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# Respiratory rhythm modulates membrane potential and spiking of non-olfactory neurons

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1 RESEARCH ARTICLE

2

3 RUNNING HEAD: Respiratory modulation in the brain: deep in the cells

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5 ARTICLE TITLE: Respiratory rhythm modulates membrane potential and spiking of non-  
6 olfactory neurons

7

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27 ABSTRACT

28 In recent years, several studies have shown a respiratory drive of the local field potential  
29 (LFP) in numerous brain areas so that the respiratory rhythm could be considered as a master  
30 clock promoting communication between distant brain locations. However, outside of the  
31 olfactory system it remains unknown whether the respiratory rhythm could shape membrane  
32 potential (MP) oscillations. To fill this gap, we co-recorded MP and LFP activities in different  
33 non-olfactory brain areas: medial prefrontal cortex (mPFC), primary somatosensory cortex  
34 (S1), primary visual cortex (V1), and hippocampus (HPC), in urethane-anesthetized rats.  
35 Using respiratory cycle-by-cycle analysis, we observed that respiration could modulate both  
36 MP and spiking discharges in all recorded areas during episodes that we called Respiration-  
37 Related oscillations (RRO). Further quantifications revealed that RRO episodes were transient  
38 in most neurons (5 consecutive respiratory cycles in average). RRO development in MP was  
39 largely correlated with the presence of respiratory modulation in the LFP. By showing that the  
40 respiratory rhythm influenced brain activities deep to the MP of non-olfactory neurons, our  
41 data support the idea that respiratory rhythm could mediate long-range communication  
42 between brain areas.

43

44 NEW & NOTWORTHY

45 In this study, we evidenced strong respiratory driven oscillations of neuronal membrane  
46 potential and spiking discharge in various non-olfactory areas of the mammal brain. These  
47 oscillations were found in medial prefrontal cortex, primary somatosensory cortex, primary  
48 visual cortex and hippocampus. These findings support the idea that respiratory rhythm could  
49 be used as a common clock to set the dynamics of large-scale neuronal networks on a same  
50 slow rhythm.

51

52 KEY WORDS: freely breathing anesthetized rat, intracellular activities, local field potential,  
53 membrane potential, respiration-related oscillations.

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## 58 INTRODUCTION

59 In recent years, a resurgence of publications has proposed respiration as a master clock for  
60 brain rhythms, following many observations that reported the breathing rhythm as being able  
61 to modulate complex behaviors or cognitive process (1–4). The exploratory behavior of  
62 rodents, consisting in rhythmical sampling of the environment, is a perfect example since the  
63 onset of each respiratory cycle initiates a “snapshot” of the orofacial sensory environment,  
64 comprising sniffing, whisking and head movements (5–7). Similarly, licking synchronizes  
65 with breathing (8, 9). In humans, respiration modulates memory consolidation (10),  
66 associative learning (11), cognitive performances (12–14), sensory perception (15, 16), and  
67 motor behaviors (17, 18). Respiratory phase influences the initiation of a voluntary action (19)  
68 or a cognitive task and its performance (13). All these data therefore suggest that the brain  
69 could have at least one processing mode depending on the respiratory phase.

70 Parallel to this literature on the effects of breathing on behavior has appeared an equally  
71 important literature on a respiratory drive of brain activity, both in human and rodent. In  
72 humans, intracerebral EEG-breathing coherence has been observed particularly in the  
73 hippocampus, amygdala, insula and the parietal lobe (14, 20) and the inhalation phase is  
74 correlated with an increase in the power of delta oscillations (14). In rodents, a respiration-  
75 locked local field potential (LFP) oscillation has been described in the hippocampus (21), the  
76 somatosensory cortex (22), the prefrontal cortex (23, 24), neocortical regions as posterior as  
77 visual cortex and even subcortical areas (25, 26). Breathing also modulates other rhythms in  
78 several brain regions. In the hippocampus, the timing of hippocampal sharp-waves and ripples  
79 is respiration-coupled (27, 28). In the somatosensory cortex, delta oscillations are respiration-  
80 locked whereas gamma power is respiration-modulated (22). In the prefrontal cortex, fast  
81 gamma LFP oscillations (29) and unitary activities (23) are phase-coupled with respiration.

82 This respiratory drive, described in such a large cerebral network, is at the moment assumed  
83 to arise via the activation of the olfactory bulb (OB) *via* mechanical stimulation of olfactory  
84 receptor cells by nasal respiratory airflow (30). Indeed, respiration-brain activity coupling  
85 dissipates in human when subjects breathe through the mouth (14) or in rodents when OB is  
86 silenced (21, 22, 28, 31). This respiration-related activity was first found in the OB where it  
87 has been largely described (For review, see (1)): respiration modulates both LFP and  
88 individual cells activities, including spiking discharge and membrane potential dynamics. In  
89 LFP signal, fast rhythms occurrence is shaped by the slow respiration-related oscillation  
90 (RRo), beta and gamma waves alternating on expiratory and inspiratory phases, respectively  
91 (33, 34). Mitral/tufted cells spiking discharge is strongly patterned by respiratory rhythm both  
92 in anesthetized (34–37) and awake rodent (38, 39). Importantly, even the membrane potential  
93 of mitral/tufted cells is influenced by respiration (35, 40, 41). Particularly, RRo of membrane  
94 potential constrain fast oscillations to occur concomitantly with LFP signal, hence favoring  
95 interaction between fast LFP and spiking (41). We and others have demonstrated that most of  
96 OB respiratory modulation is related to the amplitude of the inspiratory airflow (36, 42–44).  
97 Respiratory influence is also present, to a lesser extent, in the olfactory cortex both at the LFP  
98 and cellular levels (Piriform cortex: (1–4); Olfactory tubercle: (49)). Directly in contact with  
99 nasal respiratory airflows, the olfactory system is thus strongly impacted by respiration  
100 dynamics.

101 Oppositely, while LFP activity in non-olfactory regions has been described as respiration-  
102 modulated, very little is known about respiratory modulation of individual cell activities. Only  
103 a few reports described spiking discharge (extracellularly recorded) modulated by respiration  
104 (23, 24). Only one article reported intracellular recordings in parietal cortex (50). The authors  
105 showed membrane potential oscillations that were coherent with respiration in 6 out of 29  
106 parietal neurons, no further studies were done. Here we asked to what extent respiratory

107 modulation could shape cellular activity, including MP and spiking activity, in non-olfactory  
108 areas. To this purpose, we co-recorded membrane potential and LFP activities in widespread  
109 brain areas, namely the medial prefrontal cortex (mPFC), the primary somatosensory cortex  
110 (S1), primary visual cortex (V1), and hippocampus (HPC), in urethane-anesthetized rats.  
111 Using respiratory cycle-by-cycle analysis, we tracked respiratory modulation of cellular  
112 activities. We observed that both MP and spiking discharges could be respiration-modulated  
113 in all recorded areas, but more transiently than what we previously described in the OB (35).  
114 Particularly, respiratory modulation of MP was highly variable both between structures and  
115 between cells, very transient for most of cells and largely influenced by LFP state. Finally,  
116 moderate hyperpolarization of MP reduced the probability of RRo.

117



## 118 MATERIALS AND METHODS

### 119 Experimental procedures

#### 120 *Animal care*

121 The 25 male Wistar rats (325.2±32.1g, Charles River) used were housed in groups of four in a  
122 temperature (22±1 °C) and humidity (55±10%) controlled room and exposed to a 12/12 h  
123 light/dark cycle (light onset, 6:00 am). Experiments were conducted during the light period  
124 (between 9:00 am and 3:00 pm). Food and water were available *ad libitum*. All experiments  
125 were carried out in accordance with Directive 2010/63/EU of the European Parliament and of  
126 the Council of the European Union regarding the protection of animals used for scientific  
127 purposes and in compliance with the ARRIVE guidelines. The experimental protocols were  
128 approved by the National Ethics Committee “Animal Experimentation Committee of Univ.  
129 Claude Bernard Lyon 1—CEEA-55” (Agreement APAFIS #17088).

#### 130 *Animal preparation*

131 Rats were anesthetized with an intraperitoneal injection of urethane (1.5 g/kg), then, placed in  
132 a stereotaxic apparatus. Respiration was recorded with a homemade bidirectional airflow  
133 sensor placed at the entrance of the right nostril. Positive and negative flows corresponded  
134 respectively to inspirations and expirations. Body temperature was kept at 37 °C using a  
135 heating pad (Harvard Apparatus, Holliston, MA USA). A craniotomy of about 3x3 mm was  
136 performed above the site of recording: medial prefrontal cortex, primary visual cortex,  
137 somatosensory barrel cortex or hippocampus. Dura was removed, and Ringer’s lactate  
138 solution was regularly applied onto the brain to prevent from drying. At the end of the  
139 experiments, rats were euthanized by intracardiac injection of Dolethal©.

#### 140 *In vivo Electrophysiological Recordings*

141 We made simultaneous intra- and extracellular recordings in freely breathing anesthetized  
142 rats. Intracellular recordings (n = 69 cells) were performed in four different areas of the left  
143 hemisphere: the medial prefrontal cortex (mPFC, AP:  $3.1 \pm 0.4$  mm, MD:  $0.7 \pm 0.2$  mm), the  
144 primary somatosensory cortex (S1, AP:  $-2.4 \pm 0.4$  mm, MD:  $5.0 \pm 0.1$  mm), the primary visual  
145 cortex (V1, AP:  $-5.3 \pm 0.2$  mm, MD:  $4.5 \pm 0.8$  mm) and the hippocampus (HPC,  $-3.5 \pm 0.7$  mm,  
146 MD:  $2.6 \pm 0.7$  mm). Input resistance of the neurons was  $52.7 \pm 4.7$  M $\Omega$  (Supplemental Figure  
147 S1). Borosilicate glass capillaries (o.d. = 1.5 mm; i.d. = 0.86 mm, Harvard Apparatus,  
148 Holliston, MA, USA) were pulled with a horizontal puller (model P-97, Sutter Instruments,  
149 Novato, CA, USA). The micropipettes were filled with a 2 M potassium acetate solution, and  
150 their resistances ranged from 50 to 120 M $\Omega$ . Microelectrodes were lowered using a piezo  
151 manipulator (PM-10, World Precision Instruments, Sarasota, FL, USA). The  
152 electrophysiological signal was amplified and low-pass filtered at 10 kHz by an intracellular  
153 amplifier (Axoclamp 2B, Axon Instruments, Foster City, CA, USA). Local field potential  
154 (LFP) was recorded simultaneously with intracellular signal using silicon probes (Neuronexus  
155 Technology, Ann Arbor, MI, USA) placed as close as possible to the glass microelectrode.  
156 The signal was amplified, and low-filtered at 5 kHz with a homemade amplifier. Respiration  
157 was recorded with an airflow sensor (described in (51)). Positive and negative values  
158 corresponded to expiration and inspiration respectively. All signals were then digitalized at 25  
159 kHz (NI USB-6211, National Instruments, Austin, TX, USA) and stored on a computer using  
160 Neuroscope, a homemade software.

