




Rhythmic sampling revisited: Experimental paradigms and neural mechanisms

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Abstract

Sampling of information is thought to be an important aspect of explorative behaviour. Evidence for it has been gained in behavioural assessments of a variety of overt and covert cognitive domains, including sensation, attention, memory, eye movements and dexterity. A common aspect across many findings is that sampling tends to exhibit a rhythmicity at low frequencies (theta, 4–8 Hz; alpha, 9–12 Hz). Neurophysiological investigations in a wide range of species, including rodents, non-human primates and humans have demonstrated the presence of sampling related neural oscillations in a number of brain areas ranging from early sensory cortex, hippocampus to high-level cognitive areas. However, to assess whether rhythmic sampling represents a general aspect of exploratory behaviour one must critically evaluate the task parameters, and their potential link with neural oscillations. Here we focus on sampling during attentive vision to present an overview on the experimental conditions that are used to investigate rhythmic sampling and associated oscillatory brain activity in this domain. This review aims to (1) provide guidelines to efficiently quantify behavioural rhythms, (2) compare results from human and non-human primate studies and (3) argue that the underlying neural mechanisms of sampling can co-occur in both sensory and high-level areas.

KEYWORDS

attention, behavioural rhythms, neural oscillations, perception, sampling

1 | INTRODUCTION

A fundamental task of consciousness is to orchestrate the sheer multitude of parallel external events and internal

cognitive processes to enable a stable perception of the environment. For example, when viewing a flying tennis ball, we certainly have the phenomenological impression of continuous movement. But is the underlying mental

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process that tracks the ball in space and time truly continuous over space and time? In 1956, Stroud democratized an overarching proposal to this problem specifically stating that conscious sensory experience would rely on the rhythmic sampling of information (Stroud, 1956; for review Dugué & VanRullen, 2017; VanRullen, 2016a, 2016b; VanRullen & Koch, 2003). While a growing body of literature reports rhythmic fluctuations of behavioural performance measures in this context, the significance of behavioural sampling as a fundamental mechanism underlying cognitive functions is—to some extent—still under discussion, partly due to potential pitfalls that can hinder its quantification and thus comparison with brain activity. In this review we therefore revisit the evidence in favour of rhythmic dynamics of cognitive activity in the domain of vision. We focus on recent studies in human and non-human primate models suggesting that various overt and covert visual cognitive functions exhibit slow rhythmic effects on task performance, which would be supported by low-frequency brain oscillations mainly in the theta (4–8 Hz) frequency range. We start with an overview of the different behavioural paradigms during which rhythmic performance has been observed and describe in detail experimental parameters that are necessary to be able to quantify such behavioural rhythms. This is followed up with what insights have been gained on the neural underpinnings of these rhythms from electrophysiological recordings.

2 | BEHAVIOURAL RHYTHMS

Behavioural sampling has been observed in multiple sensory modalities, including vision (see next sections) but also audition (e.g., Ho et al., 2019, 2021; VanRullen et al., 2014) and somatosensation (e.g., Baumgarten et al., 2015), and across a large set of behavioural responses, such as finger/hand/arm movement (e.g., Benedetto et al., 2019; Tomassini et al., 2015, 2017) and saccadic eye movement (e.g., Benedetto & Morrone, 2019; Chota et al., 2018; Kienitz et al., 2018; Landau, 2018), across a variety of behavioural measures (e.g., Reaction Time [RT], d-prime, accuracy; see next sections for more details). Here, we focus on perception and attention as cognitive functions of interest, and on the visual sensory modality, which evolved as the predominant sense in primates and provides a rich basis to investigate higher cognitive processes (Scott & Mishkin, 2016; Senoussi & Dugué, 2020; Sereno et al., 1994). Note that most of the reports on behavioural sampling rhythms are for perception and attention, and a lot less for other cognitive functions, such as memory (e.g., Balestrieri et al., 2021; Peters et al., 2020) and

decision-making (e.g., Kayser, 2019). Additionally, although such rhythmic behaviour has been also observed in other sensory modalities, and in non-primate species, characterizing rhythms in these other dimensions is beyond the scope of the present review.

2.1 | Uncovering temporal rhythms

In the second half of the 20th century, a few experimental studies reported rhythmic fluctuations of RT measures in humans. They reasoned that the time it would take an observer to react to a brief, threshold stimulus should depend on the precise moment at which this event occurred relative to the ongoing cognitive sampling (VanRullen & Dubois, 2011). Authors hence observed periodicity in the histograms of RTs, in various experimental tasks such as auditory and visual detection or discrimination, saccadic response, pursuit eye movement initiation, and verbal choice response (Dehaene, 1993; Harter & White, 1967; Latour, 1967; Pöppel & Logothetis, 1986; Venables, 1960; White & Harter, 1969). Critically, although the observation of rhythmic RT fluctuations might suggest the presence of rhythmic cognitive processes, it does not unambiguously demonstrate so. Indeed, as argued by (VanRullen & Dubois, 2011), an alternative interpretation would be that each stimulus onset triggers the motor system to resonate rhythmically, thus imposing a rhythmic motor response. Such rhythms in behavioural response would thus not be the result of truly endogenous rhythms but rather the by-product of the external stimulation. Finally, variation of RTs can be due to other factors than actual changes in sensitivity (e.g., decision criteria; Carrasco & McElree, 2001; Dugué et al., 2018, 2020; Reed, 1973; Wickelgren, 1977). Other measures of behavioural variability may be worth considering.

