

Advances in Experimental Medicine and Biology 1455

Hugo Merchant  
Victor de Lafuente *Editors*

# Neurobiology of Interval Timing

*Second Edition*

 Springer

---

# Advances in Experimental Medicine and Biology

Volume 1455

## Series Editors

Wim E. Crusio, Institut de Neurosciences Cognitives et Intégratives  
d'Aquitaine, CNRS and University of Bordeaux Pessac Cedex, France

Haidong Dong, Departments of Urology and Immunology  
Mayo Clinic Rochester, USA

Heinfried H. Radeke, Institute of Pharmacology and Toxicology  
Clinic of the Goethe University Frankfurt Main Frankfurt am  
Main, Germany

Nima Rezaei, Research Center for Immunodeficiencies, Children's Medical  
Center Tehran University of Medical Sciences Tehran, Iran

Ortrud Steinlein, Institute of Human Genetics  
LMU University Hospital Munich, Germany

Junjie Xiao, Cardiac Regeneration and Ageing Lab, Institute  
of Cardiovascular Sciences School of Life Science, Shanghai University  
Shanghai, China

*Advances in Experimental Medicine and Biology* provides a platform for scientific contributions in the main disciplines of the biomedicine and the life sciences. This series publishes thematic volumes on contemporary research in the areas of microbiology, immunology, neurosciences, biochemistry, biomedical engineering, genetics, physiology, and cancer research. Covering emerging topics and techniques in basic and clinical science, it brings together clinicians and researchers from various fields.

*Advances in Experimental Medicine and Biology* has been publishing exceptional works in the field for over 40 years, and is indexed in SCOPUS, Medline (PubMed), EMBASE, Reaxys, EMBiology, the Chemical Abstracts Service (CAS), and Pathway Studio.

2022 CiteScore: 6.2

---

Hugo Merchant • Victor de Lafuente  
Editors

# Neurobiology of Interval Timing

Second Edition

 Springer

*Editors*

Hugo Merchant  
Instituto de Neurobiología  
UNAM, Campus Juriquilla  
Querétaro, Mexico

Victor de Lafuente  
Institute of Neurobiology  
National Autonomous  
University of Mexico  
Querétaro, Mexico

ISSN 0065-2598

ISSN 2214-8019 (electronic)

Advances in Experimental Medicine and Biology

ISBN 978-3-031-60182-8

ISBN 978-3-031-60183-5 (eBook)

<https://doi.org/10.1007/978-3-031-60183-5>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2014, 2024

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG  
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

*To our kids: Carla, Matías, Fernanda  
and Nina. Mateo and Emilia*

---

## Preface

The ability to process temporal information in the scale of hundreds of milliseconds to seconds is critical for a wide range of behaviors, from collision avoidance and target interception—present since the invertebrates—to highly complex behaviors such as language and music. In the second edition of the book *Neurobiology of Interval Timing*, we compile the newest and most exciting research in the brain sciences of timing. We gave special emphasis to the neural underpinnings of temporal processing in behaving human and non-human primates, as well as in rodents. Thus, the new edition of *Neurobiology of Interval Timing* integrates the thrilling and revealing developments on the psychophysics of time and timing neurophysiology, as well as fascinating modelling efforts to understand the clocks of the brain across a wide variety of behaviors, including perception and production of single intervals and rhythms in music and language. It is our sincere opinion that this constitutes an excellent book for graduate programs in neuroscience.

Querétaro, Mexico

Hugo Merchant  
Victor de Lafuente

---

# Contents

## Part I Neurobiology of Interval Timing

- A Second Introduction to the Neurobiology of Interval Timing** . . . . . 3  
Hugo Merchant and Victor de Lafuente
- Creating a Home for Timing Researchers: Then, Now,  
and the Future** . . . . . 25  
Argiro Vatakis and Sundeep Teki
- The Processing of Short Time Intervals: Some Critical Issues** . . . . . 35  
Simon Grondin
- Neurocomputational Models of Interval Timing:  
Seeing the Forest for the Trees** . . . . . 51  
Fuat Balçı and Patrick Simen

