



## Review article

## Prominence of delta oscillatory rhythms in the motor cortex and their relevance for auditory and speech perception

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## ARTICLE INFO

## Keywords:

Neural oscillations  
Delta  
Speech perception  
Audio-motor coupling  
Rhythm  
Active sensing  
Active inference

## ABSTRACT

In the motor cortex, beta oscillations (~12–30 Hz) are generally considered a principal rhythm contributing to movement planning and execution. Beta oscillations cohabit and dynamically interact with slow delta oscillations (0.5–4 Hz), but the role of delta oscillations and the subordinate relationship between these rhythms in the perception-action loop remains unclear. Here, we review evidence that motor delta oscillations shape the dynamics of motor behaviors and sensorimotor processes, in particular during auditory perception. We describe the functional coupling between delta and beta oscillations in the motor cortex during spontaneous and planned motor acts. In an active sensing framework, perception is strongly shaped by motor activity, in particular in the delta band, which imposes temporal constraints on the sampling of sensory information. By encoding temporal contextual information, delta oscillations modulate auditory processing and impact behavioral outcomes. Finally, we consider the contribution of motor delta oscillations in the perceptual analysis of speech signals, providing a contextual temporal frame to optimize the parsing and processing of slow linguistic information.

## 1. Intrinsic oscillatory activity in the motor cortex

Cortical rhythms reflect synchronous, periodic shifting of neuronal ensembles between high and low excitability states, that coordinates neural communication (Schroeder et al., 2008; Schroeder and Lakatos, 2009; Buzsáki and Draguhn, 2004; Wang, 2010). In the motor cortex, the vast majority of existing data point to beta oscillations (~12–30 Hz; frequency borders based on Buzsáki, 2006, p.112) as a predominant and specific rhythm during rest and to coordinate information transfer in action planning and execution (Murthy and Fetz, 1992; Mellem et al., 2017; Groppe et al., 2013; Hillebrand et al., 2012; Ramkumar et al., 2014; Brookes et al., 2011). Spectral peaks in the beta band visibly stand out in frequency-domain representations of neural recordings of cortical motor areas, when analysed during cognitive tasks or rest (e.g., Keitel and Gross, 2016; Shin et al., 2017; Haegens et al., 2011; Hillebrand et al., 2012). However, using finer-grained spectral analysis methods to analyze recordings from the motor cortex reveals a much more complex picture (Keitel and Gross, 2016; Groppe et al., 2013; Hall

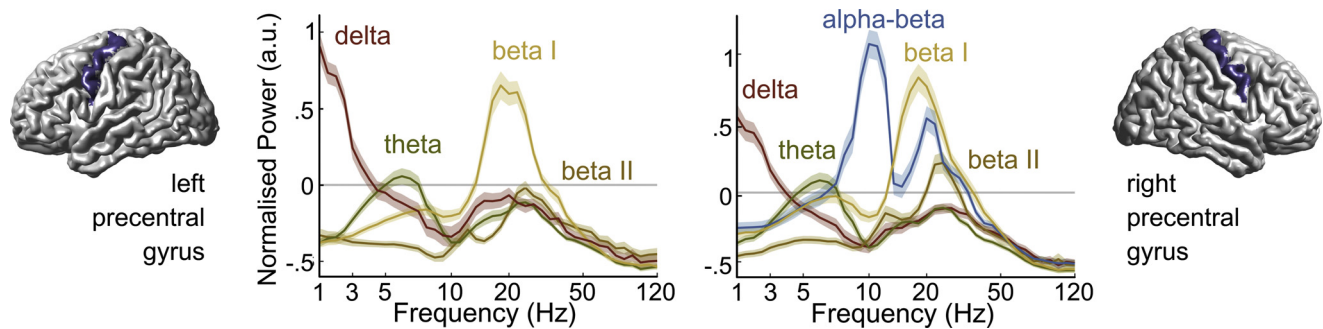
et al., 2014). In humans, for instance, the analysis of ongoing oscillatory activity of the primary motor cortex (bilateral precentral gyrus) is characterized by consistent spectral peaks, principally in the delta (0.5–4 Hz) and beta frequency ranges (Fig. 1; Keitel and Gross, 2016).