In the early 2000s, the topic of behavioural rhythms received revived interest (VanRullen & Koch, 2003), with alternative approaches to measure temporal fluctuations in performance. Illusory visual stimuli have been used to approximate the mechanism underlying perceptual sampling (for review Sokoliuk & VanRullen, 2019; VanRullen, 2016b). Using the Wagon Wheel Illusion (Andrews & Purves, 2005; VanRullen et al., 2005), the Flickering Wheel Illusion (Sokoliuk & VanRullen, 2013) and the Triple-Flash Illusion (Gulbinaite et al., 2017), authors suggested a perceptual sampling at the alpha frequency. In other words, illusory percepts would be due to the rhythmic sampling of sensory information at ~10 Hz. More complex behavioural assessments have further been used such as classification images technique (Blais et al., 2013) to investigate rhythms in face processing, or

Fourier decomposition (Dugué & VanRullen, 2014) and probability estimation (Dugué et al., 2017; Dugué, McLelland, et al., 2015b) to characterize rhythms in attention during visual search tasks. In the last decade, research has concentrated on designing new paradigms and developing new analysis algorithms to further our understanding of behavioural sampling in various overt and covert cognitive domains.

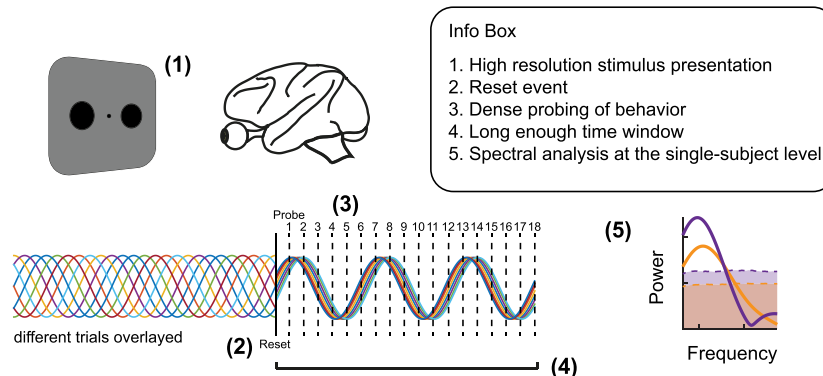
2.2 | Quantifying behavioural rhythms in attention

Over the years, several research paradigms have been specifically designed to reveal behavioural rhythms (e.g., Blais et al., 2013; Drewes et al., 2015; Dugué, McLelland, et al., 2015b; Dugué & VanRullen, 2014; Fiebelkorn et al., 2013; Huang et al., 2015; Landau & Fries, 2012; Senoussi et al., 2019; Song et al., 2014; Tomassini et al., 2015, 2017; VanRullen & Dubois, 2011). In what follows, we first present the key psychophysical parameters that have helped to identify rhythms during attention tasks (see Figure 1 for a summary and Info Box). The subsequent section will then describe the central results obtained using this approach.

Let us consider there is an optimal cognitive rhythm in the brain—an oscillatory brain signal that drives a given cognitive function and leads to rhythmic behavioural performance. Delineating such a rhythm in the context of a laboratory setting in which behaviour is tested on a trial-by-trial basis requires a common starting

point, a reset of the phase of the oscillatory cognitive process, for each trial. In other words, one needs to use an event—a visual stimulus for instance—controlling the starting point of the rhythm. The choice of this resetting event will depend on which rhythm is being investigated. One line of research is concentrating on characterizing the spatio-temporal dynamics of attentional exploration and has shown that attention can explore multiple stimulus locations rhythmically, periodically switching from one location to the other at a low frequency (see next section for further details). In this case of investigating the spatial dynamics of the attention focus, the resetting stimulus will allocate the participant's attention to a specific spatial location, which, when testing performance at this location, will translate into increased performance, that is, 'good' phase (peak of the reset rhythm in Figure 1).

Second, one needs to probe the reset rhythm at various moments, that is, phases. As we will see in the next section, this can be done using several approaches depending again on which rhythm is being investigated. One can present a second sensory stimulus following the reset event at another spatial location to probe rhythmic attentional exploration (Figure 2b, top panel), or one can use Transcranial Magnetic Stimulation (TMS) as a probe if interested in the rhythmic involvement of a given brain region in the attentional exploration (Figure 2a, top panel). Successful resetting and measurement of the oscillatory cognitive process will result in the emergence of an oscillatory performance pattern (Figure 2a,b, bottom panels), when sufficient trials have been acquired



Info Box

1. High resolution stimulus presentation
2. Reset event
3. Dense probing of behavior
4. Long enough time window
5. Spectral analysis at the single-subject level

FIGURE 1 Quantifying behavioural rhythms: Factors necessary to observe and quantify behavioural rhythms. In addition to an experimental set-up allowing for high-resolution stimulus presentation and good synchronization between different equipment components (1), ongoing brain rhythms need to be reset (2). In the graphic this is represented as sinusoidal curves in different colors. To capture the rhythmic process in a behavioural assay, the reset can be implemented with a sensory event, for example, that serves to capture the participant's attention at the specified time point. The paradigm then involves probing the reset rhythm at various moments to estimate its phasic effect on behaviour (3). Note that the reset event cannot always be optimal, thus some trial-to-trial phase variability is expected; see (Dugué, Marque, & VanRullen, 2015a, for further discussion). The probing (3) needs to be dense enough and the time window long enough (4) for appropriate analysis of the desired frequency band. Finally, spectral analysis is individually performed on the data of each participant (5 depicts an example of amplitude reliability analysis; adapted from Kienitz et al., 2018)