### 161 *Internal polarity state*

162 Internal polarity states were encoded based on the sign (positive or negative) and intensity of  
163 direct current (DC) injection, amplitude of MP variation and firing activity. We identified 4  
164 states: strong hyperpolarization (Hyp2), light hyperpolarization (Hyp1), basal level (Base),  
165 depolarization (Dep). A given cell was not systematically recorded in each of the 4 states.

166 *Post hoc* verification confirmed our classification (Supplemental Figure S2). Whatever the  
167 structure, basal level (Base) represented the state where no (N = 42 cells) or a very low  
168 stabilizing current ( $-0.07 \pm 0.06$  nA, N = 14 cells) was injected. Hyp1 level corresponded to a  
169 MP hyperpolarization of around 7 mV relative to the basal level, at which the spike discharge  
170 decreased by around 60%. This level was reached with a  $-0.29 \pm 0.04$  nA (N = 25 cells) DC  
171 injection. Hyp2 level corresponded to a MP hyperpolarization of around 12 mV relative to the  
172 basal level, at which the spike discharge decreased by 90% to 100%. This level was reached  
173 with a  $-0.42 \pm 0.04$  nA (N = 31 cells) DC injection. Dep level corresponded to a MP  
174 depolarization of around 7 mV relative to the basal level, at which the spike discharge  
175 increased by at least 10%. This level was reached with a  $0.19 \pm 0.03$  nA (N = 21 cells) DC  
176 injection. For the cell-by-cell analysis, in order to limit the influence of external factors, we  
177 selected pair of recordings close in time. In the mPFC, cells (N = 9 cells) received  $-0.17 \pm 0.02$   
178 nA for Hyp1, resulting in a hyperpolarization of  $7.6 \pm 2.5$  mV and a decrease in spike  
179 discharge of  $74.4 \pm 7.5$  %. Latency between Base and Hyp1 recordings was  $3.2 \pm 1$  min. In S1,  
180 cells (N = 4 cells) received  $-0.19 \pm 0.06$  nA for Hyp1 resulting in a hyperpolarization of  
181  $8.4 \pm 5.2$  mV and a decrease spike discharge decrease of  $50.0 \pm 26.6$  %. Latency between Base  
182 and Hyp1 recordings was  $3.3 \pm 1.4$  min. In HPC, cells (N = 3 cells) received  $-0.26 \pm 0.05$  nA for  
183 Hyp1 resulting in a hyperpolarization of  $7.6 \pm 3.0$  mV and a decrease in spike discharge of  
184  $50.5 \pm 10.0$  %. Latency between Base and Hyp1 recordings was  $1.3 \pm 0.2$  min.

## 185 Data analysis

186 All following analyses have been made using homemade Python scripts.

## 187 *Respiratory signal processing*

188 Respiratory cycles were detected as previously described in (51). Respiration was monitored  
189 with an airflow sensor. Positive, respectively negative, values corresponded to expiration,

190 respectively inspiration. Null values corresponded to transition between inspiration and  
191 expiration. Briefly, respiratory signal was low-pass filtered (8Hz) to reduce noise, then zero-  
192 crossing points were detected to delineate the start points of inspiration and expiration.  
193 Finally, the time of each respiratory cycle was linearly converted to phases ranging from 0 to  
194 1. In summary, all respiratory cycles were detected, inspiration and expiration phases were  
195 well determined, and respiratory phases were computed.

#### 196 *Rescaling time basis of signals with respiratory phase*

197 We wanted to track variations in the signals of interest (LFP, MP, AP discharge) in relation to  
198 respiratory rhythm. However, respiratory cycles exhibited variability in duration, and the  
199 inspiration-expiration ratio in two cycles with similar duration may be different. The  
200 respiratory phase is therefore the appropriate time scale for reducing jitter due to respiratory  
201 cycle variability. Following (51), we rescaled the signals of interest as a function of the  
202 respiratory phase. Briefly, after detecting the respiratory cycles, the signal for each cycle was  
203 interpolated into a 2000-points vector. To account for the asymmetry of respiratory cycles, the  
204 average inspiration ratio (inspiration duration/cycle duration) was computed for each  
205 recording. Cycle by cycle interpolation preserved the ratio, *i.e.*, for a 0.33 ratio, interpolation  
206 attributed 33% of the 2000 points to the inspiration period and the remainder to the expiration  
207 period. This rescaling allowed the construction of respiration-triggered MP average (Figure  
208 2C bottom) or respiration-triggered AP histogram (Figure 2C top). We made one exception to  
209 construct Figure 4B as we wanted to compare the preferred phase of depolarization between  
210 cells, so we rescaled all recordings with the same ratio 0.4 in order to align all cell respiratory  
211 phases. The average inspiration-expiration ratio of our dataset was  $0.41 \pm 0.01$ .

#### 212 *Time dynamics of respiration-related oscillations*

213

214 In this section, we will describe how we detected **respiration-related oscillations (RRO)** in  
215 oscillatory signals (membrane potential and LFP). We proceeded in 5 steps (Figure 1A).

216 (i) Preprocessing and deformation to respiratory phase. For the membrane potential,  
217 preprocessing consisted in removing the APs, in order to focus on membrane potential  
218 oscillations. As the duration of APs in our population of neurons was homogeneous  
219 (Supplemental Figure S3), we used the same cutting values for all our neurons. To remove  
220 APs, single APs were cut from 4 ms before to 5 ms after the peak while bursts (defined by  
221 interspike interval < 20ms) were cut from 30 ms before the first AP to 30 ms after the last AP.  
222 The cut signal was replaced by a linear interpolation between the two extremities. For the  
223 LFP, preprocessing consisted in high-pass filtering (0.1 Hz). Once preprocessed the signal of  
224 interest was deformed to respiratory phase (see *Rescaling time basis of signals with*  
225 *respiratory phase*).

226 (ii) Detection of synchronization with respiration in local windows. As we wanted to track the  
227 temporal dynamics of respiration-related oscillations, we scanned the recordings with  
228 windows of 4 respiratory cycles, with an overlap of 3 cycles between consecutive windows  
229 (Figure 1B.2). For each window, we computed the median signal from the 4 respiratory cycles  
230 (example in Figure 1C.2 left, green trace), which represented a proxy for estimating a local  
231 oscillation at respiratory frequency. To assess the importance of the respiratory modulation,  
232 we measured the amplitude of this median signal (example in Figure 1C.2 left, red bar), which  
233 is expected to be high when the oscillations are synchronized with the respiration. To test the  
234 significance of such a local respiration-related oscillation, we compared the actual amplitude  
235 with amplitudes of 500 surrogates (example in Figure 1C.2 and C.3). We considered the  
236 oscillation of the windows to be respiration-related if the actual amplitude was larger than 95<sup>th</sup>  
237 percentile of surrogate amplitudes (example in Figure 1C.3). The construction of the  
238 surrogates (see Figure 1C.1) consisted in creating pairs of cycles (cycles 118&119, and

239 121&120 in our example Figure 1C.1), and then phase-shifting the signal. For one pair, we  
240 shifted the first cycle with a random phase ( $\varphi_1$ ). The other cycle of the pair was shifted in  
241 phase opposition ( $\varphi_1+\pi$ ). We repeated this transformation for the second pair of cycles with  
242 another random phase shift ( $\varphi_2$ ). This manipulation neutralized the respiratory component of  
243 the signal.

244 (iii) Verification of the similarity between individual cycles and local oscillation. From the  
245 windows previously identified as respiration-related (windows 118 to 120 in our example  
246 Figure 1B.2), we wanted to identify the cycles that actually contributed to this respiration-  
247 related oscillation. To verify that individual cycles within the window were similar to the  
248 local waveform, we computed the scalar product of each cycle with the window median signal  
249 (example for one cycle in Figure 1D.1). Since we focused on the waveform, not on the  
250 amplitude, we z-scored the signals before performing the scalar product. We assessed the  
251 significance by comparing the scalar product of actual data with the scalar product from the  
252 500 surrogate window signals (Figure 1D.1 and D.2). We considered the individual cycle  
253 significantly similar to the local waveform if the scalar product value was greater than the 95<sup>th</sup>  
254 percentile of surrogated scalar product values (detailed histogram for cycle 118 with window  
255 118 in Figure 1D.2).

256 (iv) Cycle by cycle encoding. To switch toward a cycle-by-cycle encoding, we wanted to  
257 make sure that the individual cycles, constituting the windows previously identified as  
258 respiration-related, actually displayed respiration-related oscillations. To do so we scored  
259 each cycle as follows. Each time the Vm of a cycle was similar (black rectangle in Figure  
260 1B.3) to the waveform of a respiration-related window (red windows in Figure 1B.2), the  
261 score was incremented by one. For example, the cycle 121 (Figure 1B.3) participated in three  
262 windows identified as respiration-related (windows 118-120). The cycle 121 was similar to  
263 the waveforms of these 3 respiration-related windows and was not tested for the non-

264 modulated (window 121). The cycle 121 reached the score of 3. Since a cycle can be scanned  
265 up to four times (in four consecutive windows), score of a cycle ranged from 0 to 4. We  
266 classified cycles in three respiration-related categories as follows: 0 and 1: non-modulated  
267 cycles, 2: undetermined, 3 and 4: modulated cycles. In our example (see Figure 1B.4) cycles  
268 120 and 121, with a score of 3, were then considered as RRo.

269 (v) Curation of isolated events. Finally, we eliminated all single or doublet cycles identified as  
270 RRo, and they were reassigned to the undetermined category. Indeed, we considered that  
271 respiratory related episodes lasting less than 3 consecutive cycles were not statistically  
272 relevant and too much susceptible to false detection.

