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Rhythms of interaction – the timescales of social coordination and why they matter

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A B S T R A C T

Social interaction involves coordination between individuals across multiple domains, including neural activity, behaviour and physiology. An increasing number of studies shows that interpersonal coordination and synchrony can be detected in each of these modalities, but the functional significance of these different types of coordination remains unclear. This paper examines the challenge of understanding coordination in terms of the timescales of interaction. We provide a novel mapping of interaction types and measurement methods across timescales spanning from milliseconds to minutes. We review candidate mechanisms of synchrony and coordination in both neural systems and behaviour, and consider how these measures relate to real world outcomes such as learning and development. Overall, we provide an integrative approach that, by taking timescales into account, aims to offer a better understanding of the origins and interpretation of interpersonal coordination.

1. Introduction

Coordinated behaviours, where people produce temporally aligned behaviours, occur on many different timescales throughout human life, from millisecond synchronization in a piano duet to turn taking in conversation, and from daily meal times to annual religious festivals. Within this wide variety of types of coordination, social synchrony arises when rhythmic behaviours are coordinated between two or more people (Fig. 1). An increasing body of research suggests that successful synchronization with others is important for people to learn and build social relationships. It has been linked to affiliation (Hove and Risen, 2009), cooperation (Wiltermuth and Heath, 2009), successful negotiation (Pentland, 2008) and prosocial behaviour in adults (Reddish et al., 2013) and infants (Cirelli et al., 2014). In parallel with behavioural synchronization, reports show that neural signals measured with electroencephalography (EEG) and functional near infrared spectroscopy (fNIRS) are often synchronized at above-chance levels when people are engaged in a social interaction (Czeszumski et al., 2020; De Felice et al., 2025a; Dumas et al., 2010; Hakim et al., 2023). (Schilbach and Redcay, 2025). However, it is not yet clear if and how different types of coordination are linked, what mechanisms drive coordination nor what these phenomena mean for our psychological theories.

In order to better understand social coordination phenomena, this paper will attempt to map them in relation to the *timescales* at which coordination occurs and at which synchrony can be measured. Timescales matter because coordination arises across various contexts and may be driven by different mechanisms or have different consequences at different timescales. These timescales of interpersonal coordination (IPC) may also depend on the measurement methods used, e.g., from video recording to EEG and physiological monitoring. Fig. 2 provides an overall map of behaviour at different timescales which we review and explore in detail below, and Fig. 4 extends this to interpersonal coordination. To preview the conclusion, we will argue that both fast and slow timescales are important in different ways, and that often more robust effects may be seen at slower timescales with stronger real-world outcomes.

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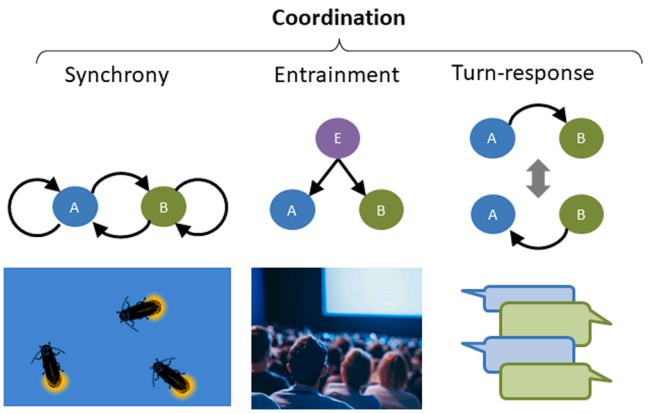

Fig. 1. Coordination is an umbrella term that encompasses a number of different mechanisms including true synchrony, entrainment and turn-responsiveness.

2. Definitions and mechanisms – synchrony, entrainment and coordination

Within the domain of interpersonal behaviour, the same terms are sometimes used in different contexts. While synchrony is often used as an umbrella term for a wide range of behavioural phenomena (daSilva and Wood, 2024), a stricter definition of *true synchronization* applies only to a subset of these effects (Harding et al., 2025). With its origin in physics, *true synchronization* is defined as phase locked behaviour between self-sustained oscillators arising through mutual interaction (Zamm et al., 2024). Applied to human behaviour, this definition implies that each individual's behaviour must be intrinsically periodic, with coordination emerging from the interaction itself rather than from external pacing or coincidence (Pikovsky, et al., 2001; Rosenblum et al., 1996). *Entrainment* has also been used broadly (Wass et al., 2020) and describes a situation where an external signal (e.g., a musical beat, audio-visual input from a movie, or similar) drives synchronized or correlated patterns of behaviour and brain activity in two or more individuals (Chen et al., 2016; Madsen and Parra, 2022). There are also many forms of coordinated behaviour that are not synchronous in time. For example, *turn-responsiveness* describes a situation where two individuals can act in response to each other (e.g. taking turns in conversation) without a requirement for a driving rhythm. Different neural and cognitive mechanisms may be at play in each of these cases, but experimentally it can often be hard to distinguish between them. Here, we use the umbrella term 'coordination' to encompass all three types of interpersonal behaviour, and return to a more detailed consideration of mechanisms at the end of the paper.

When we turn to experimental measures of the coordination between two people, there are again a range of terminologies and methods that are used. Box 1 summarises some of the different statistical measures that can be used to determine if two signals recorded from two people are related to each other or not. Some of these measures (e.g. phase locking value) are informative about high-precision coordination, yielding higher values when the phase relationship between two people's behaviours is consistent over time (Zamm et al., 2024). Amplitude coupling reflects a more correlational measure, capturing covariation between the amplitudes of two person's signals. Other measures, such as wavelet coherence, capture how the relationship between two signals

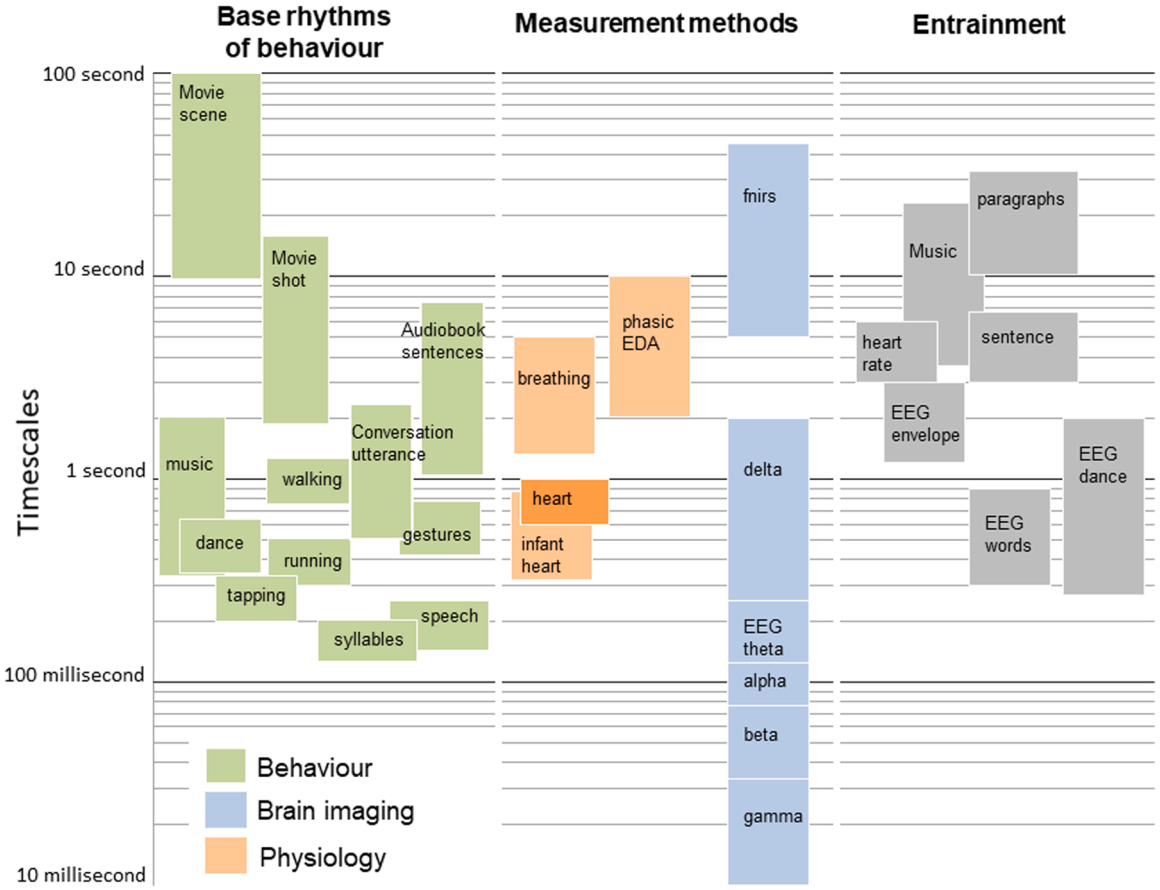

Fig. 2. Timescales across behaviour and brain illustrated on a single plot spanning the range from 10 ms to 100 s on a logarithmic axis. left: timescales found in human behaviour that can provide base rhythms for synchrony between people. middle: timescales in physiological signals and brain imaging measures. right: timescales where entrainment has been found for a variety of stimuli.

