augmented and rendered homogeneous in terms of gender differences. Future research might include more precise manipulation checks to ensure that participants were solely concentrating on their breath and not on other body correlates. At a methodological level, future studies should control for the order effect or even consider including the order of the experimental condition or tasks as an experimental variable of the study. In fact, observing the presence of significant effects deriving from the order of execution of tasks could be useful for rehabilitation therapists to choose the order of exercises when implementing rehabilitation plans. Moreover, future statistical steps may include the application of multivariate models (such as repeated measures MANOVA) on the data. Finally, to demonstrate the non-additive nature of the effects found in the current study, future research could include the computation of a behavioral performance index, showing that, in case of explicit IA condition, the concurrent tasks are performed better.

Finally, to demonstrate the non-additive nature of the effects found in the present study and confirm their different qualitative-quantitative nature, future research could include the calculation of a behavioral performance index, demonstrating that, in case of explicit IA condition, the concurrent synchronization tasks (in this case, the cognitive synchronization task) are performed better.

To summarize, future research should deepen on the impact of the combination of IA manipulation and cognitive synchronization tasks in rehabilitation contexts, such as speech therapy or neurocognitive rehabilitation. Most crucially, on a methodological level, recording a dyad's brain activity while performing these activities could be useful (for example, using the hyperscanning paradigm) for determining how the inter-brain synchronization and relation between the therapist and patient may have an impact both at the neural and behavioral level.

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