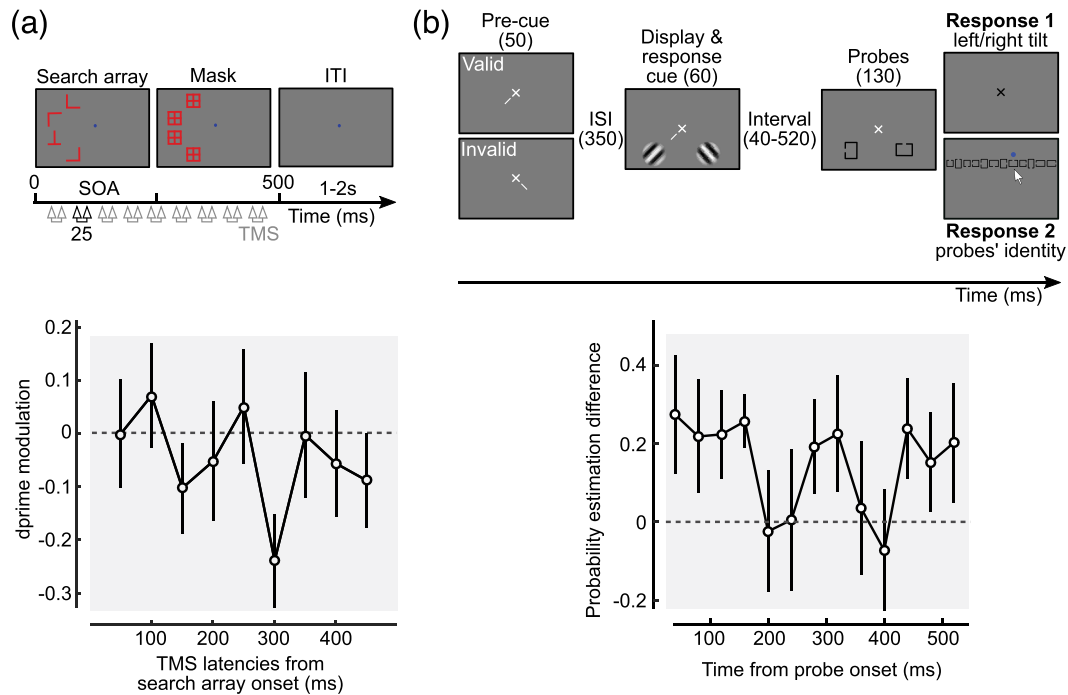


FIGURE 2 Behavioural rhythms in attention tasks. A and B show two examples extracted from Dugué et al. (2019) and Senoussi et al. (2019), respectively. A (adapted from Dugué et al., 2019, Figures 1 and 2). In this task, the rhythm is reset by the onset of a search array in which participants are instructed to search for the letter T among L distractors (top panel). They maintain fixation at the central dot (covert attention is manipulated). The trial lasts 500 ms from search array onset to mask offset (the mask is used to constrain visual processing and manipulate each participant's averaged level of performance). Specifically, the stimulus onset asynchrony (SOA; duration of the search array) is adjusted individually to attain 75% correct on average (note that the total trial duration is always 500 ms, that is, when increasing the SOA, the duration of the mask decreases). The rhythm is then probed using double-pulses of TMS (25 ms interval) applied over the FEF at various delays during the trial to interfere with neural processes at specific moments during the search (two pulses are used to increase its impact on neural activity). For each participant, performance is calculated as per dprime modulation (test-control; see Dugué et al., 2019, for further details), and further averaged across participants ($n = 21$) and represented as a function of the TMS latencies (bottom panel). Error bars represent ± 1 SEM (standard error of the mean). A fast Fourier transform (FFT) performed on this data showed a rhythmic modulation of behaviour at 6.5 Hz (note that this theta-frequency peak was shared by all participants as measured by phase-alignment). B (adapted from Senoussi et al., 2019, Figures 1 and 2). A cueing task is represented in which attentional orienting is first manipulated using a pre-cue (top panel). After a 300-ms inter-stimulus interval (ISI), two grating patches appear, and participants are instructed to report the tilt (response 1; clockwise or counter-clockwise relative to the vertical) of the target grating indicated by the response cue. A trial is valid when the target appears at the pre-cued location, and invalid when it appears at the opposite location thus requiring attentional reorienting. In this task, the rhythm is reset by the onset of the response cue in invalid trials. The rhythm is then probed using landolt squares and rectangles appearing at various intervals after display offset. Participants are instructed to report the identity of both probes (response 2), and the probability to attend to each probe is estimated (see Senoussi et al., 2019, for further details). The difference between each probe's report probability, for invalid trials, is represented as a function of the probe latencies (bottom panel). Error bars represent ± 1 SEM. A FFT performed on this data showed a rhythmic modulation of behaviour at 4 Hz (note that this theta-frequency peak was shared by all participants as measured by amplitude spectra of each participant's data)

and averaged. For all methods, the paradigm requires a high accuracy in measuring the timing between the onset of the reset event and behavioural response. During visual testing, this means measurements of the stimulus onset on the screen and good synchronization between different equipment components. Furthermore, capturing the oscillatory cognitive process benefits from dense probing on a long enough time window. The denser the probing, the better the estimation of the frequency. And

the longer the time window, the more cycles are observable. One thus needs to consider the trade-off between the required frequency resolution and the experiment feasibility as probing for many delays will necessarily require a high number of trials, with the same number of trials across all conditions for a fair comparison of the phases across rhythms (sub-sampling procedures are often performed). When able to overcome these practical challenges, resulting in enough trials and a sufficient

frequency resolution, rhythms can be assessed for each participant, that is, FFT performed on each individual's data which allows analysis of the reliability of the amplitude and/or phase of a given spectral peak across participants (e.g., Dugué et al., 2016, 2019; Dugué, McLelland, et al., 2015b; Michel et al., 2021; Senoussi et al., 2019; a summary of the above-mentioned considerations is represented in Figure 1). If these measures are not all applied correctly, behavioural rhythms are difficult to observe in individual participants, and thus require averaging across participants in order to further eliminate variability and to reveal the oscillatory process. Finally, the behavioural sampling literature is showing a large variety of analysis approaches to assess rhythms in performance (e.g., some detrend the data while others do not and some filter it while others do not). In the future, a full assessment of such analysis pipelines is warranted.