Box 1
Analysis methods for finding coordination.

How precisely must two signals be related to be classified as 'synchrony'? Fig. 3 illustrates some possible relationships between pairs of signals (left column) and the common analysis approaches used to identify these relationships (right column). The null case occurs if two rhythmic signals are at different frequencies without n:m coupling (Fig. 3A) while perfect synchrony arises when two signals have the same frequency and the same phase (Fig. 3B). Analyses of phase-locking value (PLV) can identify phase coupling strength, yielding high values when the relative phase difference between signals is constant. However, many other patterns are also incorporated into synchrony analyses. In addition to in-phase and anti-phase synchrony, there could be cases where one signal consistently lags behind another, which is captured using the phase lag index (PLI) or by looking at the distribution of relative phase. If two rhythmic signals have power at the same frequency (regardless of phase), they can be described as *coherent* (Fig. 3B and C) and this pattern is often captured with a wavelet coherence analysis (Issartel et al., 2014) which provide an accessible and robust measure of coherence useful for many biological signals.

It is also possible to analyse pairs of signals using methods that identify more global changes in amplitude, which may be particularly relevant when a high-frequency signal acts as a carrier for a slower signal (Fig. 3D & H). Envelope correlations or amplitude correlations are one valuable method of this type (Koul et al., 2023). This works even if the two underlying signals are at different frequencies, and so could be particularly useful in cases where different frequencies might be expected between people (e.g. adult & child EEG). In addition to these, there are a host of other signal processing options to identify relationships between different signals. These include lagged cross-correlations and windowed lagged cross-correlations, granger causality, and correlated inter-beat-intervals. This diversity of methods illustrates that, when a research paper discusses synchrony, it is critical to understand exactly what type of synchrony is under consideration and what timescales it operates on.

evolves over time and across different frequencies, but often provides more temporally and spectrally diffuse estimates of coupling. It is important to note that the statistical measure of coordination used does not necessarily tell us about the underlying mechanism that causes two people to be coupled. For example, entrainment or true synchronization could both cause two signals to be related in terms of phase-locking values. We reserve the term 'true synchronization' for the small number of cases where an interpersonal coordination mechanism can be definitively identified (normally with advanced computational modelling, for example Heggli et al., 2019) but will use the term 'measured synchrony' or just 'synchrony' in cases where a study measures a pattern of coordination without strong claims about the mechanisms.

Despite the variety of terminologies and statistical methods used in the study of coordination between people, there are core principles that generalize across phenomena. An episode of coordinated behaviour must have a timescale, with a pattern of events that repeat in a regular or near-regular cycle. This is clearest in the context of true synchronization. For example, each firefly in a group flashes to its own beat but is also weakly coupled to the other fireflies; this means that each firefly tends to adjust the timing of is flashes to match the timing of the other fireflies, so that the whole group is likely to fall into synchrony (Sarfati and Peleg, 2022). Here the timescale is the frequency at which the fireflies flash. However, timescales are also present across other types of coordination phenomena. The entrainment of people's behavioural or brain signals driven by watching the same movie can align to the timescale of events in the movie, which may not have a consistent rhythm (Zacks et al., 2001). Similarly, the back-and-forth of conversation occurs at the timescale of utterances, sentences, or ideas with distinct turns taken by the people in the room. Timescales can also be hierarchically nested, such that faster, short-term dynamics unfold within and are constrained by slower, longer-term processes (Wijnants et al., 2012). For example, moment-to-moment adjustments in movement or speech timing, on the order of milliseconds, occur within slower-evolving interactional contexts, such as shared task goals or social roles, which develop over minutes or longer. These have previously been explored in the context of single-brain cognition (Hasson et al., 2015; Kiebel et al., 2008). Here, we suggest that, by making social or environment-driven timescales more explicit, we may gain a better understanding of the kinds of mechanisms that drive different types of coordination at various timescale.

3. Mapping the base rhythms of human social behaviour

Fig. 2 illustrates timescales (on a logarithmic scale along the y-axis) for a range of behaviours which are relevant to the study of human interpersonal coordination. We will describe all effects in this paper in terms of the timescale of the rhythm (also known as the period) which is easier to compare and interpret across a wide range of behaviours. This mapping aligns somewhat with the broader mapping of timescales suggested by (Newell, 1994) who distinguishes different timescales of neural and cognitive processes from 10msec to decades. Beginning with the fastest behavioural signals, rhythms of speech and syllables have timescales around 200 msec (Ding et al., 2017). Rapid finger movements, either in lab tasks or contexts like piano playing can also have base rhythms in this range (Truman and Hammond, 1990). Natural walking (Lamoreux, 1971), running (Cavagna et al., 1997), dance (van Noorden and Moelants, 1999) and postural sway (Soames and Atha, 1982) have base rhythms ranging from 200 to 1000 msec.

In the domain of speech and language, many different timescales contribute, ranging from syllables (around 200 msec) to words (200–1000 msec) to conversational turns (500msec−5 s) (Liesenfeld and Dingemanse, 2022). These frequencies are found across many languages and speech production settings such as conversation or reading aloud (Ding et al., 2017). In turn taking, the gap between one person ending their turn and the next beginning to speak averages 250 msec (Stivers et al., 2009) but is highly variable (Templeton et al., 2023). Non-verbal cues can have a similar rhythm, for example, pikes (distinctive beats or gestures in hands, speech, blinks or body) are coordinated across modalities and speakers, and occur with a tempo around 600 msec (Loehr, 2007).

Slower rhythms are not often quantified, but event boundaries in the actions of a solo actor performing household tasks fall in the 4–12 s range (Newtson, 1973). Event boundaries in narrative and movies fall in the 11–180 s range (Chen et al., 2016). On longer timescales, circadian rhythms are influenced primarily by daylight but also by social interaction (Weissová et al., 2019), while the social rhythms of the week, month and year have much longer base frequencies. While fascinating studies suggest that coordination at these longer timescales is important to people (Brown et al., 2020; Foss, 2004), consideration of timescales longer than 1 min is beyond the scope of this paper.

4. Base rhythms and entrainment of physiological and brain signals

Moving on in our map to Fig. 2, we can consider the different rhythms commonly seen in physiological and brain signals. With regards to physiological signals, heartbeat rhythms have a timescale from 0.3 to 1 s (infants and adults), while breathing unfolds over slower cycles of around 1.5–5 s (Wallis et al., 2005). A large body of work has focused on respiratory sinus arrhythmia (RSA), a measure of heart rate variability associated with vagal regulation. Because RSA is intrinsically tied to the respiratory cycle, the timescale matches that of breathing. Empirically, RSA is estimated over temporal windows ranging from a few seconds to tens of seconds (e.g., 5–60 s epochs, often ~30 s), with more recent approaches using shorter sliding windows to capture continuous fluctuations (Abney et al., 2021; Miller et al., 2023; Nguyen et al., 2021a). Cross-recurrence quantification analysis applied to these RSA time-series reveals moment-to-moment coupling patterns, with interpersonal physiological synchrony highly modulated by social and affective contexts (Davis et al., 2018).