273 For each recording, we were then able to compute the probability of RRo (expressed in  
274 percent), defined as the ratio between the number of respiratory cycles with respiration-related  
275 oscillations and the total number of cycles. This probability was not biased by the recording  
276 duration (Supplemental Figure S4A, which varies from cell to cell), the absolute respiratory  
277 frequency (Supplemental Figure S4B, proxy for depth of anesthesia), the input resistance of  
278 the cells (Supplemental Figure S4C). On the contrary, the RRo probability was correlated  
279 with coherence to respiration (Supplemental Figure S4D,  $p = 5.6 \cdot 10^{-16}$ ).

280 We performed a last refinement to identify **respiration-modulated cells or LFP**: For further  
281 quantification of membrane potential or LFP respiration-related dynamics, we wanted to keep  
282 only **cells or LFP** recordings that were significantly synchronized with respiration. If we  
283 considered every recording for which RRo were detected as an overall respiration-modulated  
284 recording, longer recordings would present greater chance to be defined as “respiration-  
285 modulated”. Therefore, to counterbalance this bias, we computed a cell-by-cell threshold on  
286 the proportion of required RRo cycles in order to classify the cell or LFP recording as  
287 respiration-modulated. To do so, for each recording, we first estimated the respiratory

288 frequency by taking the peak frequency from the respiration power spectrum. The breathing  
289 rhythm being extremely stable during anesthesia, a narrow notch filter (mne.notch filter,  
290 'spectrum\_fit' method, notch width = 1 Hz, mne version 0.20.1) applied on the signal of  
291 interest (membrane potential or LFP) removed the respiratory component of the signal, while  
292 preserving the other oscillations. The signal was then randomized using Fourier phase  
293 randomization technique. Spurious respiration-related oscillations were detected with the  
294 previously described algorithm. These steps were repeated 200 times. The number of cycles  
295 with respiration-related oscillations detected out of the 200 respiration-deprived signals were  
296 gathered and, the 95<sup>th</sup> percentile was computed. This percentile represented our threshold of  
297 significance. If the number of cycles with respiration-related oscillation detected on the true  
298 signal was above the threshold, we considered the recording as respiration-modulated. As a  
299 result, this selection excluded one V1 neuron from our Base polarity population, (indicated  
300 with the black cross on cell 3 from V1 in Figure 3A). One cell in HPC was excluded from  
301 Hyp1 population. Two cells in HPC were excluded from Hyp2 population.

### 302 *Respiration-triggered membrane potential*

303 Using the classification method described previously, we could isolate membrane potential  
304 cycles related to respiration. These cycles were then stacked, and we computed the median  
305 signal. For each respiration-modulated cell, the amplitude of respiration-related oscillations  
306 was defined as the maximum/minimum difference of this median signal. To analyze the  
307 depolarization preferred phase, we computed the median respiration-triggered signal, then we  
308 extracted the mean vector from which we finally measured the angle. For this latter analysis  
309 we only used RRo cycles of respiration-modulated cells.

### 310 *Respiration-triggered spiking pattern*



311 AP times were rescaled to a respiratory cycle phase basis. Therefore, AP were identified by  
312 the number of the respiratory cycle they belong to, and their respiratory phase within that  
313 cycle. Once respiratory cycles were classified in respiratory-related categories, we could sort  
314 AP according to these categories. Then, for each cell and each respiratory-related category we  
315 built a respiration-triggered discharge histogram. For each cell, three experts, independently,  
316 visually encoded spiking patterns associated to each respiratory-related category. Spiking  
317 patterns were classified as: respiration-related, not respiration-related, or undetermined (not  
318 enough spikes to conclude). This classification was inspired from (32).

#### 319 *Power spectrum*

320 For the 4 examples in Figure 2, Morlet wavelet time-frequency maps (0.4-6Hz) for respiratory  
321 signal and AP-removed membrane potential were computed for whole recordings. We then  
322 extracted the 4-second time windows showed in the figure and averaged across time to  
323 estimate the power spectrum. Spectra were normalized by their sum to obtain a density.

#### 324 *Extracellular signal (LFP) processing*

325 The LFP signal was 0.1 Hz high pass filtered. Then, similarly to membrane potential  
326 oscillations, LFP-respiration relationship was classified cycle by cycle. Using this  
327 classification, the relationship to respiratory rhythm was then compared between membrane  
328 potential and LFP.

#### 329 *Conditional probabilities*

330 For this analysis, we kept recordings for which both membrane potential and LFP exhibited  
331 significant respiration-modulation (as described in *Time dynamics of respiration-related MP*  
332 *oscillations*). In Figure 5D, we examined the conditional probability to observe membrane  
333 potential RRo in relation to LFP dynamics. In other words, we split recording according to the

334 LFP RRo encoding. On the one hand we computed membrane potential RRo probability  
335 among cycles with LFP RRo. On the other hand, we again computed the membrane potential  
336 RRo probability among cycles during which LFP activity was not related to respiration (other  
337 LFP activity). Figure 5E is the complementary view, since we computed the conditional  
338 probability to observe LFP RRo according to membrane potential dynamics (RRo versus  
339 other activity).

#### 340 *Statistics*

341 Statistics were made with Scipy (version 1.4.1) python package (scipy.stats.wilcoxon,  
342 scipy.stats.mannwithneyu, scipy.stats.kruskal). All averages are presented under the format  
343 mean  $\pm$  SEM. Where this is not the case, it is explicitly stated.

344

345

346 RESULTS

347 **Evidence of respiratory modulation of cell membrane potential in non-olfactory**  
348 **structures**

349 *In vivo* intracellular activities recordings were obtained from 4 non-olfactory structures in 25  
350 freely breathing anesthetized rats; all polarity states combined, 34 cells were recorded in  
351 medial prefrontal cortex (mPFC, N = 9 rats), 13 cells in somatosensory cortex (S1, N = 4  
352 rats), 5 cells in visual cortex (V1, N = 4 rats), and 17 cells in hippocampus (HPC, N = 8 rats).  
353 The respiratory frequencies ranged from 1.44 Hz to 2.08 Hz ( $1.78 \pm 0.03$  Hz, N = 25 rats).

354 In all these four areas, we found cells exhibiting respiration-related oscillations (RRO) in their  
355 membrane potential (MP) and respiration-related (RR) spiking discharge, as shown in the raw  
356 traces examples (Figure 2A). To highlight the RRO, the filtered respiratory signal (light gray)  
357 was superimposed on the raw traces of the intracellular MP oscillations. In Figure 2B, the  
358 power spectral density analysis of the MP signal (black PSD) showed a clear power peak at  
359 the respiratory frequency (gray PSD) confirming that MP follows the respiratory rhythm in  
360 these examples.

361 In order to properly characterize the relation between MP and respiratory rhythm, we  
362 developed a cycle-by-cycle method for detecting the respiratory cycles during which MP  
363 oscillated at the respiratory frequency (see Figure 1 and materials and methods for details).  
364 We plotted the median of respiration-triggered membrane potential (Figure 2C bottom panels)  
365 and the histograms of spiking occurrence during these cycles (Figure 2C top panels). In the  
366 examples in Figure 2, MP RRO were large (median amplitude  $\pm$  95% confidence interval:  
367 mPFC =  $5.5 \pm 0.9$  mV, S1 =  $14.5 \pm 2.1$  mV, V1 =  $8.8 \pm 2.2$  mV, HPC =  $3.1 \pm 0.8$  mV; Figure 2C  
368 bottom panels), and APs occurrences were clearly related to respiratory cycle (top panels in  
369 Figure 2C). Moreover, on these examples, MP RRO and firing pattern were similarly phase-

370 locked to respiration, suggesting a strong correlation between MP RRo and the associated  
371 firing. Indeed, spikes appeared on the top of the oscillation, where the MP exhibited the  
372 greatest depolarization.

373

374 In this way, we evidenced that a respiratory modulation could be expressed in the intracellular  
375 activity (MP and spiking) of cells in the four non-olfactory areas we recorded. The next step  
376 aimed to better characterize this MP respiratory modulation in each structure.

377

378 We first quantified the percentage of cells exhibiting MP RRo at resting membrane potential  
379 (Base polarity). As explained in Methods, we considered RRo only if the episode lasted at  
380 least 3 consecutive respiratory cycles. We measured in each cell, and in the 4 structures, the  
381 percentage of respiratory cycles during which an MP RRo was detected (Figure 3A), then we  
382 plotted the cumulative percentage of MP RRo cycles across cells for mPFC, S1 and HPC  
383 (Figure 3B). Since too few V1 recordings were available, V1 will not be included in the  
384 following comparative analyses. Additional shuffling statistics (see methods) revealed  
385 respiration-modulated cells represented 65.6% of cells (21/32) in mPFC, 70% (7/10) in S1,  
386 and 80% (8/10) in HPC. Therefore, at least 65% of the recorded cells in each structure  
387 presented a respiratory modulation. Additionally, the two cortical structures (mPFC and S1)  
388 presented slightly lower proportions of respiration-modulated cells than HPC. Specifically,  
389 the cumulative percentage curves (Figure 3B) showed that 20% of the cells in S1 and mPFC  
390 had more than 20% of their MP cycles modulated by respiration, about 20% of HPC cells had  
391 more than 75% of their cycles modulated.

392 As shown in Figure 3A1-4, the percentages of MP RRo cycles varied greatly from cell to cell  
393 within the same structure, from one structure to another. Indeed, if only the respiration-

394 modulated cells were considered (black bars without black cross), the percentage of cycles  
395 presenting an MP RRo ranged from 1.3% to 90.5% in mPFC ( $15.3 \pm 4.7\%$ ,  $N = 21$  cells) and  
396 from 3.2% to 88.9% in HPC ( $29.5 \pm 11.4\%$ ,  $N = 8$  cells), while it only extended from 3.9 to  
397 33.3% in S1 ( $13.4 \pm 3.9\%$ ,  $N = 7$  cells) (Figure 3C). Three neurons (one in mPFC and two in  
398 HPC) exhibited an extreme proportion of MP RRo cycles (more than 90%). The low  
399 percentage of MP RRo cycles for some cells was certainly due to our highly selective method  
400 for detecting RRo cycles (see material and methods). Due to the high variability between  
401 cells, no significant difference in proportion of MP RRo cycles between structures was  
402 observed (Figure 3C, Kruskal-Wallis test,  $p = 0.53$ ,  $H(2) = 1.24$ ).

