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**Abstract**

We aimed at studying the effect of Motor Imagery (MI), i.e., the mental representation of a movement without executing it, on breath-holding performance. Classical guidelines for efficient MI interventions advocate for a congruent MI practice with regards to the requirements of the physical performance, specifically in terms of physiological arousal. We specifically aimed at studying whether an incongruent form of MI practice might enhance the breath-holding performance. In a counterbalanced design including three experimental sessions, participants engaged in maximal breath-hold trials while concomitantly engaging in *i*) MI of breathing, *ii*) MI of breath-hold, and *iii)* an "ecological" breath-holding trial, i.e., without specific instructions of MI practice. In addition to breath-hold durations, we measured the cardiac activity and blood oxygen saturation. Performance was improved during MI of breathing (73.06 s ± 24.53) compared to both MI of breath-hold (70.57 s ± 18.15) and the control condition (67.67 s ± 19.27) ($p < 0.05$). The mechanisms underlying breath-hold performance improvements during MI of breathing remain uncertain. MI of breathing might participate to decrease the threat perception associated with breath-holding, presumably due to psychological and physiological effects associated with the internal simulation of a breathing body state.

**Keywords:** motor cognition, movement imagination, apnea, breath-hold reflex

**Abbreviations list:** Heart Rate (HR), Motor imagery (MI), Root mean square of successive differences (RMSSD), Standard deviation of R-R intervals (SDNN), Blood oxygen saturation ($SO_2$).

## 1. Introduction

Motor imagery (MI) is the voluntary process of mentally representing an action without executing it [1]. MI and physical practice of the same action engage overlapping cortical and subcortical substrates [2,3]. Thus, MI is considered a "*motor cognition*" process, due to the involvement of brain motor system regions in the absence of actual movement execution [4]. At the peripheral level, MI reproduces with reduced magnitude autonomic nervous system response patterns recorded during physical practice, e.g., increases in heart and respiratory rates [5,6 for a review]. It was early postulated that MI engaged the autonomic nervous system into anticipating the physiological demands of mentally stimulated action, hence accounting for physiological response patterns reproducing the readiness states recorded during actual motor preparation [7,8].

MI has been extensively shown to be a reliable adjunctive approach to motor performance enhancement in both sport sciences and physical rehabilitation [9,10 for reviews]. In terms of practical guidelines, applied research emphasized that MI should be performed in conjunction with physical training to yield optimal results [11,12]. Conceptual frameworks specifically insist that when the aim is to enhance motor performance, e.g., improve technical components of skill execution, MI should ideally be practiced in environmental and physiological arousal contexts corresponding to those encountered during the physical performance of the corresponding task [13,14]. There is a general consensus in the field advocating for such *congruent* forms MI practice interventions, i.e., reproducing the endogenous (e.g., physiological arousal) and exogenous (e.g., environmental) contexts of the actual performance [11,12]. Intriguingly, whether *incongruent* forms of MI practice could be relevant to enhance performance in specific sporting situations has yet not been experimentally addressed. Incongruent MI practice here refers to MI practice interventions intended to affect the performance while focusing on opposite endogenous and/or exogenous constraints to those encountered during physical practice.

Apnea represents a unique model of sporting performance since the capacity to achieve reduced, rather than increased, energy expenditure is the central factor mediating performance. Earlier research underlined that the breakpoint of voluntary breath-holding may be determined by both psychological and physiological factors [15]. Autonomic nervous system arousal response patterns during breath-holding, e.g., increases in the variability of cardiac activity (inter-beat intervals), appeared to negatively correlate with the breath-hold performance [16–18]. Accordingly, conventional guidelines advocating for congruent forms of MI practice may not apply to the apnea model of performance. For instance, delaying arousal responses by eliciting through MI autonomic nervous system response patterns corresponding to a breathing body state could contribute to delay the break point of breath-holding. This issue has yet not been addressed in the existing literature, although it was previously shown that temporal estimation bias due to the effect of breath-holding on internal clock processes affected in a comparable manner the temporal organization of MI [19]. Accordingly, we aimed at evaluating the effect of congruent and incongruent MI practice on breath-hold performance and hypothesized that an incongruent, but not congruent, forms of MI practice would yield beneficial effects.

