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Shared rhythms between the brain and the environment

Charalambous, Efrosini; Djebbara, Zakaria

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Review article

On natural attunement: Shared rhythms between the brain and the environment

Efrosini Charalambous^a, Zakaria Djebbara^{b,c,*}^a University of Cyprus, Faculty of Engineering, Cyprus^b Aalborg University, Department of Architecture, Design, Media, and Technology, Denmark^c Technical University of Berlin, Biological Psychology and Neuroergonomics, Germany

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ABSTRACT

Rhythms exist both in the embodied brain and the built environment. Becoming attuned to the rhythms of the environment, such as repetitive columns, can greatly affect perception. Here, we explore how the built environment affects human cognition and behavior through the concept of natural attunement, often resulting from the coordination of a person's sensory and motor systems with the rhythmic elements of the environment. We argue that the built environment should not be reduced to mere states, representations, and single variables but instead be considered a bundle of highly related continuous signals with which we can resonate. Resonance and entrainment are dynamic processes observed when intrinsic frequencies of the oscillatory brain are influenced by the oscillations of an external signal. This allows visual rhythmic stimulations of the environment to affect the brain and body through neural entrainment, cross-frequency coupling, and phase resetting. We review how real-world architectural settings can affect neural dynamics, cognitive processes, and behavior in people, suggesting the crucial role of everyday rhythms in the brain-body-environment relationship.

1. Introduction

Recasting and expanding the boundaries of the embodied mind requires a reconsideration of the body-brain coupling processes (Klimesch, 2018), and a deeper understanding of the constraints and affordances that emerge relative to the material reality (e.g., the built environment) with which the embodied brain is constitutively coupled (Dotov et al., 2010; Malafouris, 2013). It requires an acknowledgment of the relational nature of embodied cognition as a larger organism-environment system. The concept of 'affordances' coined by (J. Gibson, 1986) has emerged as a key aspect in the field of embodied cognition, providing a framework to understand how the brain, body, and environment interact. Although this includes a neuroscientific perspective too, the camp of ecological psychology has largely neglected the important function of the central nervous system, perhaps as a strategic move towards emphasizing the importance of environmental features in adaptive behavior. This approach has revealed numerous important theoretical advances (Djebbara et al., 2022; Rietveld and Kiverstein, 2014; Withagen et al., 2017) and empirical results (Djebbara et al., 2019, 2021; Haken et al., 1985; W. H. J. Warren, 1984).

Recent interest to reintroduce neural dynamics into ecological

theories of cognition, to flesh out a mechanism for Gibson's concept of resonance (Falandays et al., 2023; Raja, 2021), can benefit from a closer look into the properties of the built environment itself. Features of the built environment can affect cognition and behavior. Yet, the literature of neuroscience broadly ignores the richness of the environment, reducing it instead to mere states, representations, and single variables. With patterns and rhythms naturally omnipresent in our environment, we ask: How do visual rhythmic stimulations of the environment couple with and affect the brain and body? To answer this, we need to explore how the design of the built environment can potentially cause rhythmic sensorimotor stimulation that can be translated into an environmental input flow. The dynamic processes of resonance by which a person's sensory and motor systems coordinate with the rhythmic elements of their environment, often underlie and act as a scaffolding for the experiential quality in *natural attunement*.

With the maturing of neuroimaging techniques (Gramann et al., 2014; Makeig et al., 2009), the inclusion of the environment for ecologically valid experimentation is a necessary next step to understanding the brain in real-world settings (Brunswick, 1956; de Wit et al., 2017; Raja and Anderson, 2019). This has been coined by Gramann et al. (2014) as 'natural cognition' from which we have borrowed the wording

* Corresponding author at: Aalborg University, Department of Architecture, Design, Media, and Technology, Denmark.

E-mail address: zadj@create.aau.dk (Z. Djebbara).

'natural' in the concept of 'natural attunement.' This concept attempts to foreground the significant role of the environment by situating the rhythmic properties of the built environment as central in the literature on the rhythmic and oscillatory nature of the human body and the brain. The main argument is that externally generated rhythmic stimulations can entrain internal neural rhythms that, in turn, affect cognition and behavior.

The most intuitive conceptualization of rhythm is repetition through intervals or durations. Although the notion of rhythm can entail much more complicated aspects, we focus on the rhythm as repetition since this has potentially stronger links to the phenomenon of entrainment. By 'rhythm,' in this paper, we mean a recurrent pattern of change through time of a signal, but we cannot exclude the possibility that non-recurrent patterns as rhythms may have a similar effect. Drawing the environment in terms of rhythms allows for considering their immediate interaction with neural (and other) oscillatory dynamics. The upshot is furthermore that the environment is not considered a static state, but rather a bundle of highly related continuous signals with which we can resonate. While resonating with others is possible too (Czeszumski et al., 2020; Dumas, 2011), we focus here on the relationship between a single agent and the built environment.

Philip Thiel, for example, whose work is substantially influenced by concepts and ideas of environmental psychology, argues about the importance of focusing on how we experience the built environment *over time* and not just as a snapshot from a fixed viewpoint. Thiel's comment that "Architecture may well be 'frozen music', like a phonograph record; but man is the pickup whose movement realizes the experience" (Thiel, 1961, p. 33), revolves around the idea of perception as active information picking up over time and thus creates an immediate reference to theories of direct perception, e.g., ecological psychology (Michaels and Carello, 1981). Similarly, a feature of the built environment that plays a significant role in our experience is rhythm as repetition, which in turn makes movement and time important aspects. As we will argue, the design of the built environment can shape the type of sensory and motor change we experience. However, the change itself requires more than designed external signals. It requires active participation and coupling with the external signal, which in ecological psychology is often referred to as *resonance* (Heft, 2001; Raja, 2018, 2021).

The idea of resonance as a property of perceptual and neural systems has gained popularity in the literature on brain-body-environment relationships. Although it is a widely observed phenomenon of dynamic systems, the term has been mainly used as a metaphor in ecological psychology, to denote the form of coupling between active perceptual systems and informational variables in the energy flows of the environment (J. Gibson, 1986; Raja, 2021). It occurs when there is an alignment between the organism's behavioral patterns and the informational structure of the environment, resulting in a smooth and efficient interaction between the two. Ecological informational variables are thus the bridge between agents and their environment and are important for the specification of both (Michaels and Carello, 1981, p. 38). The agent's perceptual systems are attuned to the perceptual information, or as Gibson comments: "[...] the perceptual system simply extracts the invariants from the flowing array; it *resonates* to the invariant structure or is *attuned* to it" (J. Gibson, 1986, p. 249; original emphasis).

The term attunement, which is defined in more detail in Section 4, is a concept with a more intentional connotation (Heft, 2001) capturing,

for example, the ability of the brain to selectively engage with or self-tune to the environmental variables. The idea of the perceiver as "a *self-tuning* system"¹ (J. J. Gibson, 1966, p. 271; original emphasis) has been central in Gibson's discussions regarding the role of perceptual systems during active exploration. Our perceptual system (as a set of organs that include sensory receptors) as a self-tuning system attends to and detects certain classes of information that are available and useful to the perceiver as affordances (J. J. Gibson, 1966). Being sensitive and responsive to relevant cues and affordances an organism adjusts its perceptual and motor systems to the information in the environment. It is a continuous and dynamic process of becoming attuned to the properties and possibilities of the environment.

On the other hand, in the empirical neuroscience literature, the focus has been on the phenomenon of neural entrainment, which can be defined as "[...] the alignment of one or more oscillating systems to an external rhythm, whereby the interactions are unidirectional, that is, the external rhythm influences the oscillating system(s) but not vice versa" (Lakatos et al., 2019). In the case of neural entrainment, the endogenous neural oscillations become temporally aligned to the systemic regularities in the environment (Obleser and Kayser, 2019; Thut et al., 2011). Interestingly, evidence from studies on neural entrainment also suggests that the "act of resonating" (Reed, 1989, p. 115) is supported by processes of active sensing and dynamic attending (Lakatos et al., 2019; Large and Jones, 1999).

Both entrainment and resonance are properties of non-linear dynamic systems. However, both concepts still lack a clear definition in cognitive neuroscience (Helfrich et al., 2019). It is not within the scope of the paper to provide a detailed definition of these properties or describe their relationship in full detail. However, we think it is important to clarify that we consider entrainment and resonance as measurable empirical properties that support coordination while we use the term attunement to refer to the experiential dimension of such phenomena.

Despite the rich evidence that rhythms alter behavior, the vast majority of empirical neuroscience has yet to acknowledge the richness of the environment. Thus, to place the environment back into its rightful place as a resonant structure in the interaction between agent and environment, we organize our paper in the following way. Section 1 offers a detailed account of the phenomenon of resonance at different scales and from different viewpoints. We first provide an ecological psychology perspective on resonance and then briefly review evidence of resonance and entrainment at the neuronal scale. This section exemplifies the many ways in which we can naturally attune to the environment. Section 2 shifts the focus from lab-based findings to real-world complex dynamics to situate the possibility of natural attunement. The objective here is to examine how the 'act of resonating' with useful perceptual information can lead to environmental resonance. Finally, the discussion naturally leads back to the built environment component. Section 3 considers the experiential dimension of the coupling processes as a possibility for natural attunement in real-world architectural spaces.

2. From resonance to neural entrainment

The phenomenon of resonance can be observed at different scales, from the ecological scale of body-brain-environment interactions to spontaneous oscillations of neuronal networks (Thompson and Varela, 2001; Varela, 1995) and even to spiking bursts of single neurons

¹ Gibson notes that we should not consider this as a passive process: "The 'resonating' or 'tuning' of a system suggests the analogy of a radio receiver. This model is inadequate because there would have to be a little man to twiddle the knobs. A perceiver is a *self-tuning* system. What makes it resonate to the interesting broadcasts that are available instead of to all the trash that fills the air? The answer might be that the pickup of information is reinforcing" (J. J. Gibson, 1966, p. 271)

(Izhikevich et al., 2003). This section examines key properties underlying these interactions, such as spontaneous oscillations, nonlinearity, and entrainment, which are also linked to evidence of neural entrainment from the field of empirical cognitive neuroscience. While the phenomenon of neural entrainment can lead to absolute coordination there are also cases characterized by relative coordination or entrainment in a broader sense.

2.1. Agent-environment interactions

The compatibility between dynamic systems theory (DST) and ecological psychology is not new (Di Paolo et al., 2017; see for instance; Thelen and Smith, 1994), and the advantage is the materialization of concepts like resonance. Resonance in DST refers to the frequency-specific response of a driven system when triggered by a single transient event as well as repeated events (Helfrich et al., 2019). However, Raja (2018) suggests that the foundation for resonance in ecological psychology rests on informational coupling, which is when the dynamics of both agent-environment interactions are coupled to the dynamics of the agent's central nervous system (CNS) in terms of the same ecological information. Raja's (2018, 2019) proposal of an operational account of ecological resonance is heavily based on *behavioral dynamics*, evident in the work of Warren (2006) as well as Anderson's *neural reuse* (Anderson, 2010), and *coordination dynamics* (Kelso and Tognoli, 2007) offering an appropriate account at the neuronal level. This level is often omitted from discussions within ecological psychology. Furthermore, it is grounded in theories of system dynamics (Chemero, 2013), suggesting interactions between different hierarchical scales: the two systems of agent and environment constrain each other (according to behavioral dynamics), and the dynamics at this ecological or intentional scale constrain the nested scales of the muscular or neuronal systems (Raja, 2018).

Neuronal dynamics are thus understood as being constrained by the information generated in agent-environment interactions. An illustrative case of ecological resonance is the study by van der Weel and van der Meer (Van der Weel and van der Meer, 2009) on infants' brain responses to looming objects. Researchers reported that the theta rhythm oscillations in babies' visual cortex correlated with perceptual information. That is the ecological variable τ ² (Lee, 2009), a relational measure between sensory and motor information generated at the agent-environment scale. Although τ is not our phenomenon of focus, it serves as a good example of the importance of the CNS in understanding resonance and the mechanisms of neural entrainment.