403 To go one step further, we quantified for each respiration-modulated cell the average duration  
404 of RRo episodes (*i.e.*, the number of consecutive cycles in an MP RRo). As shown in Figure  
405 3D, there was no significant difference in the duration of RRo episodes between structures  
406 (Figure 3D), (Kruskal-Wallis test,  $p = 0.58$ ,  $H(2) = 1.07$ ). In fact, the average number of  
407 consecutive MP RRo cycles was around five regardless of the structure (mPFC:  $5.0 \pm 0.7$ ,  $N =$   
408 21 cells; S1:  $5.3 \pm 1.4$ ,  $N = 7$  cells; HPC:  $5.8 \pm 1.2$ ,  $N = 8$  cells).

409

410 Taken together, these results showed that at least 65% of cells of each recorded structures  
411 could synchronize their MP oscillations with respiration. However, this respiratory  
412 modulation of MP was 1) highly variable both between structures and between cells, 2) very  
413 transient for most cells (with a mean episode duration of 5 cycles).

414 Next, to further explore the intrinsic dynamics of these RRo episodes, we studied both their  
415 amplitudes and phases. We first measured the amplitude of the median respiration-triggered  
416 MP (see material and methods for details) for each modulated cell (Figure 4A). Figure 4A  
417 revealed that amplitude of MP RRo was higher in S1 ( $10.7 \pm 2.4$  mV,  $N = 7$  cells) compared to

418 mPFC ( $4.0 \pm 0.5$  mV, N = 21 cells) and HPC ( $4.4 \pm 0.9$  mV, N = 8 cells) (Kruskal-Wallis test, p  
419 = 0.01,  $H(2) = 9.1$ , *post hoc* Mann-Whitney U test S1–mPFC: p = 0.002 and S1-HPC: p =  
420 0.02).

421

422 To pursue, we characterized the respiratory phase of the MP RRo. As already suggested by  
423 the illustrative examples in Figure 2, the MP RRo phases were not unique. Indeed, while MP  
424 exhibited maximal depolarized values around the transition phase between inspiration and  
425 expiration in S1 and HPC examples (Figure 2C2 and 2C4), MP of mPFC and V1 examples  
426 exhibited hyperpolarized values at this same respiratory phase (Figure 2C1 and 2C3). On the  
427 whole dataset, we extracted, for each cell the phase of the most depolarized value of the  
428 median MP RRo (see Figure 2, panels C-bottom for examples of median MP RRo). Figure 4B  
429 shows for each structure the preferred phase for each cell. For mPFC, S1 and HPC these  
430 phases seemed to be distributed according to two preferential values, one between 130-170  
431 degree and the other between 315-340 degree. These ranges of values approximately  
432 corresponded respectively to a period between the end of inspiration and the beginning of  
433 expiration, *i.e.* near inspiration to expiration (I/E) transition (at 140 degree) and another  
434 around the end of expiration, before expiration to inspiration (E/I) transition (at 0 degree).

435 Finally, we examined in detail the relationship between MP RRo and spiking discharge  
436 (Respiration-Related (RR) or not). Table 1 presented the different association's possibilities  
437 between MP (RRo or no-RRo) and discharge (RR discharge and no-RR discharge). To  
438 construct this table, we considered the distribution of spikes as a function of respiratory phase  
439 (see Figure 2C, top panels) using previously described method used in the olfactory bulb (34,  
440 35) (see Material and Methods for details). For a given cell, we could compute two spike  
441 distributions on the respiratory phase, one with the spikes occurring during period of MP RRo

442 and the other with the spikes occurring during MP no-RRo. The two spike distributions were  
443 then classified as either respiration-related (RR) discharge or non-respiration-related (no-RR)  
444 discharge. However, if the cell had no MP RRo period or if there were too few AP, spike  
445 distribution could not be classified, which explains the N in table 1 are lower than those  
446 observed in Figure 3. Table 1 summarized this classification across cells for each structure. It  
447 showed the percentages of each association between spiking discharge patterns (columns) and  
448 respiration-triggered MP types (lines). In mPFC and S1, the MP RRo was mostly associated  
449 with the RR discharge pattern (80% for both structures) and conversely the MP no-RRo was  
450 mostly associated with the No RR discharge pattern (71.4% and 85.7% respectively). The  
451 results for HPC did not show the same association profile. Indeed, only 25% of the MP RRo  
452 was associated with RR discharge pattern.

453

454 In summary, we showed that MP RRo were larger for cells in S1. The respiratory phases were  
455 mainly around I/E and E/I transitions for mPFC, S1 and HPC cells. Moreover, respiratory  
456 coupling between MP and spiking discharge was much more frequent in mPFC and S1 (80%  
457 each) than in HPC (25%).

458 Given the transient nature of MP RRo and their variability in amplitude and phase, we  
459 wondered whether parameters such as cell intrinsic state or local network state could  
460 influence respiratory modulation of MP.

461

462 **Influence of intrinsic excitability and network activity on the respiratory modulation of**  
463 **membrane potential**

464 Our second aim was then to examine to what extent MP RRo could be influenced by (i)  
465 intracellular excitability, and (ii) by local field potential (LFP) state.

466 (i) Effect of intracellular excitability.

467 First, we investigated the effect of excitability level on the probability for MP to be modulated  
468 by the respiration. Briefly, we tested two hyperpolarization levels (Hyp1 and Hyp2) and one  
469 depolarized level (Dep) by progressive direct intracellular DC current injection. As described  
470 in materials and methods, we used 3 criteria (firing, MP value, and injected current) to  
471 classify these excitability states.

472 The proportions of respiration-modulated cells (mPFC, S1 and HPC were pooled) were  
473 relatively stable between the four different excitability levels (Supplemental Figure S5A,  
474 Hyp2: 58% - 18 out 31 cells, Hyp1: 52% - 13 out of 25 cells, Base: 69% - 36 out of 52 cells,  
475 Dep: 62% - 13 out of 21 cells). Thus, considering the whole population, excitability level did  
476 not clearly influence the proportion of respiration-modulated cells.

477 Next, we compared the percentages of MP RRo cycles for a same cell when it was  
478 hyperpolarized from Base to Hyp1 level (Supplemental Figure S5B). This cell-by-cell  
479 analysis was necessary because of the great variability of MP RRo cycles proportion at base  
480 level within a same structure (*cf.* Figure 3). This analysis indicated that, the percentage of MP  
481 RRo cycles was reduced upon hyperpolarizing the cell (Base:  $19.6 \pm 6.8\%$ , Hyper1:  
482  $13.3 \pm 7.0\%$ , Wilcoxon test  $p = 0.01$ ,  $Z = 7.0$ ,  $N = 16$  cells)

483 These data showed that, although the internal excitability state had a weak influence on the  
484 proportion of respiration-modulated cells at the whole population level, moderate  
485 hyperpolarization of a cell decreased its percentage of MP RRo cycle.

486 (ii) Effect of LFP state.



487 As it is now well established that LFP in these brain structures can be modulated by  
488 respiration (25, 26), we then wondered how MP and LFP respiratory rhythms could interact.  
489 The raw traces in Figure 5A1 showed an example where neither MP nor LFP displayed RRo.  
490 Conversely, for the same recording, a few minutes later (Figure 5A2, after 2 min), respiratory  
491 frequency appeared simultaneously in MP and LFP signals. The similarity between both  
492 signals is highlighted when superimposing filtered respiratory signal (light gray traces on MP  
493 and LFP raw signals).

494 LFP RRo cycles were detected in the same way than MP RRo cycles, in order to be able to  
495 compare their temporal dynamics (see Methods). LFP RRo were found in the three structures.  
496 Figure 5B showed the average percentage of LFP RRo per recording (gray dots) and the  
497 percentages per structure (dark-gray squares). mPFC showed a significantly higher percentage  
498 of LFP RRo cycles than S1 (Kruskal-Wallis test,  $p = 0.03$ ,  $H(2) = 6.96$ , *post hoc* Mann-  
499 Whitney U test mPFC-S1,  $p = 0.01$ ). The same tendency was observed with HPC, but  
500 significance was not reached (Mann-Whitney U test mPFC-H,  $p = 0.07$ ). In the same way as  
501 for the MP recordings, we quantified for each LFP recording the mean duration of LFP RRo  
502 episodes. The mean number of consecutive LFP RRo cycles (Figure 5C) was significantly  
503 higher for mPFC ( $10.6 \pm 2.2$  cycles,  $N = 21$  recordings) than for S1 ( $3.8 \pm 0.2$  cycles,  $N = 5$   
504 recordings), and HPC ( $4.2 \pm 0.4$  cycles,  $N = 4$  recordings). (Kruskal Wallis  $p = 7.10^{-3}$ ,  $H(2) =$   
505  $10.0$ , *post hoc* Mann-Whitney U test mPFC-S1:  $p = 0.005$ , mPFC-HPC:  $p = 0.02$ )

506 We then investigated the extent to which LFP and MP respiration-modulation could be  
507 correlated. To do this, we calculated the percentage MP RRo cycles when the LFP exhibited  
508 RRo or not (Figure 5D). It became clear that, irrespective of the structure considered, the  
509 probability of the MP displaying RRo was higher when the LFP displayed RRo. For mPFC,  
510 the increased MP RRo probability when LFP switched from no RRo to RRo was significant  
511 (Wilcoxon test  $p = 0.02$ ,  $Z = 44$ ,  $N = 20$  cells). HPC exhibited the same tendency (Wilcoxon

512 test,  $p = 0.07$ ,  $Z = 0$ ,  $n = 4$ ), and, to a lesser extent S1 also (Wilcoxon test,  $p = 0.14$ ,  $Z = 1$ ,  $n = 4$ ).  
513 Reciprocally, we wondered whether the probability of the LFP displaying RRo could be  
514 different when the MP displayed RRo or not (Figure 5E). We found that in mPFC, S1 and  
515 HPC, the probability of the LFP displaying RRo was higher when the MP displayed RRo, but  
516 this result was statistically significant only for mPFC (Wilcoxon test mPFC:  $p = 0.001$ ,  $Z =$   
517  $21$ ,  $N = 20$  cells). This confirmed that, most of the time, the respiratory modulation of a cell  
518 MP is coherent with the respiratory modulation of its network environment. Note that the lack  
519 of statistical significance in regions others than mPFC is probably due to the small sample  
520 size.