Our measures of neural coordination also span a wide range, given that different methods can pick up signals at different time scales. EEG detects local field potentials related to rapid neural firing and thus can detect fast changes in brain activity. Data is typically analysed in terms of named frequency bands – delta, theta, gamma, beta and alpha, and these rhythms are believed to reflect different types of neural processing. For example, alpha (8–12 Hz) in primary visual cortex is typically suppressed by external stimulation (Bazanova and Vernon, 2014); and similarly, the mu rhythm (with 2 components centred at 10 and 20 Hz) desynchronizes (i.e., suppresses in power) over the Rolandic region during motor tasks (Pfurtscheller et al., 2006). Meanwhile, gamma band changes have been related to diverse functions, such as attention, memory, visual feature integration, integration across sensory and motor systems, and aspects of conscious perception (Senkowski et al., 2008).

Studies of intrinsic brain rhythms also suggest that there are notable patterns at slower timescales (Wolff and Dumas, 2026). Different brain regions have different intrinsic timescales as shown in both human (Honey et al., 2012) and primate (Murray et al., 2014) data. Scales in the monkey were reported to range from around 70 msec (early visual areas) to 350 msec (anterior cingulate cortex). fMRI studies in humans can also capture intrinsic timescales in resting-state data, and a study using simultaneous EEG and fMRI found EEG timescales around 10–30 msec correlated with fMRI timescales of 1–3 s from the same brain region (Watanabe et al., 2019). Such differences in intrinsic timescales may have clinical relevance, as variations have been observed in neurodevelopmental disorders. For example, (Watanabe et al., 2019) reported altered intrinsic timescales in participants with autism.

A different way to examine the natural timescales of the brain is to measure how brain activity patterns entrain to an external stimulus. For example, if individual participants complete a solo fMRI or EEG scan while watching a rich audiovisual stimulus, their brain activity will entrain to features of the stimulus. Taking data from multiple individual participants entraining to the same stimulus allows researchers to calculate the inter-subject correlation (ISC) which provides a measure of how similarly the different brains respond to the same stimulus (Hasson et al., 2012). EEG and MEG studies of entrainment to language stimuli show that the linguistic input can drive inter-subject entrainment across language-related areas of the brain (Alday, 2019). Similarly, a study using electrocorticographic (ECoG) recordings in five participants showed that signals across a wide range of frequencies can be related to the temporal structure of the movies that the participants watched (Honey et al., 2012). In particular, low frequency signals with timescales from 1 to 10 s were related to the structure of the movie. This stimulus-entrainment has been shown to be relevant to social and learning outcomes of a task. For example, an EEG study of over 100 typical young adults that watched educational videos alone showed presence of ISC at relatively slow timescales (500msec – 10 s), which were related to subsequent learning (Madsen and Parra, 2022). Inter-subject correlation of brain activity at these slower timescales, as a result of common stimulus locking, may thus reflect participants' attentiveness towards the stimuli. ISC has thus been proposed to be a potential marker of engagement (Dmochowski et al., 2012).

Inter-subject entrainment has also been demonstrated across participants' heart rhythms when they listened to auditory narrative stimuli i.e., stories, which was modulated by attention (Pérez et al., 2021). Interestingly, ISC of heart-rhythm fluctuations was dominant at slow timescales of 5–10 s. Entrainment can also be studied using fMRI, and both audio-alone and movies have been used as stimuli. Results show that ISC is modulated by attentional engagement (Ki et al., 2016) and the interpretation of the stimulus (Sievers et al., 2024; Yeshurun et al., 2017). A further series of studies show how different features of the stimulus, such as words / sentences / paragraphs, can drive ISC at different timescales which map to the timing of the real-world events (Hasson et al., 2008). These 'temporal receptive windows' map onto different regions of the brain, with some areas responding to complete sentences while others are sensitive to words or phrases. That is, the temporal structure of language is reflected in different brain areas responding to information that accumulates at different timescales (Chang et al., 2022).

All these data illustrate that there are fundamental rhythms in brain and physiology that span a wide range of timescales (Fig. 1). These rhythms provide a potential starting point to explore interpersonal neural coordination between people, which is driven by reciprocal social interaction, rather than stimulus-locking alone. Before reviewing research on interpersonal coordination, we provide a short summary of analysis methods used to quantify synchrony and coordination (Box 1) because these can have a substantial effect on the results obtained in analyses of interpersonal coordination. Then, we review studies of coordination in both behaviour and brain before considering the real-world implications of these coordination studies.

5. Timescales of coordination in behaviour

There are a large range of timescales at which people can show behavioural coordination, ranging from milliseconds to years. Here, we focus on actions faster than 1 min, as illustrated in Fig. 4 middle column. In some contexts, people can synchronise their movements with exquisite precision. This arises both in expert rehearsed performances like a piano duet, but also in everyday actions like passing an object to another person (Mason and MacKenzie, 2005). Similarly, in the domain of speech, it is easy for two (or more) people to speak a novel text aloud in sync with each other with coordination of word and syllable timing (Bowling et al., 2013), showing that expertise or practice are not essential to coordination.

Many studies of precision synchrony have used finger movement tasks, showing that people tend to spontaneously fall into sync when they can see each other's movements (Oullier et al., 2008), reviewed in (Repp and Su, 2013). This type of behaviour can be described with mutual prediction and adaptation measures (Konvalinka et al., 2010) or models (van der Steen and Keller, 2013). Strategies to reduce variability may also make an important contribution to precise synchronization both for finger movement tasks (Vesper et al., 2011) and for breathing rhythms (Konvalinka et al., 2023).

Coordination in bodily movements can be seen across a wide variety of contexts and timescales. People spontaneously synchronize their walking strides (van Ulzen et al., 2008), which average 0.5–0.8 s per step, and this effect is stronger when holding hands (Zivotofsky and Hausdorff, 2007). When pairs of adults tell jokes together, there is coordination of postural sway at all the timescales studied from 6 s to 0.75 s (Schmidt et al., 2014). Pairs of adults coordinate their rocking spontaneously when seated in rocking chairs next to each other (and with visual feedback of each other), even when the natural frequencies