2.2. Mechanisms underlying rhythmic activity

2.2.1. Spontaneous oscillations

At the scale of populations of neurons, oscillations occur due to communication through their electrochemical interactions (Buzsáki, 2006). Neurons' action potentials can be in the form of a single spike or a burst of spikes that exhibit specific resonant interspike frequencies (Izhikevich et al., 2003). They generate spontaneous oscillation at their preferred frequency and they respond better to inputs with frequencies falling within a specific frequency range. This results in communication between neurons being selective based on their resonance frequencies, which plays a key role in coherent brain dynamics (Fries, 2005; Hutcheon and Yarom, 2000). However, under certain conditions (e.g., chemical changes in the neuron's membrane) the neuron's natural frequency can shift in and out of its resonance range enabling resonance at the scale of different neuronal networks (Lau and Zochowski, 2011). On

a global level, changes in resonance frequency depend on the current transient network configuration, which is influenced by cognitive content, perceptual flow, and top-down control mechanisms such as attention (Helfrich et al., 2019). On a local level, the rhythmic modulations in local excitability result in spontaneous neural oscillations within specific frequency bands contributing to a self-organizing brain system. They are considered instrumental to brain functions and their intrinsic synchronization most likely plays a key role in perception³ and different cognitive phenomena (Buzsáki, 2006; Schroeder and Lakatos, 2009).

It is imperative to emphasize that these are spontaneous oscillations, not driven by external factors or interactions. These oscillations are believed to give rise to a nonlinear phenomenon, i.e., stochastic noise or resonance, that appears to help transfer information and optimize a system's response to a weak signal (Deco et al., 2009; McDonnell and Abbott, 2009; Moss, 1997). Spontaneous activity has also recently been proposed as the basic model for self-specificity, i.e., how the embodied brain distinguishes between internal and external stimuli (Northoff, 2016, 2018; Raichle et al., 2001).

2.2.2. Internal nonlinear coupling

Internal couplings of neural assemblies often rely on coordinating mechanisms of phase alignment. (Fries, 2005; Uhlhaas et al., 2009; Varela, 1995). Phase alignment describes how action potentials from different neurons are timed to fire at the same phase of a rhythmic cycle, which can give rise to oscillatory entrainment. Oscillatory entrainment entails two important underlying mechanisms (Calderone et al., 2014): phase-reset and cross-frequency coupling (Fig. 1A-D & 2B). Phase-reset refers to the modulation or resetting of the timing of oscillatory activity in response to a stimulus or perturbation.⁴ Cross-frequency coupling occurs through temporal alignments across different amplitudes and frequencies, which can exhibit nonlinear patterns of resonance. Neural assemblies can become phase-locked not only to the intrinsic frequency but to the harmonics of the entraining frequency as well (Klimesch, 2018; Large, 2008).

Thus, brain regions with different intrinsic dynamics can be quasi-synchronized through different cross-frequency couplings such as amplitude-amplitude coupling, phase-phase coupling, or phase-amplitude coupling (Fig. 1A-D; Lakatos et al., 2019). In amplitude-amplitude coupling and phase-phase coupling, a phasic relationship is needed between the frequencies of the two oscillations, whereas in the phase-amplitude coupling, the amplitude of a higher frequency, e.g., gamma (~40 Hz), is modulated by the phase of a lower frequency, e.g., theta (~4 Hz). Additionally, it is worth noting that if an external signal or mechanism successfully affects the lower rhythms of the brain, it can potentially modulate the phase-amplitude coupling with higher frequencies, which are thought to be related to sensation and perception (Rodríguez et al., 1999). Our grip and understanding of the world appear to hinge on the neural capacity of frequency coupling. Notably, such cross-frequency couplings have been documented between body-brain oscillations, forming a single rhythmic hierarchy

³ For example, Cosmelli et al. (2007) describe such a case as a resonant assembly where the transient binding of different neuronal populations associated with features of a visual object (shape, color, motion) can be involved in the transient perception of the visual object.

⁴ Phase reset is observed across different modalities (e.g., visual, and auditory during speech). An ongoing oscillatory behavior is observed to reset its phase in tandem with an external stimulus.

² The perceptual variable τ is defined as the relative rate of expansion of an approaching object (looming figure) projected on the screen constraining the perceptual system (Raja, 2019) or more generally as "the time-to-closure of the action-gap at the current rate of closure" (Lee, 2009).

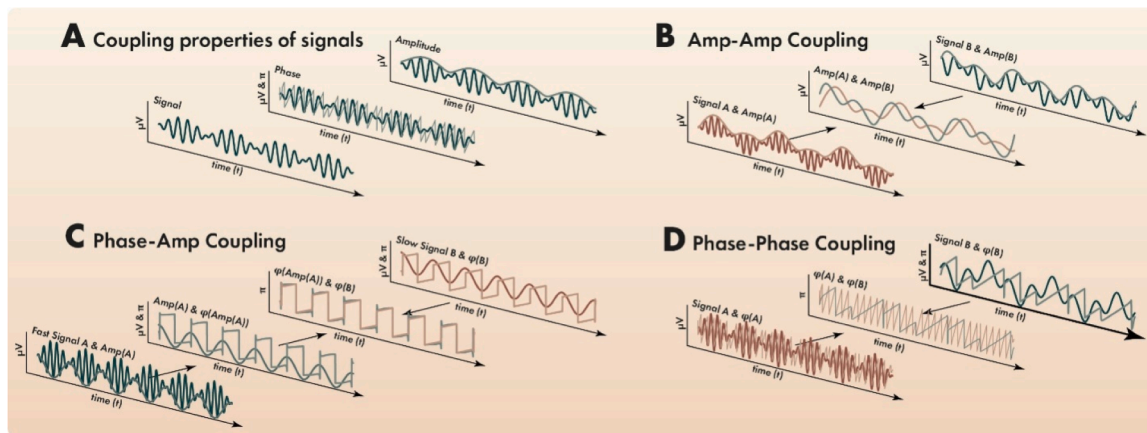


Fig. 1. There are mainly three kinds of couplings between signals, namely amplitude-amplitude coupling, phase-phase coupling, and phase-amplitude coupling. **A.** Several spectral properties can be extracted from signals, among others the phase and the amplitude. **B.** Amplitude-amplitude coupling is the coupling through synchronization of the amplitude of two different frequency bands. For example, when alpha (8–12 Hz) and beta (13–30 Hz) oscillations are both active, they may synchronize their amplitude such that peaks and troughs of the two frequencies align. **C.** Phase-amplitude coupling refers to the modulation of the phase (timing) of one frequency by the amplitude (power) of another frequency. For example, when alpha oscillations modulate the phase of gamma oscillations, the timing of gamma oscillations may be influenced by the amplitude of alpha oscillations. **D.** Phase-phase coupling refers to the synchronization of the phase (timing) of two different frequency bands. For example, when theta (4–8 Hz) and gamma (30–80 Hz) oscillations are both active, they may synchronize their phase such that the peaks of one frequency align with the peaks of the other frequency.

(Klimesch, 2018).⁵

2.3. Empirical evidence of neural entrainment

Neural oscillations can be entrained to external rhythms across different frequencies and different modalities (Calderone et al., 2014; Haegens and Zion Golumbic, 2018; Schroeder and Lakatos, 2009; Thut et al., 2011). Alignment of neural rhythms to environmental regularities in the auditory domain, e.g., speech or music, is mainly observed at frequencies below 10 Hz (Doelling and Poeppel, 2015; Golumbic et al., 2013; Obleser and Kayser, 2019). Engaging in a conversation at a cocktail party is a very popular real-world example that demonstrates our ability to tune to a specific signal in a noisy environment (Golumbic et al., 2013). This presumably entails perceptual entrainment to a specific audiovisual rhythm of speech production supporting interpersonal interactions. Selective entrainment to behaviorally relevant events demonstrates active shaping of perceptual input and can be influenced by predictive mechanisms, as suggested by reduced reaction times in target detection (Golumbic et al., 2013; Lakatos et al., 2008; Stefanics et al., 2010; Teng et al., 2018).

During visual entrainment, several researchers report increased sensitivity of attended cues associated with delta modulations on high-frequency activity associated with sensory processes (Lakatos et al., 2008; Saleh et al., 2010). Cross-frequency modulations were also related to a top-down predictive mechanism during 10 Hz flicker entrainment of parieto-occipital alpha associated with rhythmic sampling (Helfrich et al., 2017; VanRullen, 2016). In general, most evidence suggests that rhythmic flickering light at an alpha frequency entrains intrinsic occipital alpha rhythm associated with periodicity in visual perception and

behavioral performance (De Graaf et al., 2013; Mathewson et al., 2012; Spaak et al., 2014).

While the scope of this paper is limited to entrainment through sensory channels, we briefly mention a few studies that used electric stimulation to generate rhythm and perturb cognitive performances to demonstrate the mechanism of neural entrainment. For instance, behavioral effects of neural entrainment have been demonstrated with the use of transcranial alternating current stimulation (tACS), which is a non-invasive brain stimulation technique that uses weak electrical currents to modulate neuronal activity in the brain. Alekseichuk et al. (2016) successfully recorded improved spatial working memory performance when theta and gamma waves were co-stimulated, but this effect is observed only when repetitive gamma bursts are synchronized with the peaks of the theta rhythm. Additionally, the study demonstrated that the most effective high gamma frequencies for retaining multiple items range between 80 and 100 Hz in the prefrontal cortex. Furthermore, the use of transcranial magnetic stimulation (TMS), which is also a non-invasive stimulation technique used to modulate brain activity by using electromagnetic coils placed near the scalp to generate rapidly changing magnetic fields, has also demonstrated behavioral effects. Albouy et al. (2017) linked theta oscillations in the dorsal stream to participants' auditory memory manipulation abilities. Applying theta-rhythmic TMS over a targeted area significantly improved accuracy in memory tasks, establishing a causal relationship between theta activity in the dorsal stream and memory manipulation.

The causal role of neural rhythms on cognition (Hanslmayr et al., 2019) has also been demonstrated in a study by Riddle et al. (2020) who sought to understand the role of theta and alpha waves during a working memory task. They found that the effect of rhythmic TMS on memory performance depended on the mismatch with the task-driven oscillation. Furthermore, Di Gregorio et al. (2022), using TMS too, affected pre- and post-stimulus alpha in a visual perception task, and successfully demonstrated that subjective experience could be linked to the alpha rhythm of the brain. Their results suggest a split between alpha speed and alpha amplitude, connecting alpha frequency to spatiotemporal sampling capabilities and alpha amplitude to the internal, subjective perception, and interpretation of sensory experiences. Supramodal regions of the brain, too, can be entrained and affect cognitive processes. Albouy et al. (2022) established causal evidence for the supramodal role of the frontoparietal network in human cognition, linking frontoparietal theta oscillations to auditory working memory performance and

⁵ Klimesch (2018) mentions several interesting cases such as lung-heart coupling, muscles- motor cortex coupling as well as the coupling between phase of gastric basal rhythms and the amplitude of spontaneous alpha rhythm fluctuations. He postulates that the different frequencies do not vary randomly and that these couplings follow a doubling/halving ratio (e.g., 1:2) characterizes the relationship between neighboring center frequencies of traditional brain frequency bands while non-neighboring frequencies can be harmonically coupled at other ratios (e.g., 1:3, 1:6). For example, midline frontal theta at 6 Hz co-occurs with alpha at about 12 Hz (twice as fast) during increased working memory demands (Jensen et al., 2002).

demonstrating enhancement through theta rhythmic visual stimulation.

2.3.1. Multisensory integration and memory

Perceptual systems flexibly use temporal information of contextual structures not only within but also across sensory modalities to predict upcoming events, which can lead to phase alignment in relevant modalities that are not necessarily directly stimulated (Daume et al., 2021; Lakatos et al., 2007; Ten Oever et al., 2014). For example, such multisensory integration is manifested during speech perception, where continuous non-rhythmic visual input affords predictable temporal regularities regarding upcoming auditory events, and relevant oscillations are then modulated so that auditory input arrives at phases of high excitability (Schroeder et al., 2008). Though not directly related to the built environment, it attests to the possibility of getting entrained to non-rhythmic events in the built environment.