521 To summarize, we observed that MP and LFP are often respiratory co-modulated.

522

523

524 DISCUSSION

525 While many studies have recently evidenced a respiration-related activity in LFPs of many  
526 brain regions (21–26, 28, 29), our study is the first to describe respiratory-related oscillations  
527 in the MP activity in widespread brain areas, namely mPFC, S1, and HPC. We showed  
528 respiration-related oscillations of MP in a large proportion of cells (65.6% in mPFC, 70% in  
529 S1, and 80% in HPC). Before us, very sparse and scarce data existed reporting MP  
530 oscillations coherent with LFP respiration-related oscillation ((26, 29): 1 cell recorded in  
531 parietal cortex; (21): 3 cells out of 7 recorded in dentate gyrus after brainstem stimulation,  
532 (50) : 6 cells in parietal cortex). Our study goes further by comparing the probability of MP  
533 respiration-related oscillations in three different brain regions and by detailing how such  
534 oscillation could be influenced by excitability state or network activity. These results suggest  
535 that respiratory rhythm can entrain brain activity down to the membrane potential. In addition,  
536 we recorded in a preliminary study two prefrontal neurons whose membrane potential RRo  
537 was suppressed by ipsilateral nostril obstruction (Supplemental Figure S6). If extended, such  
538 results would definitively show that MP RRo in mPFC are entrained by respiratory nasal  
539 airflow. Contrarily to anesthetized animals, awake animals display various pattern of  
540 respiration. It has been shown that respiratory modulation is stronger for low frequency  
541 respiration (52–54), more precisely for short and deep inspirations (25, 55). During  
542 anesthesia, respiration tends to have a slow frequency and the inspiration tends to be shorter  
543 than the expiration. In our dataset, the mean respiratory frequency was 1.78Hz and the mean  
544 inspiration duration was 230ms. This inspiration duration is close to the optimal inspiration  
545 duration (100-200ms) previously observed during quiet wake (25, 55). Since the anesthesia  
546 brought the animal's respiration in a pattern close to the optimum, it could explain the extent  
547 of the respiratory modulation that we observed in this study. Finally, it would also be  
548 interesting to test whether the MP of cells in some brain structures could still be respiration

549 modulated in the absence of any OB afferents since it has been shown that cerebral activity  
550 can also be modulated due to the presence of an intracerebral respiratory corollary discharge  
551 originating from the brainstem (27).

552 Accumulating data showed that respiration can influence LFP from almost all brain areas (20,  
553 25, 26), the unitary activity of several areas (22, 24, 27) and cognition (10, 13, 14). We  
554 complementarily showed that membrane potential and action potential can be modulated by  
555 respiration, and thus we reinforce the idea that respiratory rhythm could act as a common  
556 clock for the brain. In this view, we expected the respiratory rhythm to synchronize  
557 hyperpolarization and depolarization from distant neurons, facilitating their communication.  
558 However, we rather observed that RRo displayed variable phase-locking to the respiration  
559 (Figure 4B). Indeed, independently from the brain areas, neurons' depolarization tended to  
560 phase-lock either to the inspiration-expiration transition or to the expiration-inspiration  
561 transition. However, is this finding completely against the hypothesis of a communication  
562 through respiratory rhythm? The same variability in phase-locking was observed in the  
563 olfactory bulb (35, 40). In addition, Ackels and colleagues (40) showed mitral cells tended to  
564 be depolarized during inspiration, while tufted cells depolarization occurred during expiration,  
565 suggesting that the phase of respiratory rhythm could mediate information multiplexing. The  
566 variability in phase-locking observed here (Figure 4B) suggests this multiplexing continues  
567 beyond the olfactory bulb.

568 We first evidenced that the proportions of cells expressing MP respiration-related oscillations  
569 were disparate between brain regions. In fact, cells were more likely to display RRo in HPC  
570 than in S1 or mPFC (Figure 3B). Moreover, the amplitude of MP RRo was larger in S1 than  
571 in other brain regions, at least in a sub-population of cells (see Figure 4A). Interestingly,  
572 extracellularly recorded spiking activity in S1 has been previously described as rhythmically  
573 correlated with respiration (22). This stronger relation between respiration and S1 barrel

574 cortex cells could have something to do with the fact that respiration binds different orofacial  
575 rhythms as whisking and sniffing particularly during olfactory search (7, 56, 57). Even if there  
576 is no whisker movement in the anesthetized preparation, olfactory and whisker cortices could  
577 be functionally linked since a crosswire between piriform and barrel cortices has been  
578 revealed in mouse brain slices after whiskers are trimmed, leading to a cross-modal sensory  
579 plasticity (58). Such a link could explain our observation.

580 We expected cells in mPFC to display more clearly respiration-related oscillations in their  
581 MP, given the strong modulation of LFP described in this region in the freely moving animal  
582 (25, 27, 59, 60). However, neither the duration of MP respiration-modulated episodes nor the  
583 amplitude of MP RRo is more pronounced in mPFC than in the three other areas. The fact that  
584 anesthetics have voltage-dependent effects on resting MP (61) could lower MP sensitivity to  
585 respiration. However, even in the awake head-fixed mouse, (24) reported that spiking  
586 discharges of neurons in mPFC are much less coupled to breathing than neurons in orbito-  
587 frontal cortex. This different probability of respiration-related oscillation between LFP and  
588 intracellular signals raises the question of a possible contamination of LFP signals by volume  
589 conduction coming from distant generators (62, 63).

590 Oppositely, we showed a very clear respiration-related activity in MP of HPC cells (80% of  
591 cells expressed RRo and 20% of them displayed at least 75% of modulated cycles). This  
592 probably reflects the strong relationship between olfactory and limbic structures. Very  
593 recently, Zhou et al. (64) reported that human hippocampal connectivity is stronger with  
594 olfactory cortex than other sensory cortices and that olfactory-hippocampal connectivity  
595 oscillates with nasal breathing. Interestingly, several recordings of HPC neurons exhibiting  
596 MP RRo revealed that, when emitted in bursts, action potentials were locked to the I/E  
597 transition point of respiratory cycle while single action potentials were more loosely  
598 distributed over the respiratory cycle (data not shown). It is commonly admitted that bursts

599 could facilitate synaptic transmission (65) and induce synaptic plasticity, LTP or LTD,  
600 depending on the theta oscillatory cycle phase of the burst (66). Furthermore, bursts increase  
601 detection of presynaptic events (67), thanks to their higher signal to noise ratio compared to  
602 single action potential. The fact that the MP of HPC cells could be paced by breathing could  
603 thus influence place cells coding notably during sniffing where respiratory and theta rhythms  
604 are in the same frequency range (25, 26).

605 We only recorded 4 cells in V1, 2 of them showed episodes of MP RRo. In these cells, the  
606 percentage of MP RRo did not exceed more than about 25% of total cycles. This confirms the  
607 observation that LFP in posterior areas are less susceptible to respiratory drive (25, 26). It is  
608 nevertheless interesting to observe that, even in a region as posterior as V1 and so improbably  
609 connected to the olfactory input, respiration can affect subthreshold activity.

610 We previously showed that the MP of mitral/tufted cells, the principal neurons of the  
611 olfactory bulb, is strongly respiration-modulated (35). We cannot compare the percentages of  
612 modulated cells between the non-olfactory structures recorded here and olfactory bulb  
613 neurons because we did not use the same experimental paradigm, neither the same detection  
614 method nor data processing. However, it can be noted that hyperpolarization of mPFC and S1  
615 cells appears to reduce the number of cells exhibiting MP RRo. On the contrary, in the  
616 olfactory bulb, hyperpolarization induced an increase in the proportion of respiratory  
617 modulated cells, which could suggest a reversal potential of MP RRo more hyperpolarized in  
618 non-olfactory structures than in olfactory bulb. It would be necessary to undertake a fine  
619 characterization of the different types of RRo that may exist (as in mitral/tufted cells) in order  
620 to be able to formulate hypotheses. However, we could postulate that a greater inhibition  
621 would be implicated in the oscillatory dynamics of these non-olfactory cells, which is in line  
622 with recent findings (50). Indeed, it has been shown that inhibitory interneurons appear to be  
623 more respiratory modulated than pyramidal neurons (23, 27). It would be of great interest to

624 test the possibility that the consequence of a hyperpolarization (increase or a decrease of the  
625 respiratory modulation) would come from the fact that the respiratory influence could rather  
626 impinge on inhibitory interneurons (as it could be in mPFC) or on a balanced excitatory-  
627 inhibitory network (as in OB).

628 LFP RRo episodes were variable between regions, with duration up to 10 cycles in mPFC and  
629 between 3 and 6 cycles for other structures. This longer LFP RRo episode duration in mPFC  
630 is not surprising since several studies observed a particularly strong respiratory modulation in  
631 the prelimbic cortex. Then, the respiratory rhythm may take over more often than other  
632 rhythms. Alternating populations of cells could transiently express respiratory modulation in  
633 their MP resulting in a longer duration of LFP respiratory modulation. In other structures, the  
634 competition between several other LFP rhythms (such as slow rhythm or theta) probably does  
635 not favor the emergence of this rhythm. Additionally, for all the structures, the sensitivity of  
636 each individual cell MP to LFP respiratory modulation likely differs according to its  
637 excitability state, limiting episodes of MP RRo to short durations. This could be supported by  
638 our observation that cells could show less MP RRo when hyperpolarized (see Figure S5B).

639 Although our study focused on the respiratory rhythm, the influence of other LFP rhythms on  
640 cellular activity (MP and discharge) should not be ignored. For examples, in few cases, we  
641 observed a spiking discharge that was RR while MP displayed no RRo. We could suppose  
642 that if the spiking discharge is influenced by a rhythm twice slower or twice faster than the  
643 respiratory rhythm, they will appear locked on respiratory cycle on spike histograms. We also  
644 observed more complicated patterns with several rhythms nested. For example, on the MP  
645 spectrum analysis of Figure 2B3 we can distinguish a slow oscillation (around 1 Hz) which  
646 could compete with the respiratory rhythm.