Given these challenges to delineate ongoing cognitive rhythms using the reset approach, it is perhaps not surprising that alternative approaches have been developed in which interventional procedures are used to entrain rhythmic brain activity and measure its behavioural consequences. These approaches, however, are indirect since they do not allow to assess the natural state of the system and are thus beyond the scope of the present review.

2.3 | Experimental evidence for spatio-temporal behavioural rhythms

Our environment, both external (i.e., sensory input) and internal, is formed by a multitude of information to process, to explore. How does the system solve this problem?

One line of research has used visual search tasks because they allow testing predictions both in terms of temporal and spatial dynamics of information processing. In difficult (or conjunction) search tasks, two competing theories postulate different spatial attentional selection processes. While one proposes that attention sequentially samples stimuli one (or one group) after the other (Treisman & Gelade, 1980; Wolfe et al., 1989), the other one states that attentional selection is distributed in parallel on all stimuli simultaneously (Eckstein, 1998; Eckstein et al., 2000; McElree & Carrasco, 1999; Palmer et al., 1993). Critically, the sequential model naturally predicts a rhythmic processing of information (although one could also imagine a-rhythmic exploration of the visual scene). This has been empirically observed in several studies, using various behavioural measures such as RT (Buschman & Miller, 2009), d-prime (Dugué & VanRullen, 2014), hit rates (Dugué et al., 2019; Dugué,

Marque, & VanRullen, 2015a) and probability estimation (Dugué et al., 2017; Dugué, McLelland, et al., 2015b). TMS further demonstrated that early visual areas (V1/V2) were involved in such rhythms (Dugué, Marque, & VanRullen, 2015a). Additionally, a recent study (Dugué et al., 2019) used double-pulses of TMS applied over the Frontal-Eye Field (FEF) at various delays after the onset of a search array (Figure 2a, top panel) and further showed that performance (d-prime) in detecting the presence or the absence of a target among distractor elements was periodically modulated at the theta frequency (~6 Hz; Figure 2a, bottom panel). This study demonstrated the rhythmic involvement of the FEF in an attentional search task.

It is important to notice, however, that parallel models of visual search are theoretically not incompatible with temporal behavioural sampling. Indeed, attention could be divided between all stimuli while still being modulated periodically over time (although it has not been explicitly tested). In visual search tasks, the spatial dynamics of information processing is inferred rather than specifically assessed.

In the last decade, multiple studies were specifically designed to investigate spatio-temporal, behavioural rhythms. The experimental manipulation critically involved initializing the position of the attention focus at a known first spatial location to further assess its exploration behaviour. A cue would direct attention to a particular location on the visual field, and behavioural performance would be measured at several moments (probing delays; see Figure 1) and positions following this event. Based on this logic, several authors reported rhythms in attentional exploration of the visual space at the theta frequency. This was reflected in various measures of behavioural performance such as RT (Chota et al., 2018; Song et al., 2014), accuracy (Fiebelkorn et al., 2013, 2018; Helfrich et al., 2018; Landau & Fries, 2012) and mixture modelling (Michel et al., 2021). In a recent study (Senoussi et al., 2019), attentional reorienting was manipulated and probed at various delays during the trial (Figure 2b, top panel). Using a probability estimation approach (see also Dugué et al., 2017; Dugué, McLelland, et al., 2015b), the probe report probabilities at the most and least attended locations were estimated (Figure 2b, bottom panel). The results showed that attention alternated—reoriented—between the two stimulus locations rhythmically at the theta frequency.

The same logic has been applied to several other tasks such as priming (e.g., RT: Huang et al., 2015), contrast sensitivity and action response (accuracy: Tomassini et al., 2015), integration versus segregation (accuracy: Wutz et al., 2016) and rapid visual categorization

(accuracy: Drewes et al., 2015), as well as tools such as TMS (Dugué et al., 2016) and behavioural modelling (VanRullen et al., 2007).

Note that while the above-mentioned results mostly show rhythms at the theta frequency, it is important to mention that rhythmic performance has also been observed in the alpha frequency range (e.g., Bowen, 1989; Michel et al., 2021; Senoussi et al., 2019). One important idea that requires further testing is that the sampling frequency might depend on the number of stimuli—that sampling of one stimulus occurs at the alpha frequency (i.e., when attention is sustained at one location), which decreases to theta in the presence of more than one stimulus (Holcombe & Chen, 2013; Re et al., 2019; for review: Dugué & VanRullen, 2017).

Taken together, there is now substantial evidence for rhythmic sampling from a wide set of sensory and cognitive paradigms using psychophysics methods and recording of behavioural responses. Across these studies the most common assumption is that neural oscillations in the brain are the underlying neural substrate of this sampling process. And yet, as we will see in the next section, although neural oscillations have been observed in many brain areas across a wide set of experimental conditions, there is to date only very limited evidence that directly links neural oscillations to rhythmic sampling that is behaviorally observable. In the next section we will therefore start with an overview of the experimental approaches that have been taken to identify sampling related brain activity, before advancing to a description of recent research findings.