## 2. Methods

### *2.1. Participants*

Healthy adult participants without history of chronic disease or neurologic disorders were recruited from the Sports Sciences department of the University Claude Bernard Lyon 1 (n = 18, 9 men, age range: 20-25 years old). They had no previous experience of breath-hold but a regular practice of terrestrial sports (soccer, climbing, jogging, and rugby). Any medical history of psychological disorders (e.g., anxiety disorders) and/or respiratory/cardiovascular diseases were considered exclusion criteria. All participants volunteered to participate in the experiment, and provided a written consent form in agreement with the statements of the declaration of Helsinki (1982).

### *2.2. Experimental design*

The repeated-measures design involved three distinct experimental sessions of 30 min. To prevent carryover effects, experimental sessions were separated by a minimum of 24 h. The three experimental sessions were scheduled within a maximum span of 5 days. Experimental sessions took place in a quiet room of the Sport Sciences department of the University Claude Bernard Lyon 1. Experimental sessions were scheduled at the same daytime to avoid the influence of circadian rhythms (i.e., 12 pm before lunch). Participants were specifically instructed not to consume coffee during the 3 hours preceding each experimental session. Experimental sessions consisted in measures of the maximal breath-hold performance according to three experimental conditions: *i*) maximal breath-hold performance while concomitantly engaging MI of kinesthetic information associated with breathing movements

($MI_{INCONGRUENT}$), ii) maximal breath-hold performance while concomitantly engaging MI of kinesthetic information associated with the intention of holding breath ($MI_{CONGRUENT}$) and finally, iii) maximal breath-hold performance without concomitantly engaging into any form of mental practice (CONTROL). Each experimental session only involved one experimental condition. For $MI_{INCONGRUENT}$, the following MI script was used: "*Focus on the sensations associated with ventilatory movements. Feel the air coming into your nose, and the pressures within your lungs and chest. Feel the muscles contractions and stretches associated with natural inspiratory and expiratory movements*". For $MI_{CONGRUENT}$, the following MI script was used: "*Focus on the sensations associated with the effort of voluntary breath-holding. Feel the muscles contractions pressuring your lungs and the stretches associated with the control of your motionless chest. Focus on the absence of movements from the respiratory tract*". A mental calculation task during CONTROL may have controlled for the state of attentional focus under $MI_{INCONGRUENT}$ and $MI_{CONGRUENT}$. However, it would have interfered with the breath-hold performance due to well-established relationships between the cognitive load and aerobic performance [for an overview, see 20]. The choice of the present control condition aimed at providing an ecological breath-hold performance.

For each experimental session/condition, three maximal breath-hold performance trials were performed from a seated position, with hands and forearms placed on the thighs. Five min of passive recovery allocated between each trial [e.g., 21]. Participants remained motionless, with the knees at 90º. To avoid distraction effects, participants faced a white wall and stared at a cross mark placed in front of them [15]. Participants were blinded to the outcome of their maximal breath-hold performance trials. Experimental conditions were administered in a counterbalanced order across experimental sessions [block randomization, 22].

The expected duration for one experimental session was 30 min, but most of the time about 40 min were required to complete the measures. This varied according to participants' performance (affecting breath-hold trials duration), and punctual need for additional instructions while completing a given experimental condition.