Interestingly, a wealth of experimental studies have supported the notion that these oscillatory rhythms can be hierarchically structured in time (Schroeder et al., 2008; Schroeder and Lakatos, 2009; Buzsáki and Draguhn, 2004), with a large variety of possible types of cross-frequency coupling (phase-phase, phase-amplitude etc.). Although arguably the most common type is a phase-amplitude coupling between theta (4–8 Hz) and high-gamma (80–150 Hz) bands respectively (e.g. Canolty et al., 2006), recent evidence has revealed the same type of cross-frequency relationship between the phase of delta- and power of beta-oscillations in the motor cortex. For example, a functionally relevant delta-beta phase-amplitude coupling has been shown in the motor cortex during auditory (Morillon and Baillet, 2017; Arnal et al., 2015; Keitel et al., 2018) and visual (Saleh et al., 2010) perception: This specific spectro-spatial pattern of activity represents temporal

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**Fig. 1.** Intrinsic oscillations in the motor cortex at rest (left and right precentral gyri respectively) as captured by MEG recordings. Lines illustrate power peaks that coexist in one area but are present at different times. Dominant peaks are consistently present across participants principally in the delta and beta frequency ranges (indicated by red and yellow lines; shaded areas represent SEM across participants). Please note that delta activity follows a  $1/f$  (power law-like) distribution across frequencies with a critical deviation at around 2 Hz, reflecting respectively neural noise and spontaneous oscillatory activity (Adapted from Keitel and Gross, 2016).

information and is directly related to participants' behavioural outcome in tasks involving temporal processing (see below). Whether delta and beta rhythms are intrinsically inter-related or whether they can occur independently remains to be formally determined. Studying how brain oscillations occur over time during rest, a recent study (Keitel and Gross, 2016) showed that while delta oscillations in the motor cortex tend to co-occur with beta oscillations (red lines in Fig. 1), beta activity (yellow lines) can occur independently of delta activity. Both in vitro modelling (Carracedo et al., 2013) and empirical studies (Lakatos et al., 2005; Hall et al., 2014) however indicate that neocortical local circuits can generate delta rhythms without concurrent beta activity. Studying the occurrence of delta rhythms in the monkey motor system, there is also clear-cut evidence that reliable delta oscillatory patterns intervene in various states (while performing a motor task, as well as during sleep and sedation) and that these delta patterns can occur independently of beta oscillations (Hall et al., 2014). While computational studies provide compelling neurophysiological and functional models for the generation of sensorimotor beta rhythms (Sherman et al., 2016; Lee et al., 2013), how motor delta rhythms emerge remains poorly understood. The asymmetrical relationship between delta and beta rhythms needs to be further characterized at the cellular and network level, in particular to understand how these two rhythms are generated cortically and whether/when they emerge from distinct versus overlapping circuits (Hyafil et al., 2015; Carracedo et al., 2013; Shin et al., 2017).