## Part II Neurophysiology of Timing

- Neural Sequences and the Encoding of Time** . . . . . 81  
Saray Soldado-Magraner and Dean V. Buonomano
- Temporal Information Processing in the Cerebellum  
and Basal Ganglia** . . . . . 95  
Masaki Tanaka, Masashi Kameda, and Ken-ichi Okada
- Diverse Time Encoding Strategies Within the Medial  
Premotor Areas of the Primate** . . . . . 117  
Hugo Merchant, Germán Mendoza, Oswaldo Pérez,  
Abraham Betancourt, Pamela García-Saldivar, and Luis Prado
- The Interactions of Temporal and Sensory Representations  
in the Basal Ganglia** . . . . . 141  
Pavel E. Rueda-Orozco, Ana E. Hidalgo-Balbuena,  
Perla González-Pereyra, Mario G. Martínez-Montalvo,  
and Ana S. Báez-Cordero
- Estimating Time and Rhythm by Predicting External Stimuli** . . . . . 159  
Mildred Salgado-Méñez, Marisol Espinoza-Monroy,  
Ana M. Malagón, Karla Mercado, and Victor de Lafuente



---

<b>Cognition of Time and Thinking Beyond</b> .....	171
Zedong Bi	
<b>Part III Timing in Humans</b>	
<b>The Motor of Time: Coupling Action to Temporally Predictable Events Heightens Perception</b> .....	199
Jennifer T. Coull, Inga Korolczuk, and Benjamin Morillon	
<b>Coordinate-Based Meta-Analyses of the Time Perception Network</b> .....	215
Martin Wiener	
<b>Probing Beat Perception with Event-Related Potentials (ERPs) in Human Adults, Newborns, and Nonhuman Primates</b> ....	227
Fleur L. Bouwer, Gábor P. Hádén, and Henkjan Honing	
<b>Rhythms in Speech</b> .....	257
M. Florencia Assaneo and Joan Orpella	
<b>Timing Patterns in the Extended Basal Ganglia System</b> .....	275
Michael Schwartze and Sonja A. Kotz	
<b>Index</b> .....	283

---

## Contributors

**M. Florencia Assaneo** Instituto de Neurobiología, Universidad Autónoma de México, Santiago de Querétaro, Mexico

**Ana S. Báez-Cordero** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

**Fuat Balci** Department of Biological Sciences, University of Manitoba, Winnipeg, MB, Canada

**Abraham Betancourt** Instituto de Neurobiología, UNAM, Campus Juriquilla, Querétaro, Mexico

**Zedong Bi** Lingang Laboratory, Shanghai, China

Institute for Future, Qingdao University, Qingdao, China

School of Automation, Shandong Key Laboratory of Industrial Control Technology, Qingdao University, Qingdao, China

**Fleur L. Bouwer** Cognitive Psychology Unit, Institute of Psychology, Leiden Institute for Brain and Cognition, Leiden University, Leiden, The Netherlands

Department of Psychology, Brain & Cognition, University of Amsterdam, Amsterdam, The Netherlands

**Dean V. Buonomano** Department of Neurobiology, University of California, Los Angeles, Los Angeles, CA, USA

**Jennifer T. Coull** Centre for Research in Psychology and Neuroscience (UMR 7077), Aix-Marseille Université & CNRS, Marseille, France

**Victor de Lafuente** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

**Marisol Espinoza-Monroy** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

**Pamela García-Saldivar** Instituto de Neurobiología, UNAM, Campus Juriquilla, Querétaro, Mexico

**Perla González-Pereyra** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

**Simon Grondin** École de Psychologie, Université Laval, Québec, Canada

**Gábor P. Hádén** Institute of Cognitive Neuroscience and Psychology, Budapest, Hungary

Department of Telecommunications and Media Informatics, Faculty of Electrical Engineering and Informatics, Budapest University of Technology and Economics, Budapest, Hungary

**Ana E. Hidalgo-Balbuena** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

**Henkjan Honing** Music Cognition group (MCG), Institute for Logic, Language and Computation (ILLC), Amsterdam Brain and Cognition (ABC), University of Amsterdam, Amsterdam, The Netherlands

**Masashi Kameda** Department of Physiology, Hokkaido University School of Medicine, Sapporo, Japan

**Inga Korolczuk** Department of Pathophysiology, Medical University of Lublin, Lublin, Poland

**Sonja A. Kotz** Department of Neuropsychology and Psychopharmacology, Faculty of Psychology and Neuroscience, Maastricht University, Maastricht, The Netherlands