The mechanism that supports predictability relative to the temporal onset of upcoming events in sequential structures inherently involves aspects of episodic memory (Kurby and Zacks, 2008). At the same time, episodic memories are also rich in contextual information about events involving the integration of different sensory modalities. Theta oscillations are often associated with the binding of contextual information and episodic memory (Staudigl and Hanslmayr, 2013). Behavioral results of increased memory performance have been reported in several studies that examined neural entrainment using visuoauditory stimulation at the theta frequency (Clouter et al., 2017; Guan et al., 2018; Köster et al., 2019; Roberts et al., 2018).

2.4. Neural entrainment: a narrow and broad definition

Brain responses to external periodic input do not necessarily always involve phase alignment of endogenous neural oscillations. ‘Stimulus-tracking’ or ‘neural-tracking’, for example (Fig. 2A), can elicit repeated transient event-related responses to a series of temporal regularities but because it is not clear if it interferes with related cognitive and perceptual processes, it can only be considered as entrainment in the broad sense (Bánki et al., 2022). In contrast, entrainment in the narrow sense is when the input flow ‘hijacks’ the frequency of the ongoing neural oscillation. Several authors have argued about the importance of this distinction. This is mainly because it is only in the latter case that we can assume alternation of spontaneous neural oscillations (phase alignment) and, most importantly, that these alterations are behaviorally-relevant (Bánki et al., 2022; Haegens, 2020; Helfrich et al., 2019; Keitel et al., 2014; Obleser and Kayser, 2019).

A stricter definition of what constitutes true entrainment suggests that besides the presence of a driving and a driven oscillator, another requirement is frequency selectivity (Haegens and Zion Golumbic, 2018). In other words, true coupling between external and internal periodicities occurs for a range of rhythms that are close to the intrinsic frequency of the oscillatory brain, e.g., theta (4–8 Hz). Entrainment effects are strongest when the two oscillators overlap in frequencies, but it can also be observed if the stimulation frequency does not exactly match the neural eigenfrequency. This is captured by the characteristic triangular shape of the theoretical model of entrainment called ‘Arnold Tongue’ (Fig. 3B). It illustrates that the further the external frequency is to the neural eigenfrequency, the higher its intensity needs to be in order to entrain the endogenous oscillator (Notbohm et al., 2016; Zoefel et al., 2018).

It is, thus, not unreasonable to consider neural entrainment as one mechanism (at the nested neural scale) closely linked to resonance in the ecological sense. For instance, Raja (2021, p. 122) states that “[...] models of networks composed by nonlinear neural oscillators [...] exhibit a feature known as nonlinear resonance that accounts for some network properties as stimuli filtering, neural entrainment, or stimuli anticipation”. Gibson’s insightful metaphor of the brain as a resonant organ is a theoretical framework that may find support in empirical neuroscience. Even further, this suggests that entrainment is not a

precise phenomenon. It enables approximations of rhythmic stimulations rooted in the built environment to be effective too.

3. Environmental resonance in real-world settings

Neural tracking (Fig. 2A) of environmental regularities at the perceptual and behavioral level (neural entrainment in the broad sense) is not only amenable to the technical constraints of neuroscientific studies (Obleser and Kayser, 2019), but it also embraces the different degrees of complexity that are linked with different phenomena. Paraphrasing Lakatos (2019), entrainment tolerates input sequences that are not completely predictable or isochronous. However, an underlying assumption in some studies focusing on the perception of musical events or natural speech is that there is sufficient regularity in the auditory signal and the perceptual phenomenon to fit the narrow definition of entrainment but fail to quantify the regularity of the stimulus signal, e.g., continuous speech. As part of the recent attempts for a critical re-evaluation of entrainment, Meyer et al. (2020) ask if entrainment, in the narrow sense, denotes synchronization of brain rhythms in the sensory systems with rhythmic stimuli features and if the external stimuli are not strictly rhythmic, then how can something that does not have clear physicality in the external world trigger this sort of coordination? This is a relevant question in the context of the built environment, as it is unlikely to have a strictly rhythmic stimulation to induce neural entrainment in the narrow sense.

An illustrative real-world example of how we can perceive a periodic pulse in non-periodic stimuli is the perception of the beat in music, to which we can spontaneously coordinate motor activity (Large et al., 2015). While the rhythms of music are not periodic but rather complex temporal auditory structures, our perceptual system has the ability to capture the pulse or beat (perceived periodicity) and meter (perceived patterns of alternation between weak and strong pulses). According to the ‘Neural Resonance Theory’ (Large, 2008; Large and Snyder, 2009), pulse perception arises as spontaneous endogenous oscillatory activity of neural populations (rhythmic bursts) resonating with rhythmic stimulation while influencing attention and expectation. Because neural systems exhibit higher-order resonance characteristics as nonlinear oscillators, they can become coupled to the stimulus through phase entrainment not only in terms of 1:1 synchrony but also under other multifrequency modes of coordination with rhythmic stimuli. As a result, oscillations may fluctuate at frequencies that are not present in the rhythmic stimulation, giving rise to ‘pulse perception’ whose frequency is not physically present in the input flow (Large et al., 2015). In other words, if the interaction with certain features of the built environment appears rhythmic, they may not be found to affect the neural oscillations at the exact same frequency, but at another.

Similar to music and natural speech, the natural sensory environment involves dynamic visual input with temporal structures of varying frequencies that are very rarely, strictly rhythmic. Interestingly, it has been demonstrated that neural entrainment is possible beyond ‘frequency-tagging’ with neural phase-locking to stimulation of varying frequencies (Henry et al., 2014; Keitel et al., 2017). It is thought that in cases where stimulation is not strictly rhythmic, i.e., when the input is complex and irregular, entrainment shifts to an average repetition value (Lakatos et al., 2008, 2013). This can be demonstrated with temporal predictability being evident in a more naturalistic context where sensory input is not strictly rhythmic (Calderone et al., 2014; Mathewson et al., 2012). These findings suggest that the phenomenon of neural entrainment may be extended and generalized to other forms of temporally predictive contextual structures that do not as such entail discontinuous rhythmic stimulation.

Furthermore, it has been demonstrated that a dynamic systems model of a weakly coupled neural networks in combination with Hebbian plasticity can be used to model rhythm perception in infants (Tichko and Large, 2019), which also demonstrated that early auditory-motor interactions influence infants’ rhythmic preferences

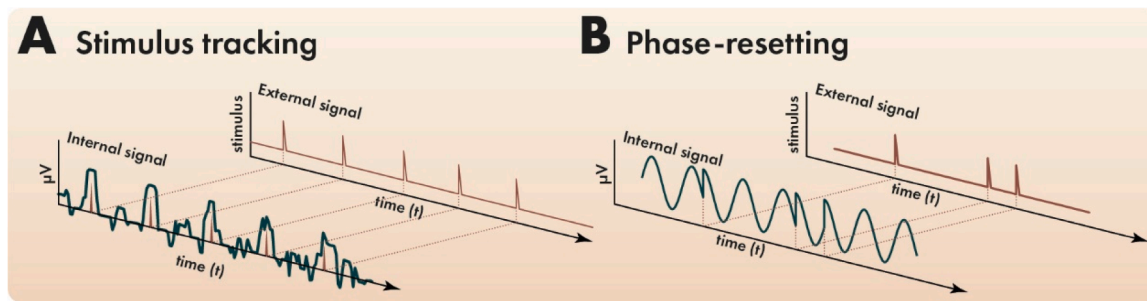


Fig. 2. A. Stimulus or neural tracking refers to the ability to follow and measure the neural response to a specific stimulus over time. This is done through time-locked brain responses that occur in response to a temporally regular stimulus, such as a visual or auditory cue. Such brain responses are known as Event-Related Potentials (ERPs) and may wrongfully appear as an oscillator. B. Phase-resetting refers to the ability of an oscillatory system to reset its phase in response to a transient input or perturbation. This phenomenon is observed when a neural oscillator receives an external input, such as a sensory stimulus or an electrical pulse, and its phase is shifted, or reset, to a new value. The magnitude and direction of the phase shift depend on the timing and strength of the input relative to the phase of the ongoing oscillation.

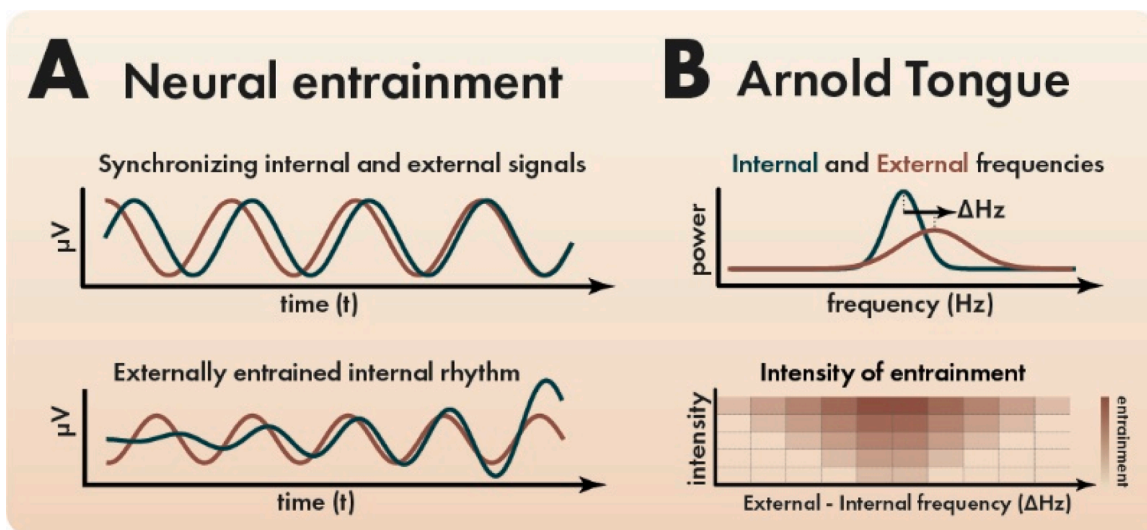


Fig. 3. A. Neural entrainment, in the narrow sense, refers to the synchronization between an eigenfrequency of a population of neurons with rhythmic external stimuli, such as sounds or visual stimuli. This synchronization is thought to enhance cognitive processing and behavioral performance. Entrainment can occur at various frequencies and with a variety of external stimuli. Importantly, entrainment in the narrow sense is expressed with an increase in the amplitude of the targeted eigenfrequency. B. The Arnold tongue is a concept in the field of neural entrainment that refers to a region of parameter space where an oscillator, such as a neuron or a population of neurons, can be entrained to an external rhythmic signal. It is a visual representation of the relationship between the frequency and phase of the external signal and the frequency and phase of the oscillator's response. The tongue is typically shaped like a tongue or a comb, and its shape is determined by the strength and phase of the coupling between the oscillator and the external signal.

(Tichko et al., 2021). With outset in Neural Resonance Theory (NRT), Tichko et al. (2022) approximate a Gibsonian embodied perspective of rhythms in a similar sense as presented here. In the context of NRT, living organisms adapt to consistent patterns in their surroundings by adjusting the strength of connections and the relative phases between natural rhythms and biological oscillations. This adaptation takes place across various nested timescales, contributing to the development of rhythmic perception and behavior throughout the organism's lifespan. Essentially, by applying a systems approach, their view suggests that a non-linear dynamical systems approach may be useful for detecting the emerging resonant landscape.

The temporal regularities embedded in the environment afford predictions and anticipation about future sensory events, which optimize behavior (Cravo et al., 2013; Spaak et al., 2014). In contrast to complex auditory stimuli, visual stimulation through movement (e.g., in the built environment) entails temporal structures of perceptual information. These are amenable to alternations through movement and at the same time can impact movement, e.g., sensorimotor coupling (Djebbara et al., 2019, 2021, 2022). This suggests the possibility of resonance with

continuous environmental stimulation as opposed to discrete structures of sensory flows. The temporal structure of the perceptual information in real-world settings is rarely as clearly rhythmic as in lab-based conditions. Therefore, focusing on environmental resonance as a response to a naturalistic degree of rhythmic complexity may expand our understanding of the mechanisms underlying coordinated behavior and temporal prediction and, most importantly, enhance the concept of ecological relevance. It is the quality of the experience that emerges from this coupling with the built environment that we refer to as 'natural attunement,' which is relevant to the discourse of perception of atmosphere (Canepa, 2022; Griffero, 2014) and the immediate gist of scene perception (Djebbara et al., 2019; Oliva and Torralba, 2006).

