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Introduction

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Communicative rhythms in brain and behaviour

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What is rhythm? An immediate answer to this question appears simple and might be linked with everyday examples of rhythmic events or behaviours like dancing, listening to a heartbeat or rocking a baby to sleep. However, a unified scientific definition of rhythm remains elusive. For decades, research programmes concerning rhythm and rhythmic organization have developed largely independently in areas such as music and poetry, language and language disorders, and behaviour and cognition more generally, and in this process have identified many other everyday phenomena, including nodding one's head to words, selectively attending to particular moments in time, and finishing the sentences of one's dialogue partner, that can be interpreted as cases of rhythmic behaviour. Most recently, the rhythmic nature of neural oscillations has received much attention, contributing an additional perspective to the notion of rhythm in communication systems. We believe that at this stage, it is essential to start a cross-disciplinary conversation around the unified theme of rhythm. The aim of this theme issue is to provide the vocabulary for the conversation, and to update the common ground across disciplines with understanding of fundamental concepts, current issues and methodologies, in the hope that this will help a new, more integrative view of rhythmic, human perception and action to emerge.

The papers gathered in this issue come from the fields of cognitive neuroscience, psychology (musical, social, developmental) and linguistics (phonetics, clinical linguistics). The choice of papers was based on the presentations and discussions at the *Perspectives on Rhythm and Timing* (*PoRT*) workshop which we held at the University of Glasgow, UK, on 19–21 July 2012. PoRT was one of the largest interdisciplinary events on the topic of rhythm to date, with more than 100 academics and practitioners in attendance. PoRT was built on three main 'pillars' (neurobiological, linguistic and clinical) with invited contributions to the three orientation sessions designed to make key findings in each area accessible to other disciplines. The programme was supplemented by research papers and posters, a tutorial on coupled oscillator modelling of dynamical systems, and plenty of time for cross-disciplinary discussion. What the conversations at the workshop revealed above all was the appetite that exists, among early-career and senior rhythm researchers alike, to exchange ideas across disciplinary divides and translate them into newly informed research questions.

The issue seeks to link perspectives from brain and behaviour. Behavioural work on rhythm now exploits the full range of instrumental techniques for researching the physiology, kinematics and dynamics of rhythmic movements, as well as cognitive influences on such movements, their acoustic or visual consequences and their sensory processing. Sophisticated methods are developing to investigate rhythmic behaviour in interpersonal, interactive contexts, which provide rich data for understanding the hierarchical organization of rhythm, the interplay of perception and action, and the relationship of rhythmic entrainment to social facilitation, pleasure and emotional arousal. Within the field of cognitive neuroscience, the last 10 years have seen a growing interest in the idea that perceiving musical and speech rhythms might relate in important ways to ongoing oscillatory activity in the brain. According to this view, cortical rhythms adapt, or 'entrain', to structured acoustic signals. Because neural oscillations are hierarchically organized across multiple frequencies, this entrainment may support a highly flexible process of attentional selection that allows people to tune into, predict, and respond emotionally to events on multiple timescales. Future research into oscillatory responses may be able to determine why rhythm is commonly found to be more salient in audition than in other modalities [1,2]. Cognitive neurobiological models offer the possibility of understanding the biological bases of the subjective experience of rhythm. In this context, clinical data are proving to be of particular value to shed light on the relationships between specific brain regions and processes, and particular deficits.

Further, regardless of the perspective, data or methodology, each of the aspects of rhythm discussed in this issue serves a communicative purpose. The collection of papers showcases the wide range of functions attributed to the domain of rhythm, ranging from effectively making sense of the world and improving on impaired cognitive functions and motor control, to increasing prosociality, empathy, social bonding and coordinating social action in time, capturing attention and creating a sense of joy. Rhythmicity comes and goes in response to the pressures of creating and sharing meaning, and sometimes it is the deviation from an established rhythmic pattern that is crucial for a communicative exchange, not the pattern itself [3,4]. As intentions and interpretations of rhythmic structures differ vastly, can a single monolithic concept of rhythm be developed at all? At present, we would like to emphasize the plurality of *rhythms* that emerges from consideration of the papers in the issue, but which may ultimately pave the way to identifying commonalities and shared insights.