647 Overall, our results evidenced a consequent proportion of RRo within electrophysiological  
648 signals, which could only have been revealed thanks to respiration co-recording. We  
649 evidenced a strong respiratory coupling between MP and spike discharge in PFC, S1 and to a  
650 lesser extent in HPC. Furthermore, MP and LFP RRo dynamics showed strong covariations.  
651 Even if our experiments in anesthetized animal are purely descriptive, our results show that, at  
652 very different places in the brain, the MP of neurons can be depolarized and hyperpolarized  
653 according to the respiratory rhythm. These findings contribute to the evidence that the  
654 respiratory rhythm could be used as a common clock to set the dynamics of large-scale  
655 networks on the same slow rhythm.

656

657



658 SUPPLEMENTAL MATERIAL

659 Figure S1: **Input resistance**

660 Figure S2: **Polarity states**

661 Figure S3: **AP waveform**

662 Figure S4: **Verification of possible correlations**

663 Figure S5: **Effect of excitability changes**

664 Figure S6: **Obstruction of the nostril**

665

666 Supplemental figures availability: <https://doi.org/10.5281/zenodo.8165176>

667

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671

672 AUTHOR CONTRIBUTIONS

673 C.A. and N.B. conceived and designed research; M.J. and M.Z. performed experiments; M.J.,  
674 N.F-T., S.G., C.A developed the RRo detection method; M.J analyzed data; M.J, N.F-T., N.B.  
675 and C.A. interpreted results of experiment; M.J. and C.A. prepared figures. M.J., N.B. and  
676 C.A. drafted manuscript; M.J., M.Z., N.F-T., N.B. and C.A. edited and revised manuscript;  
677 M.J., M.Z., N.F-T., S.G., N.B. and C.A approved final version of manuscript.

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855

856

857 FIGURE LEGENDS:

858 **Figure 1 Description of the RRo detection method.** Common color code: real data  
859 measurements are in red, median signals are in green, surrogate measurements are in light  
860 blue. **A)** Schematic description of the processing chain. **B)** Detailed description of the  
861 processing chain. **B.1)** Preprocessed membrane potential (APs removal and deformation to  
862 respiratory phase) along 7 respiratory cycles. **B.2)** Encoding of the 4 windows associated to  
863 the 7 previous cycles (B.1). The encoding of the window 118 is detailed in the panel C.  
864 Windows 118 to 120 are found to be related to respiration (in red), while the window 121 is  
865 not (blue). The median signals associated to each window are shown in green. **B.3)** Encoding  
866 of the similarity associated with the 4 windows presented above (B.2). The encoding of the  
867 cycle 118 as part of the windows 118 is detailed in panel D. Individual cycles similar to the  
868 window they belong to are shown in black. Dissimilar cycles are in gray. Cycles that are not  
869 tested (because the associated window is not respiration-related) are in light gray. **B.4)** Cycle-  
870 by-cycle encoding. The score of a cycle corresponds to the number of times this cycle is  
871 found similar to the waveform of a respiration-related window. For example, the cycle 121 is  
872 found similar to 3 respiration-related window waveforms and thus reached the score of 3  
873 (B.3). Cycles with score of 3 or 4 are classified as RRo. Cycles with score of 2 are classified  
874 as undetermined. Cycles with score of 0 or 1 are classified as no RRo. **C)** Detailed detection  
875 on local windows. **C.1)** Construction of surrogates. The left-hand column corresponds to  
876 actual cycles. The right-hand column corresponds to surrogates. Surrogates are constructed in  
877 two steps. First, the cycles are randomly paired (here cycle 118 with 119, and 121 with 120).  
878 Then, the cycles are phase-shifted, so that they are two by two in phase opposition. **C.2)** The  
879 median signal of the 4 actual cycle, on the left, or of the 4 surrogates, on the right. The red,  
880 respectively the light-blue, line indicates the amplitude of the actual signal, respectively the  
881 surrogate **C3.)** Distribution of the surrogate amplitudes. Blue bars represent the distribution of  
882 surrogate amplitudes. Black arrow highlights the p-values (95<sup>th</sup> percentiles). Red arrow

883 highlights the amplitude of actual data (C.2 left). **D)** Detailed verification of the similarity.  
884 **D.1)** To assess the similarity between individual cycles (gray) and the local window  
885 oscillation (green), we compute the scalar product of these z-scored signals. **D.2.)** Distribution  
886 of the surrogate scalar products. Blue bars represent the distribution of surrogate scalar  
887 products. The black arrow highlights the p-values (95<sup>th</sup> percentiles). The red arrow highlights  
888 the scalar product of actual data (D.1 left).

889

890 **Figure 2 : Intracellular activity of widespread brain areas correlates with respiratory**  
891 **rhythm. A)** Raw traces of intracellular activity from mPFC, S1, V1 and HPC (respectively  
892 subpanels 1, 2, 3, 4). Top trace: intracellular raw trace in black, overlaid with a filtered (3 Hz  
893 low pass) respiratory signal, in gray, which has been time-shifted to highlight MP RRo. Mid  
894 trace: Respiratory signal. Bottom: Respiratory phase, with gray bars representing inspiration  
895 phases, white bars representing expiration phases. Time scale bar = 1s, amplitude scale bar =  
896 10 mV. E = expiration, I = inspiration. AP have been truncated. **B)** MP (black) and respiratory  
897 signal (gray) power density spectrum over the 4s of signal presented in A. Arrow heads  
898 highlight 1<sup>st</sup> harmonic of the spectrum. **C)** Respiration-triggered AP firing histogram (top) and  
899 respiration triggered MP (bottom). Data of respiration-triggered figures are extracted from  
900 several cycles during which MP is identified as correlated with respiration. Cycles and AP  
901 numbers are indicated on the right top. To visually reinforce oscillatory behavior, plots have  
902 been duplicated. Respiratory phase is reminded in between the two respiration-triggered  
903 figures. Bottom: respiration triggered MP where black line corresponds to the median, shaded  
904 areas delineate the 25<sup>th</sup> and 75<sup>th</sup> percentiles.

905



906 **Figure 3 : A significant number of cells in each structure exhibit MP RRo, yet individual**  
907 **episodes are short.** Only recordings at basal MP are considered. **A)** Distribution of MP en-  
908 coding by cell in mPFC, S1, V1 and HPC (respectively subpanels 1, 2, 3, 4). Black, gray and  
909 white, bars correspond to the probability of RRo cycles, undetermined cycles and no RRo  
910 cycles respectively. The total number of respiratory cycles recorded in each cell is indicated at  
911 the top of the corresponding bar. Black crosses indicated cells which are not considered as  
912 modulated by respiration despite showing some MP RRo (see methods) **B)** Cumulative distri-  
913 bution of RRo percentages of each structure. Blue, orange and pink curves correspond to  
914 mPFC, S1 and HPC respectively. **C)** MP RRo probabilities across structures. Gray dots repre-  
915 sent MP RRo probability for individual cells, blue squares represent the mean by structure and  
916 black lines represent SEM. Only respiration-modulated cells are considered. No significant  
917 differences are observed (Kruskal-Wallis test,  $p = 0.53$ ,  $H(2) = 1.24$ ,  $N_{\text{mPFC}} = 21$ ,  $N_{\text{S1}} = 7$ ,  
918  $N_{\text{HPC}} = 8$ ). **D)** MP RRo episodes duration across structures. Gray dots represent mean MP  
919 RRo episode duration of individual cells, blue squares represent the mean by structure and  
920 black lines represent SEM. The same cell pool as in B is used. No significant differences are  
921 observed (Kruskal-Wallis test,  $p = 0.58$ ,  $H(2) = 1.07$ ,  $N_{\text{mPFC}} = 21$ ,  $N_{\text{S1}} = 7$ ,  $N_{\text{HPC}} = 8$ ).  
922

923 **Figure 4 : Phase and amplitude characterization of MP RRo.** Only recordings at basal MP  
924 and respiration-modulated cells are considered. **A)** Amplitude of MP RRo by structures. Gray  
925 dots represent MP RRo amplitude of individual cells, dark gray squares represent the mean by  
926 structure and black lines represents SEM. Significant differences are observed (Kruskal-  
927 Wallis test,  $p = 0.01$ ,  $H(2) = 9.1$ ,  $N_{\text{mPFC}} = 21$ ,  $N_{\text{S1}} = 7$ ,  $N_{\text{HPC}} = 8$ ). *Post hoc* two-sided Mann-  
928 Whitney U test reveals amplitude of MP RRo is higher in S1 cells than in mPFC ( $p = 0.002$ )  
929 and HPC ( $p = 0.02$ ). **B)** Preferred respiratory phase MP RRo by structures. Preferred phases

930 are presented on a trigonometric circle, phase progression is anticlockwise. Shaded and white  
931 areas, correspond respectively to inspirations and expirations.

932

933 **Figure 5: MP RRo probability increases when RRo are concomitantly present in LFP.**

934 Only recordings at basal MP are considered. In addition, for B and C, only recording with  
935 respiration-modulated LFP are considered. While for D and E, only recordings with both  
936 respiration-modulated LFP and cells are considered. **A)** MP (Top), respiratory signal (mid)  
937 and LFP (bottom) raw traces of the same cell when LFP and MP do not display RRo (A1) and  
938 two minutes later when LFP and MP display RRo (A2). On A2 panel, light gray traces show  
939 filtered and time-shifted respiratory signal superimposed on MP and LFP traces. Time scale  
940 bar: 1s. **B)** LFP RRo probability by structures. Gray points represent LFP RRo probability,  
941 dark gray squares represent the mean by structure and black lines represent SEM. Significant  
942 differences are observed (Kruskal-Wallis test,  $p = 0.03$ ,  $H(2) = 6.96$ ,  $N_{\text{mPFC}} = 21$ ,  $N_{\text{S1}} = 5$ ,  
943  $N_{\text{HPC}} = 4$ ). The LFP in mPFC presents more RRo than S1 (Mann-Whitney U test,  $p = 0.01$ ).  
944 **C)** LFP RRo episode duration by structures. Gray dots represent mean LFP RRo duration of  
945 individual traces, dark gray squares represent the mean by structure and black lines represent  
946 SEM. The same pool of traces as in B is used. Significant differences are observed (Kruskal-  
947 Wallis test,  $p = 7.10^{-3}$ ,  $H(2) = 10.0$ ,  $N_{\text{mPFC}} = 21$ ,  $N_{\text{S1}} = 5$ ,  $N_{\text{HPC}} = 4$ ). The mPFC presents  
948 longer LFP RRo episodes than S1 (Mann-Whitney U test,  $p = 0.005$ ) and HPC (Mann-  
949 Whitney U test,  $p = 0.02$ ). **D)** Conditional probability of MP RRo given LFP dynamics. The  
950 columns “LFP RRo” represent the probability to observe MP RRo when LFP is also RRo. On  
951 the other hand, the columns “other LFP” represent MP RRo probability when LFP is no RRo.  
952 In the mPFC, the probability of MP RRo increases when LFP is RRo (Wilcoxon test,  $p =$   
953  $0.02$ ,  $Z = 44$ ,  $n = 20$ ). S1 (Wilcoxon test,  $p = 0.14$ ,  $Z = 1$ ,  $n = 4$ ) and HPC (Wilcoxon test,  $p =$   
954  $0.07$ ,  $Z = 0$ ,  $n = 4$ ) presented the same tendency. **E)** Conditional probability of LFP RRo given

955 MP dynamics. The columns “MP RRo” represent the probability to observe LFP RRo when  
956 MP is also RRo. On the other hand, the columns “other MP” represent the probability of LFP  
957 RRo when MP is no RRo. In the mPFC, LFP RRo probability increases when MP is RRo  
958 (Wilcoxon test,  $p = 0.002$ ,  $Z=21$ ,  $n=20$ ). S1 (Wilcoxon test,  $p = 0.14$ ,  $Z= 1$ ,  $n=4$ ) and HPC  
959 (Wilcoxon test,  $p = 0.07$ ,  $Z= 0$ ,  $n=4$ ) presented the same tendency.