3.1. Real-world behavioral effect of resonance

The effect of neural entrainment on multisensory integration and cognitive functions related to attention (Helfrich et al., 2018; VanRullen, 2016) and memory (for a review: Hanslmayr et al., 2019) suggests an impact on behavior. These are, however, laboratory experiments that do

not allow for freely moving human beings. Thus, we briefly review real-world cases and empirical studies of high ecological validity that offer evidence of natural attunement in dynamic settings. During movement, the perceivable structure of the built environment that constrains or affords different activities can change in a periodic manner. The rate of change of visual input flow in urban spaces or the interior of buildings is often rhythmic or has temporal regularities able to entrain, for example, neural oscillations of sensory receptors in peripheral vision. Evidence suggests that the sensed rate of change of visual elements in optical flow appears to modulate walking speed. Ludwig et al. (2018) projected vertical lines with varying distances on the floor of a walkway and reported a decrease in walking speed when traversing a pattern of lines with a high frequency as opposed to a low frequency. That is, the fast changes in the peripheral vision suggest that one is moving fast whereas the natural behavioral adjustment is to slow down. Modulations in speed have also been reported in a driving simulation study. By changing the width of the vertical lines that appeared in a rhythmic visual pattern along a tunnel, it was demonstrated that speed adjustments could be controlled (Manser and Hancock, 2007). Increasing the distance between the vertical lines in the tunnel was perceived by the driver as slowing down, which consequently resulted in increasing driving speed. The opposite was observed when the distance between the visual elements was decreased. Similarly, in a real-world case (Thaler and Sunstein, 2021), decreasing the distance between the white stripes painted onto the road near dangerous curves along the east coast of Lake Michigan most likely had an effect on the sensorimotor dynamics associated with high velocity, which effectively resulted in a reduction of drivers' speed. Further evidence of implicit behavioral effects of natural attunement was reported by Leonards and colleagues (Leonards et al., 2015), who investigated the impact of tile-pattern direction on the walking direction. Their findings suggest that in contrast to significant rotations, subtle rotations of tile patterns (close to the straight line) resulted in participants veering away from the straight trajectory. Overall, these behavioral effects suggest that the rhythmic structure of environmental features may trigger processes related to natural attunement (for a comprehensive review: Djebbara et al., 2022).

3.2. The 'act of resonating': active exploration, attention, and detection

Active sensing and dynamic attending (Lakatos et al., 2019; Large and Jones, 1999) are two essential components that can modulate in a top-down fashion the intrinsic (and entrained) neural oscillations of the perceptual systems.⁶ These skills also play an important role in rhythmic stimulation rooted in the built environment. Active sensing is based on a collaboration of motor and sensory rhythms (e.g., sniffing, eye movement, and saccades or microsaccades) and serves as a gating mechanism for sensory inflow, optimizing perceptual sensitivity by temporally aligning the high-excitability phase of oscillations. This involves actively detecting and then enhancing the sensing of behaviorally relevant environmental information (while suppressing other irrelevant aspects), as well as preparing the system for future input flows through the formation of rhythmic expectations (Schroeder et al., 2010; VanRullen, 2016). Rhythmic temporal predictions, inferred from both periodic and

aperiodic patterns (Rimmele et al., 2018), enable modulation of the entrained oscillations⁷ through top-down control mechanisms, e.g., by shaping attention allocation, manifested in cyclical alternations between optimal and sub-optimal behavioral performance that are not directly linked to eye-movement or saccades (Helfrich et al., 2019; VanRullen, 2016).

Evidence suggests that visual detection performance fluctuates at 4 Hz when two different locations are alternatively visually sampled, while an overall sampling of the visual scene is thought to operate at 8 Hz (Landau and Fries, 2012). It has been proposed that active sensing of the environmental space is facilitated by dynamic periodicities in visuospatial attention (4 – 8 Hz) alternating between two modes of sampling: an *exploratory mode* as a continuous exploration of space when visual information is unpredictable, and a *rhythmic mode* in the presence of predictable events and of perceptual information relevant to the agent's intention (Gaillard and Ben Hamed, 2022; Schroeder et al., 2010; VanRullen, 2018). Even when attention is sustained at a behaviorally relevant location, there is a rhythmic fluctuation between periods of heightened and reduced perceptual sensitivity (Fiebelkorn and Kastner, 2019; Helfrich et al., 2018; Lakatos et al., 2008; Landau and Fries, 2012). During epochs of reduced perceptual sensitivity, attention can be shifted to explore other locations and reassess the value of the object of attention. Furthermore, it has been speculated that the resonant frequency of neural networks can be under top-down control of attention, which can, in turn, modulate bottom-up entrainment effects (Helfrich et al., 2017, 2018, 2019). If attention operates as a process at the higher-level intentional scale that supports the detection of ecological information based on our intentions, then a constraint on the resonant attentional networks can also modulate the entrainment of neural oscillations driven by sensory input flow. Brain rhythms are thus used as active instruments of perceptual selection, calibrating (and calibrated by) attention⁸ to external input based on its extrinsic structural salience or its intrinsic value, e.g., the agent's intention (Gaillard and Ben Hamed, 2022). It is worth noting that the latter case is closely linked to the idea of ecological resonance, where the dynamics of a higher-level intentional scale constrain the dynamics of the nested neural scale (Raja, 2018).

4. Natural attunement: rhythmic built environments

So far, not much has been said about natural attunement. We clarify with a definition that is deeply inspired by Vara Sánchez (2023, p. 61): Attunement refers to the quality of an experience, perceiving our actions, emotions, or thoughts as being influenced by and influencing elements within the surrounding world. It can sometimes be associated with the process of entrainment, where there is an alignment of our experiences with external rhythms or patterns. Attunement captures the sense of connection we feel with a particular thing, event, or person. 'Natural Attunement', may arise from a state of partial or complete entrainment. There are circumstances where we perceive our movements or emotions aligning with a song, a text, or the rhythms of the city, even in the absence of measurable entrainment. Nonetheless, in many cases, the experience of attunement is a result of being entrained to some degree.

We can naturally become attuned to qualities encountered through our rhythmic interaction and coupling with the world. Now whether and

⁶ The idea of active sensing is fundamental to the concept of direct perception and resonance in ecological psychology: "That is, perceivers must learn to put their perceptual systems in the appropriate resonant state-configuration. As examples, rubbing a surface with the fingers is being in an appropriate state-configuration for detecting texture, hefting is the state-configuration for detecting weight" (Michaels and Carello, 1981, p. 81). A similar idea is discussed by Gibson: "The state of a perceptual system is altered when it is attuned to information of a certain sort. The system has become sensitized. Differences are noticed that were previously not noticed. Features become distinctive that were formerly vague" (J. Gibson, 1986, p. 249).

⁷ Temporal and spatial expectations linked to entrainment of low-frequency neuronal oscillations may result in cross-frequency coupling influencing the power fluctuation of relevant faster oscillations, such as alpha power associated with inhibition mechanisms (Haegens and Zion Golumbic, 2018; Kizuk and Mathewson, 2017; Rohenkohl and Nobre, 2011).

⁸ The idea of 'calibration' is also found in ecological psychology and refers to the process by which a system might change in terms of what response it generates given a particular input variable (Jacobs and Michaels, 2007).

under what condition such experiential quality has its physical scaffolding in neuronal couplings is an avenue to be explored. We assume that: when the specific rhythmic event is quantifiable, such as in cases of repetition or predicted intervals, then this experience can be the result of the phenomenon of entrainment. Furthermore, in cases where a singular event in the sensory stream is powerful (e.g., due to its unexpectedness or aesthetic experience) it is possible that the concept ‘resonance’ can be used to explain this impact. The empirical and measurable dynamics of entrainment and resonance are often behind the process of coordination and of attunement.

As we have shown above, natural attunement can happen on a variety of scales, from perception and action to complex neural dynamics caused by actual environments. We argue that the alignment of a person’s neural and physiological processes with the environment can influence their cognition, perception, and behavior. A key concept to elucidate natural attunement stems from ecological psychology, namely sensing the affordances that are available in the environment. Affordances shape the way the brain registers sensory information and the continuous response (Bonner and Epstein, 2017; Cisek, 2007; Djebbara et al., 2021). Natural attunement to the affordances of the environment also has an impact on the affective experience. During disorientation, for example, spontaneous affordance-sensing (Proust, 2015) can be significantly weakened as the active navigation process becomes unreliable, causing feelings of anxiety and confusion (Fernández Velasco, 2022; Fernández Velasco and Casati, 2020). On the other hand, the re-attunement to the affordances of the visuospatial environment can cause the well-known euphoric Aha!-feeling of sudden re-orientation (Charalambous et al., 2021). We can also enhance our navigational skills by becoming attuned to different features in the environment. For example, attunement to the tile pavement for impaired people in urban areas enhances their perception of the environment by translating the rhythm of the tiles into auditory and haptic sensory wave-like input flows. Given this extraordinary neural capacity, it is, however, also possible for an external signal to interfere with internal signals and disrupt neural communication. Exposure to acoustic noise, for instance, can negatively affect the processing of speech in the auditory cortex, making it harder to understand spoken words.

In his recent book, *Vara Sánchez* (2023) explores various perspectives on the notion of rhythm, for instance, rhythm as movement, form, energy, and even of rhythmic events as consisting of time-space-energy (i.e., Lefebvre’s view) or of time-rhythms and affect-rhythms (i.e., Nietzsche’s view). One of the most relevant to architectural experience is Plato’s view, which is that rhythm is order in movement as opposed to seeing rhythm as a regular construction of patterns (Vara Sánchez, 2022). As *Vara Sánchez* (2023) comments, it prevents movement from disappearing by narrowing its possibilities down to a few relevant ones. Accordingly, rhythm can also refer to a quality of an event that interrupts the regular flow of experience and invites a new particular way of looking. Such views of rhythmicity suggest a multilayer and complex phenomenon particularly relevant to the discourse in aesthetics beyond the neural domain. Indeed, a rhythm cannot always be reduced to regular repetitions (Large et al., 2015; Obleser et al., 2017). However, the more intuitive, narrow notion of rhythm as enacted repetition has a greater possibility of leading to absolute body-brain entrainment. In the built environment, rhythmic structures are present not only in the urban fabric but can be also expressed in the design of doors, pavements, windows, columns, and other architectural elements (Chan, 2012). However, what empirically measurable units are these rhythms? What do these external signals consist of?

4.1. Built rhythms

Insofar, the unit and quantification of the said external signal have not been explicitly named. This is because rhythmic stimulation by the built environment can occur through several mediums. For instance, Olafur Eliasson is famous for finding innovative ways of playing with

rhythm through light and atmosphere (see Fig. 4A, ‘Your Black Horizon’ with David Adjaye, Venice, Italy), while Santiago Calatrava manages to obtain a similar rhythmic effect through repetition of massive structures (see Fig. 4B, ‘World Trade Center Transportation Hub,’ New York, US). Aldo Rossi, the Italian architect, rose to fame due to his rhythmic and patterned structural work (see Fig. 4C, ‘San Cataldo,’ Modena, Italy). Carlo Scarpa pioneered a tight formalism of staircases that not only afforded sensory entrainment but motor entrainment beyond active sampling (see Fig. 4D, ‘Brion cemetery,’ San Vito d’Altivole, Italy). Furthermore, the use of certain materials can also engender attunement such as the eucalyptus wood wraps on the exterior walls at the Burkina Institute of Technology (Fig. 4E) in Koudougou, Burkina Faso by Diébédo Francis Kéré, which convey a unique natural rhythm experienced from the exterior and interior as a rhythmic shading of the corridors. Greek architecture, too, displayed rhythmic columns (see Fig. 4F, the Stoa of Attalos, Athens, Greece, circa 120 BCE). Acoustic landscapes too carry the potential for natural attunement with the environment. Jørgen Utzon famously drew the Sydney Opera with acoustic properties in mind—a technique he reused for Bagsværd Kirke, Copenhagen, Denmark.