3 | NEURAL CORRELATES OF BEHAVIOURAL RHYTHMS

Brain oscillations, that is, rhythmic brain activity, are routinely observed in electro/magneto-encephalographic (EEG/MEG) activity and can sometimes be also observed at the level of single neurons during intracranial recordings. Authors have proposed different functions for oscillations in different areas of the brain and in different frequency bands, as well as different functional roles. One theory proposes an overarching mechanism, that is, rhythmic information sampling (for review Dugué & VanRullen, 2017; Gaillard & Ben Hamed, 2020; Menétrey et al., 2021; VanRullen, 2016a, 2016b; VanRullen & Koch, 2003). Indeed, if the brain's signal is rhythmic, it is only natural to predict that its behavioural consequences and communication strategies are periodic as well. Brain oscillations would thus provide the neurophysiological basis for rhythmic behavioural performance.

3.1 | Experimental approaches to identify sampling related neural oscillations

Over the past few years, two mutually complementary approaches have emerged in the search of a neural correlate of behavioural rhythms. The first approach starts on the behavioural side and establishes a psychophysics paradigm where behavioural rhythms can reliably be detected. Then, neural data can be recorded in areas presumably involved in the given cognitive paradigm, potentially revealing a corresponding neural rhythm (e.g., Fiebelkorn et al., 2013, 2018; Helfrich et al., 2018). Eventually a neural-behavioural phase-relation can be established. As we will describe in further details below, a number of research groups successfully identified the neural underpinnings of sampling using this approach.

The second approach identified sampling mechanisms by first characterizing ongoing or stimulus evoked neural oscillations (see Donoghue et al., 2021, for useful recommendations) and then studying their effect on behaviour. Several groups have initially measured the occurrence of neural oscillations and characterized the specific conditions which could trigger the neural rhythm (e.g., Bosman et al., 2012; Lewis et al., 2016; Moldakarimov et al., 2005; Rollenhagen & Olson, 2005; Spyropoulos et al., 2018). Then, in order to establish the functional significance of the encountered neural oscillations, some groups went on to carry out behavioural tests examining whether neural rhythms would affect or even translate into performance directly (e.g., Kienitz et al., 2018) or indirectly (e.g., Mayo & Maunsell, 2016). Indeed, similar behavioural performance fluctuations could be observed with a direct neural-behavioural phase-relation that was similarly interpreted as evidence for cognitive sampling.

Both approaches have yielded advantages and pitfalls. While the first approach has the great advantage of starting with an established paradigm resulting in a behavioural rhythm, a potential risk remains that—besides providing a neural-behavioural phase-relation—the exact mechanisms of the neural oscillation might remain unclear. The second approach, however, might uncover detailed mechanisms of a given oscillation in the brain, but fail in revealing a corresponding rhythm in behaviour. Whether each neural oscillation results in a behavioural one if an optimal experiment is designed is unclear and might depend a lot on the investigated brain area. By nature, oscillations in early sensory cortices might result in a detectable behavioural rhythm of the given sensory modality more easily due to their 'bottle-neck' location in the cortical hierarchy. The necessity to carefully design the psychophysical paradigm that

accompanies the neural recording (e.g., reset ongoing rhythmic activity and the importance of measuring this activity accurately) has already been stressed in previous sections and is equally important for measuring the emergence of neural oscillations and their relation to performance fluctuations.

3.2 | Neurophysiological recordings in humans have established the influence of neural oscillations on behavioural performance

First direct evidence for a neural basis of behavioural rhythms was found in non-invasive recordings in humans, building up on prior successes to delineate sampling using psychophysical methods. Several EEG studies revealed a dependence of behavioural measures of performance during perception and attention tasks on pre-stimulus phases in the lower frequency range (Busch et al., 2009; Busch & VanRullen, 2010; Dugué et al., 2011; Dugué, Marque, & VanRullen, 2015a; Fakche et al., 2021; Mathewson et al., 2009), post-stimulus phase-locking (Dugué, Marque, & VanRullen, 2015a), power (VanRullen et al., 2006) or power modulations (Jia et al., 2017). Further evidence stems from MEG recordings in humans (Landau et al., 2015) showing that the phase of theta-modulated lateralized gamma activity (30–100 Hz) over the occipital and parietal cortex predicted accuracy in a target detection task for which the authors had originally identified evidence for sampling during distributed attention (Landau & Fries, 2012). These findings gained from the combination of behavioural assessment with EEG/MEG measurements were extended by causal interference with local neural activation using TMS in the occipital cortex which revealed a theta-range rhythm in the reorientation of attention to one out of two stimuli (Dugué et al., 2016; see also Dugué, Marque, & VanRullen, 2015a, for a causal behavioural assessment with TMS and related EEG results).

In comparison to this rich knowledge gained from noninvasive measurements on how rhythmic neurophysiological activity affects cognitive processes in humans, evidence at the microscopic level of single or groups of neurons requiring investigations in experimental animals is still limited. We will review this emerging literature in the following sections.

3.3 | Nested oscillations in the brain's attention network predict rhythmic behaviour