### *2.3. Dependent variables*

#### *2.3.1. Performance recordings*

Before each breath-hold trial, participants were equipped with a nose clip (Ergonomic shaped Pro Nose Clip Arena®) and a thoracic accelerometer (2014, Delsys Incorporated). This enabled to control for absence of ventilatory movements during the breath-hold trials [23,24]. 15 s before each trial, participants were instructed to engage an inspiration immediately before the onset of the breath-hold trial. Breath-stacking was not allowed. Participants were instructed to hold their breath as long as possible after the trial onset. Ventilatory movements detected after the trial onset, either from accelerometers measures or the subjective evaluation of participant's behavior by the experimenter, determined the breakpoint of breath-holding. Breath-hold performance was quantified as the duration from the onset of breath-holding, up to the breakpoint. No trial was discarded, since any breathing movement detected at the behavioral level from the accelerometers and/or from the visual inspection of participant's behavior by the experimenter, determined the break point of the trial. There was thus no breath-hold trials rejection. We did not face attempts to engage in micro-ventilatory movements, hence attesting participant's compliance with experimental instructions. This might be due to the fact that voluntary breath-holding represented simple instructions to follow.

*2.3.2. Physiological recordings*

*1. Heart rate and heart rate variability*

Before each experimental condition, participants remained motionless for 10 minutes lying on their back. This standardized position enabled a baseline measure of heart rate (HR) and HR variability, using a thoracic monitor (SUUNTO® Ambit 3, Finland). HR and HR variability were calculated in the central 5-minutes time window of the 10 minutes baseline recording. During breath-hold trials, HR and HR variability were calculated from a time window corresponding a cardiac signal plateau $\geq$ 30 s (Figure 1). Indeed, HR variability measures specifically require a stationary signal [25]. In healthy subjects, a cardiac beat is measured as a sequence of signal waves [26,27]. The left ventricular contraction elicits the wave with the most pronounced amplitude (i.e., R-wave). R-waves are then used to estimate both HR and HR variability. Specifically, the R-R interval refers to the time window separating two successive R-waves in the ongoing cardiac signal. The root mean square of successive differences (RMSSD) and the standard deviation of R-R intervals (SDNN) can then be calculated. These variables are known to, respectively, reflect the parasympathetic nervous system activity and provide a global index of the activity of the autonomic nervous system [25]. HR variability measures were processed using the Kubios

HRV Standard 3.0.1 software (MATLAB®, © 2017 The Mathworks, Inc). HR variability was finally normalized relative to the baseline recording.

**** Please insert Figure 1 about here ****

*2. Blood oxygen saturation*

Blood oxygen saturation ($SO_2$) was estimated using finger-pulse oximetry (AccU-Rate® Pro Series CMS 500DL). $SO_2$ was collected after completion of the 10 min rest period, before each breath-hold trial, and immediately after each breath-hold trial. We checked that the $SO_2$ returned to basal values before each breath-hold trial, using the $SO_2$ value collected after completion of the 10 min rest period as the reference. The $SO_2$ values collected immediately after the break point of breath-hold trials were included in the breath-hold performance analysis (see Statistical analysis).

#### *2.3.3. Psychometric recordings*

After $MI_{CONGRUENT}$ and $MI_{INCONGRUENT}$ and CONTROL, participants were asked whether they experienced any difficulty to comply with the experimental instructions. After completion of the design, participants were requested to determine which condition they perceived as their best breath-hold performance ($MI_{CONGRUENT}$, $MI_{INCONGRUENT}$ and CONTROL). To do so, they reported their perceived commitment to engage in a maximal breath-hold performance on a Likert-type scale ranging from 1 ("*I did not engage in a maximal breath-holding trial, I just hold my breath up to the first feelings of discomfort")* to 10 *("I did engage in a maximal breath-holding trial, I could not hold breath any longer by any means*"). After $MI_{CONGRUENT}$ and $MI_{INCONGRUENT}$, they rated their level of perceived vividness of MI on a Likert-type scale ranging from 1 ("*No feeling at all, I only though about the movement*") to 10 ("*Similar breathing/hold my breath sensations to those experienced during the actual practice*").

### *2.4. Statistical Analyses*

We used R [29] and *nlme* [30] to run a linear mixed effects analysis of the effect of the experimental conditions on breath-hold performance and psychometric measures. Accordingly, we built random-coefficient regression models with a by-subject random intercept. We first entered the fixed effect of EXPERIMENTAL CONDITION ($MI_{CONGRUENT}$, $MI_{INCONGRUENT}$ CONTROL). We then added the fixed effect of $SO_2$ (recorded at the break point of breath-holding) as well as the fixed effect of HR, RMSSD and SDNN (recorded from the signal plateau recorded during breath-hold trials), with interaction term.