Different layers of rhythm within a particular structure (or urban configuration and landscape) also appear in the built environment. For instance, as Pallasmaa comments, Alvar Aalto’s use of the forest metaphor at Villa Mairea (Fig. 4G) results in a ‘haptic fusion of tectonic architectural space and an amorphous and spontaneously rhythmic ‘forest space’” (Pallasmaa, 2014, p. 31). Also, the convent of ‘Saint Marie de la Tourette’ (Fig. 4H) in Eveux-sur-l’Arbresle in Lyon, France by Le Corbusier demonstrates a multi-rhythmic structure through the ‘undulating glass panes’ of Iannis Xenakis. This holds the potential for both phase resetting and neural interference. Based on the structure of Le Corbusier’s corridor, and for illustrative purposes, we include here an example of how the visual cortex reporting on the peripheral vision can be entrained by rhythms in the built environment (Fig. 5).

Furthermore, it is worth mentioning that there are different qualities of rhythm that we can experience in the built environment. Rhythm can be linked to the experience of a tension between oppositions and the particular way in which something appears to us and in turn affects us and our rhythms (Vara Sánchez, 2023). We can become attuned not because of a repetitive wave-like rhythm, but due to the quality of the event and the invitation to look at things in a particular way. The ‘Bunker 599’ (Fig. 4I) designed by studio RAAAF (Rietveld and Rietveld, 2017) is an illustrative example that can potentially lead to partial perceptual entrainment or transient resonance. The stairway that cuts through the bunker invites the visitors to inspect the otherwise invisible interior while at the same time, their attention is constrained by the built form to a well-defined view of the exterior landscape and the water. The path reveals the coastline of the Netherlands and the historical significance of the bunker evoking an experience that connects the present with the past. Such architectural elements that constrain our movement and attention invite us to a particular form of experience to which we become attuned.

4.2. Towards an empirical inquiry

At least two things stand clear: (1) the unit and quantification of naturally occurring rhythmic stimulations can emerge in various forms and through various modalities and (2) though used often, rhythms and patterns are by no means novel to architects. However, their relation to the brain remains an untouched potential that could explain the trans-historical existence of rhythms and patterns throughout numerous cultures independently. This brings to mind Semir Zeki’s opinion on artists throughout history. Architects, too, may have been “[...] neurologists, studying the brain with techniques that are unique to them and reaching interesting but unspecified conclusions about the organization of the brain” (Zeki, 1998, p. 77). Patterns, beyond their visual aesthetics, may have been attractive due to the emerging natural attunement when

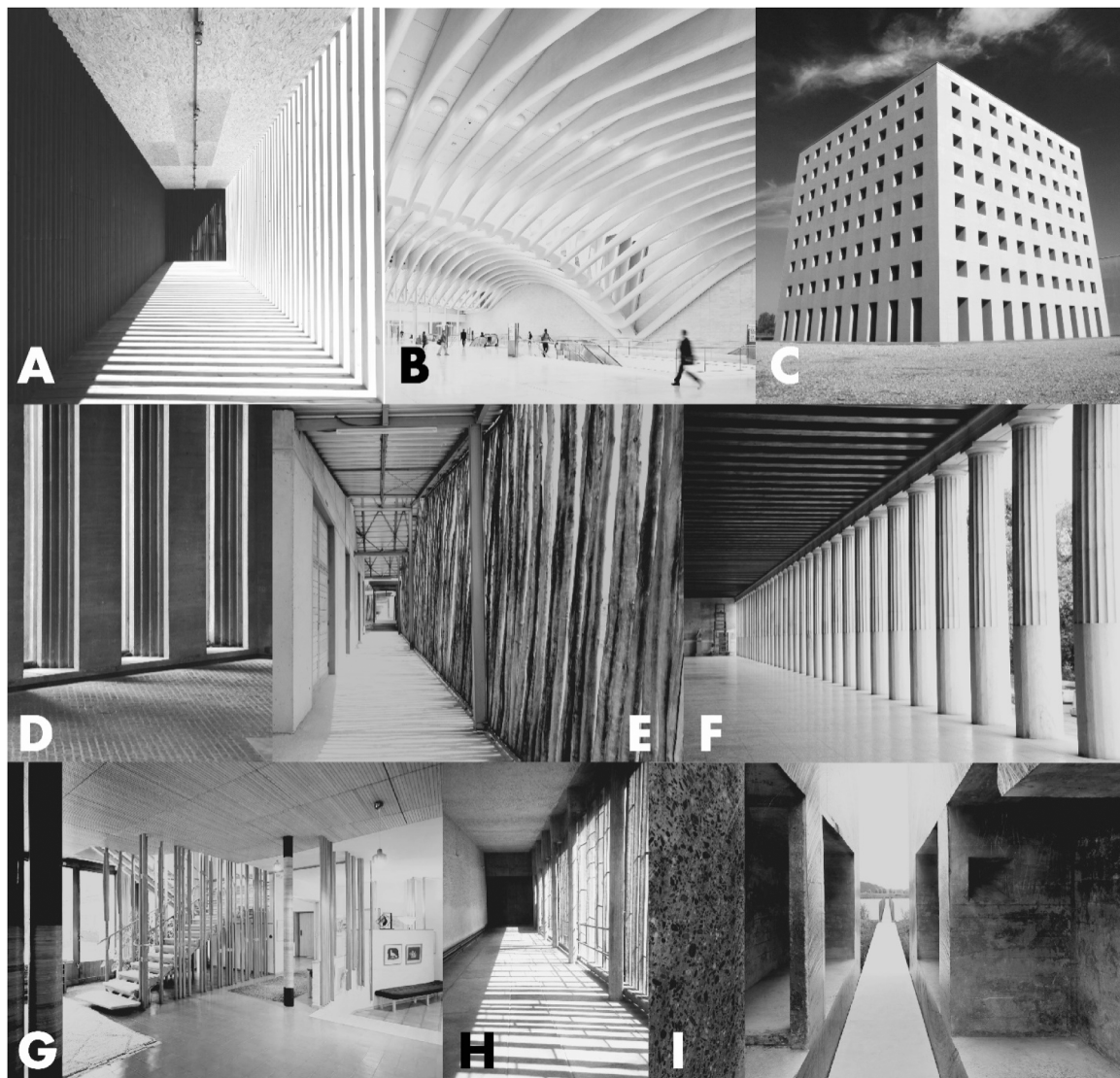


Fig. 4. A. 'Your Black Horizon' by Olafur Eliasson + David Adjaye. Image credit: Olafur Eliasson/TBA21. B. 'World Trade Center Transportation Hub' by Santiago Calatrava. Image credit: Photo © Alan Karchmer. C. 'San Cataldo' by Aldo Rossi. Image credit: Maria Lucia Lusetti Paolo Tedeschi. D. 'Brion Cemetery' by Carlo Scarpa. Image credit: seier+seier. E. 'Burkina Institute of Technology' by Kéré Architecture. Image credit: Jaime Herraiz Martínez/Kéré Architecture. F. Stoa of Attalos in Athens, Greece. Image credit: Jorge Láscar. G. 'Villa Mairea' by Alvar Alto. Image credit: © Åke E:son Lindman. H. Saint Marie de la Tourette by Le Corbusier. Image credit: jpm. I. 'Bunker 599' by RAAAF Studio. Image credit: RAAAF Studio.

interacting with the built environment.

Visual rhythms are more likely not to occur in a strict oscillatory fashion. Due to the variance of the movement, saccades, and structure of the environment, it is difficult to precisely induce a specific frequency in any sensory receptor. While visual dynamics vary a great deal, the structure of the environment remains invariant. The external signal can trigger a modulation of the oscillations of the visual periphery offering possibilities of coordination with the environmental features as well as the emergence of the experiential quality of attunement. However, the phase of the external signal depends greatly on the movement of the body. Adults' typical walking speeds vary depending on several variables, including age, level of fitness, health, and terrain. On flat ground, however, the typical average walking speed for adults is generally thought to be between 4.8 and 6.4 kilometers per hour (Fitzpatrick et al., 2006). This pace can change depending on the individual and may be influenced by factors like the purpose of the walk (e.g., stroll vs. brisk walk), the terrain (e.g., uphill vs. downhill), and other individual factors such as age (Montufar et al., 2007). Due to their physical condition, walking style, or personal preferences, some people may walk slower or

faster than the average of a normally distributed estimate of walking speed. With the possibility of generating estimates, it allows for the design of experimental conditions where the peripheral vision can fluctuate according to some desired frequency under some uncertainty. Combining this with Mobile Brain/Body Imaging (Gramann et al., 2014; Makeig et al., 2009) allows for simultaneous measures of neural activity, body posture, and the built environment, i.e. brain, body, and environment, respectively, which is the hallmark of embodied cognition (Parada and Rossi, 2020; Wang et al., 2022).

Although built rhythms may cause a flicker in our visual periphery throughout our everyday lives, we do not perceive it the same way as a flickering light in the hallway. One possible reason for that is that we expect a change in sensory patterns and optic flow when we move in the world, which in turn corrects for detected sensory changes caused by self-movement. The contingency between sensory and motor processes is a critical feature for the emergence of perception (Di Paolo et al., 2017; O'Regan and Noë, 2001), and thus occurs without deliberate attention. Due to limited cognitive resources, it is necessary for such automatic processes to strategically rely on prior experiences, habits,

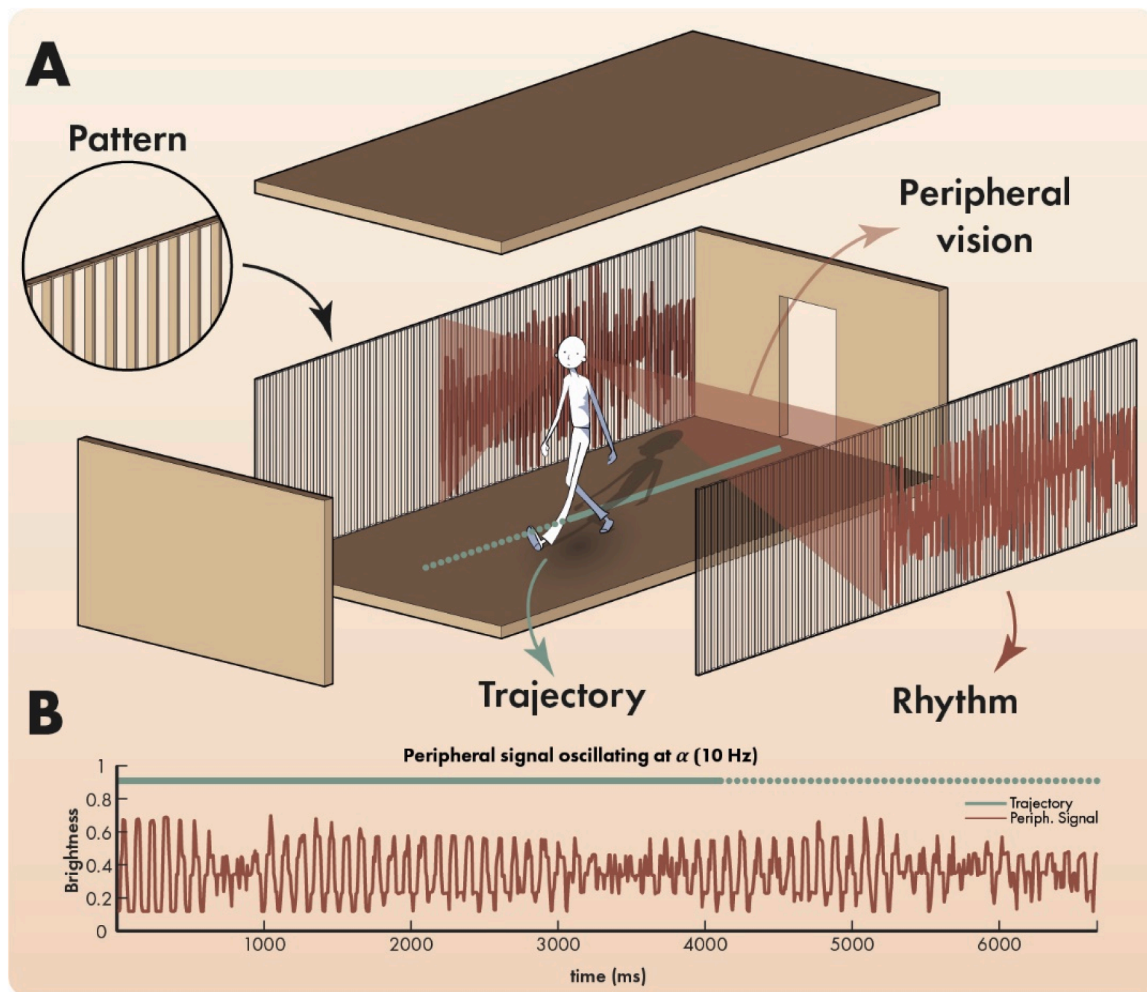


Fig. 5. A. An example of how architectural features, such as a recurrent pattern operating in the periphery of our vision, may essentially induce a rhythmic and entraining signal. The figure illustrates the difference between a pattern and a rhythm. While a pattern is a spatial concept, a rhythm is the enactment of patterns through time. The transparent red triangles illustrate the peripheral limits and how these may cause a rhythmic signal, illustrated on the walls. The solid green line on the floor represents the passed trajectory, whereas the dotted lines represent the trajectory to come. B. Externally induced peripheral signal oscillating at the cortical alpha band. The red signal represents the rhythmic trajectory of brightness as perceived from the periphery of vision, while the green line represents the position in space. The dotted green lines represent the future trajectory, while the solid one represents the past trajectory. The illustrated data is from a single participant, where the walking speed was not indicated by the researchers. A natural attunement occurs, informing the movement velocity through optical resonance with the peripheral dynamics.