The issue opens with a group of papers that concern the role of rhythm in the organization of joint behaviour. The review article by Keller *et al.* [5] summarizes cognitive neuroscience research on the topic of rhythmically structured joint action. Music making is, of course, the quintessential domain in which rhythm serves to structure collective behaviour, and it provides most of the examples considered here, but Keller *et al.* point out that the insights may extend to consideration of other forms of rhythmic behaviour such as walking, rowing and indeed tapping in a psychologist's laboratory. The authors make the case that musical behaviour provides us with a ready-made microcosm of human social interaction. The review covers the way in which shared goals are represented, as well as the neurophysiological mechanisms thought to underpin interpersonal coordination. It goes beyond an exclusively cognitive neuroscientific account in also considering interpersonal psychological topics such as empathy and trust, without which coordinated joint activity would be impossible.

These interpersonal psychological aspects are developed by Cirelli *et al.* [6]. Cirelli *et al.* review a large body of previous work which has demonstrated that being engaged in a joint rhythmic action leads group members to perceive strong bonding with others from their group, and to increase prosocial behaviours towards them. They ask the question: does synchronous movement encourage infants' helpfulness indiscriminately, or only selectively towards those individuals with whom they have previously experienced movement in synchrony? Through experiments with 14-month-old infants, the authors provide evidence for selective helpfulness and conclude that joint rhythmic activities act as a cue to direct prosocial behaviour towards in-group members only.

A different aspect of joint action—interpersonal coordination of breathing—is addressed by Rochet-Capellan & Fuchs [7]. Breathing is one of the most crucial physiological rhythms, and the individual rhythm of breathing can be modified in different situations, most commonly in speaking or listening to speech. Rochet-Capellan and Fuchs ask what modifications take place in natural face-to-face conversations. Do conversational partners converge in their breathing behaviour? Their study showed no evidence for the idea that speakers adopt their breathing to resemble that of their partners. Breathing rates remained speaker-specific throughout the conversations. Nevertheless, coordination in breathing was observed locally and correlated with the success of a turn-taking attempt. Turns tended to be taken smoothly and without conflict if they occurred just after a new speaker's inhalation, in coordination with the partner's exhalation. Turn-taking attempts that were less coordinated with both partners' breathing cycles tended to fail. These results suggest that breathing is relevant to the rhythmic structure of conversations.

The next two papers address the idea that rhythm is a key structuring principle of cognition. They build on the classic idea—proposed by Mari Riess Jones nearly 40 years ago as Dynamic Attending Theory (DAT) [8] and the focus of much recent attention in musical rhythm research—that perceiving pulse and metre in music involves synchronization of endogenous perceptual rhythms to acoustic rhythms.

McAuley & Fromboluti [9] report behavioural investigations into how perceivers distribute attention in time. According to DAT, attention is cyclical and rhythmically structured, such that perceivers show enhanced discrimination of events that occur at rhythmically expected time points. Alternative models such as scalar expectancy theory are based around an internal clock that times events in a context- and thus rhythm-independent manner. McAuley & Fromboluti test these views by investigating how rhythmic context affects listeners' judgements of the duration of an 'oddball' tone, presented within a sequence of standard tones. They show that once a listener has entrained to an isochronous tone sequence, an oddball is perceived as shorter if it occurs earlier than expected, and longer if it occurs later than expected, consistent with the predictions of DAT.

Nozaradan's paper [10] explores how rhythm processing might capitalize on the intrinsic oscillatory dynamics of brain activity. She reviews a range of experiments using the electrophysiological approach of 'frequency-tagging'. Here, periodic presentation of a repeated stimulus generates a stable electrophysiological response, a steady-state evoked potential (SS-EP), whose spectrum shows peaks directly related to the frequency(ies) present in the stimulus. Nozaradan's review demonstrates, *inter alia*, that the neural response to rhythm shows a selective enhancement of the frequencies of the perceived beat and metre. The enhancement occurs even when the beat and metre frequencies are not physically prominent within the stimulus, as in syncopated rhythms, or when the metre is imagined rather than physically signalled. These results may support the patterns predicted by modelling the neural response using a network of nonlinear oscillators, although more work is needed to establish the precise relationships between SS-EPs, transient event-related potentials (ERPs) and background oscillations.