**Ana M. Malagón** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

**Mario G. Martínez-Montalvo** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

**Germán Mendoza** Instituto de Neurobiología, UNAM, Campus Juriquilla, Querétaro, Mexico

**Karla Mercado** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

**Hugo Merchant** Instituto de Neurobiología, UNAM, Campus Juriquilla, Querétaro, Mexico

**Benjamin Morillon** Aix Marseille Université, INSERM, INS, Institut de Neurosciences des Systèmes, Marseille, France

**Ken-ichi Okada** Department of Physiology, Hokkaido University School of Medicine, Sapporo, Japan

**Joan Orpella** Department of Neuroscience, Georgetown University Medical Center, Washington, DC, USA

**Oswaldo Pérez** Instituto de Neurobiología, UNAM, Campus Juriquilla, Querétaro, Mexico

**Luis Prado** Instituto de Neurobiología, UNAM, Campus Juriquilla, Querétaro, Mexico

**Pavel E. Rueda-Orozco** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

---

**Mildred Salgado-Menez** Institute of Neurobiology, National Autonomous University of México, Querétaro, Mexico

**Michael Schwartz** Department of Neuropsychology and Psychopharmacology, Faculty of Psychology and Neuroscience, Maastricht University, Maastricht, The Netherlands

**Patrick Simen** Department of Neuroscience, Oberlin College, Oberlin, OH, USA

**Saray Soldado-Magraner** Department of Neurobiology, University of California, Los Angeles, Los Angeles, CA, USA

**Masaki Tanaka** Department of Physiology, Hokkaido University School of Medicine, Sapporo, Japan

**Sundeep Teki** University College London, London, UK  
Independent AI consultant, Delhi, India

**Argiro Vatakis** Multisensory and Temporal Processing Laboratory (MultiTimeLab), Department of Psychology, Panteion University of Social and Political Sciences, Athens, Greece

**Martin Wiener** George Mason University, Fairfax, VA, USA

---

## About the Editors

**Hugo Merchant, PhD** is Professor of Neurobiology and Systems Neuroscience at the Institute of Neurobiology, Universidad Nacional Autonoma de Mexico, Juruquilla, Mexico. His research focuses on the neural basis of time. He has served as Associate Editor of the *Journal of Neuroscience* and the *Journal of Neurophysiology*, and on the Editorial Boards of *eLife*, *Frontiers in System Neuroscience*, and *Frontiers in Integrative Neuroscience*.

**Victor de Lafuente, PhD** is Professor of Neurobiology at the Institute of Neurobiology, Universidad Nacional Autonoma de Mexico, Queretaro, Mexico. His research interests are centered on the neuronal correlates of sensory perception, motor planning, and decision making. He is on the Board of Senior Editors of *Neuroscience* and is on the Editorial Boards of *Frontiers in Molecular Neurobiology* and *Frontiers in Systems Neuroscience*.

---

**Part I**

**Neurobiology of Interval Timing**



# A Second Introduction to the Neurobiology of Interval Timing

Hugo Merchant and Victor de Lafuente

## Abstract

Time is a critical variable that organisms must be able to measure in order to survive in a constantly changing environment. Initially, this paper describes the myriad of contexts where time is estimated or predicted and suggests that timing is not a single process and probably depends on a set of different neural mechanisms. Consistent with this hypothesis, the explosion of neurophysiological and imaging studies in the last 10 years suggests that different brain circuits and neural mechanisms are involved in the ability to tell and use time to control behavior across contexts. Then, we develop a conceptual framework that defines time as a family of different phenomena and propose a taxonomy with sensory, perceptual, motor, and sensorimotor timing as the pillars of temporal processing in the range of hundreds of milliseconds.

## Keywords

Time perception · Sensory timing · Motor timing · Timing models

H. Merchant (✉)

Instituto de Neurobiología, UNAM, Campus Juriquilla, Querétaro, Mexico  
e-mail: [hugomerchant@unam.mx](mailto:hugomerchant@unam.mx)

V. de Lafuente

Institute of Neurobiology National Autonomous University of Mexico, Querétaro, Mexico