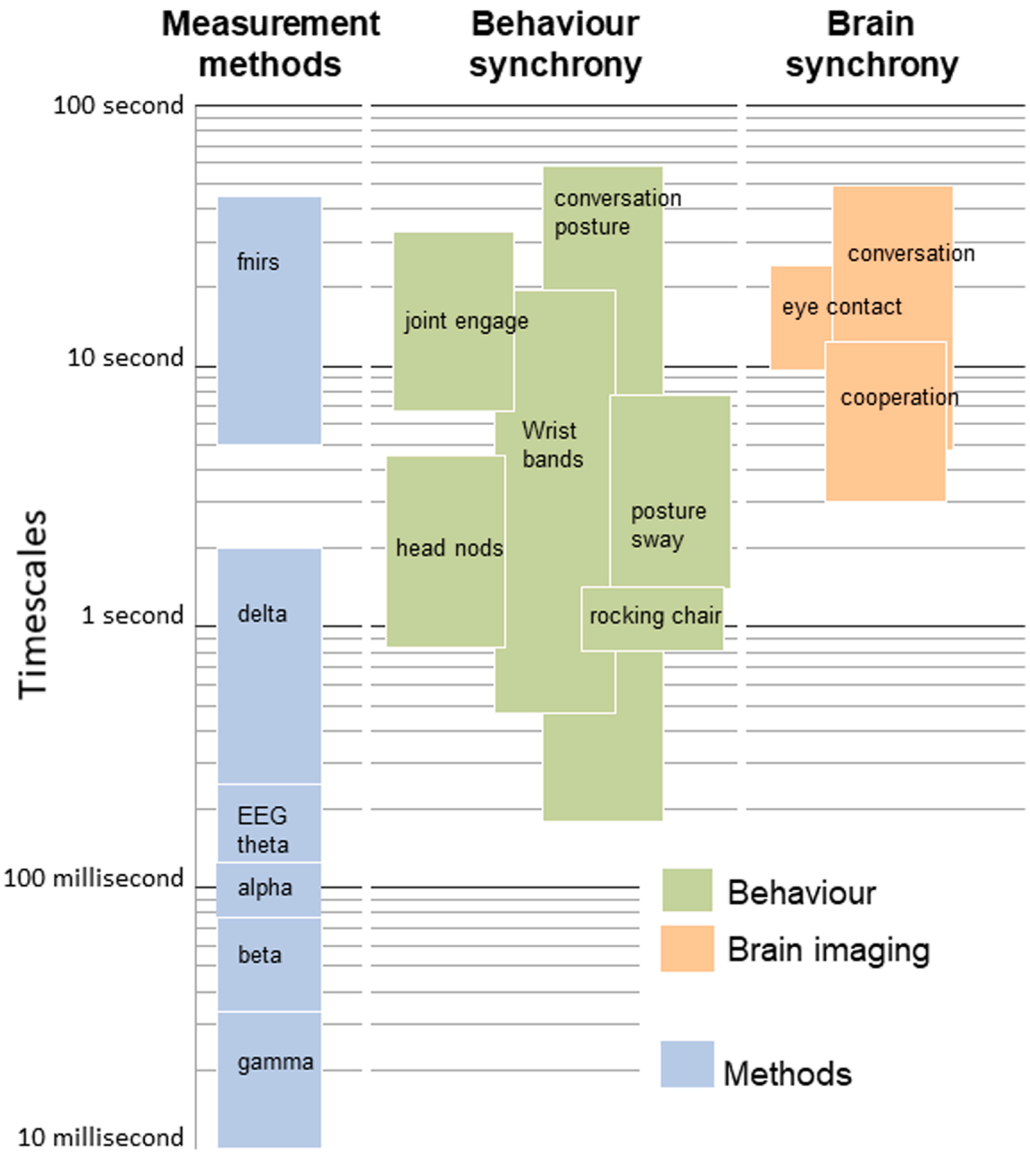

Fig. 4. Timescales of synchrony in brain and behaviour. The scale and column titled 'measurement methods' match Fig. 2. Behavioural synchrony is seen across a range from 200msec to over 50 s. Brain synchrony is depicted for fNIRS studies that cover the 5-50 s range. Brain synchrony has also been reported in EEG data but few provide the timescale information needed to depict the data on this plot.

of their chairs (1.5 s / 1.7 s) are different (Richardson et al., 2007). During conversation, coordination is also commonly seen in smiling and laughing. Head nodding is coordinated between adults in conversation at timescales from 0.9 to 4.7 s (Hale et al., 2019) (Hadley et al., 2019). A detailed study of facial actions, speech and gesture found rapid coordination (0–1 s lag) in smiles, slower coordination of nods and backchannel behaviours (around 1 s) and much longer lags in self-touch gestures (12–40 s) (Louwerse et al., 2012). Similarly, an electromyography (EMG) study found time delays around 200–1000 msec in smiling behaviour (Riehle et al., 2017). Patterns of facial synchrony increased in tasks where language was not permitted (Zhao et al., 2023). All these results illustrate that coordination is common and arises spontaneously in a range of head and body movements in a range of different types of interaction settings.

Moving outside the lab, research using wearable sensors allows us to quantify the patterns and timescales of coordination in a range of settings. Ward et al. used wristband accelerometers to capture movement coherence in autistic children and adult actors during an interactive theatre performance (Ward et al., 2018) and found effects over 0.5–40 s. In a second study, adult actors and audiences showed synchronization over a wide band from 5 to 60 s with peaks around 10 s during interactive segments of the performance (Sun et al., 2023). Recent work shows that behavioural coordination together with other physiological measures can predict student engagement in classes in secondary schools (Gao et al., 2020). In this study, teenagers wore sensors that tracked physiological signals (heart rate variability and electrodermal activity) and motion (accelerometers) in 144 lessons over 4 weeks; cognitive and emotional engagement was measured for each lesson with questionnaires. Among the many measures explored, motion synchrony to classmates predicted cognitive engagement and motion synchrony to the teacher predicted overall engagement. These studies provide evidence that slow behavioural coordination measures can link to real-world outcomes.

Overall, these studies show that people coordinate across a wide range of timescales, from precision movements at $<$ 200 msec to slow effects at 10–60 s. There is no obvious priority for one particular timescale, but different social contexts may lead to dominant signals at different timescales. Different cognitive mechanisms are also likely to be dominant at different timescales. This is partly because the timing of action coordination in the motor system acts as inherent limit on how

well people can coordinate. In the human visual-motor system, it takes at least 120 msec for a visual input to impact on a preplanned motor response (Paulignan et al., 1991); rapid pre-prepared reaction time tasks typically have responses around 300–400 msec and an unprepared response to a novel input might take around 600 msec to occur. This means that any behavioural coordination that takes place faster than around 600 msec is likely to involve processes of *prediction* and *true synchrony*, while coordination at slower timescales could be purely *responsive*. For example, the mid-range effects seen in coordination of nodding and facial actions around 600–700 msec could arise from a simple reaction to seeing another person (Hale et al., 2019). Finally, slow effects seen over longer timescales might reflect social responsiveness, or also a common response to a shared environment that varies in a slow fashion.

This links back to the mechanisms illustrated in Fig. 1 – true synchrony where two individuals act in sync with precise timing requires a predictive rhythmic mechanism, while turn-responsiveness at slower time scales does not. Entrainment to an external cue can also lead to highly precise coordination, but without any prediction. Distinguishing entrainment effects from true synchrony effects can thus be complex, and is likely to depend on the precise task and context under investigation. However, it is clear that the computational models that apply at one particular timescale and task might not generalise to a different task that takes place at a different timescale. This means that attempts to develop an overarching theory that applies to all types of synchrony or coordination based purely on behaviour will be hard. In the next section, we consider how these different measures might relate to neural mechanisms.

6. Timescales of interpersonal neural coordination

Interpersonal neural coordination (INC) has been the focus of intense study over the last few years, even though the origins and interpretation of this phenomenon are still debated (Hamilton, 2020; Holroyd, 2022; Novembre and Iannetti, 2021). Many different methods are available to capture INC, and most examine only a small band of frequencies and leave out information on other timescales. We begin this review by focusing on the small number of studies which have reported INC across a wide range of timescales allowing a fair comparison across scales. For researchers seeking to understand the fundamental mechanisms driving synchrony and coordination, animal studies provide essential information. Kingsbury et al. used calcium imaging to record from thousands of neurons in the cortex of pairs of mice with a 30 Hz resolution during 10-minute sessions while the animals engage in natural behaviours such as grooming or advancing / retreating in a narrow space. The behaviour of each mouse could be classified from video, revealing that natural push, approach or retreat bouts of behaviour lasted approximately 0.5 – 2 s. The behaviours were then used to classify individual neurons as those sensitive to 'self-behaviour' or 'other behaviour'. Over the whole recording session, the sum of the 'self-behaviour' and 'other behaviour' neurons in mouse A correlates closely with the sum of the self--behaviour' and 'other behaviour' neurons in mouse B, which reflects the fact that the two mice are engaged in a process of mutual prediction or adaptation (Kingsbury et al., 2019). The INC is stronger at slower timescales (>60 s) than at faster timescales (<10 s) [See Fig. 5C], which reflects the notion that continuous social interaction drives INC.