Finally, we added the fixed effects of SESSION (numeric regressor controlling for habituation effects across experimental sessions) and TRIAL (numeric regressor controlling for habituation effects across trials). For psychometric scores, we entered the fixed effect of EXPERIMENTAL CONDITION. For the analysis of MI vividness scores, we also included the fixed effect of TRIAL (with interaction term). A backward stepwise procedure was used to fit the random-coefficient regression model formulae [31,32]. Effect sizes were calculated in terms of proportion of explained variation (i.e., partial coefficients of determination, $R_P^2$) using an *ad hoc* procedure for linear mixed effects models implemented in the *r2glmm* package [33,34]. $R_P^2$ were interpreted based on the rule of thumb provided by Cohen [35]: $0.01 < R_P^2 < 0.13$ was considered a small effect size, $0.13 < R_P^2 < 0.26$ was considered a medium effect size and $R_P^2 > 0.26$ was considered a strong effect size. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. The statistical significance threshold was set for a type 1 error rate of 5%. Main effects and interactions were post hoc investigated using general linear hypotheses testing of planned contrasts from the *multcomp* package [36,37]. We applied Holm's sequential corrections to control the false discovery rate [38].

## 3. Results

### *3.1. Analysis of the breath-hold durations*

All statistical interactions were removed during the backward stepwise model selection (all $p > 0.05$). Breath-hold durations were affected by the main effect of EXPERIMENTAL CONDITION ($\chi^2(2) = 6.41$, $R_P^2 = 0.06$, $p = 0.04$). Post-hoc analyses revealed that the breath-hold durations during $MI_{INCONGRUENT}$ were higher compared to $MI_{CONGRUENT}$ (+ 5.45 s ± 2.38, $p = 0.02$) and CONTROL (+ 4.73 s ± 2.54, $p = 0.05$) (Figure 2A). There was no difference between $MI_{CONGRUENT}$ and CONTROL ($p = 0.95$). The linear mixed effects analysis further revealed that TRIAL (+ 4.02 s ± 1.26; $\chi^2(1) = 10.17$, $R_P^2 = 0.02$, $p < 0.01$, Figure 2B), HR (+0.39 s ± 0.12; $\chi^2(1) = 10.90$, $R_P^2 = 0.07$, $p < 0.001$, Figure 2C), SDNN (-0.15 s ± 0.05; $\chi^2(1) = 8.50$, $R_P^2 = 0.03$, $p < 0.001$, Figure 2C) and $SO_2$ (-1.45 s ± 0.55; $\chi^2(1) = 7.03$, $R_P^2 = 0.04$, $p < 0.01$, Figure 2D) influenced the response variable, i.e., breath-hold durations (Figure 2). By contrast, the main effect of SESSION only approached statistical significance ($\chi^2(1) = 3.82$, $R_P^2 = 0.02$, $p = 0.06$). Breath-hold durations were 70.31 s ± 20.69 during the first, 70.63 s ± 19.07 during the second and 70.19 s ± 22.80 during the third experimental session. Finally, breath-hold durations were not affected by RMSSD ($p > 0.05$).

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### *3.2. Analysis of the psychometric data*

Participants reported no difficulty to comply with the experimental instructions. When asked about their attentional states during CONTROL, they reported a state of empty mind and willingness to achieve the best breath-hold performance. Conformity Chi-squared test on the proportions of experimental condition perceived as the best breath-hold performance revealed that CONTROL (55 %), outperformed $MI_{INCONGRUENT}$ (38 %) and $MI_{CONGRUENT}$ (5 %) ($\chi^2(2) = 7.18$, $p < 0.02$). Self-reports of perceived commitment to engage in a maximal breath-hold performance was 8.40 ± 0.20 on the 10-points Likert scale (Figure 3A).