Delta oscillations have been traditionally associated with resting functions such as deep sleep and memory consolidation (Huber et al., 2004). However, multiple findings converge to support the relevance of intrinsic delta oscillations at the functional and behavioral levels, where rhythmicity, i.e. periodic recurrences, are observed. For instance, a most basic motor act, walking, is intrinsically rhythmic and operates within the delta range (2 Hz; MacDougall and Moore, 2005), strikingly mirroring spontaneous motor oscillatory activity (see the deviation at  $\sim 2$  Hz from the  $1/f$  distribution of delta activity in Fig. 1). Spontaneous motor rhythmic behaviors such as finger tapping operate at a preferred tempo of  $\sim 1.5$ –2 Hz, and motor tapping has an optimal temporal precision within the range of  $\sim 0.8$ –2.5 Hz (Frasse, 1982; Moelants, 2002; McAuley, 2010; Repp and Su, 2013). Moreover, during production of complex motor behaviors such as speech, the coordination of articulatory movements is encoded in kinematics trajectories characterized by damped oscillatory dynamics (Chartier et al., 2018). And even during non-periodic motor behaviors, such as reaching, motor trajectories are encoded in neural dynamical patterns that oscillate around 1–2 Hz (Churchland et al., 2012; Sussillo et al., 2015; Hall et al., 2014). Delta oscillations in the motor cortex also anticipate the timing of informative cues in a motor planning task (Saleh et al., 2010), facilitate coherence between motor and parietal regions during decision making (Nácher et al., 2013), organize oscillatory activity in the cortico-striatal network (López-Azcárate et al., 2013), and predict hand selection for reaching (Hamel-Thibault et al., 2018). Thus, motor delta oscillations

shape the dynamics of motor behaviors and motor neural processes.

## 2. Rhythmic sampling of perceptual information

In an active sensing framework, perception is shaped by motor dynamics (Morillon et al., 2015). Indeed, our sensory organs are not passive receptacles for stimulation but are part of an action-perception closed-loop system (Kleinfeld et al., 2006; Schroeder et al., 2010; Ahissar and Assa, 2016; Rajkai et al., 2008; Barczak et al., 2019). Consequently, motor acts and associated oscillatory dynamics temporally structure the activity of sensory cortices, and, as a consequence, the processing of incoming sensory inputs. Corollary discharge signals provided by motor areas to sensory processing also convey system-specific content information (spatial, spectral, etc.) as well as its underlying temporal frame (i.e., contextual temporal information; Crapse and Sommer, 2008). Hence, temporal sampling of perceptual information is not restricted to the rhythms of overt actions but is also shaped by covert motor and/or attentional dynamics. As exemplified by whisking and sniffing in rodents and saccadic sampling during free viewing in primates, our motor-driven information sampling routines follow periodic patterns (Crochet et al., 2011; Wachowiak, 2011; McAuley et al., 1999). Each sensing organ alternates between operational modes, characterized respectively by low (delta) and high ( $> 4$  Hz) modal frequencies: 1–2 vs. 6–12 Hz for olfaction (respiration vs. sniffing in rodents; Wachowiak, 2011), 1–5 vs. 5–20 Hz for somatosensation (whiskers' wakefulness vs. exploration in rodents; Crochet et al., 2011), 3 vs. 10–12 Hz for vision (fixational microsaccades vs. saccadic search in both human and non-human primates; McAuley et al., 1999; Bosman et al., 2009; Ahissar and Arieli, 2012). These rhythmic tendencies are sufficiently conserved, so that characteristic intrinsic time courses associated stems for overtly controlling perception impose periodicity even during covert sampling of the environment: On the one hand, in the auditory domain –where overt active sensing appears to be lacking (as bottom-up auditory processing is remarkably divorced from movements; (Schroeder et al., 2010; Morillon et al., 2015)–, recent frameworks describe a covert form of active sensing, whereby oscillatory influences from motor cortex modulate activity in auditory regions during perception (see below; Arnal, 2012; Patel and Iversen, 2014; Morillon et al., 2015; Merchant et al., 2015). On the other hand, during visual sustained spatial attention, fronto-parietal network-level interactions organize environmental sampling of visual regions outside the attentional focus into rhythmic cycles (Fiebelkorn et al., 2018; see also VanRullen, 2016). In regard to delta activity, the accumulation of visual evidence during perceptual decision making is also constrained by a serial processing bottleneck operating in the delta ( $\sim 2$  Hz) range (Wyart et al., 2012). Delta-range oscillatory dynamics are even argued to be responsible for phenomena such as attentional blink, inhibition of return and the psychological refractory period (Wyart et al., 2012; Schroeder and Lakatos, 2009). Overall,

intrinsic (motor and attentional) neural dynamics thus appear to impose a temporal frame that constrains perceptual sampling in time. Future models and experiments need to investigate how these multiple neural structures –devoted to specific algorithmic processes and having specific temporal constraints– are dynamically coordinated to subserve or facilitate perceptual processing.