## What Is Timing?

Timing is the tracking or planning of events that are constantly changing. “Time refers to the continued sequence of happenings that occur in apparently irreversible succession from the past, through present, and into the future” (Wikipedia). Organisms have developed different mechanisms to quantify the time between successive events, which could span ten orders of magnitude. The microseconds scale ( $10^{-4}$  s) is the scenario for binaural hearing and echolocation, engaging the auditory system to determine the spatial origin of sounds and objects (Joris & van der Heijden, 2019; Schnupp & Carr, 2009; Jeffress, 1948; O’Neill & Suga, 1979). At the other end, circadian timing ( $10^5$  s) organizes all the fundamental body functions within 24-h oscillations. We now know that the master clock for this circadian timing is the hypothalamic suprachiasmatic nucleus, which synchronizes the internal time with the external light–dark cycle, entraining the overall rhythmicity of a wide variety of peripheral clocks in the organism (Hastings et al., 2018), as well as the wake–sleep cycle in the brain (Drucker-Colín & Merchant-Nancy, 1996). Between very fast and the very slow bordering scales, we have the scale that spans hundreds of milliseconds ( $10^{-2}$ – $10^1$  s), seconds, and minutes ( $10^1$ – $10^2$  s). Timing within the seconds-and-minutes scales relies on conscious and cognitive control and is the context in which behavior is mapped onto the

external world. This timing range is related to foraging (Henderson et al., 2006), decision making (Brody et al., 2003), sequential motor performance (Bortoletto et al., 2011), as well as multiple-step arithmetic (Sohn & Carlson, 2003), and associative conditioning (Gallistel & Gibbon, 2000). In addition, temporal processing within the seconds-to-minutes scale is highly influenced by other processes, such as attention and memory, which interact with the mechanism of a presumed internal clock (Lewis & Miall, 2003). On the other hand, timing in the hundreds of milliseconds is crucial for behaviors such as object interception and collision avoidance, which we know are present since the invertebrates (Merchant & Georgopoulos, 2006; Merchant et al., 2001, 2003; 2009; 2004a, 2004b). Complex human behaviors such as speech perception and articulation, and the execution and appreciation of music and dance also develop in the millisecond-to-second scale (Kotz & Schwartz, 2010; Poeppel & Assaneo, 2020; Merchant et al., 2015a; Lenc et al., 2021). Motion processing in the visual and tactile modalities, as well as the coordination of fine movements occurs also in this time range (Merchant et al., 1997, 2001; Romo et al., 1995, 1996; Georgopoulos et al., 2007; Narselaris et al., 2006).

In trying to define time, we often include two critical processes: (Joris & van der Heijden, 2019) tracking events that change with time, and (Schnupp & Carr, 2009) predicting the occurrence of future events. Tracking events rely on the quantification of the elapsed time that has spanned since a relevant sensory or motor event and is critical to perceive the length of an interval. It is also critical to make decisions about the length of a stimulus in tasks that demand categorization, discrimination, or identification of a duration based on a cognitive rule (Merchant et al., 2013a). Predicting the occurrence of future events relies on the quantification of the remaining time that we must wait before an expected event. We know that the ability to predict future events is intrinsically linked to time intervals that had been learned through trial and error (Merchant & Yarrow, 2016). As we review in the

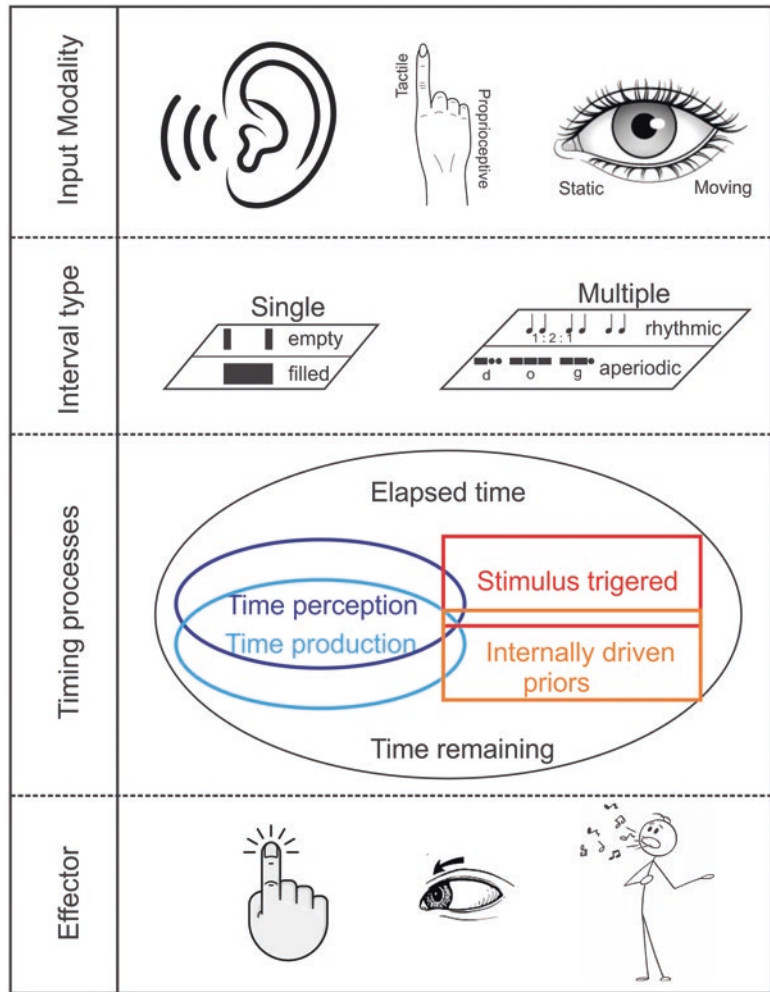
section on the *taxonomy of timing*, recent neurophysiological and imaging studies support the notion that tracking elapsed time (how long) and anticipating a future event (when) might rely on different neuronal mechanisms and possibly different brain areas.