How can neurobiological and cognitive accounts of rhythm production and perception contribute to clinical applications, and what can clinical data in turn bring to the development of theory? These questions motivate the next group of papers. Schaefer's review [11] takes as its starting point the close connection between rhythmic sounds and movement. Schaefer asks to what extent rhythmic auditory cueing can help to rehabilitate movement impaired by brain injury or neurodegenerative disease and shows that only certain interventions for certain disorders have achieved unambiguous success. Yet, she argues, closer consideration of different cue types, patient (sub-)groups and mechanisms of facilitation may enable a wider range of benefits to be identified. For example, some patient groups might benefit most from the simple cueing of a metronome beat, while for others, rhythmically complex music could lead to richer temporal predictions and a better fine-tuning of movement control. There is more to the use of rhythmic cues in movement control than a simple stimulus–response relationship, and Schaefer argues for the cognitive processes and mental models involved in rhythm perception and production to be placed at the heart of research into disorders and their rehabilitation.

Answering this call, Kotz *et al.* [12] present a fine-grained investigation into the electrophysiology of auditory temporal processing by patients with cerebellar lesions, and its relationship to prediction. In an oddball paradigm similar to that used by McAuley & Fromboluti [9], tones deviant in pitch were embedded in a sequence of standard tones, with the sequence timing being either isochronous or irregular. Regular timing should optimize the listener's ability to detect pitch deviance and integrate it into a mental model of the situation. But what happens when the cerebellum—a brain area classically linked to representing temporal structure—is damaged? Kotz *et al.*'s ERP data suggest that while cerebellar patients are not impaired in all aspects of deviance detection, they are generally less able than controls to take full advantage of temporal predictability in this process.

As outlined in several papers in the issue, sensorimotor entrainment to a steady beat is increasingly recognized as a central feature of human musical behaviour. Nevertheless, the ability to accurately move in time to music can vary widely across the population. Palmer *et al.* [13] introduce the idea that individuals with deficits in beat-tracking skills can shed light on theories of temporal adaptation and timekeeping mechanisms. They present two case studies of 'beat-deaf' individuals who find it difficult to synchronize to music, comparing their performance on three different tapping tasks with that of a control group. Results show that these individuals exhibit normal spontaneous tapping tempos and anticipatory patterns when synchronizing with a beat, but also tend to miss more taps, are more variable in their performance generally and show significant difficulties in returning to a baseline tempo after perturbations of the beat. These data are then shown to fit well with a computational model estimating underlying neural oscillator parameters [14], indicating a specific deficit with error correction in perception–action coupling for these individuals. The authors conclude that the hypothesis of intrinsic dynamical oscillations provides a useful framework for understanding beat-tracking behaviour, across a range of performance abilities.

Lowit [15] raises the important issue of the use of 'rhythm metrics' with clinical populations with speech disorders, cautioning that there is still a great deal of research to be done in this area before such metrics of durational aspects of speech can be considered diagnostic, or indeed valid, measures of disordered speech. After a review of the increased use of rhythm metrics in recent research, Lowit introduces an exploratory study in which a range of different rhythm metrics are applied to data from two different speech tasks and compared between six patients with rhythmic speech problems and six control participants. While perceptual ratings reveal significant performance differences between the controls and the patients, the rhythm metrics do not reveal such statistically significant differences. Lowit concludes, among other things, that features of rhythmic speech production such as intensity and timbre need to be taken into consideration alongside durational aspects of rhythmic speech, in future research.

Lowit's critique leads into the focus of the final group of papers in the volume: speech rhythm. Despite a perennial desire within the speech research community to explore parallels with music and acknowledgement of a key role for rhythm at the centre of approaches to speech perception, we still lack consensus on how best to describe and explain speech rhythm, even in non-disordered speech. Indeed, Nolan & Jeon [16] debate the question whether or not speech can be considered rhythmic at all. Speech acoustics lack regularity, and even the existence of strong versus weak elements is not universally present in the languages of the world. After a critical review of linguistic rhythm research to date, the authors somewhat controversially conclude that rhythm cannot be considered an integral part of language, and that speech may even be described as anti-rhythmic. Therefore, the concept of rhythm, when applied to speech and language, has to be seen as a metaphor. It is the metaphorical extension of rhythm that allows speech to be matched to external rhythms, in a manner which depends strongly on the particular language being spoken.