cultural norms, etc., which in turn allows freeing up mental capacity for other purposes. According to the predictive coding hypothesis of the brain, automatic processes depend on ascending prediction errors conveying unexpected information through various sensory channels not anticipated by descending signals (Friston, 2010). These ascending signals modify descending predictions with varying levels of certainty encoded within them (Djebbara et al., 2022). This process is mirrored in the excitability of neuronal groups, where sensory channels with high confidence levels are allowed to pass through the filter and impact the descending predictions in multiple cortical regions. Increasing evidence displays the pulvinar, which is a key nucleus for early visual processing in the thalamus, as holding an integrative and bridge-like function between cortical regions (Blot et al., 2021; Saalman et al., 2012; for review: Halassa and Kastner, 2017).

While the pulvinar has for long been described as the generator of the alpha oscillation in the brain (Lopes da Silva et al., 1974), there is now emerging evidence (e.g.: Halgren et al., 2019) that demonstrates how the pulvinar can generate alpha oscillation that in turn can carry descending predictions and ascending prediction errors (Friston, 2019; Alamia and VanRullen, 2019). These waves of predictions have been coined the “travelling alpha waves” and portray predictive coding as a

rhythmic phenomenon. As the pulvinar plays a role in the alpha generation while also being sensitive to early visual processing, it can be hypothesized that built rhythms can bias, through perturbation, the ascending confidence levels of each sensory channel, which in turn may affect the generated alpha waves. Interestingly, if built rhythms can affect the generation of the alpha waves at the level of the pulvinar, which plays an integrative role between cortical regions, it may further be hypothesized that cognitive processes that require the integration of cortical regions can be affected by built rhythms. This not only speaks to the importance of understanding built rhythms, but further to embrace naturalistic paradigms as the structure of the environment itself may affect cognition to an extent that renders static laboratory experiments futile.

The example provided in Fig. 5 is not the culmination of natural attunement, but merely an example of how rhythms from the visual periphery can have an entraining effect. As demonstrated above, rhythms may dive as deep as the pulvinar and attest to the importance of advancing our understanding of their role. The empirical inquiry of natural attunement and underlying dynamic processes offers a novel approach to understanding the interactive relationship between different rhythmic phenomena in the built environment, the body, and

the brain, through modulations in cognition and behavior. Additionally, it advances a richer quantification of the environment than the neuroscientific literature currently offers. Converting the built environment to wave-like rhythms could potentially change how we conceptualize the built environment in neuroscience. Its fundamental significance for cognition and behavior is clear, and hopefully, future neuroscience research will acknowledge the role of the built environment as a key variable in empirical studies.

5. Closing remarks

Rhythms are everywhere in our daily interaction with the built environment. Similarly, the nature of the brain and body is inherently rhythmic (Buzsáki, 2006). Expectedly, different brains, bodies, and environments rhythms influence each other through different physical relational processes and, according to enactivist views are "dynamically coupled in a way that forms a system" (Gallagher, 2017, p. 8). The presented perspective on bridging the agent and environment through rhythms will hopefully function as a novel and tractable approach for several disciplines, e.g., computer science, neuroscience, psychology, and architecture.

In exploring how visual rhythmic simulations of the environment couple with and affect the brain and body, the paper has provided multiple ways in which this can occur, including neural tracking, entrainment, active sampling, cross-frequency coupling, and phase resetting. Furthermore, numerous examples have been given of everyday interactions with the built environment that can give rise to rhythmic stimulation. We acknowledge that environmental features are rarely characterized by such strictly rhythmic forms that can produce fully periodic oscillations as typically employed in neural entrainment experiments. The real world is chaotic and will most likely give rise to nonperiodic oscillations within a band of frequencies. Although periodicity is not required for neural entrainment, including either in the narrow or broad sense, there is a possibility that environmental characteristics can elicit sensory dynamics that are adequate, i.e. Arnold's tongue, for entraining the brain. Dynamic coupling between our brains and bodies with environmental features, defined neurophysiological mechanisms of neural entrainment can trigger automated sensorimotor responses (Djebbara et al., 2022), which we can experience as natural attunement. This is only possible due to the existence of multiple interconnected rhythms. Although patterns continue to make up a large part of our homes, cities, and workplaces, the concept of rhythms (and thereby time and action) remain arguably dimensions not yet fully explored.

The practical argument we make is that the agent's action and environmental features together, over time and in orchestration, contribute to the neural dynamics that are critical for a range of capacities, including memory, attention, multisensory integration, and motor behavior. Consequently, the built environment may be influencing us more deeply and in more ways than we realize, as our brains become attuned to the rhythms and sensory inputs of the built environment. In an entirely natural way, we become rhythmically connected to our environment. Perhaps in the future, architects will not only design cities and buildings but also neuroscience-informed designs that enable possibilities that align with the very workings of our minds.

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References

- Alamia, A., VanRullen, R., 2019. Alpha oscillations and traveling waves: signatures of predictive coding? *PLoS Biol.* 17 (10), e3000487 <https://doi.org/10.1371/journal.pbio.3000487>.
- Albouy, P., Weiss, A., Baillet, S., Zatorre, R.J., 2017. Selective entrainment of theta oscillations in the dorsal stream causally enhances auditory working memory performance. *Neuron* 94 (1), 193–206.e5. <https://doi.org/10.1016/j.neuron.2017.03.015>.
- Albouy, P., Martinez-Moreno, Z.E., Hoyer, R.S., Zatorre, R.J., Baillet, S., 2022. Supramodality of neural entrainment: rhythmic visual stimulation causally enhances auditory working memory performance. *Sci. Adv.* 8 (8), eabj9782.
- Alekseichuk, I., Turi, Z., Amador de Lara, G., Antal, A., Paulus, W., 2016. Spatial working memory in humans depends on theta and high gamma synchronization in the prefrontal cortex. *Curr. Biol.: CB* 26 (12), 1513–1521. <https://doi.org/10.1016/j.cub.2016.04.035>.
- Anderson, M.L., 2010. Neural reuse: a fundamental organizational principle of the brain. *Behav. Brain Sci.* 33 (4), 245–266.
- Bánki, A., Brzozowska, A., Hoehl, S., Köster, M., 2022. Neural entrainment vs. stimulus-tracking: a conceptual challenge for rhythmic perceptual stimulation in developmental neuroscience. *Front. Psychol.* 13, 878984 <https://doi.org/10.3389/fpsyg.2022.878984>.
- Blot, A., Roth, M.M., Gasler, I., Javadzadeh, M., Imhof, F., Hofer, S.B., 2021. Visual intracortical and transthalamic pathways carry distinct information to cortical areas. *e6 Neuron* 109 (12), 1996–2008. <https://doi.org/10.1016/j.neuron.2021.04.017>.
- Bonner, M.F., Epstein, R.A., 2017. Coding of navigational affordances in the human visual system. *Proc. Natl. Acad. Sci. USA* 114 (18), 4793–4798. <https://doi.org/10.1073/pnas.1618228114>.
- Brunswick, E., 1956. Perception and the representative design of psychological experiments. Univ of California Press.
- Buzsáki, G., 2006. Rhythms of the brain. Oxford University Press.
- Calderone, D.J., Lakatos, P., Butler, P.D., Castellanos, F.X., 2014. Entrainment of neural oscillations as a modifiable substrate of attention. *Trends Cogn. Sci.* 18 (6), 300–309. <https://doi.org/10.1016/j.tics.2014.02.005>.
- Canepa, E. (2022). *Generators of Architectural Atmosphere*.
- Chan, C.-S., 2012. Phenomenology of rhythm in design. *Front. Archit. Res.* 1 (3), 253–258. <https://doi.org/10.1016/j.foar.2012.06.003>.
- Charalambous, E., Hanna, S., Penn, A., 2021. Aha! I know where I am: the contribution of visuospatial cues to reorientation in urban environments. *Spat. Cogn. Comput.* 21 (3), 197–234.
- Chemero, A., 2013. Radical embodied cognitive science. *Rev. Gen. Psychol.* 17 (2), 145–150.
- Cisek, P., 2007. Cortical mechanisms of action selection: the affordance competition hypothesis. *Philos. Trans. R. Soc. B: Biol. Sci.* 362 (1485), 1585–1599. <https://doi.org/10.1098/rstb.2007.2054>.
- Clouter, A., Shapiro, K.L., Hanslmayr, S., 2017. Theta phase synchronization is the glue that binds human associative memory. *Curr. Biol.* 27 (20), 3143–3148.
- Cosmelli, D., Lachaux, J.-P., Thompson, E., 2007. Neurodynamics of consciousness. *Camb. Handb. Conscious.* 2, 229–239.
- Cravo, A.M., Rohenkohl, G., Wyart, V., Nobre, A.C., 2013. Temporal expectation enhances contrast sensitivity by phase entrainment of low-frequency oscillations in visual cortex. *J. Neurosci.* 33 (9), 4002–4010.
- Czeszumski, A., Eustergerling, S., Lang, A., Menrath, D., Gerstenberger, M., Schubert, S., Schreiber, F., Rendon, Z.Z., König, P., 2020. Hyperscanning: a valid method to study neural inter-brain underpinnings of social interaction. *Front. Hum. Neurosci.* Vol. 14. (<https://www.frontiersin.org/articles/10.3389/fnhum.2020.00039>).
- Daume, J., Wang, P., Maye, A., Zhang, D., Engel, A.K., 2021. Non-rhythmic temporal prediction involves phase resets of low-frequency delta oscillations. *Neuroimage* 224, 117376.
- De Graaf, T.A., Gross, J., Paterson, G., Rusch, T., Sack, A.T., Thut, G., 2013. Alpha-band rhythms in visual task performance: phase-locking by rhythmic sensory stimulation. *PLoS One* 8 (3), e60035.
- de Wit, M.M., de Vries, S., van der Kamp, J., Withagen, R., 2017. Affordances and neuroscience: steps towards a successful marriage. *Neurosci. Biobehav. Rev.* 80, 622–629.
- Deco, G., Rolls, E.T., Romo, R., 2009. Stochastic dynamics as a principle of brain function. *Prog. Neurobiol.* 88 (1), 1–16.
- Di Gregorio, F., Trajkovic, J., Roperti, C., Marcantoni, E., Di Luzio, P., Avenanti, A., Thut, G., Romei, V., 2022. Tuning alpha rhythms to shape conscious visual perception. *Curr. Biol.* 32 (5), 988–998. <https://doi.org/10.1016/j.cub.2022.01.003>.
- Di Paolo, E., Buhrmann, T., Barandiaran, X., 2017. Sensorimotor life: an enactive proposal. Oxford University Press.
- Djebbara, Z., Fich, L.B., Gramann, K., 2021. The brain dynamics of architectural affordances during transition. *Sci. Rep.* 11 (1), 2796 <https://doi.org/10.1038/s41598-021-82504-w>.
- Djebbara, Z., Fich, L.B., Petrini, L., Gramann, K., 2019. Sensorimotor brain dynamics reflect architectural affordances. *Proc. Natl. Acad. Sci. USA* 116 (29), 14769–14778. <https://doi.org/10.1073/pnas.1900648116>.
- Djebbara, Z., Jensen, O.B., Parada, F.J., Gramann, K., 2022. Neuroscience and Architecture: modulating behavior through sensorimotor responses to the built environment. *Neurosci. Biobehav. Rev.*, 104715 <https://doi.org/10.1016/j.neubiorev.2022.104715>.
- Doelling, K.B., Poeppel, D., 2015. Cortical entrainment to music and its modulation by expertise. *Proc. Natl. Acad. Sci.* 112 (45), E6233–E6242.