### 3. Temporal predictions in auditory attention

When sensory signals hold a recurring temporal structure, they enable a proactive and temporally selective preparation for anticipated relevant events (Nobre and van Ede, 2018; Rimmele et al., 2018). Acoustic signals such as speech and music exhibit reliable temporal regularities that can be used to generate temporal predictions (Ding et al., 2017). Behavioral experiments demonstrate that anticipating the temporal occurrence of an upcoming event optimizes its processing by improving the quality of auditory information (Jaramillo and Zador, 2011; Morillon et al., 2016; Wollman and Morillon, 2018). This enhancement correlates with the reorganisation of low-frequency neural oscillations, which temporally modulates the excitability of task-relevant neural populations, and thus act as instruments of sensory selection (Cravo et al., 2013; Schroeder and Lakatos, 2009; Stefanics et al., 2010; Lakatos et al., 2008). This neural reorganisation is not only visible in sensory cortices, but also in a distinct network of areas including posterior parietal, inferior motor, inferior frontal and superior midline frontal cortex (Besle et al., 2011).

Recently, attentional modulation of auditory information was shown to depend on the downward propagation of temporal predictions, which originate at least in part in the motor cortex (Morillon and Baillet, 2017). Temporal information is represented in the motor cortex in delta-beta phase-amplitude coupled oscillations (Fig. 2A; Saleh et al., 2010; Arnal et al., 2015; Morillon and Baillet, 2017), and both delta phase and beta amplitude seem to modulate auditory processing and predict behavioral outcome (Fig. 2; Iversen et al., 2009; Stefanics et al., 2010; Arnal and Kleinschmidt, 2017; Morillon and Baillet, 2017). It was recently proposed that time estimation relies on the neural recycling of action circuits and is implemented by internal, non-conscious ‘simulation’ of movements in most ecological situations (Coull, 2011; Arnal, 2012; Arnal and Giraud, 2012; Schubotz, 2007). This idea mirrors the central proposition of the premotor theory of attention, that covert shifts in spatial attention utilize much of the same fronto-parieto-collicular circuitry that controls overt shifts in eye position (Rizzolatti et al., 1987). In this view, the transmission of temporal information from motor to auditory regions could be implemented through corollary discharge signals (Crapse and Sommer, 2008). However, the route(s) by which activity in motor areas may modulate auditory processing and perception remain currently unknown (Morillon et al., 2015). Despite these uncertainties, overall, these results indicate that motor delta oscillations play a key functional role in human auditory perception, both enabling and constraining the temporal flow of information.