A recent study aimed at closing this gap and used a paradigm known to involve attentional sampling that can

be detected in behaviour (first established in humans; Fiebelkorn et al., 2013) and recorded intracranial data from non-human primates performing a similar task. Demonstrating first that monkeys indeed exhibited similar sampling in the behavioural assays as humans do, the authors then performed electrophysiological recordings in frontal (FEF) and parietal (LIP) cortices, two areas well-known for their involvement in attention (Gottlieb et al., 1998; Thompson & Bichot, 2005). The results showed that the phase of the local field potential (LFP) in the theta band predicted behavioural accuracy during the attentional sampling paradigm. Furthermore, 'good' theta phases were accompanied by beta (13–30 Hz) (FEF) and gamma (LIP) oscillations and associated phase-to-amplitude coupling between these oscillations (Figure 3a,b). 'Bad' theta phases were in contrast characterized by additional alpha oscillations in LIP. The amplitude of these higher frequency oscillations was shaped as well by the theta phase. Interestingly, despite the effect of the theta phase on behavioural measures and higher frequencies, no actual increase in low frequency power could be detected after stimulus onset. These results were further solidified in observations of alpha rhythmic decoding of spatial attention in monkey FEF (Gaillard et al., 2020; for review: Gaillard & Ben Hamed, 2020) and in human intracranial recordings of brain activity in epileptic patients (Helfrich et al., 2018). Here, the high frequency band amplitude was used as a proxy for neural spiking and found to be rhythmically modulated by theta band fluctuations in the raw unfiltered data (i.e., likely comparable to LFP). Similar to the non-human primate study, the phase of this theta modulation influenced behavioural hit rate on a single-trial and electrode level in a similar detection task involving more than one target location. Additional recordings from a subcortical thalamic nucleus, the Pulvinar, suggest that these cortical interactions might be coordinated by this thalamic nucleus (Fiebelkorn et al., 2019).

3.4 | Theta oscillations at different stages of the cortical hierarchy observed in recordings from non-human primates

Neural theta oscillations have been observed in recordings from the non-human primate brain including a wide range of areas, such as area V4 (Lee et al., 2005; Liebe et al., 2012), inferotemporal cortex (IT) (e.g., Nakamura et al., 1991; Rollenhagen & Olson, 2005; Sheinberg & Logothetis, 1997), hippocampus (Jutras et al., 2013) and prefrontal cortex (PFC) (Raghavachari et al., 2001) during a variety of tasks. Unfortunately, no assessment of a behavioural rhythm was performed and therefore it

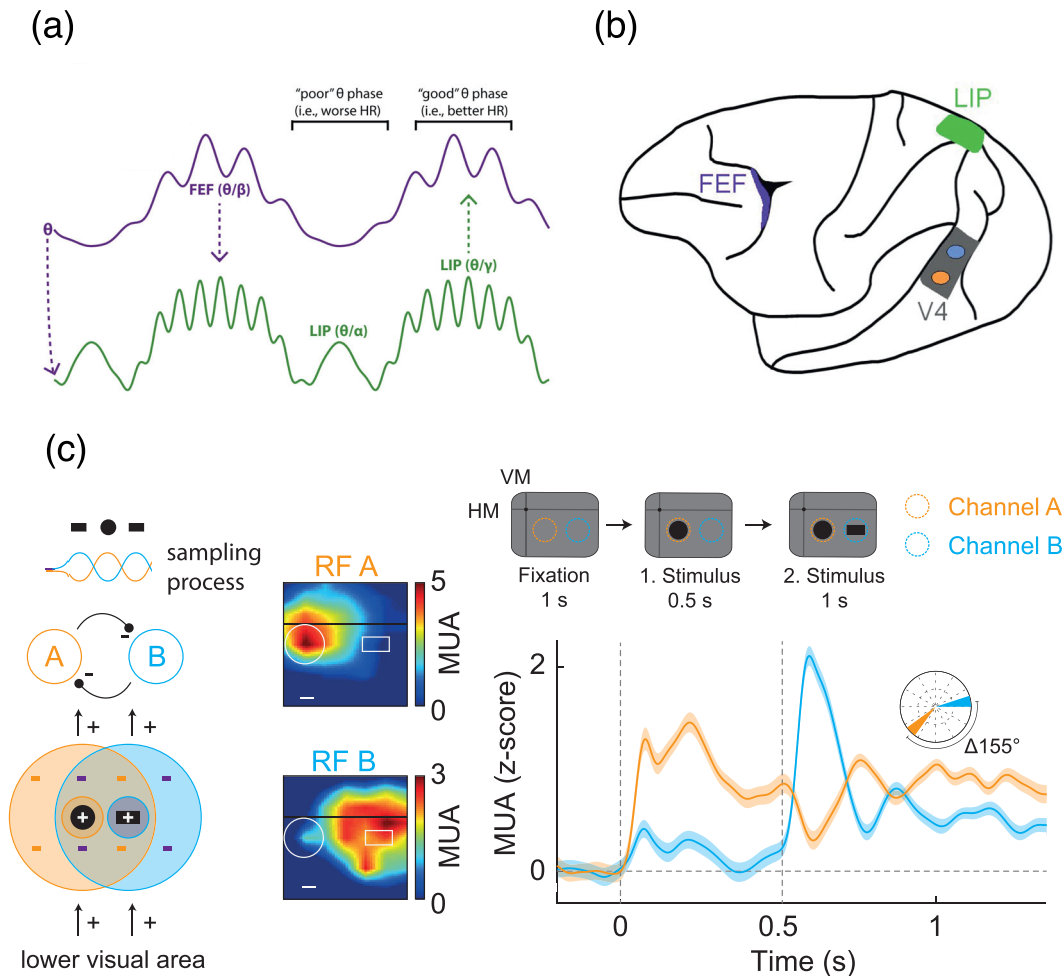


FIGURE 3 Sampling related neurophysiological activity in primate cortex. (a) Summary of how phase-to-amplitude coupling between theta, beta and gamma oscillations are thought to underlie attentional sampling in FEF and LIP according to (Fiebelkorn et al., 2018), highlighted in purple and green in panel (b), respectively. Reprinted from *Neuron*, 99/4, Ian C. Fiebelkorn, Mark A. Pinsk, Sabine Kastner, A Dynamic Interplay within the Frontoparietal Network Underlies Rhythmic Spatial Attention, 842-853.e8, Copyright (2021), with permission from Elsevier. (b) Brain sketch with areas highlighted (FEF, LIP and V4) where neural correlates of attentional sampling were found. (c) Adapted from Kienitz et al. (2018, Figure 2). Neural mechanism in V4 showing that local theta oscillations can be explained by centre-surround receptive field interactions in the presence of neighbouring stimuli (Kienitz et al., 2018). In an attentional detection task, the neural theta oscillation was shown to translate into a corresponding behavioural rhythm