**** Please Insert Figure 3 about here ****

The statistical interaction between EXPERIMENTAL CONDITION and TRIAL was removed during the backward stepwise procedure ($p > 0.05$). However, MI vividness was affected by the main EXPERIMENTAL CONDITION effect ($\chi^2(1) = 3.97$, $R_P^2 = 0.04$, $p = 0.04$, Figure 3B). Indeed, self-reports of MI vividness on the 10-points Likert scale were higher during $MI_{CONGRUENT}$ compared to those measured during $MI_{INCONGRUENT}$ (+0.48 ± 0.24, $p = 0.04$). Finally, the main effect TRIAL positively influenced self-reports of perceived MI vividness (+0.48 ± 0.15, $p < 0.001$, Figure 3C).

## 4. Discussion

The purpose of the present study was to investigate the effect of congruent and incongruent MI practice on breath-hold performance. We implemented a maximal breath-hold paradigm where sparing of energy expenditure through reduced physiological arousal was crucial to achieve a high performance [39–41]. Motivation also represents one a critical factor involved in maximal breath-hold performance [15]. Participants reported high and comparable levels of comittment across experimental conditions to engage in a maximal breath-hold effort. Yet, we found that $MI_{INCONGRUENT}$, i.e., where participants mentally recreated the sensations of breathing during breath-holding, but not $MI_{CONGRUENT}$, where participants mentally rehearsed the sensations associated with the effort of holding breath during breath-holding, increased the duration of breath-hold trials compared to CONTROL. This result did not originate from a general state of increased attentional focus under MI conditions since no difference was present between

$\text{MI}_{\text{CONGRUENT}}$ and CONTROL. The breath-hold durations for each experimental session (independently from the experimental condition) did not reveal a linear trend towards habituation. Habituation effects from one experimental session to another nonetheless represents an important factor to control from a methodological standpoint. Small partial effect sizes were recorded for both the breath-hold performance and psychometric analysis. This was somehow expected considering the multivariate nature of the factorial model, particularly concerning the breath-hold performance analysis. This might be congruent with the nature of the experimental intervention, which consisted in embedding MI practice during maximal breath-hold performance trials. Also, the outcome of the experimental intervention was quantified at the single-session level.

According to the early conceptual framework by Paivio [42], MI positively affects cognitive and motivational processes involved in the generation and maintenance of the motor performance. Paivio [42]'s conceptual framework was updated at the scope of recent applications of MI practice in sport sciences and rehabilitation. There are well-accepted complementarities between cognitive and motivational functions of MI accounting for the benefits of training interventions [12]. Fear and anxiety negatively affect breath-hold performance [43–46]. Barwood et al. [47] reported that 2 weeks of experimental intervention including MI, goal-settings, and coping strategies such as self-talk and relaxation significantly increased breath-hold durations in cold water immersion without concomitant alterations of breath-hold performance in a normal, non-threatening air environment. MI thus participated to decrease threat perception associated with breath-holding under the hostile environment condition. In keeping with these findings, a first interpretation to the present benefits of $\text{MI}_{\text{INCONGRUENT}}$ is the greater appraisal of threat perception associated with breath-holding due to the motivational functions of MI. In other words, $\text{MI}_{\text{INCONGRUENT}}$ could have participated to decrease the psychophysiological response patterns usually triggered by the cardiac and ventilatory distress corollary of breath-holding. These were described as part of the "*Integrated survival system*" [48], which is known to increase the neural excitability within pathways targeting the cerebral respiratory centers controlling ventilatory reflexes.