- Dotov, D.G., Nie, L., Chemero, A., 2010. A demonstration of the transition from ready-to-hand to unready-to-hand. *PLoS One* 5 (3), e9433.
- Dumas, G., 2011. Towards a two-body neuroscience. *Commun. Integr. Biol.* 4 (3), 349–352. <https://doi.org/10.4161/cib.4.3.15110>.
- Falandays, J.B., Yoshimi, J., Warren, W., Spivey, M., 2023. A potential mechanism for gibsonian resonance: behavioral entrainment emerges from local homeostasis in an unsupervised reservoir network. February.
- Fernandez Velasco, P., Casati, R., 2020. Subjective disorientation as a metacognitive feeling. *Spat. Cogn. Comput.* 20 (4), 281–305.
- Fernández Velasco, P., 2022. Group navigation and procedural metacognition. *Philos. Psychol.* 1–19.
- Fiebelkorn, I.C., Kastner, S., 2019. The Puzzling Pulvinar. *Neuron* 101 (2), 201–203. <https://doi.org/10.1016/j.neuron.2018.12.032>.
- Fitzpatrick, K., Brewer, M.A., Turner, S., 2006. Another look at pedestrian walking speed. *Transp. Res. Rec.* 1982 (1), 21–29.
- Fries, P., 2005. A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. *Trends Cogn. Sci.* 9 (10), 474–480. <https://doi.org/10.1016/j.tics.2005.08.011>.
- Friston, K., 2010. The free-energy principle: a unified brain theory? *Nat. Rev. Neurosci.* 11 (2), 127–138. <https://doi.org/10.1038/nrn2787>.
- Friston, K.J., 2019. Waves of prediction. *PLOS Biol.* 17 (10), e3000426 <https://doi.org/10.1371/journal.pbio.3000426>.
- Gaillard, C., Ben Hamed, S., 2022. The neural bases of spatial attention and perceptual rhythms. *Eur. J. Neurosci.* 55 (11–12), 3209–3223.
- Gallagher, S., 2017. *Enactivist interventions: rethinking the mind*, first ed. Oxford University Press.
- Gibson, J., 1986. *The Ecological Approach to Visual Perception*. Psychology Press - Taylor & Francis Group.
- Gibson, J.J., 1966. *The Senses Considered as Perceptual Systems*, first ed. Houghton Mifflin.
- Golumbic, E.M.Z., Ding, N., Bickel, S., Lakatos, P., Schevon, C.A., McKhann, G.M., Goodman, R.R., Emerson, R., Mehta, A.D., Simon, J.Z., 2013. Mechanisms underlying selective neuronal tracking of attended speech at a “cocktail party.”. *Neuron* 77 (5), 980–991.
- Gramann, K., Ferris, D.P., Gwin, J., Makeig, S., 2014. Imaging natural cognition in action. *Int. J. Psychophysiol.: Off. J. Int. Organ. Psychophysiol.* 91 (1), 22–29. <https://doi.org/10.1016/j.ijpsycho.2013.09.003>.
- Griffero, T., 2014. Architectural affordances: The atmospheric authority of spaces. *Archit. Atmosph.* 15–47.
- Guan, F., Xiang, Y., Chen, O., Wang, W., Chen, J., 2018. Neural basis of dispositional awe. *Front. Behav. Neurosci.* 12, 209.
- Haegens, S., 2020. Entrainment revisited: a commentary on Meyer, Sun, and Martin (2020). *Lang., Cogn. Neurosci.* 35 (9), 1119–1123.
- Haegens, S., Zion Golumbic, E., 2018. Rhythmic facilitation of sensory processing: a critical review. *Neurosci. Biobehav. Rev.* 86, 150–165. <https://doi.org/10.1016/j.neubiorev.2017.12.002>.
- Haken, H., Kelso, J.A.S., Bunz, H., 1985. A theoretical model of phase transitions in human hand movements. *Biol. Cybern.* 51 (5), 347–356.
- Halassa, M.M., Kastner, S., 2017. Thalamic functions in distributed cognitive control. *Nat. Neurosci.* 20 (12), 1669–1679. <https://doi.org/10.1038/s41593-017-0020-1>.
- Halgren, M., Ulbert, I., Bastuji, H., Fabó, D., Eröss, L., Rey, M., Devinsky, O., Doyle, W.K., Mak-McCully, R., Halgren, E., Wittner, L., Chauvel, P., Heit, G., Eskandar, E., Mandell, A., Cash, S.S., 2019. The generation and propagation of the human alpha rhythm, 23772 LP – 23782 Proc. Natl. Acad. Sci. 116 (47). <https://doi.org/10.1073/pnas.1913092116>.
- Hanslmayr, S., Axmacher, N., Inman, C.S., 2019. Modulating human memory via entrainment of brain oscillations. *Trends Neurosci.* 42 (7), 485–499.
- Heft, H., 2001. *Ecological psychology in context: James Gibson, Roger Barker, and the legacy of William James's radical empiricism*. Psychology Press.
- Helfrich, R.F., Breska, A., Knight, R.T., 2019. Neural entrainment and network resonance in support of top-down guided attention. *Curr. Opin. Psychol.* 29, 82–89. <https://doi.org/10.1016/j.copsyc.2018.12.016>.
- Helfrich, R.F., Huang, M., Wilson, G., Knight, R.T., 2017. Prefrontal cortex modulates posterior alpha oscillations during top-down guided visual perception. *Proc. Natl. Acad. Sci.* 114 (35), 9457–9462.
- Helfrich, R.F., Fiebelkorn, I.C., Szczepanski, S.M., Lin, J.J., Parvizi, J., Knight, R.T., Kastner, S., 2018. Neural mechanisms of sustained attention are rhythmic. *Neuron* 99 (4), 854–865.
- Henry, M.J., Herrmann, B., Obleser, J., 2014. Entrained neural oscillations in multiple frequency bands comodulate behavior. *Proc. Natl. Acad. Sci.* 111 (41), 14935–14940.
- Hutcheon, B., Yarom, Y., 2000. Resonance, oscillation and the intrinsic frequency preferences of neurons. *Trends Neurosci.* 23 (5), 216–222.
- Izhikevich, E.M., Desai, N.S., Walcott, E.C., Hoppensteadt, F.C., 2003. Bursts as a unit of neural information: selective communication via resonance. *Trends Neurosci.* 26 (3), 161–167.
- Jacobs, D.M., Michaels, C.F., 2007. Direct learning. *Ecol. Psychol.* 19 (4), 321–349.
- Jensen, O., Gelfand, J., Kounios, J., Lisman, J.E., 2002. Oscillations in the alpha band (9–12 Hz) increase with memory load during retention in a short-term memory task. *Cereb. Cortex* 12 (8), 877–882. <https://doi.org/10.1093/cercor/12.8.877>.
- Keitel, C., Quigley, C., Ruhnau, P., 2014. Stimulus-driven brain oscillations in the alpha range: entrainment of intrinsic rhythms or frequency-following response? *J. Neurosci.* 34 (31), 10137–10140.
- Keitel, C., Thut, G., Gross, J., 2017. Visual cortex responses reflect temporal structure of continuous quasi-rhythmic sensory stimulation. *NeuroImage* 146, 58–70. <https://doi.org/10.1016/j.neuroimage.2016.11.043>.
- Kelso, J.A.S., Tognoli, E., 2007. Toward a complementary neuroscience: metastable coordination dynamics of the brain. In: Perlovsky, L.I., Kozma, R. (Eds.), *BT - Neurodynamics of Cognition and Consciousness*. Springer Berlin Heidelberg, pp. 39–59. https://doi.org/10.1007/978-3-540-73267-9_3.
- Kizuk, S.A.D., Mathewson, K.E., 2017. Power and phase of alpha oscillations reveal an interaction between spatial and temporal visual attention. *J. Cogn. Neurosci.* 29 (3), 480–494. https://doi.org/10.1162/jocn_a.01058.
- Klimesch, W., 2018. The frequency architecture of brain and brain body oscillations: an analysis. *Eur. J. Neurosci.* 48 (7), 2431–2453. <https://doi.org/10.1111/ejn.14192>.
- Köster, M., Martens, U., Gruber, T., 2019. Memory entrainment by visually evoked theta-gamma coupling. *NeuroImage* 188, 181–187. <https://doi.org/10.1016/j.neuroimage.2018.12.002>.
- Kurby, C.A., Zacks, J.M., 2008. Segmentation in the perception and memory of events. *Trends Cogn. Sci.* 12 (2), 72–79.
- Lakatos, P., Gross, J., Thut, G., 2019. A new unifying account of the roles of neuronal entrainment. *Curr. Biol.* 29 (18), R890–R905. <https://doi.org/10.1016/j.cub.2019.07.075>.
- Lakatos, P., Chen, C.-M., O'Connell, M.N., Mills, A., Schroeder, C.E., 2007. Neuronal oscillations and multisensory interaction in primary auditory cortex. *Neuron* 53 (2), 279–292.
- Lakatos, P., Karmos, G., Mehta, A.D., Ulbert, I., Schroeder, C.E., 2008. Entrainment of neuronal oscillations as a mechanism of attentional selection. *Science* 320 (5872), 110–113.
- Lakatos, P., Musacchia, G., O'Connell, M.N., Falchier, A.Y., Javitt, D.C., Schroeder, C.E., 2013. The spectrotemporal filter mechanism of auditory selective attention. *Neuron* 77 (4), 750–761.
- Landau, A.-N., Fries, P., 2012. Attention samples stimuli rhythmically. *Curr. Biol.* 22 (11), 1000–1004.
- Large, E.W., 2008. Resonating to musical rhythm: theory and experiment. *Psychol. Time* 189–231.
- Large, E.W., Jones, M.R., 1999. The dynamics of attending: how people track time-varying events. *Psychol. Rev.* 106 (1), 119–159. <https://doi.org/10.1037/0033-295X.106.1.119>.
- Large, E.W., Snyder, J.S., 2009. Pulse and meter as neural resonance. *Ann. N. Y. Acad. Sci.* 1169 (1), 46–57.
- Large, E.W., Herrera, J.A., Velasco, M.J., 2015. Neural networks for beat perception in musical rhythm. *Front. Syst. Neurosci.* 9, 159.
- Lau, T., Zochowski, M., 2011. The resonance frequency shift, pattern formation, and dynamical network reorganization via sub-threshold input. *PLoS One* 6 (4), e18983.
- Lee, D.N., 2009. General Tau Theory: evolution to date. *Perception* 38 (6), 837–850. <https://doi.org/10.1068/pmklee>.
- Leonards, U., Fennell, J.G., Oliva, G., Drake, A., Redmill, D.W., 2015. Treacherous pavements: paving slab patterns modify intended walking directions. *PLoS One* 10 (6), e0130034. <https://doi.org/10.1371/journal.pone.0130034>.
- Lopes da Silva, F.H., Hoeks, A., Smits, H., Zetterberg, L.H., 1974. Model of brain rhythmic activity. The alpha-rhythm of the thalamus. *Kybernetik* 15 (1), 27–37. <https://doi.org/10.1007/BF00270757>.
- Ludwig, C.J.H., Alexander, N., Howard, K.L., Jedrzejewska, A.A., Mundkur, I., Redmill, D., 2018. The influence of visual flow and perceptual load on locomotion speed. *Atten., Percept. Psychophys.* 80 (1), 69–81. <https://doi.org/10.3758/s13414-017-1417-3>.
- Makeig, S., Gramann, K., Jung, T.-P., Sejnowski, T.J., Poizner, H., 2009. Linking brain, mind and behavior. *Int. J. Psychophysiol.* 73 (2), 95–100. <https://doi.org/10.1016/J.IJPSYCHO.2008.11.008>.
- Malafouris, L., 2013. *How things shape the mind*. MIT press.
- Manser, M.P., Hancock, P.A., 2007. The influence of perceptual speed regulation on speed perception, choice, and control: tunnel wall characteristics and influences. *Accid. ; Anal. Prev.* 39 (1), 69–78. <https://doi.org/10.1016/j.aap.2006.06.005>.
- Mathewson, K.E., Prudhomme, C., Fabiani, M., Beck, D.M., Lleras, A., Gratton, G., 2012. Making waves in the stream of consciousness: entraining Oscillations in EEG alpha and fluctuations in visual awareness with rhythmic visual stimulation. *J. Cogn. Neurosci.* 24 (12), 2321–2333. https://doi.org/10.1162/jocn_a.00288.
- McDonnell, M.D., Abbott, D., 2009. What is stochastic resonance? Definitions, misconceptions, debates, and its relevance to biology. *PLoS Comput. Biol.* 5 (5), e1000348.
- Meyer, L., Sun, Y., Martin, A.E., 2020. Synchronous, but not entrained: exogenous and endogenous cortical rhythms of speech and language processing. *Lang., Cogn. Neurosci.* 35 (9), 1089–1099. <https://doi.org/10.1080/23273798.2019.1693050>.
- Michaels, C.F., & Carello, C. (1981). *Direct perception*. Prentice-Hall Englewood Cliffs, NJ.
- Montufar, J., Arango, J., Porter, M., Nakagawa, S., 2007. Pedestrians' normal walking speed and speed when crossing a street. *Transp. Res. Rec.* 2002 (1), 90–97.
- Moss, F., 1997. Noise is good for the brain. *Phys. World* 10 (2), 15.
- Northoff, G., 2016. Spatiotemporal psychopathology I: No rest for the brain's resting state activity in depression? Spatiotemporal psychopathology of depressive symptoms. *J. Affect. Disord.* 190, 854–866. <https://doi.org/10.1016/j.jad.2015.05.007>.
- Northoff, G., 2018. *The Spontaneous Brain: From the Mind-Body to the World-Brain Problem*. MIT Press.
- Notbohm, A., Kurths, J., Herrmann, C.S., 2016. Modification of brain oscillations via rhythmic light stimulation provides evidence for entrainment but not for superposition of event-related responses. *Front. Hum. Neurosci.* 10, 10.
- O'Regan, K., Noë, A., 2001. A sensorimotor account of vision and visual consciousness. *Behav. Brain Sci.* 24 (5), 939–1031.