INC has also been captured in a series of studies of the Egyptian fruit bat (a highly social species). Zhang et al. (Zhang and Yartsev, 2019)

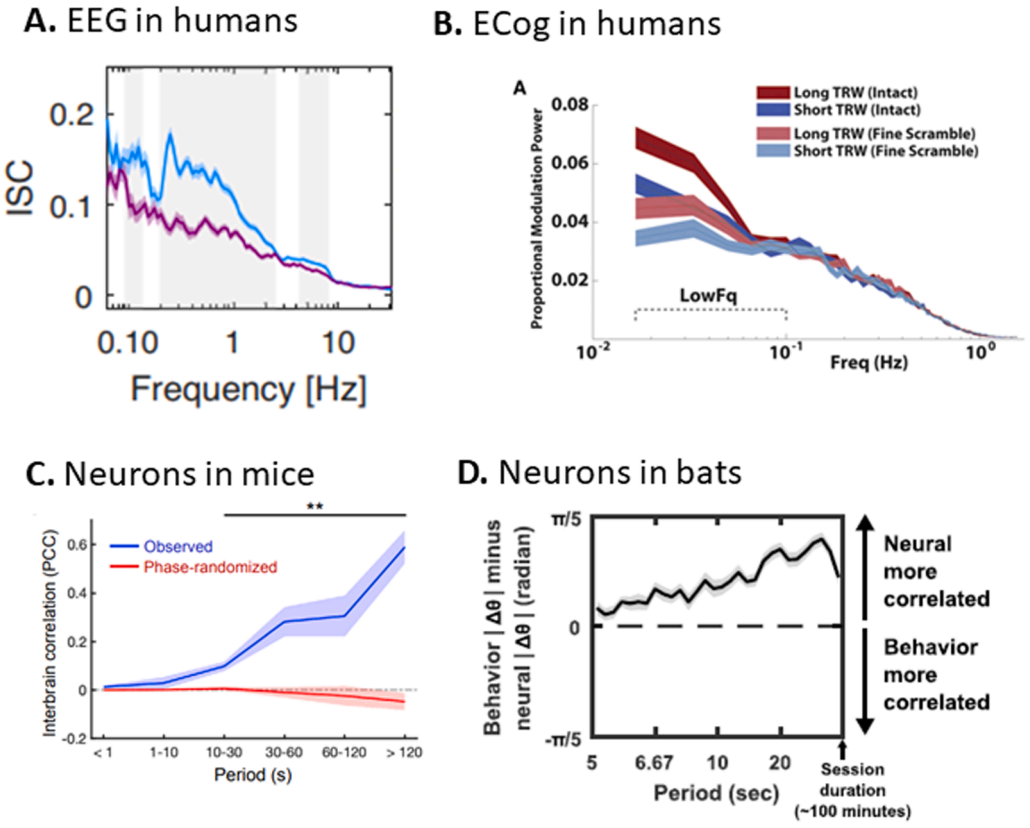

Fig. 5. Examples of synchrony across timescales. Panel A (from Madsen et al.) shows EEG intersubject correlations for human adults watching videos alone while attending (blue) or not attending (purple). Robust ISC was found at the frequencies marked with grey background including 250msec - 5 s and around 10 s. Panel B (from Honey et al.) shows low frequency Ecog signals are modulated by whether a viewed movie is intact or scrambled, especially in brain regions with long temporal receptive windows (dark red-light red comparison). Panel C (from Kingbury et al.) shows interbrain neural correlations between pairs of interacting mice (blue) or pseudodata (red) with greater correlations at longer timescales (10–120 s). Panel D (from Zhang et al.) shows the difference between neural correlations and behavioural correlations in pairs of bats on the same space. Neural correlations were stronger at the slower timescales (20 s – 100 mins).

found that both local field potential (LFP) power and spiking activity was highly correlated in pairs of bats in the same space, and that these correlations were strongest over slow timescales (over 10 s) [see Fig. 3D]. A second paper used computational modelling to suggest an inter-bat feedback mechanism that enhances slow effects leading to strong long-timescale correlations between the bats, while faster differences between the two bats tended to be suppressed (Zhang et al., 2022). Overall, these animal studies with direct brain recordings find that the strongest coordination effects are those that occur at long timescales, over about 10 s or more.

To draw together these findings on the overarching timescales of neural synchrony, Fig. 5 draws together plots from 4 papers that have examined coordination across a wide range of timescales. Subplots A and B illustrate stimulus-driven entrainment effects whereby EEG signals (Madsen and Parra, 2022) or eCOG signals (Honey et al., 2012) are tracked when participants watch movies individually. Subplots C and D reflect the inter-individual neural coordination in mice and bats described above. In all 4 plots, robust patterns of entrainment or coordination are seen at slow timescales, from 1 to 10 s or even longer. This suggests that it will be valuable to examine human INC at slow timescales as well.

In human research, fNIRS is well suited to capturing INC at slow timescales, and there are many reports of INC in a range of contexts. For example, a pioneering project by (Jiang et al., 2012) asked 10 dyads to converse while facing towards or away from each other and found that INC in left inferior frontal cortex increased during face-to-face dialogue. Similarly, (Osaka et al., 2015) studied pairs of participants who were singing or humming when face-to-face or face-to-wall and found robust INC (compared to shuffled controls) at 3–13 s timescales with marginally stronger effects for face-to-face conditions. Other tasks include conversation (Jiang et al., 2015), puzzle-building (Fishburn et al., 2018) and eye-contact (Hirsch et al., 2017), with the common feature that slow timescales tend to be studied because of the slow nature of the haemodynamic response function.

To find evidence for INC in the human brain at faster timescales, it helps to turn to EEG studies. Effects have been reported across all EEG frequency bands (delta, theta, alpha, beta, gamma), and shown both as (faster) phase locking of signals as well as (slower) amplitude coupling (Babiloni and Astolfi, 2014; Czeszumski et al., 2020; Konvalinka and Roepstorff, 2012). Phase synchronization of neural oscillations (Fig. 3F) has been found between guitarists playing a melody in sync with each other at slower frequencies (delta, theta) corresponding to timescales ranging from 140 ms to 1 s, which are proximal to rhythms of behavioural coordination, and hence INC was likely driven by the shared sensorimotor input, i.e., phase locking of auditory stimuli and movements (Lindenberger et al., 2009; Sänger et al., 2012). To address the relationship between behavioural rhythms and INC more concretely, a study by (Zamm et al., 2018) found correlated amplitude envelopes of cortical oscillations (Fig. 3H) between pianists playing in sync, which were computed for EEG signals filtered at the corresponding musical duet performance beat frequencies. The beat frequencies were centred at ~500 ms in duration (range: 300–650 ms) corresponding to the EEG delta frequency range. Hence, the study found temporally correlated energy fluctuations (amplitudes) of neural signals corresponding to the rhythm of individual and joint performance behaviour, showing a direct consequence of behavioural rhythms on the modulation of neural rhythms. Similarly, a study from (Koul et al., 2023) found INC in a similar envelope correlation measure for gamma-band activity (31–95 Hz) when two participants sat opposite each other without a structured task. Hence, INC of EEG envelopes may be a consequence of interpersonal coordination of natural behaviours.

INC measured in terms of phase synchronization has also been reported during hand movement synchrony in a joint imitation task where two people had to imitate each other's movements, at EEG frequencies corresponding to the Rolandic mu-rhythm (Dumas et al., 2010). The mu rhythm is known to suppress in amplitude both during action production, action observation, and motor interaction (Gastaut and Bert, 1954; Pfurtscheller and Lopes da Silva, 1999) as well as during anticipation of one's own or other's movements in both adults (Hari, 2006; Kilner et al., 2004; Konvalinka et al., 2014) and infants (Southgate and Begus, 2013). Hence, phase-based INC at this motor rhythm may be a consequence of fast mutual prediction, as both interacting partners have to predict the timing of one another's hand actions in order to synchronize. Crucially, the study did not find INC to be modulated by imitative movements, but rather temporal coordination of movements.

Overall, this short review of the timescales of INC looked at animal research, and human EEG and fNIRS studies to find evidence that INC arises across a wide range of timescales. Rapid effects in EEG phase may reflect different mechanisms such as e.g., action prediction, compared to the slower fNIRS and EEG signal envelope effects. The coordination of EEG envelopes and fNIRS signals appears to correspond to the timescale of behavioural rhythms, and may thus reflect alignment in behaviour. However, when we map the timescales of our neuroimaging methods in relation to behaviour (Fig. 2), we see that there may be a gap in the tracking of timescales between 1 and 5 s, as the majority of EEG studies focus on faster effects, and the majority of fNIRS studies focus on slower effects. Understanding interpersonal coordination of brain and behaviour may be related to other psychologically relevant measures, in particular learning, social connectedness and clinical outcomes. Understanding this functional relevance is an important next step so the final section of this paper focuses on the interpretation of coordination data.