MI involves central processing of motor command signals targeting autonomic organs [49–51]. Motor command signals targeting autonomic effectors are incompletely inhibited during MI, hence eliciting responses from autonomic effectors. These reproduce, albeit with a reduced magnitude, several features of the response patterns observed during the physical performance of the corresponding task [6 for reviews,50]. For instance, ventilatory responses during MI mirrored the actual intensity of the imagined exercise [7,8]. It was hypothesized that residual autonomic motor command signals during MI conveyed feedback information to the central nervous system [for a more exhaustive discussion, see 52]. $MI_{INCONGRUENT}$, but not $MI_{CONGRUENT}$, could thus participate to the perception of a central respiratory rhythm in spite of the current breath-hold state, hence delaying the breakpoint of breath-hold. This remains a working hypothesis, since it is impossible to perform direct analyses of the phrenic nerve to understand central respiratory rhythm regulation in humans [53–56]. Yet, it is well-established that the activation of limbic structures controlling ventilation can be influenced by voluntary cognition [57; for a recent review]. Upregulation of the neural excitability within the cerebral respiratory centers determine the breakpoint of breath-holding [15]. Hypoxia, hypercapnia, decreased lung volume and increased metabolic rate all participate to elevate the physiological demand upon central respiratory centers. Eventually, brainstem respiratory centers trigger the breath reflex through a feedforward control over phrenic motor neurons [15,55].

Participant's maximal breath-hold performance was influenced by the SDNN, HR and $SO_2$. Yet, the relationships between HR, SDNN, $SO_2$ and the maximal breath-hold performance does not help understanding the difference in favor of $MI_{INCONGRUENT}$ compared to $MI_{CONGURENT}$ and CONTROL with regards to the outcome of maximal breath-hold performance trials. The absence of two-way interactions involving the HR, SDNN, $SO_2$ and the experimental condition indicates, on the contrary, that the influence of HR, SDNN, $SO_2$ on the breath-hold performance trial outcome was comparable across experimental conditions. SDNN reflects cyclic components responsible for HR variability during the recording time window, and thus provide a global index of autonomic nervous system activity. SDNN increases reflects the elevation of the autonomic demand to balance homeostasis. SDNN decreases, on the contrary, were associated with reduced physiological arousal [58]. Decreases in HR variability were associated with reduced physiological arousal during breath-hold [16–18,59]. Hence, the negative relationship between SDNN and breath-hold durations is not surprising. An HR increase occurs during the early stages of breath-hold, but a subsequent decrease occurs as the autonomic nervous system regulates physiological arousal to spare energy [17]. This might appear, at first sight, contradictory with the positive relationship measured here between the HR and the maximal breath-hold performance. HR represents an index of energy supply to the cells throughout the breath-hold trial. This postulate is congruent with the fact that HR was calculated by averaging HR recordings at the level of the breath-hold trial. Interestingly, participant's maximal breath-hold performance was negatively influenced by the $SO_2$ values recorded immediately after completion of the corresponding breath-hold trial (i.e., at the break point of breath-holding). The $SO_2$ values thus appeared to represent a marker of participants' capacity to maintain the breath-holding state in spite of the ongoing reduction in blood oxygen saturation. Hence, reduced $SO_2$ values after trials completion were associated with increases in breath-hold durations.

Participants reported higher levels of vividness during $MI_{CONGRUENT}$. This is congruent with MI frameworks underlining that MI quality is increased when mental rehearsal reproduces features of the actual performance [11–13]. Present data shows that an incongruent form of MI practice with regards to the behavioral and neurophysiological correlates of the task was the most relevant approach to increase performance. Increased breath-hold durations were recoreded in spite of reduced MI vividness compared to other experimental conditions. Also, participants experienced a greater performance perception during CONTROL. Considering that participants did not engage in cognitive motor operations during breath-hold trials under CONTROL, they possibly experienced reduced mental strain under this specific experimental condition. Indeed, contrary to $MI_{INCONGRUENT}$ and $MI_{CONGRUENT}$, participants did not have to comply with experimental instructions requiring them to engage in voluntary processes of motor simulations along with a maximal breath-hold performance. In other words, the absence of dual task involving motor simulation potentially biased positively participant's performance perception. This could originate from increased perceived comfort during the maximal breath-hold trials during CONTROL compared to $MI_{INCONGRUENT}$ and $MI_{CONGRUENT}$, albeit no subjective measures likely to confirm this postulate were part of the design. Participants finally percieved that their breath-hold performance during $MI_{INCONGRUENT}$ was higher to that during $MI_{CONGRUENT}$. It is thus suggested that the beneficial effects of $MI_{INCONGRUENT}$, operating either through a motivational function of MI and/or by the effects of MI on autonomic nervous system response patterns, triggered participant's awareness of increased performance.