- Obleser, J., Kayser, C., 2019. Neural entrainment and attentional selection in the listening brain. *Trends Cogn. Sci.* 23 (11), 913–926. <https://doi.org/10.1016/j.tics.2019.08.004>.
- Obleser, J., Henry, M.J., Lakatos, P., 2017. What do we talk about when we talk about rhythm? *PLoS Biol.* 15 (9), e2002794.
- Oliva, A., Torralba, A., 2006. Building the gist of a scene: the role of global image features in recognition. *Prog. Brain Res.* 155, 23–36.
- Pallasmaa, J. (2014). *Space, Place, and Atmosphere: Peripheral Perception in Existential Experience*. (C. Borch (ed.); pp. 18–41). Birkhäuser. <https://doi.org/doi:10.1515/9783038211785.18>.
- Parada, F.J., Rossi, A., 2020. Perfect Timing: Mobile Brain/Body Imaging scaffolds the 4E-cognition research program. *Eur. J. Neurosci.*, ejn 14783. <https://doi.org/10.1111/ejn.14783>.
- Proust, J. (2015). Feelings as evaluative indicators. In *Open MIND*. Open MIND. Frankfurt am Main: MIND Group.
- Raichle, M.E., MacLeod, A.M., Snyder, W.J., Gusnard, D.A., Shulman, G.L., 2001. A default mode of brain function, 676 LP – 682 *Proc. Natl. Acad. Sci.* 98 (2). <https://doi.org/10.1073/pnas.98.2.676>.
- Raja, V., 2018. A theory of resonance: towards an ecological cognitive architecture. *Minds Mach.* 28, 29–51.
- Raja, V., 2019. From metaphor to theory: the role of resonance in perceptual learning. *Adapt. Behav.* 27 (6), 405–421.
- Raja, V., 2021. Resonance and radical embodiment. *Synthese* 199 (1), 113–141.
- Raja, V., Anderson, M.L., 2019. Radical embodied cognitive neuroscience. *Ecol. Psychol.* 31 (3), 166–181. <https://doi.org/10.1080/10407413.2019.1615213>.
- Reed, E.S., 1989. Neural regulation of adaptive behavior. *Ecol. Psychol.* 1 (1), 97–117.
- Riddle, J., Scimeca, J.M., Cellier, D., Dhanani, S., D'Esposito, M., 2020. Causal evidence for a role of theta and alpha oscillations in the control of working memory. *Curr. Biol.* 30 (9), 1748–1754.
- Rietveld, E., Kiverstein, J., 2014. A rich landscape of affordances. *Ecol. Psychol.* 26 (4), 325–352. <https://doi.org/10.1080/10407413.2014.958035>.
- Rietveld, E., Rietveld, R., 2017. Hardcore heritage: Imagination for preservation. *Front. Psychol.* 1995.
- Rimmele, J.M., Morillon, B., Poeppel, D., Arnal, L.H., 2018. Proactive sensing of periodic and aperiodic auditory patterns. *Trends Cogn. Sci.* 22 (10), 870–882.
- Roberts, B.M., Clarke, A., Addante, R.J., Ranganath, C., 2018. Entrainment enhances theta oscillations and improves episodic memory. *Cogn. Neurosci.* 9 (3–4), 181–193.
- Rohenkohl, G., Nobre, A.C., 2011. Alpha oscillations related to anticipatory attention follow temporal expectations. *J. Neurosci.* 31 (40), 14076–14084. <https://doi.org/10.1523/JNEUROSCI.3387-11.2011>.
- Saalmann, Y.B., Pinsk, M.A., Wang, L., Li, X., Kastner, S., 2012. The pulvinar regulates information transmission between cortical areas based on attention demands. *Science* 337 (6095), 753–756. <https://doi.org/10.1126/science.1223082>.
- Saleh, M., Reimer, J., Penn, R., Ojakangas, C.L., Hatsopoulos, N.G., 2010. Fast and slow oscillations in human primary motor cortex predict oncoming behaviorally relevant cues. *Neuron* 65 (4), 461–471.
- Schroeder, C.E., Lakatos, P., 2009. Low-frequency neuronal oscillations as instruments of sensory selection. *Trends Neurosci.* 32 (1), 9–18.
- Schroeder, C.E., Wilson, D.A., Radman, T., Scharfman, H., Lakatos, P., 2010. Dynamics of active sensing and perceptual selection. *Curr. Opin. Neurobiol.* 20 (2), 172–176.
- Spaak, E., de Lange, F.P., Jensen, O., 2014. Local entrainment of alpha oscillations by visual stimuli causes cyclic modulation of perception, 3536 LP – 3544 *J. Neurosci.* 34 (10). <https://doi.org/10.1523/JNEUROSCI.4385-13.2014>.
- Staudigl, T., Hanslmayr, S., 2013. Theta oscillations at encoding mediate the context-dependent nature of human episodic memory. *Curr. Biol.* 23 (12), 1101–1106.
- Stefanics, G., Hangya, B., Hernádi, I., Winkler, I., Lakatos, P., Ulbert, I., 2010. Phase entrainment of human delta oscillations can mediate the effects of expectation on reaction speed. *J. Neurosci.* 30 (41), 13578–13585.
- Ten Oever, S., Schroeder, C.E., Poeppel, D., Van Atteveldt, N., Zion-Golumbic, E., 2014. Rhythmicity and cross-modal temporal cues facilitate detection. *Neuropsychologia* 63, 43–50.
- Teng, X., Tian, X., Doelling, K., Poeppel, D., 2018. Theta band oscillations reflect more than entrainment: behavioral and neural evidence demonstrates an active chunking process. *Eur. J. Neurosci.* 48 (8), 2770–2782.
- Thaler, R., & Sunstein, C. (2021). *Nudge* (Final Edit). Penguin Books.
- Thelen, E., Smith, L.B., 1994. *A dynamic systems approach to the development of cognition and action*. MIT press.
- Thiel, P., 1961. A sequence-experience notation: for architectural and urban spaces. *Town Plan. Rev.* 32 (1), 33–52.
- Thompson, E., Varela, F.J., 2001. Radical embodiment: neural dynamics and consciousness. *Trends Cogn. Sci.* 5 (10), 418–425. [https://doi.org/10.1016/S1364-6613\(00\)01750-2](https://doi.org/10.1016/S1364-6613(00)01750-2).

Added references

- Thut, G., Schyns, P.G., Gross, J., 2011. Entrainment of perceptually relevant brain oscillations by non-invasive rhythmic stimulation of the human brain. *Front. Psychol.* 2, 170.
- Tichko, P., Large, E.W., 2019. Modeling infants' perceptual narrowing to musical rhythms: neural oscillation and Hebbian plasticity. *Ann. N. Y. Acad. Sci.* 1453 (1), 125–139. <https://doi.org/10.1111/nyas.14050>.
- Tichko, P., Kim, J.C., Large, E.W., 2021. Bouncing the network: a dynamical systems model of auditory–vestibular interactions underlying infants' perception of musical rhythm. *Dev. Sci.* 24 (5), e13103 <https://doi.org/10.1111/desc.13103>.
- Tichko, P., Kim, J.C., Large, E.W., 2022. A dynamical, radically embodied, and ecological theory of rhythm development. *Front. Psychol.* Vol. 13. (<https://www.frontiersin.org/articles/10.3389/fpsyg.2022.653696>).
- Uhlhaas, P., Pipa, G., Lima, B., Melloni, L., Neunenschwander, S., Nikolić, D., Singer, W., 2009. Neural synchrony in cortical networks: history, concept and current status. *Front. Integr. Neurosci.* 17.
- Van der Weel, F.R., van der Meer, A.L.H., 2009. Seeing it coming: infants' brain responses to looming danger. *Naturwissenschaften* 96, 1385–1391.
- VanRullen, R., 2016. Perceptual cycles. *Trends Cogn. Sci.* 20 (10), 723–735. <https://doi.org/10.1016/j.tics.2016.07.006>.
- VanRullen, R., 2018. Attention cycles. *Neuron* 99 (4), 632–634.
- Vara Sánchez, C., 2022. Enacting the aesthetic: a model for raw cognitive dynamics. *Phenomenol. Cogn. Sci.* 21 (2), 317–339.
- Vara Sánchez, C. (2023). *Aesthetic Rhythms. Mimesis*.
- Varela, F.J., 1995. Resonant cell assemblies: a new approach to cognitive functions and neuronal synchrony. *Biol. Res.* 28 (1), 81–95.
- Wang, S., Sanches de Oliveira, G., Djebbara, Z., Gramann, K., 2022. The embodiment of architectural experience: a methodological perspective on neuro-architecture. *Front. Hum. Neurosci.* Vol. 16. (<https://www.frontiersin.org/article/10.3389/fnhum.2022.833528>).
- Warren, W.H., 2006. The dynamics of perception and action. *Psychol. Rev.* 113 (2), 358–389. <https://doi.org/10.1037/0033-295X.113.2.358>.
- Warren, W.H.J. (1984). Perceiving affordances: visual guidance of stair climbing. *Journal of Experimental Psychology. Human Perception and Performance*, 10(5), 683–703. <https://doi.org/10.1037/0096-1523.10.5.683>.
- Withagen, R., Araújo, D., de Poel, H.J., 2017. Inviting affordances and agency. *N. Ideas Psychol.* 45, 11–18. <https://doi.org/10.1016/j.newideapsych.2016.12.002>.
- Zeki, S., 1998. Art and the brain. *Daedalus* 127 (2), 71–103.
- Zoefel, B., Ten Oever, S., Sack, A.T., 2018. The involvement of endogenous neural oscillations in the processing of rhythmic input: more than a regular repetition of evoked neural responses. *Front. Neurosci.* 12, 95.