7. Interpreting and using coordination measures

Studies that quantify the coordination between people can, in general, explore two different types of questions. Some studies examine mechanistic questions, to try to reveal the neural mechanisms underlying certain behaviours, or computational models that can mimic those behaviours. Other studies examine more applied questions, asking if measures of coordination can predict real-world outcomes, for example in education, therapy, or child development. In this section, we present a selective overview of some studies which apply measures of coordination in the study of learning, development and therapy. This review aims to summarise what kind of studies can be done and how timescales are relevant to this type of research, rather than to systematically cover the entire field.

A common method in this area is to take a measure of coordination – which could be neural recordings from fNIRS or EEG, physiological tracking of heartbeats or behavioural recordings from video and motion sensors – and ask if these measures can predict a relevant real-world outcome. Compared to many others measures of human behaviour, synchrony can be captured relatively easily using wearable motion sensors, physiological sensors or neuroimaging devices, without requiring hand-coding of video with associated costs and privacy concerns. If measures of synchrony prove to be a valid predictor of real-world outcomes, it may not matter if the synchrony is caused by entrainment or by true synchrony for applied purposes. Here, we review a sample of the many studies suggesting that measures of INS and IPS may be valuable to studies of child development, education and therapy contexts.

Many social interactions involve the transfer of new information from one person to another, that is, social learning (De Felice et al., 2022) and the possibility that INS or IPS could provide an index of learning has inspired many studies. If INS reflects shared ideas between people, then the presence of INS might relate to the success of communication and learning. Such results have been reported in adults by (Holper et al., 2012) and (Pan et al., 2018) using fNIRS. Using EEG, Dikker et al. (Dikker et al., 2017) showed that EEG alpha band synchrony between students in real classrooms predicted social closeness which in turn was related to learning. In children, (Piazza et al., 2021) found that three to four-year children tended to synchronise their brain

patterns over parietal cortex during listening of story-reading, and this was associated with learning of novel words. Overall, these studies suggest that there is a relationship between INS measures during a learning opportunity and the success of the student on later tests. However, many of these results still have relatively small sample sizes and replication would be useful. It is also important to remember that very similar results have been shown with ISC, which is higher when individuals viewing movies alone have similar interpretations of the movie (Sievers et al., 2024; Yeshurun et al., 2017) and learn from it (Madsen and Parra, 2022). The positive INS-learning association here may be mediated by entrainment mechanisms, where individuals attend to the same information. In social interactive contexts, (De Felice et al., 2025b) showed that the association between INS and learning is modulated by behavioural coordination, specifically mutual gaze and joint attention, possibly supporting mutual prediction and understanding. Taken together, these studies suggest that INS may be a good predictor of learning in both social and non-social contexts, despite the underlying mechanisms may differ between contexts.

Coordination between parent and infant over the first few years of life is important in learning and development (Feldman, 2016; Hoehl et al., 2025). Neural and physiological synchrony operate as complementary but functionally dissociable systems supporting infant self-regulation and developmental outcomes. Evidence for interpersonal neural synchrony (INS) emerges early in development and can be observed across different stages of infancy. Few studies have explored the first weeks of life. One intriguing dataset shows that premature infants cared for in incubators show less neural synchrony with their parent during childhood and different brain responses to emotional stimuli in adulthood, compared to premature infants cared for in physical contact with their mother (Ulmer Yaniv et al., 2021). In 4–6 month infants, (Nguyen et al., 2021c) found significantly higher INS during turn-taking over the course of mother-infant proto--conversations. In older infants (9–15 months), prefrontal cortex showed robust INS related to behaviours like eye contact and smiling (Piazza et al., 2021).

Importantly, synchrony does not appear to operate uniformly across modalities. For example, maternal proximity and touch increases INS in 4–6 month old babies, but does not modulate physiological synchrony (Nguyen et al., 2021b). This dissociation indicates that neural and physiological synchrony may be differentially sensitive to specific interactional cues, even early in development.

Developmental research on physiological synchrony shows that the degree to which infant and caregiver synchronise is linked to affective co-regulatory demands, increasing specifically during infant distress when parasympathetic coordination is needed (Abney et al., 2021). Much of this work has centred on respiratory sinus arrhythmia (RSA), i.e. a generally normal variation in heart rate that synchronizes with breathing. Meta-analytic evidence demonstrates a modest but significant positive within-dyad RSA association across development (Miller et al., 2023), which has been linked to vocal and affect coordination in infancy, increased maternal engagement in early childhood, and fewer internalising symptoms in adolescence (Davis et al., 2018; Papp et al., 2009). However, RSA synchrony is disrupted in high-risk samples characterised by maltreatment, clinical difficulties, or socioeconomic disadvantage (Miller et al., 2023). In some high-risk families, *lower* physiological synchrony correlates with *better* behavioural synchrony and child self-regulation (Davis et al., 2018).

Across development, converging evidence indicates that disruptions in parent–child coordination are associated with adverse socio-emotional outcomes. Studies of mothers with depression or bipolar disorder highlight the impact of caregiver mental health on caregiver-infant interaction and, in turn, the infant socio-emotional development (Bjertrup et al., 2022, 2021; Stein et al., 2012, 2010; Webb and Ayers, 2019, 2015). fNIRS studies which track INS in children (aged over 5) and a parent find that this measure is related to variety of socio-emotional factors. These include parental stress (Azhari et al., 2019), emotion regulation (Reindl et al., 2018) and parental adversity (Hoyniak et al., 2021). In these three fNIRS studies, more severe parental adversity, stress, or emotional dysregulation was related to lower brain-to-brain neural synchrony between parent and child across different contexts, including passive watching, cooperation or frustration tasks.

The findings from the fNIRS studies are in line with studies using behavioural observations. For example, a recent study found less dyadic mutuality and reciprocity between mothers with bipolar disorder and their infants than in healthy control dyads (Anke et al., 2020, 2019). Similarly, mother-child dyads with a maternal history of depression showed weaker synchrony of facial affect during conversation compared with never depressed dyads (Kudinova et al., 2019). This lack of positive facial affect synchrony may impede the child's capacity for experiencing positive emotional affect and thereby enhance the risk for psychopathology (Kudinova et al., 2019).

There are also cases where mothers may show too much synchrony with their child. A study using measures of gaze and touch found that mothers with anxiety displayed abnormally *high* levels of synchrony in mother-infant touch behaviour, whereas mothers with depression showed abnormally *low* levels of synchrony compared with healthy control dyads (Granat et al., 2017). In keeping with this, emotional dysregulation together with anxiety symptoms have also been associated with more mother-infant synchrony in higher levels of gaze, motor, and verbal behaviours, which could reflect maternal intrusiveness in the interaction (Doba et al., 2022) Parents with high anxiety may up-regulate their physiological arousal in response to even small changes in their infant, showing persistent high levels of reactivity (Smith et al., 2022). Again, up-regulation of arousal could be indicative of emotional dysregulation, which could adversely intensify parent child synchrony. More emotional dysregulation has also been related to heightened mother-infant gaze synchrony across maternal depression, bipolar disorder and anxiety (Lotzin et al., 2015).

These studies suggest that emotional dysregulation in mothers may be a trans-diagnostic factor for abnormal dyadic behavioural synchrony (Lotzin et al., 2015), and also that behavioural synchrony can be 'too low' or 'too high' in different clinical conditions. There may be an optimal level of synchrony in the midrange (Lotzin et al., 2015). This is in line with consistent findings that mothers with depression often show either intrusive or withdrawn/unresponsive behaviour toward their children (Diego et al., 2006; Field et al., 2006, 2003; Guedeney, 2007), and may explain why depressive symptoms have been associated with both lowered and heightened parent-child synchrony. The idea that synchrony must be balanced rather than always increased also aligns with the idea that interpersonal coordination requires flexibility between states of synchrony and states of independent behaviour (Gordon et al.,2025), balancing self-other integration with segregation (Konvalinka et al., 2026). For example, recent studies suggest that while interpersonal synchrony may lead to positive outcomes such as strengthening of social bonds, it may come at a cost for the self, reducing self-regulation of affect (Galbusera et al., 2019) and altering intrapersonal.