The present study advocates for a beneficial effect of an incongruent form of MI practice with regards to the actual requirements of the physical performance. However, such beneficial effects might be strictly restricted to atypical sporting situations such as breath-holding. The present study thus does not allow to extrapolate the finding to other sporting activities. At the meantime, the psychological component to high-level performance in such sports should not be minimized. This emphasizes on the potential relevance of incorporating the specificities of MI practice with regards to the requirements of the physical performance in order to design fruitful training interventions. The processes underlying the efficacy of incongruent MI on breath-hold performance remain uncertain and require further experimental investigations. Future studies should consider evaluating performance in expert breath-hold athletes, which have better control strategies over the breathing reflex. Direct recordings from sympathetic nerves using microneurography could provide decisive insights on physiological arousal modulation occurring during breath-hold performance.

## 5. Conclusion

The purpose of the present study was to investigate the effect of congruent and incongruent MI practice on maximal breath-hold performance. Data confirmed the hypothesis that MI of breathing, but not MI of breath-holding, elicited increased breath-hold performance. The influence of MI of a breathing state on psychological and physiological factors determining the break-point of breath-holding might account for these beneficial effects.

## 6. Acknowledgments

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## 7. Figures caption

Figure 1. Raw HR (beats per minute) and R-R intervals (s) recordings during a breath-hold trial in a representative participant. The plateau is highlighted in blue (time window: 15-62 s). A: Bradycardia in response to the onset of breath-hold [28]. B: Breaking point (i.e., time of the first breath out). C: Signal noise artifact outside the plateau (nb. otherwise removed by the filters during data processing). D: Maximum breath-hold performance. In all participants and all experimental conditions a plateau was found, ending a few seconds before the breaking point.

Figure 2. Influence of fixed effects revealed by the linear mixed effects analysis on breath-hold durations. A: Barplot of the fitted estimates corresponding to the main effect of the experimental condition, represented with 95 % confidence interval (error bars). B: Regression slope of the relationship between the trial number and the breath-hold durations, represented with 95 % confidence interval (dotted lines). C: Regression slope of the relationship between breath-hold durations and i) SDNN (grey, triangle-shaped dots), and ii) HR (white, square-shaped dots), presented with 95 % confidence intervals (dotted lines). D: Regression slope of the relationship between breath-hold performance and $SO_2$ values at the break point of breath-holding, represented with 95 % confidence intervals (dotted lines). *$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Figure 3. A: Barplot of model estimates for the main effect of the experimental condition on participant's commitment to a maximal breath-hold performance with 95 % confidence interval (error bars). B: Barplot of the main effect of the experimental condition on MI vividness, represented with 95 % confidence interval (error bars). C: Regression slope attesting the main effect of the breath-holding trials repetition on the MI vividness, represented with 95 % confidence interval (dotted lines). * $p < 0.05$, $p < 0.001$.