remains unknown whether the observed neural oscillations in these studies translated into behavioural sampling. Interestingly, however, most non-human primate studies that reported theta rhythmic neural activity used multiple visual stimuli in their viewing paradigms, that is, conditions during which attentional sampling has been repeatedly reported in human psychophysics studies. For example, Bosman et al., by employing electrocorticography (ECoG) over primate visual cortex, found a theta modulation of inter-areal gamma synchrony between areas V1 and V4 during an attentional task in the presence of two behaviorally relevant stimuli (Bosman et al., 2012). Supported by Granger causality methods to infer directionality from the timing of oscillations in the ECoG data, the same group reported

that theta rhythms propagate in a feedforward way similar to gamma but contrary to beta rhythms (Bastos et al., 2015). Using a similar attention task, Spyropoulos et al. found actually a *decrease* of neural theta oscillations when attention was focused on one out of two stimuli (Spyropoulos et al., 2018), thus likely changing suppressive interactions between the stimulus representations (Sundberg et al., 2009). In the context of other cognitive paradigms, for example, working memory, theta rhythms could be observed in the form of local spiking and LFP rhythms as well as phase-coupling between visual and frontal areas, where only one stimulus had to be remembered in delayed matching to sample (DMS) tasks (Lee et al., 2005; Liebe et al., 2012; Rainer et al., 2004).

3.5 | Neural mechanisms underlying neural theta oscillations

Work on hippocampal circuits highlights the importance of a balance between excitation and inhibition for the generation of rhythms (Buzsáki et al., 2007; Roux & Buzsáki, 2015). But what mechanisms would lead to the generation of theta rhythms in cortical regions remained unclear. It was proposed that the prominent receptive field (RF) organization of visual cortical neurons into an excitatory centre region and a suppressive surround might provide the necessary substrate for excitation/inhibition to induce a local theta oscillation (Kienitz et al., 2018). Yet, despite intense studies of centre-surround interactions during the last decades (e.g., Bijanzadeh et al., 2018; Cavanaugh et al., 2002; Desimone & Schein, 1987; Gilbert & Wiesel, 1990; Haider et al., 2010; Pollen et al., 2002; Sillito & Jones, 1996; Sundberg et al., 2009), it is remarkable that theta oscillations have not been reported before in this context. A number of factors might have contributed to this. The majority of studies focused on averaged spike rates to characterize response properties to stimulus parameters (orientation, contrast, spatial frequency, etc.) ignoring temporal neural dynamics. Moreover, many studies used dynamic stimuli (e.g., moving gratings, dots and bars) and were conducted under anaesthesia which, by means of entrainment and distortion of excitation/inhibition balance respectively, directly influence neural dynamics and therefore might not be suited to study neural oscillatory dynamics. Furthermore, most studies simply did not perform a spectral analysis to uncover potential rhythmic dynamics of neural responses. This is usually accompanied by short stimulus presentation times and analysis windows that would not allow for the study of slow oscillations. Finally, results from Kienitz et al. (2018) and Rollenhagen (2005) suggest that a spatial and temporal onset separation of excitatory and inhibitory stimuli might facilitate or even be necessary to observe rhythmic activation in this context.

A recent study, dedicated to characterize neural correlates of a potentially present attentional sampling mechanism, used a detection paradigm where two visual stimuli were placed on opposite parts of the two visual hemifields (Mayo & Maunsell, 2016). Recording in V4 in both hemispheres, they did not find a difference in variance of neural responses between cued and neutral conditions or a correlation between activity across hemispheres, which would have been expected in the case of rhythmic activation. Cohen and Maunsell (2011), however, reported that V4 activity is coordinated across hemispheres during feature-based but not spatial attention. Also, while Kienitz et al. (2018) report local centre-

surround dynamics in V4 to account for local theta rhythms and attentional sampling, it appears likely that the underlying principle of competition-like interactions, that is, mutual inhibition of two separate neural groups in the presence of excitation, might be present in other areas as well. While in retinotopically organized areas the centre-surround structure might be the strongest source for competition between neural groups, neural competition might arise from different organizational principles in higher-order areas (e.g., between representations of stimulus identity).

3.6 | Neural receptive field interactions in visual cortex can induce theta oscillations that translate into rhythmic visual performance

Two studies carried out in non-human primates set out to directly investigate the relation between the presentation of multiple visual stimuli, RF mechanisms and the emergence of rhythmic neural activity. The first study focusing on IT cortex reported, despite IT's rather large RF, theta rhythmic spiking as soon as two adjacent visual stimuli were shown, likely involving mutual suppression (Rollenhagen & Olson, 2005). Building upon the insights gained from this previous study, Kienitz et al. recently showed that local centre-surround RF interactions at the level of V4 neurons can indeed account for the emergence of local theta oscillations in the visual cortex (Kienitz et al., 2018). Here, using long stimulus presentation times and a dedicated spectral analysis, rhythmic neural activity in the theta range could be identified when two spatially neighbouring stimuli were presented. Via local inhibitory centre-surround interactions, the excitation of one neural group representing one stimulus translated into the suppression of the neural group representing the second stimulus, and vice versa (Figure 3c). By designing a behavioural paradigm suited to uncover oscillations in reaction times, it was confirmed that this neural theta rhythm in V4 indeed translated into a phase-locked behavioural theta oscillation. Periods of high neural theta activity were associated with enhanced target representations and reaction time advantages, suggesting that this induced theta rhythm might serve as a sampling mechanism for visual detection. The observation of this neural and behavioural theta rhythm in the context of an attention demanding task seems to reflect very well predictions about attention engaging biased-competition mechanisms in visual cortex neurons (Desimone & Duncan, 1995). While behavioural rhythm is naturally observed during attention tasks, the related neural oscillation can also be observed during

fixation-only paradigms (e.g., Kienitz et al., 2018; Rollenhagen, 2005), which might speak to a local or feed-forward mechanism.