960

961

962 TABLE:

963 **Table 1: mPFC and S1 show stronger coupling between MP oscillations and spiking**  
964 **than hippocampus.**

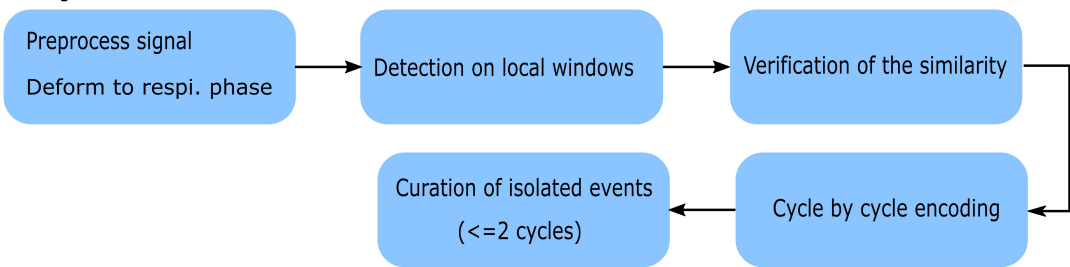
Area	MP activity		RR discharge	No RR discharge	Total cells
mPFC	RRo	N <sub>cell</sub> %	4 80%	1 20%	5
	no RRo	N <sub>cell</sub> %	6 28.6%	15 71.4%	21
S1	RRo	N <sub>cell</sub> %	4 80%	1 20%	5
	no RRo	N <sub>cell</sub> %	1 14.3%	6 85.7%	7
HPC	RRo	N <sub>cell</sub> %	1 25%	3 75%	4
	no RRo	N <sub>cell</sub> %	3 37.5%	5 62.5%	8

965

966 For each cell, spikes are sorted according to whether they occurred during MP RRo or no MP  
967 RRo. Respiration-triggered discharge histograms are computed for both categories. The  
968 histograms are then classified as either RR discharge or no RR discharge. Results are  
969 presented for each area and each MP activity. The line “N<sub>cell</sub>” represents the number of cells in  
970 each discharge class. It should be noted that spike distributions with too few spikes were  
971 not considered here or some cells never displayed MP RRo with spikes. Consequently, the  
972 total number of cells in the lines ‘RRo’ are lower than the number of respiration-modulated  
973 cells (showed in Figure 3) and the total number of cells in the lines ‘no RRo’ are lower than  
974 the total number of cells. The line “%” represents the percentage of cells in each discharge  
975 category relative to the total number of cells associated to an MP RRo category.