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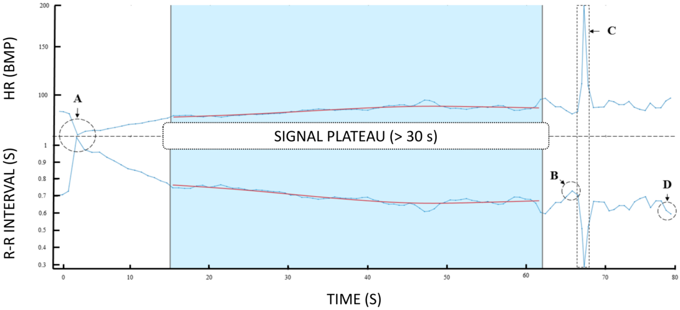
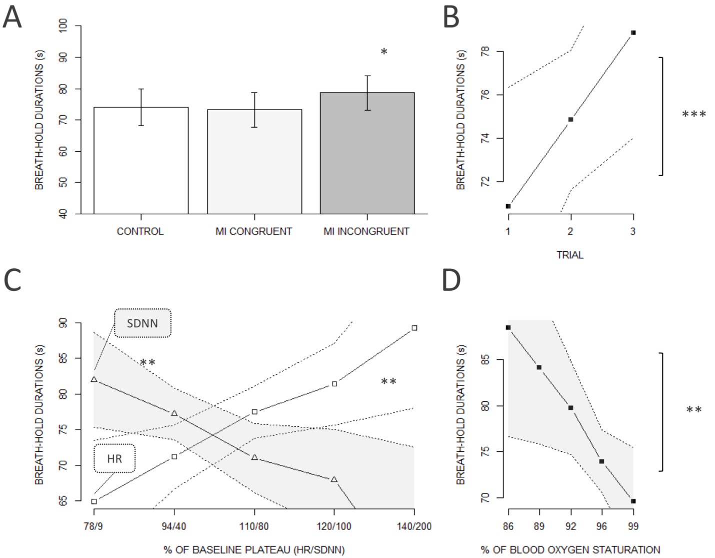
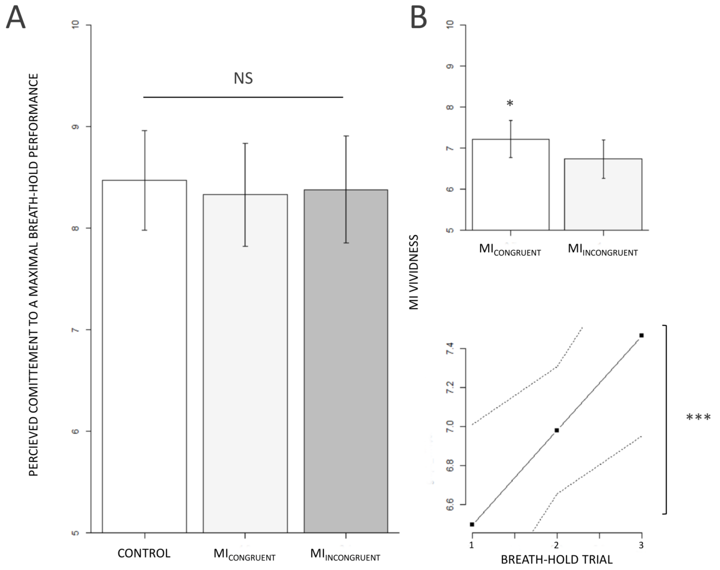


HR (BMP)
R-R INTERVAL (S)
TIME (S)
SIGNAL PLATEAU (> 30 s)
A
B
C
D
200
150
100
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
10
20
30
40
50
60
70
80



A
BREATH-HOLD DURATIONS (s)
40
50
60
70
80
90
100
*
CONTROL
MI CONGRUENT
MI INCONGRUENT
B
BREATH-HOLD DURATIONS (s)
72
74
76
78
***
1
2
3
TRIAL
C
BREATH-HOLD DURATIONS (s)
65
70
75
80
85
90
SDNN
HR
**
**
78/9
94/40
110/80
120/100
140/200
% OF BASELINE PLATEAU (HR/SDNN)
D
BREATH-HOLD DURATIONS (s)
70
75
80
85
**
86
89
92
96
99
% OF BLOOD OXYGEN STATURATION


A
NS
PERCIEVED COMITTEMENT TO A MAXIMAL BREATH-HOLD PERFORMANCE
10
9
8
7
6
5
CONTROL
MI CONGRUENT
MI INCONGRUENT
B
*
MI CONGRUENT
MI INCONGRUENT
MI VIVIDNESS
7.4
7.2
7.0
6.8
6.6
1
2
3
BREATH-HOLD TRIAL
***