Differences in INC and IPC have also been examined in children and adults with autism. For example, children with autism show less IPC with a parent when rocking in rocking chairs (Marsh et al., 2013), and adults with autism might show less IPC in conversation (Georgescu et al., 2020). Two recent reviews cover this literature in detail (McNaughton and Redcay, 2020; Murat Baldwin et al., 2022), but do not distinguish specific behaviours or timescales where frequency is impacted. Differences in synchrony patterns do not seem to be specific to autism. Reduced body motion IPC has been reported in adults with schizophrenia during conversation (Kupper et al., 2015), and increases in IPC in similar participants might predict outcomes after therapy (Galbusera et al., 2018). Other studies found that spontaneous coordination is preserved in adults with schizophrenia, but intentional coordination was less stable(Varlet et al., 2012). Similarly, intentional

synchrony is lower and less stable in adults with high borderline personality disorder traits (Gregorini et al., 2025). A series of studies which track whole body synchrony during conversation over a wide band of timescales suggests that greater synchrony was related to better therapy outcomes (Altmann et al., 2020; Ramseyer and Tschacher, 2014). However, some of these studies have small sample sizes, and it is not yet clear if effects are robust and show strong test-retest reliability. For example, in a large sample of participants, interpersonal coordination of pendulum movements was only weakly related to autistic traits or social anxiety traits (Macpherson and Miles, 2023), which suggests that synchrony might not provide a strong measure of social interaction skills.

The timescales of synchrony in clinical studies has not been explored in detail. The majority of the work reviewed here used video coding method which typically detected slow behavioural synchrony, while neuroimaging studies often find faster effects. Linking different timescales to clinical data and understanding if synchrony at some timescales is more important than others will be an interesting direction for future work. At present, these studies point to the idea that tracking behavioural and neural interpersonal synchrony in parent-child dyads could give valuable information about developmental and socioemotional regulation. In future, this could inform clinical care or interventions. However, the scarcity of studies and lack of longitudinal follow-up assessments limit our understanding of how abnormal neural, behavioural, and physiological synchrony between people relates to long-term outcomes. There is enough data at this stage to suggest that measures of synchrony are a promising approach to exploring interpersonal coordination, social bonding and social development. In particular, the potential of very simple low-resolution recording systems (e.g. wearable sensors) to provide large scale datasets about synchrony in real world conditions may lead to substantial advances in this area.

8. What about longer timescales?

The focus in the present review has been on timescales from 10 ms to 100 s, because this is the region where most of our neuroscience research is completed. However, there may be important types of synchronization that happen at even slower timescales, and that are best tapped with other methods. (Newell, 1994) sets out possible timescales of different types of cognition, ranging from neural processes (10–100msec) to cognitive skills (1 s – 10 min) and then problem solving and tasks at even slower scales. Measures like electrodermal activity, cortisol assays and blood-pressure recordings may tap into slower physiological changes in the body that might or might not be in sync with other people in the same environment. Longer-term data collection will allow more extensive analysis of how different types of social connection relate to synchrony. For example, a new study tracking groups of young people engaging in both scheduled activities and free time in New York City found that heart-rate synchrony measured over several days was related to physical and social proximity (He et al., 2025), and these findings replicated across three different trips. It emerged when people were in close proximity of each other, and was modulated by the types of activity they engaged in – e.g., heart rate synchrony between people was found when they interacted in close-proximity, or were stimulus-locked by attending the same lecture, but not when they engaged in more dispersed interactions. Synchrony was higher in socially familiar pairs, and was modulated by the acoustic environment, with more optimal listening conditions facilitating heart rate synchrony. This further demonstrates the use of longer-term recordings and wearables for measuring the relationship between synchrony and social and environmental outcomes.

Actigraph measures of steps per hour or sleep time could also potentially be explored in a social analysis. This links to the 24-hour rhythm of light and dark in a day, that drives circadian rhythms in our bodies. Few studies have explored social synchrony in these rhythms, but there are suggestions that sleep-wake synchrony is important. Married couples who differ in chronotype (one lark and one owl) report more conflict (Larson et al., 1991). Working on shifts that changes sleep-wake cycles and also puts shift-worker out of social contact with friends and family is known to have damaging effects (Haines III et al., 2008). In Stalin's Russia, an attempt to make factories more efficient by having workers take different work-days in a 10-day week collapsed because the workers could not have social contact with friends and family on their day off if others were working on that day (Richards, 1998). Today's culture of working across multiple time zones or with complex shift patterns may introduce similar problems, and measuring the impact of this long-term social synchronization is a challenge for the future. Thus, measuring synchrony at even longer timescales than those considered in this review may also be valuable.

9. Implications for theory and practice

This paper has argued that consideration of timescales is important for our understanding of coordination and synchrony between people. Timescales provide a unifying structure across the study of behaviour, physiology and brain activity, including both traditional single-participant and hyperscanning studies. These ideas have several implications for future research.

First, the timescales of alignment across people and across modalities is not merely a curiosity, but is central to interpreting social interaction. For example, if a coordinated behaviour has a base timescale around 5 s, we might expect any brain or physiological coordination related to this behaviour to also have a timescale around 5 s, and not 500 msec or 50 s. There is evidence for this cross-modal consistency of timescales in studies of language structure (Hasson et al., 2008) and in studies of intrinsic neural timescales (Golesorkhi et al., 2021; Wolff and Dumas, 2026). It is likely the same principle applies to other behaviours which have a hierarchical structure at different timescales including music (Harding et al., 2025) and event boundaries (Radvansky and Zacks, 2017). These timescales may be linked to specific brain regions and to specific patterns of behaviour.

Second, different timescales are likely to be linked to different underlying mechanisms. If two people coordinate in terms of brain or behaviour at fast timescales (<500msec), this is likely to require mechanisms of true synchrony or prediction because motor systems cannot respond fast enough to synchronize at this timescale without prediction. For example, two people who play a well-practised piano duet together can precisely align the timing of their actions because each player can predict the actions of their partner (van der Steen and Keller, 2013). In contrast, coordination at mid-range timescales (500–5000 msec) could draw primarily on responsive mechanisms, where one individual sees the actions of another and responds to it. Such mechanisms have been identified in nodding behaviour (Hale et al., 2019) and are likely to play a role in many turn-responsive situations. For example, if

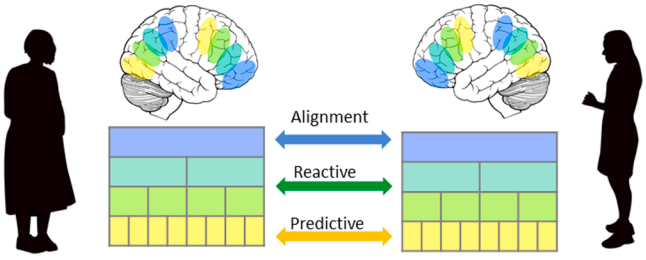

Fig. 6. Timescales of coordination. Events that happen at fast and slow timescales could coordinate in different ways and in different brain regions across participants. For example, a rapid drumming task might involve fast prediction of actions and primary motor regions while a deep conversation might involve slow alignment of concepts in prefrontal regions. Brain coloring indicates the idea that different timescales may relate to different brain systems in both sensory and motor brain systems but is not intended to make precise neuroanatomical predictions.