3.7 | Could theta oscillations be a broadcasting signal to transmit information across the cortex?

In comparison to this clear-cut rooting of theta oscillations in the visual cortex receptive field organization, the exact mechanisms underlying the emergence of theta rhythms in frontal and parietal cortices are less clear. Furthermore, while studies in the visual cortex seem to speak to a rather local, bottom-up and stimulus-driven mechanism (although some propose that the effect observed in early visual cortex may come from top-down information), the findings in fronto-parietal networks have been interpreted rather as top-down, attention-related neural correlates of behavioural sampling.

Whether theta rhythms are generated in different areas by different mechanisms (potentially by interactions of local pyramidal cells and interneurons) in parallel or whether they are initiated in one area and perhaps transmitted remotely to other areas is not very well understood. Importantly, theta oscillations, in addition to their presence in specific areas, were also found to synchronize neural activity between those areas, namely between the hippocampus and PFC and between PFC and V4 (Liebe et al., 2012; Siapas et al., 2005). More recently, granger-causality analysis applied to ECoG data collected over areas V1 and V4 suggested that theta and gamma oscillations might constitute feed-forward signal transmission from V1 to V4 (Bastos et al., 2015, see also van Kerkoerle et al., 2014; Schmiedt et al., 2014; von Stein & Sarnthein, 2000). Consistent with this finding, a recent study found that theta oscillations in extrastriate cortex critically depend on input from primary visual cortex, as V1 lesion results in the elimination of the theta rhythm but not spiking per se and gamma oscillations in V4 (Kienitz et al., 2021). Irrespective of their ultimate source, theta oscillations appear to organize faster rhythms, such as gamma oscillations, on a neural level into discrete temporal events (Lisman & Buzsáki, 2008; Lisman & Jensen, 2013). The emergence of such cross-frequency coupling has been reported as a general feature of cortex across species that may be required for long-distance integration or transfer of information to high-level association areas such as prefrontal cortex or hippocampus (Buzsáki & Wang, 2012; Liebe et al., 2012; Siapas et al., 2005; von Stein et al., 2000; Voytek et al., 2015).

The emergence of theta-rhythmic activity across different brain areas and paradigms together with phase-

to-amplitude coupling might further indicate a broader function in inter-areal neural communication. Drawing on insights from communication-through-coherence (Fries, 2015) and normalization of responses during attention (Carandini & Heeger, 2012), a single theta cycle might provide coherent depolarization levels across areas to facilitate the transmission of stimulus-encoding spiking signals from one area to the next, while at the same time suppressing the transmission of surrounding distractor information. The duration of a theta cycle (~200 ms) would allow for sufficient time for perceptual processing of at least one object (VanRullen & Thorpe, 2001) in addition to generating a behavioural reaction, such as a saccade to it. The succession of theta cycles is thought to be an efficient strategy to ensure sampling of information over time in the presence of multiple objects that is not only important for attention in visual or higher association cortices, but may extend also to other parts of the brain in the context of spatial navigation and memory (Buzsáki & Moser, 2013; Colgin, 2013; Landfield et al., 1972; Li et al., 2012), and therefore constitute a fundamental aspect of brain function.

4 | SUMMARY AND OUTLOOK

A growing number of studies report behavioural rhythms when probing the brain's processing of single or multiple stimuli in the temporal or spatio-temporal domain, respectively. Assessment of such behavioural rhythms requires a careful design of psychophysical setups. They critically need to include a reset event controlling the starting point of the rhythm and associated cognitive process that is to be assessed. Secondly, probing intervals of behavioural measures need to be chosen adequately to assess the rhythm of interest. In the face of individually designed and lab-dependent tasks, developing standard-operating procedures regarding how to record and analyze behavioural rhythms will greatly advance integration and comparability of findings from different laboratories and experimental setups.

While several studies investigate conditions under which behavioural rhythms and neural oscillations appear, only a few so far have been designed to establish a link between them. Regarding the neural basis of attentional sampling, there is evidence for both a sensory, bottom-up as well as a top-down correlate of relevant neural oscillations. While in apparent conflict at first sight, a coexistence of multiple neural mechanisms—potentially depending on the area and cognitive paradigm used—might hint to a fundamental role of oscillations in the context of attention and

perception. As attention requires an effective connectivity between high and low-level regions to select and facilitate perceptual processes, that might be implemented by oscillations. In this context, it appears likely that both internal as well as external events can trigger the relevant oscillations. Although oscillations in different frequency bands have been observed during various cognitive tasks, theta oscillations seem at present most closely linked to sampling multiple objects in the environment. The long periods of theta oscillations might be particularly suited for long-range integration of sampled information across remote brain areas. While the cited literature collectively suggests sampling rooted in theta-rhythmic neural activity as a fundamental aspect of brain function, clearly more work is required to delineate the generalizability of sampling across cognitive tasks and the mechanisms leading to the emergence of rhythmic brain activity.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY STATEMENT

Data shown in this review article in Figure 2 and Figure 3C have been published previously and are available from the corresponding author upon reasonable request.

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