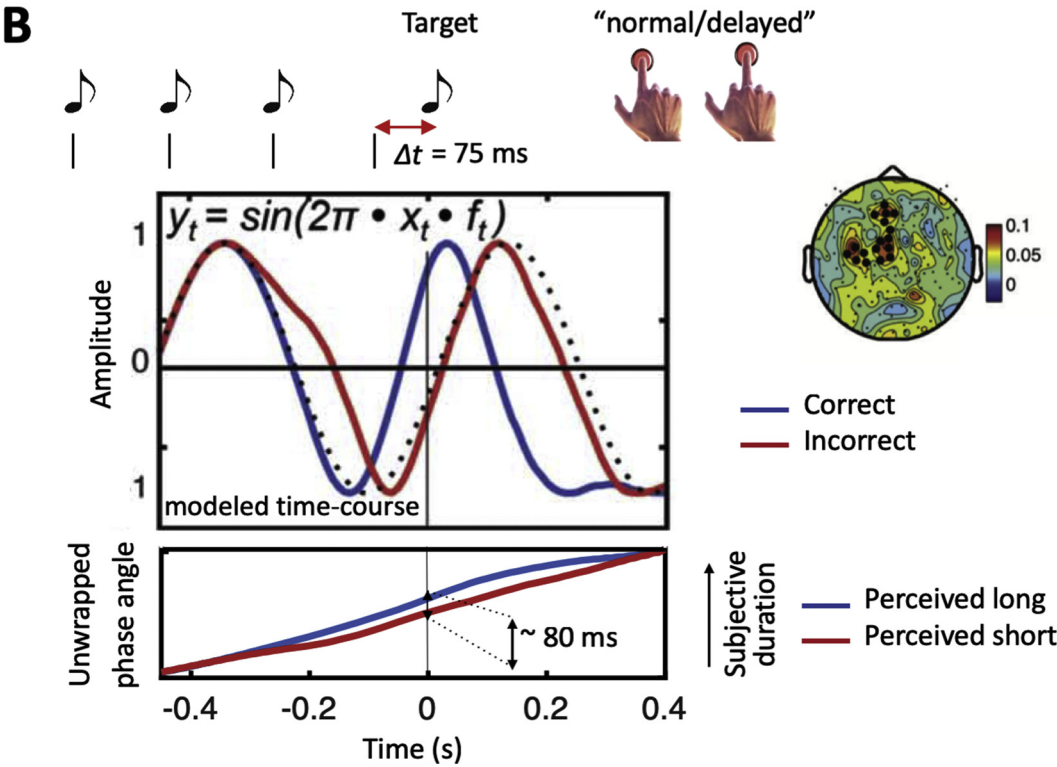
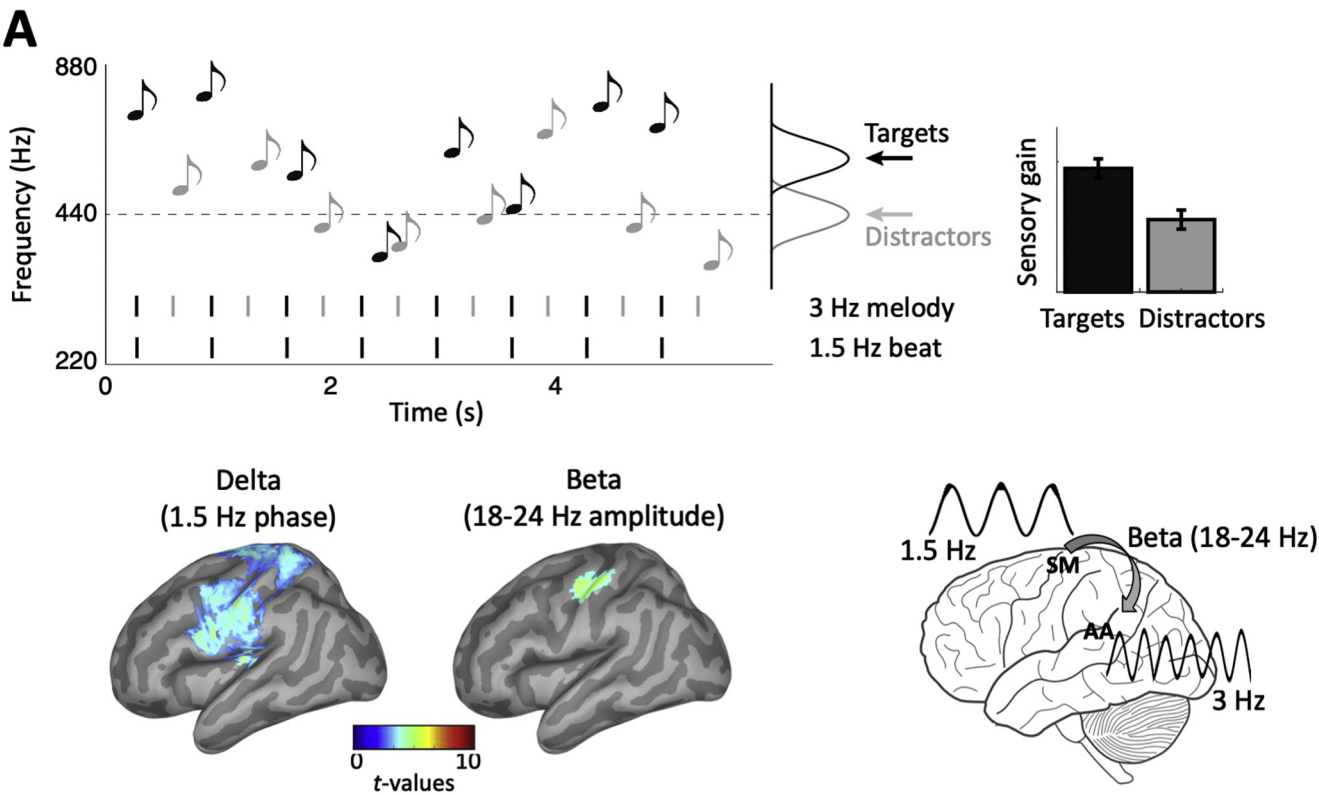
### 4. Motor contributions to speech perception