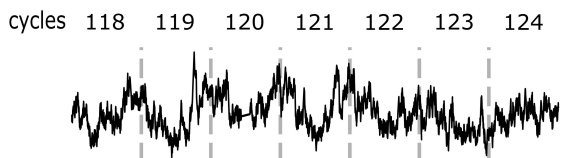
976

## A Processing chain

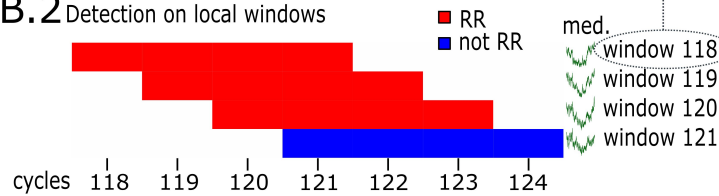


## B Detailed processing chain

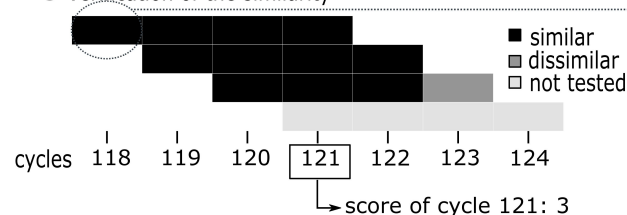
### B.1 Preprocessing and deformation



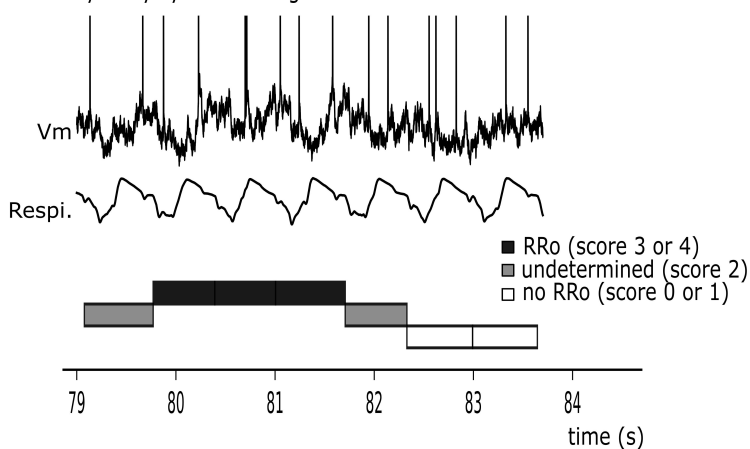
### B.2 Detection on local windows



### B.3 Verification of the similarity

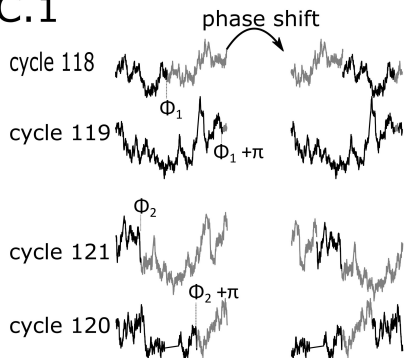


### B.4 Cycle by cycle encoding



## C Detection on local windows

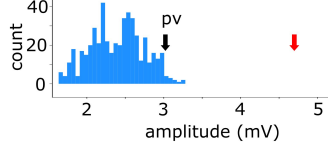
### C.1



### C.2

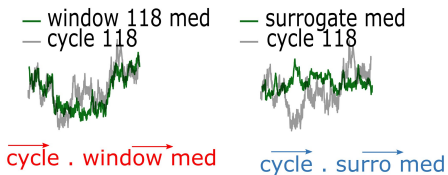


### C.3

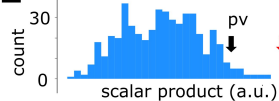


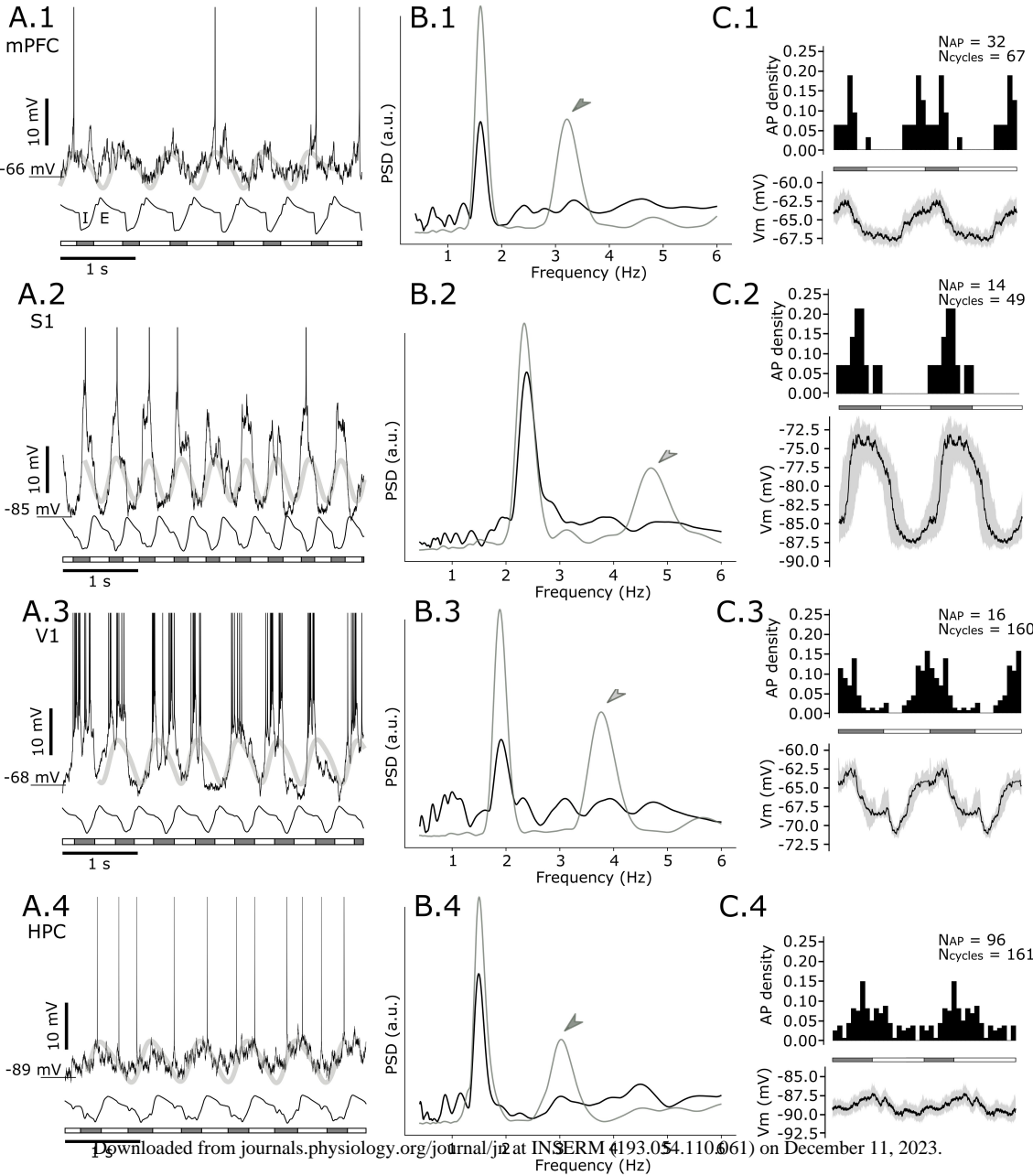
## D Verification of the similarity

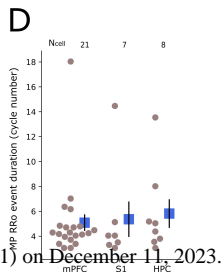
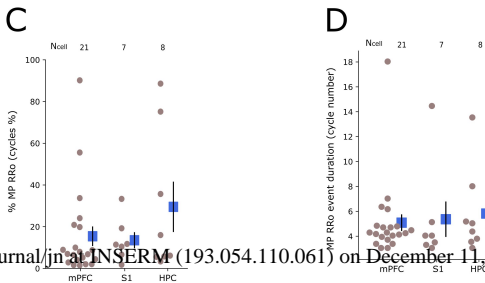
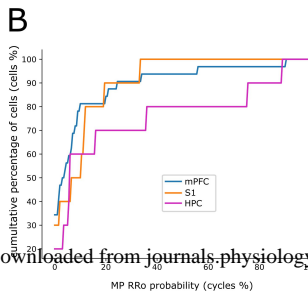
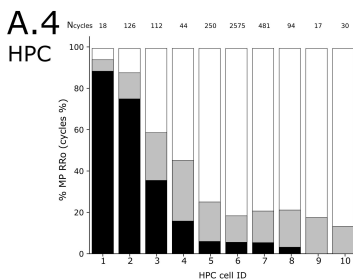
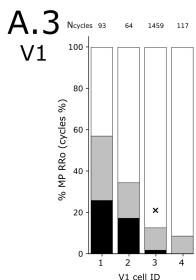
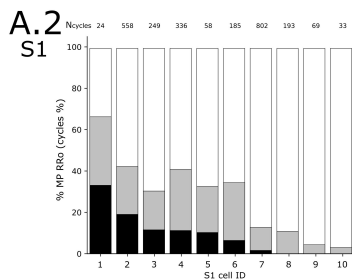
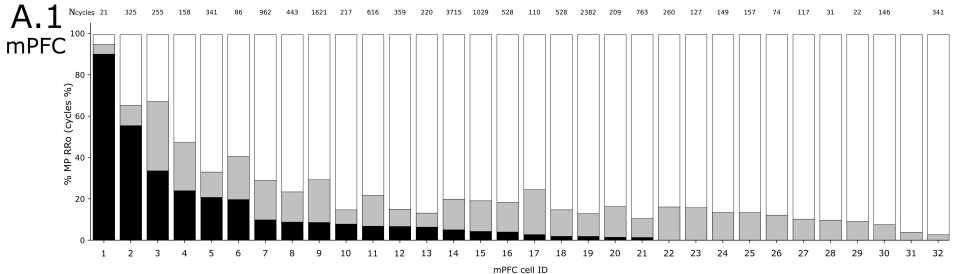
### D.1

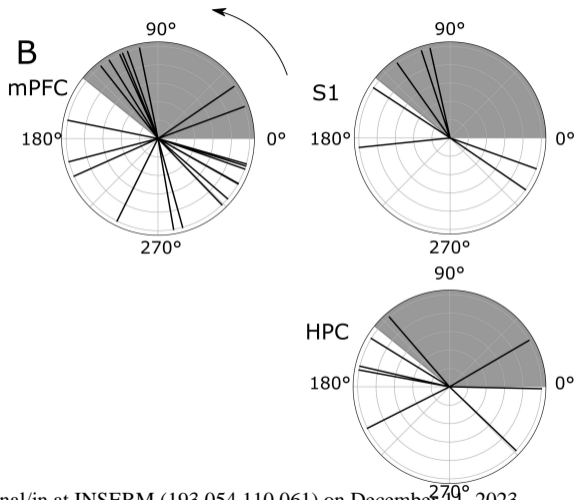
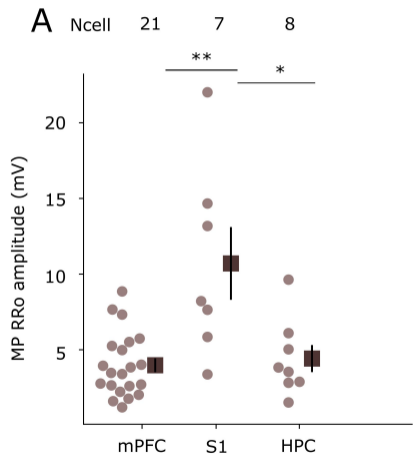


### D.2

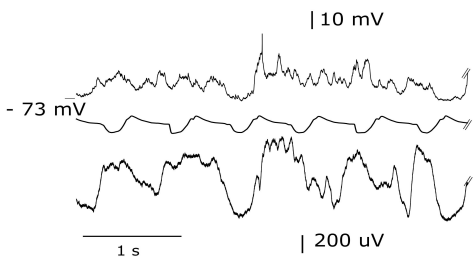
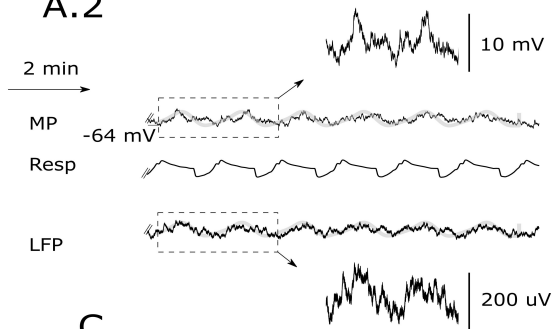
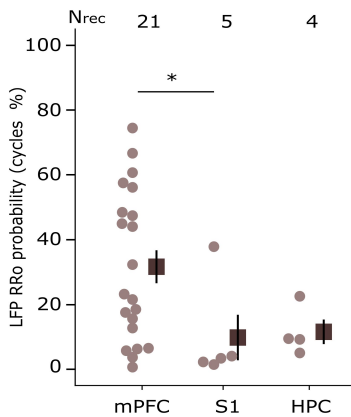
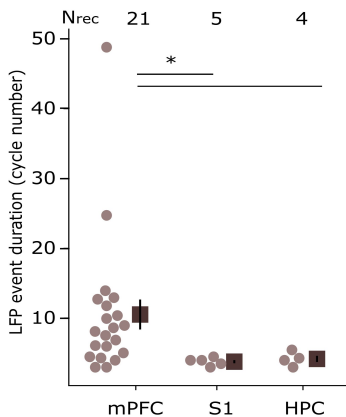
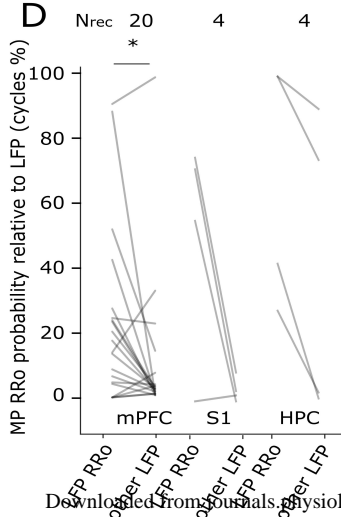
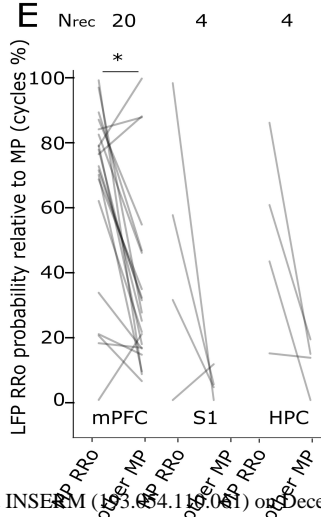










**A.1****A.2****B****C****D****E**

1 **Table 1: mPFC and S1 show stronger coupling between MP oscillations and spiking**  
 2 **than hippocampus.**

Area	MP activity		RR discharge	No RR discharge	Total cells
mPFC	RRo	N <sub>cell</sub> %	4 80%	1 20%	5
	no RRo	N <sub>cell</sub> %	6 28.6%	15 71.4%	21
S1	RRo	N <sub>cell</sub> %	4 80%	1 20%	5
	no RRo	N <sub>cell</sub> %	1 14.3%	6 85.7%	7
HPC	RRo	N <sub>cell</sub> %	1 25%	3 75%	4
	no RRo	N <sub>cell</sub> %	3 37.5%	5 62.5%	8

3

4 For each cell, spikes are sorted according to whether they occurred during MP RRo or no MP  
 5 RRo. Respiration-triggered discharge histograms are computed for both categories. The  
 6 histograms are then classified as either RR discharge or no RR discharge. Results are  
 7 presented for each area and each MP activity. The line “N<sub>cell</sub>” represents the number of cells in  
 8 each discharge class. It should be noted that spike distributions with too few spikes were  
 9 not considered here or some cells never displayed MP RRo with spikes. Consequently, the  
 10 total number of cells in the lines ‘RRo’ are lower than the number of respiration-modulated  
 11 cells (showed in **Error! Reference source not found.**) and the total number of cells in the  
 12 lines ‘no RRo’ are lower than the total number of cells. The line “%” represents the  
 13 percentage of cells in each discharge category relative to the total number of cells associated  
 14 to an MP RRo category.

15