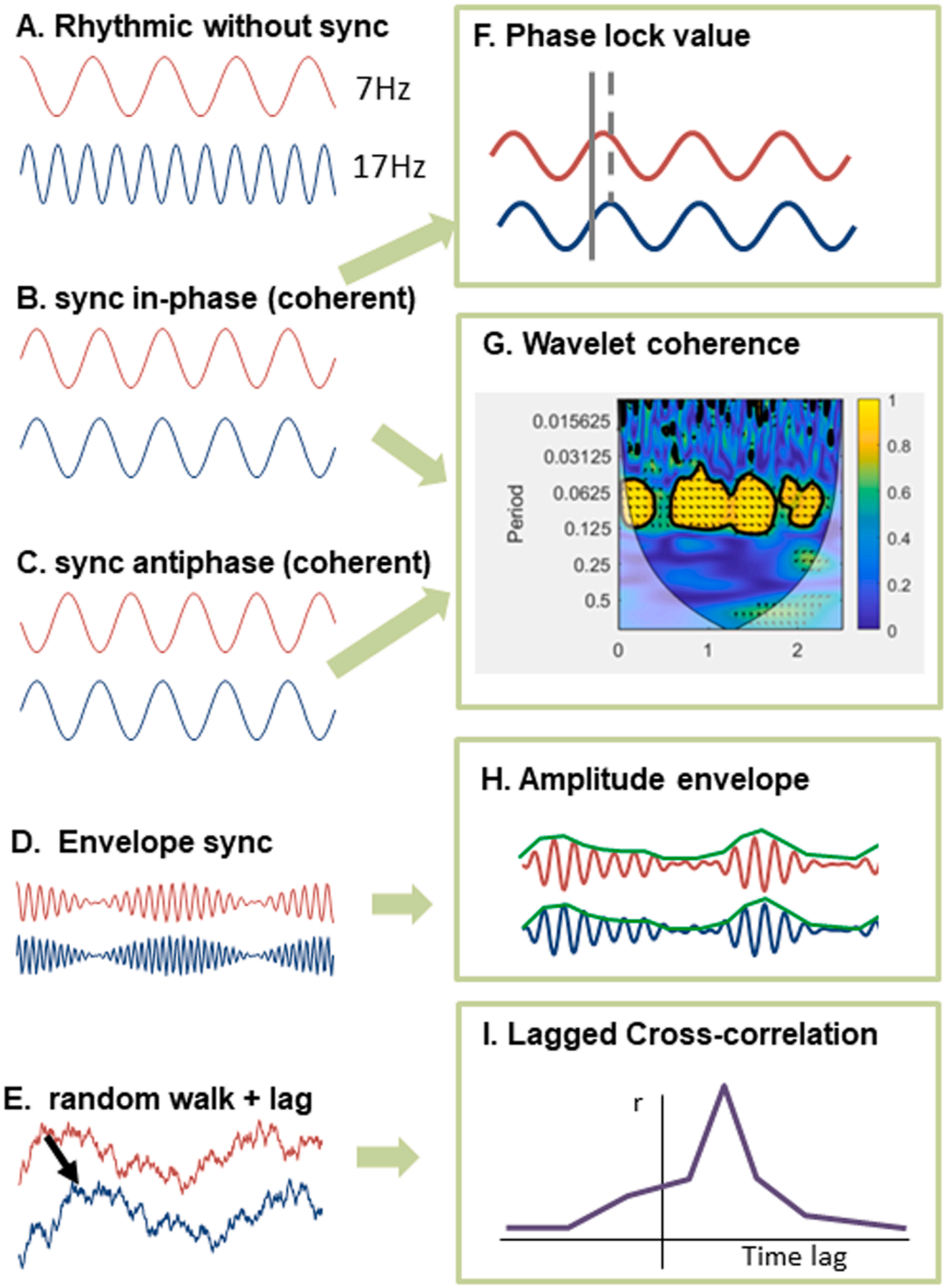

Fig. 3. Types of synchrony and their analysis methods. A illustrates signals which are rhythmic but have no synchrony. B. illustrates signals that are synchronous with the same frequency and phase. C. illustrates signals that are coherent (same frequency) but not in phase. D. illustrates signals of different frequencies with the same amplitude envelope. E. illustrates random walk signals where one replicates the other with a lag. The right column illustrates some of the analysis methods that can identify these. Phase locking analyses (F) will detect only in-phase synchrony (B). Wavelet coherence (G) will detect any coherent signals (B or C) and distinguish them from A. Amplitude envelope analysis (H) will detect D, while lagged cross-correlation will detect E.

two people take turns in Tic-Tac-Toe, each must respond to the other's move. Finally, coordination at slow timescales (>5 s) seems likely to involve more sustained patterns of behaviour and neural activity which aligns between participants. An example is the alignment of conversation topics in an fMRI hyperscanning study (Speer et al., 2023), where neural alignment was assessed via whole-brain decoding models that classified each participant's brain activity in a conceptual space and measured the similarity between models in a dyad.

The potential links between different timescales and different mechanisms are illustrated in Fig. 6 with different arrows for predictive, reactive and alignment relationships between people. There is also likely to be overlap between these processes, and many complex interactions like conversation are likely to engage all these processes simultaneously. Many replies in a conversation are predictive (Levinson, 2016) but meaningful conversations also involve slower responses (Templeton et al., 2023) and alignment of topics (Speer et al., 2023). These ideas about how different timescales relate to specific neurocognitive mechanisms are consistent with current studies, but have not yet been tested

in a systematic fashion. It will be interesting in future to design careful studies that can determine if there really are distinct mechanisms for different timescales of coordination, or if there is more continuity between the processes involved in fast and slower coordination of brain and behaviour.

Acknowledging timescales is also important because it implies that neuroimaging research should choose a method that matches with the timescale of the behaviour under investigation. For example, those seeking to measure rapid coordination might chose EEG, while studies of slower coordination of conversation topics or idea might be more suited to fNIRS or fMRI. There is also an important challenge to our methods visible in Figs. 2 and 5, because there is potentially a 'gap' in the timescales captured with the majority of our human neuroimaging studies – EEG excels for fast timescales less than 300 msec and fMRI/fNIRS dominate for slow timescales above 3 s. There are fewer studies which cover the range from 300msc to 5 s, even though there are many interesting behavioural rhythms in this range including utterances, sentences and events. Brain recording methods including EEG delta-band could probe this, as illustrated by (Rai et al., 2025) in a recent study of interpersonal neural synchrony among audiences watching dance performances. It is also possible that fNIRS (like event-related fMRI) can tap into effects faster than the 5 s rise-time of the haemodynamic response, but more modelling research and detailed studies will be required to explore this. Combined EEG-fNIRS may also be a useful possibility, but research methods that target this 1–5 s gap will be an important area for future development.

The same considerations also apply to behavioural and physiological recordings, where it is valuable to use measures that capture appropriate timescales. For example, rapid coordination in a clapping or drumming task requires recording devices with millisecond precision (van der Steen and Keller, 2013), but tracking the changes in heart-rate in a group of people over a multi-day event might organise data into bins of 10 or more seconds (He et al., 2025). Our review suggests that slow timescales are particularly interesting in the study of interpersonal coordination, which implies that data with high temporal precision may not always be required, but that datasets tracking slowly evolving behaviours may be able to give us important insights into coordination. For example, it seems plausible that the slow alignment of conversation topics between therapist and patient is more relevant to outcomes than the rapid alignment of their blinking or nods, but there is not yet data available to test this idea. Alignment at even slower timescales over an hour-long discussion or over weeks of therapy could also be studied. It will be particularly interesting in future to test if slower timescales have more clinical or educational relevance in terms of predicting outcomes of therapy or learning, and if effects found at faster timescales can predict the slower outcomes.

Finally, as highlighted in Fig. 5, our review highlights the idea that longer timescales may show more robust coordination effects than short timescales in a variety of experiments, and may be particularly important for real world outcomes. In this paper, we focus mainly on long timescales to be those lasting from 5 to 30 s, which may relate to conceptual understanding or transitions between topics in conversation. However, there may also be effects that are even slower but have rarely been studied with neuroimaging methods. In particular, changes in the coordination between people that occur over hours, days or weeks; for example, as children learn a new concept in lessons or a patient develops a therapeutic alliance with a therapist, are types of coordination with very long timescales and very meaningful real-world consequences. Finding new ways to explore the full range of timescales that matter for human interpersonal coordination, and to link data across short, long and very long timescales, will be important for understanding both the mechanisms of coordination and the consequences for learning and social connections.

10. Conclusions and wider implications

Overall, this short review shows that both behavioural coordination (IPC) and neural coordination (INC) between people arise at different timescales which might reflect different mechanisms and modes of social interaction. In particular, slow effects seem to be robust both in brain recordings and in behaviour, with support from detailed cellular studies and this slow coordination can have a range of real-world consequences. More broadly, we suggest that it may be useful for studies of coordination to match the timescale of a recording device to the timescales of the behaviour under investigation, which means that faster is not always better. The importance of slow timescales has emerged as a theme, and future studies that explicitly explore these slower effects will be valuable in identifying the types of coordination that matter in real-world contexts. Mapping patterns of coordination across a wide range of timescales will give a clearer picture of how and why coordination between people arises and what it means for clinical, educational and cognitive theories of interpersonal psychology.

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