Human speech is in essence structured in the temporal dimension, with nested dynamics organized according to a hierarchy of linguistic timescales (phoneme, syllable, word, phrase; (Giraud and Poeppel, 2012; Ding et al., 2016; Keitel et al., 2018; Schroeder et al., 2008). Although speech is not strictly periodic, its regularities are visible as peaks in the power and modulation spectrum of the speech envelope (Ding et al., 2017; Keitel et al., 2018). Remarkably, these acoustic dynamics are mirrored by neural dynamics at similar timescales (e.g., ~4–5 Hz for syllabic and theta rates; ~1–2 Hz for phrasal and delta rates) and this hierarchy of neural processes seems to underlie grammar-based internal construction of hierarchical linguistic structure (Ding et al., 2016). It is currently debated whether these low-frequency

auditory neural dynamics reflect the involvement of oscillatory processes in speech perception, or solely a succession of evoked responses or of another type of non-linear filtering process. However, during perception of (western) music, which has a salient main modulation rate around 2 Hz (Ding et al., 2017), brain responses at the delta rate are best modelled with both components of bottom-up evoked responses and internal oscillatory synchronization (Doelling et al., 2019). Auditory neural dynamics are moreover modulated in a proactive and temporally flexible manner by higher-order regions which convey temporal or linguistic predictions of the sensory input (Barczak et al., 2018; Morillon and Baillet, 2017; Gagnepain et al., 2012; Rimmele et al., 2018). This combination of local oscillatory and top-down modulatory processes could underlie the auditory tracking of the non purely-periodic speech signal (Rimmele et al., 2018).

In spoken languages, prosodic information (intonation, pauses) naturally fluctuates around 0.5–3 Hz (i.e., in the delta range) and encompasses phrasal and word-level linguistic units (Ghitza, 2017). Recent research has highlighted the distinctive role of delta rate dynamics in the temporal cortex for prosodic tracking and high-level linguistic processes (Bourguignon et al., 2013; Vander Ghinst et al., 2016; Ding et al., 2016; Keitel et al., 2018; Kösem and van Wassenhove, 2017; Molinaro and Lizarazu, 2018). Strikingly, during speech perception, spontaneous finger tapping at the perceived (prosodic) rhythm of speech occurs within the delta range (i.e. at ~2.5 Hz, c.f. Lidji et al., 2011). A similar effect is visible during music perception, with spontaneous movements occurring at the perceived beat, around 0.5–4 Hz (Rajendran et al., 2018; Merchant et al., 2015). These findings point toward a preference of attentional or motor systems for the slow temporal dynamics of auditory streams. Accordingly, neuroimaging studies show that during speech processing, delta oscillations are not only visible in temporal areas, but also in the motor cortex. Delta motor cortical dynamics uniquely contribute to both the modulation of auditory processing and comprehension. On the one hand, the tracking of acoustic dynamics by the (left) auditory cortex is principally modulated by motor areas, through delta (and to a lesser extent theta) oscillatory activity (Park et al., 2015; Keitel et al., 2017). On the other hand, in motor areas, both delta-tracking of the phrasal acoustic rate and delta-beta coupling predicts speech comprehension (Fig. 3; Keitel et al., 2018). Speech also relies on other rhythms, notably the 4–5 Hz main acoustic modulation generated by mouth movements (Chandrasekaran et al., 2009; Ding et al., 2017), which also couples auditory and motor cortical areas during speech perception (Assaneo and Poeppel, 2018). These different sensorimotor rhythms seem to have different functional contributions during speech perception (Cogan and Poeppel, 2011), but their respective role is currently unclear.