Whether or not it is rhythmic, speech is unanimously agreed to be exquisitely timed. But does that mean that there are dedicated timing elements at work? Turk & Shattuck-Hufnagel [17] review a large body of literature on the temporal structure of speech, attending both to the role of temporal information in making speech intelligible, and to the way in which speech timing patterns result from articulatory fine-tuning during speech production. The first half of the article summarizes an extensive body of research that examines the way in which timing underlies linguistic categories. In the second part, a meta-theoretical perspective considers the classes of speech production models adduced to account for such findings. One of the most powerful current models, articulatory phonology (AP), posits that spoken utterances can be understood as ensembles of articulatory actions called 'gestures' [18–20]. Each gesture (of the lips, tongue, glottis, velum, etc.) is a dynamical system characterized by a set of parameters and has a goal or 'task' to create a local constriction within the vocal tract. According to AP and its variants, speech timing may arise as an emergent property of dynamical interactions among components. This contrasts with theories such as Directions into Velocities of Articulators (DIVA) [21,22] which lean more heavily upon the explicit specification of desired durations for particular speech segments, and thus require a clock-like timer. The divergence of perspectives recalls that described by McAuley & Fromboluti [9] between oscillator-based and clock-timed approaches to attention and perception.

The review by Krivokapić [23] delves deeper into the dynamical perspective represented by AP, focusing on the prosodic relations of prominence and grouping that hold between spoken syllables. Recent extensions to the theory of AP claim that coupled oscillators can be used to model both individual articulatory gestures (such as lip closure) and also prosodic gestures (relating, for example, to syllabic prominence or utterance edges). On this dynamical view, prosodic gestures modulate the time course of the articulatory gestures that are co-active with them, while different prosodic gestures for grouping and prominence are also coupled to one another, and the interactions among the two types of gestures determine the complex timing patterns observed within utterances, for example, how much lengthening the various sounds in a word undergo at the end of a spoken phrase. Krivokapić reviews the evidence for these claims, with particular focus on coordination of gestures around utterance edges and pauses. She argues that investigation of movements of the speech articulators and also of the head and hands, during pauses can shed light on the relationship between prosodic structure and the articulatory planning processes involved in speech. A dynamical approach thus forms a common thread between research in production and perception of temporally structured events, modelling simple as well as complex acoustic signals [9,13], though it remains to be seen how close the links might be.

Finally, concluding the issue, Hawkins [3] connects the domains of speech [16,17,23 and music [5,6,11,13]. Commonalities and differences across the domains are identified, taking into account both the inherent structures of each domain, and the functions that they subserve. Special consideration is given to the link between rhythmic expression and emotion, which is argued to be manifested somewhat differently in the two domains. The role of rhythm in structuring joint action is highlighted (cf. [5–7]), in particular with respect to the way in which enhanced rhythmicity can scaffold prediction in communicative exchanges (cf. [9,10]).

We chose to conclude the issue with a paper whose focus is on the interface between music and speech research, as we believe that synergy between the two perspectives represents an exciting direction for the future, offering the opportunity for shared methodologies, resources, goals and frameworks. Musical rhythm is the area where core concepts have been most successfully elaborated; the domain of speech is more challenging, as the temporal patterns observed satisfy some but not all definitions of rhythmicity. In particular (see Schaefer [11] for more details), music researchers distinguish the *pulse* or *beat* from the *metre*, and emphasize that both are perceptual constructions rather than physical properties of signals. Thus, pulse perception can be induced from signals with little energy at the pulse frequency; metre perception is commonly supported by physical accentuation of particular beat positions, e.g. in terms of their duration, pitch or intensity, but can on occasion be merely imagined or subjectively imposed [10]. As the difficulty of inferring/inducing the beat and/or metre from an acoustic rhythm varies, so does the perceived complexity of the rhythm. Complexity can increase interest: e.g. in syncopated rhythms where weak beats are accented and strong beat positions are neglected; or in polyrhythms where two simultaneous, conflicting metrical analyses compete. As well as deviations from the beat grid, there are deviations from expected event timing, via expressive micro-timing, exquisitely controlled by skilled musical performers [5].