Overall, this indicates that one of the contributions of the motor cortex to speech processing is the analysis of the slow temporal dynamics of the speech signal, likely providing a contextual temporal frame to (at least) distant auditory regions that parse linguistic information, thereby improving the quality of speech processing. The specific contribution of motor areas to speech perception is a matter of debate which has been mostly investigated with regard to its role in the processing of phonetic features or phonological or lexico-semantic information (Hickok et al., 2011; Schomers and Pulvermüller, 2016; Skipper et al., 2017; Pulvermüller, 2018). However, these recent results crucially reveal its unique role in the analysis of speech temporal dynamics, a factor which has been mostly overlooked until now (Scott et al., 2009). This contribution of motor areas in the analysis of perceptual temporal dynamics is likely modality- and domain- general and would occur during perception of any sensory signal temporally structured with low-frequency dynamics, although it is currently unclear whether speech-specific (e.g. semantic or syntactic) processes can *additionally* contribute to motor temporal predictions. For example, top-down information from orbitofrontal areas is conveyed to motor areas during speech perception, which is a potential mechanism by which the motor cortex could receive speech-specific information (Keitel et al.,



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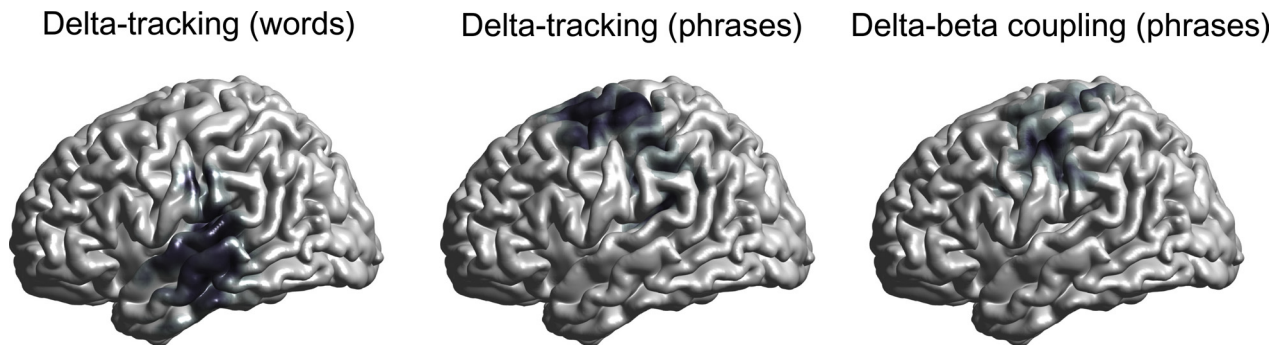
2017). Furthermore, a perceptually relevant, speech-specific function of motor predictions might be to anticipate the end of a speaker's turn to facilitate smooth turn-taking in conversations (Scott et al., 2009; Wilson and Wilson, 2005).

## 5. Conclusions

The studies reviewed above provide evidence that delta oscillations are intrinsic in the motor cortex and critically shape both overt motor



**Fig. 2.** Temporal predictions originate in the motor cortex and are mediated by delta-beta coupled oscillations. Evidence from two magnetoencephalography experiments **A.** (top) Auditory pure tones are presented at a 3 Hz rate and covert temporal attention is modulated at 1.5 Hz (based on preceding cues). Participants have thus a stronger attentional focus toward on-beat target tones than offbeat distractors. (bottom) Temporal predictions are encoded in sensory-motor cortical regions, in the phase of delta oscillations and amplitude of beta oscillations. Finally, beta oscillations are functionally directed toward auditory regions to modulate the processing of the 3 Hz auditory input. **B.** (top) Four pure tones are presented, with the last one appearing either on-beat or offbeat (positive delay of 75 ms). (middle) Accuracy effect on the modeled time-course of delta oscillations. The black dotted line indicates the time-course of an ideal oscillation at the stationary frequency of 2 Hz (center frequency of the frequency band of interest). Blue and red lines represent the time-course of correct and incorrect conditions respectively. (bottom) Unwrapped delta phase angle during pre-stimulus time period reflects subjective duration, being larger for correctly (blue, perceived ‘longer’) than incorrectly (red, perceived ‘normal’) detected delayed trials. At target’s occurrence, the phase-angle difference between correct and incorrect conditions corresponds to an 80-ms subjective time-lag (Adapted from: (A) Morillon and Baillet, 2017 and (B) Arnal and Kleinschmidt, 2017).



**Fig. 3.** Effects in the delta band that modulate speech perception in noise. (Left) Comprehension correlates with the coupling strength between acoustic and neural dynamics at the word ( $\sim 2.4$  Hz) rate in temporal regions and at the phrasal ( $\sim 1$  Hz) rate in motor regions. (Right) In motor regions, comprehension is also impacted by (phrasal) delta-beta phase-amplitude coupling (Adapted from: Keitel et al., 2018).

behaviors and covert motor-related modulation of sensory neural processes. They reflect a behavioral time-constant that is directly interpretable in a cognitive framework. This delta motor activity often seems to be intrinsically linked to beta oscillations through cross-frequency coupling, but the relationship between delta and beta rhythms is dynamic and still needs to be further characterized at the local cell circuit and network levels. However, there is emerging evidence that delta oscillations can be generated independently from beta oscillations (Carracedo et al., 2013; Hall et al., 2014). Motor delta oscillations control perceptual sampling by providing a temporal frame that both amplifies and orders sensory processing. Such effects are particularly striking during perception of temporally structured sensory signals such as speech. While the evidence we have considered indicates that the motor cortex is a constitutive part of the ‘auditory system’, the mechanisms and pathways controlling the gain of auditory processing and perception is currently unclear. In particular, while the primary motor, somatosensory, and auditory cortex seem to be strongly interconnected (Skipper and Hasson, 2017), evidence of direct projections between motor and auditory regions in humans is currently lacking (Morillon et al., 2015). Importantly, multiple neural structures related to motor or attentional (Fiebelkorn et al., 2018; Wyart et al., 2012) processes temporally constrain sensory processing. Understanding their interrelation in terms of system dynamics represents a major challenge. Delta oscillations are not unique to the motor cortex or to auditory perception. Rather, intrinsic spontaneous delta activity is also found in more inferior and anterior frontal areas (Mellem et al., 2017; Keitel and Gross, 2016) and is demonstrably involved in thalamo-cortical interactions (Barczak et al., 2018; Steriade et al., 1993; Timofeev and Steriade, 1996). Outside of the realm of sleep, it is unknown whether and how these delta rhythms are related to each other, and it is not yet clear why all of these areas spontaneously oscillate at this rate.

## Acknowledgments

B.M was supported by grants from the ANR (Agence Nationale pour la Recherche, France), the ILCB and BLRI, respectively, ANR-16-CONV-0002 (ILCB), ANR-11-LABX-0036 (BLRI) and the Excellence Initiative of Aix-Marseille University (A\*MIDEX). C.E.S. supported by R01

MH111439 and P50 MH109429.

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