Some components of the above definitions of rhythm have very obvious correlates in speech, and the parallels have been explored (especially in metrical phonology, e.g. [24]), but have rarely informed empirical inquiry. The hierarchical structural organization of speech sounds is very solidly established [17,23], as are the roles of duration, intensity and pitch in creating physical accentuation (though see Nolan & Jeon [16] for important limits on generalizability across languages). Expressive micro-timing is an evident feature—syllables that sound unusually drawn-out or clipped (relative to the listener's expectation) will normally be felt to have a particular emotional or rhetorical effect. Phrasing (grouping) also has clear similarities in both domains. But in other respects the parallels are harder to draw. While pulse and metre are central to the understanding of rhythm in music [11], we know far less about how—or even whether—they might be induced from real speech signals, and what level(s) of the prosodic hierarchy might correspond to pulse, especially when considering the wide range of rates and degrees of articulatory precision with which a given sequence of 'underlying' units can be produced in accordance with the communicative context. Speech research might usefully explore beat and metre perception using paradigms that have illuminated these phenomena in music research (e.g. tapping, [25,26]; or other methods to elicit movement in response to spoken signals), ultimately contributing to the understanding of their neural correlates in speech.

Conversely, the music research community is moving towards phenomena that are more complex than 'simple periodicity' including syncopation, joint improvisation and many styles of non-Western music. Indeed, some of the approaches to musical rhythm represented in the issue do not assume regularity to be critical. For example, Keller *et al.* [5] view temporal coordination as the key, and regularity as but one manifestation of coordination: they "consider joint actions to be rhythmic if their goals necessitate producing specific patterns of relative timing between co-acting individuals' movements, and if these prescribed temporal relationships require precision in the order of tens of milliseconds. Regularly timed movements facilitate this degree of precision, but temporal regularity does not imply rigidity in the context of rhythmic joint action" (p. 1). Speech has the potential to reciprocally inform music research here, because speech research has arrived at a solid understanding of sources of complexity in speech signals, which may be lacking in regularity but are highly systematic and precisely timed [7,16,17,23]. Our hope is that a synthesis of perspectives will bring us closer to an understanding of how rhythm works in less beat-based but more complex, and naturalistic types of signal, and accordingly its role for cognition in general.

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References

1. Grahn JA, Henry MJ, McAuley JD. 2011 FMRI investigations of cross-modal interactions in beat perception: audition primes vision, but not vice versa. *NeuroImage* **54**, 1231–43. (doi:10.1016/j.neuroimage.2010.09.033)
2. Grondin S, McAuley JD. 2009 Duration discrimination in crossmodal sequences. *Perception* **38**, 1542–1559. (doi:10.1068/p6359)
3. Hawkins S. 2014 Situational influences on rhythmicity in speech, music, and their interaction. *Phil. Trans. R. Soc. B* **369**, 20130398. (doi:10.1098/rstb.2013.0398)
4. Witek MAG, Clarke EF, Wallentin M, Kringelbach ML, Vuust P. 2014 Syncopation, body-movement and pleasure in groove music. *PLoS ONE* **9**, e94446. (doi:10.1371/journal.pone.0094446)
5. Keller PE, Novembre G, Hove MJ. 2014 Rhythm in joint action: psychological and neurophysiological mechanisms for real-time interpersonal coordination. *Phil. Trans. R. Soc. B* **369**, 20130394. (doi:10.1098/rstb.2013.0394)
6. Cirelli LK, Wan SJ, Trainor LJ. 2014 Fourteen-month-old infants use interpersonal synchrony as a cue to direct helpfulness. *Phil. Trans. R. Soc. B* **369**, 20130400. (doi:10.1098/rstb.2013.0400)
7. Rochet-Capellan A, Fuchs S. 2014 Take a breath and take the turn: how breathing meets turns in spontaneous dialogue. *Phil. Trans. R. Soc. B* **369**, 20130399. (doi:10.1098/rstb.2013.0399)
8. Jones MR. 1976 Time, our lost dimension: toward a new theory of perception, attention, and memory. *Psychol. Rev.* **83**, 323–335. (doi:10.1037/0033-295X.83.5.323)
9. McAuley JD, Fromboluti EK. 2014 Attentional entrainment and perceived event duration. *Phil. Trans. R. Soc. B* **369**, 20130401. (doi:10.1098/rstb.2013.0401)
10. Nozaradan S. 2014 Exploring how musical rhythm entrains brain activity with electroencephalogram frequency-tagging. *Phil. Trans. R. Soc. B* **369**, 20130393. (doi:10.1098/rstb.2013.0393)
11. Schaefer RS. 2014 Auditory rhythmic cueing in movement rehabilitation: findings and possible mechanisms. *Phil. Trans. R. Soc. B* **369**, 20130402. (doi:10.1098/rstb.2013.0402)
12. Kotz SA, Stockert A, Schwartze M. 2014 Cerebellum, temporal predictability and the updating of a mental model. *Phil. Trans. R. Soc. B* **369**, 20130403. (doi:10.1098/rstb.2013.0403)
13. Palmer C, Lidji P, Peretz I. 2014 Losing the beat: deficits in temporal coordination. *Phil. Trans. R. Soc. B* **369**, 20130405. (doi:10.1098/rstb.2013.0405)
14. Large EW, Fink P, Kelso J. 2002 Tracking simple and complex sequences. *Psychol. Res.* **66**, 3–17. (doi:10.1007/s004260100069)
15. Lowit A. 2014 Quantification of rhythm problems in disordered speech: a re-evaluation. *Phil. Trans. R. Soc. B* **369**, 20130404. (doi:10.1098/rstb.2013.0404)
16. Nolan F, Jeon H-S. 2014 Speech rhythm: a metaphor? *Phil. Trans. R. Soc. B* **369**, 20130396. (doi:10.1098/rstb.2013.0396)
17. Turk A, Shattuck-Hufnagel S. 2014 Timing in talking: what is it used for, and how is it controlled? *Phil. Trans. R. Soc. B* **369**, 20130395. (doi:10.1098/rstb.2013.0395)
18. Browman CP, Goldstein L. 1986 Towards an articulatory phonology. *Phonol. Yearb.* **3**, 219–252. (doi:10.1017/S0952675700000658)
19. Browman CP, Goldstein L. 1989 Articulatory gestures as phonological units. *Phonology* **6**, 201–251. (doi:10.1017/S0952675700001019)
20. Saltzman E, Kelso JAS. 1987 Skilled actions: a task dynamic approach. *Psychol. Rev.* **94**, 84–106. (doi:10.1037/0033-295X.94.1.84)
21. Guenther FH. 1995 Speech sound acquisition, coarticulation, and rate effects in a neural-network model of speech production. *Psychol. Rev.* **102**, 594–621. (doi:10.1037/0033-295X.102.3.594)
22. Guenther F. 2006 Cortical interactions underlying the production of speech sounds. *J. Commun. Disord.* **39**, 350–365. (doi:10.1016/j.jcomdis.2006.06.013)
23. Krivokapić J. 2014 Gestural coordination at prosodic boundaries and its role for prosodic structure and speech planning processes. *Phil. Trans. R. Soc. B* **369**, 20130397. (doi:10.1098/rstb.2013.0397)
24. Selkirk EO. 1984 *Phonology and syntax: the relation between sound and structure*. Cambridge, MA: MIT Press.
25. Lidji P, Palmer C, Peretz I, Morningstar M. 2011 Listeners feel the beat: entrainment to English and French speech rhythms. *Psychon. Bull. Rev.* **18**, 1035–1041. (doi:10.3758/s13423-011-0163-0)
26. Repp BH, Su Y-H. 2013 Sensorimotor synchronization: a review of recent research (2006–2012). *Psychon. Bull. Rev.* **20**, 403–452. (doi:10.3758/s13423-012-0371-2)