The perception and production of time in the hundreds of milliseconds is crucially related to a large repertoire of behaviors, it can be triggered or guided by different sensory modalities, specially audition, vision, and touch, and it can be expressed through a variety of effectors using the skeletomotor, oculomotor, and laryngeal systems (Fig. 1) (Merchant et al., 2013a; Merchant & Yarrow, 2016; Merchant & Bartolo, 2018). It is important to note that time intervals can be produced or estimated just once (called interval based timing), and they can also be generated in sequences of nonrhythmic intervals, or in sequences of periodic musical stimuli that possess a metric structure (called beat-based timing) (Fig. 1) (Merchant et al., 2015a; Lenc et al., 2021). Furthermore, some behaviors require an explicit representation of time intervals such as when tapping to a rhythm, while in other behaviors timing is carried covertly (or implicitly) such as when we draw, where timing is an emergent property of the produced hand trajectory (Merchant et al., 2008a; Zelaznik et al., 2002).

Timing can be performed in synchrony with periodic external events, as in the case of music played by an ensemble, or internally like in the case of a soloist (Repp & Su, 2013; Merchant et al., 2008b; Wing, 2002). Another property of the sensory input that we know modulate timing performance is whether the intervals are filled or empty. For example, empty intervals can be defined by presentation of brief sensory stimuli (such as auditory clicks), whereas filled intervals are defined by the onset and offset times of a continuously present stimulus. Interestingly, it has been shown that filled intervals are perceived as being longer than empty intervals of the same length, and that the discrimination threshold is smaller for empty than for filled intervals (Fig. 1) (Grondin & Rousseau, 1991; Grondin et al., 1998).



**Fig. 1** Different timing processes can be flexibly engaged depending on the input modality (hearing, touch, or sight) and the type of interval (single or multiple). Timing expression can be channeled through the skeletomotor, oculomotor, and laryngeal systems



In summary, key elements of temporal processing include (Joris & van der Heijden, 2019) the time scale being quantified, (Schnupp & Carr, 2009) the modality of the stimulus that triggers a timing behavior, (Jeffress, 1948) whether the intervals are filled or empty, (O’Neill & Suga, 1979) whether the task involves single or multiple rhythmic or arrhythmic intervals, (Hastings et al., 2018) whether there is tracking of elapsed time or prediction of future events, (Drucker-Colín & Merchant-Nancy, 1996) whether time is being measured for a movement or for a perceptual decision, (Henderson et al., 2006) the effector used to

express timing behavior, (Brody et al., 2003) whether timing is externally or internally generated, and (Bortoletto et al., 2011) the implicit or explicit nature of the timing task (Fig. 1). Thus, we would like to emphasize that timing most certainly is not a single process and probably depends on a set of neural mechanisms. Consistent with this idea, the last 10 years have seen an explosion of neurophysiological and imaging studies, suggesting that different brain circuits and different neural mechanisms are involved in the ability to tell and use time to control behavior. The second edition of our book strongly reflects this view.

## Are Different Timing Behaviors Supported by Different Timing Mechanisms?

The present book focuses mainly on the neural basis of temporal processing in the hundreds of milliseconds range, although some of the chapters also deal with the underpinnings of timing behaviors in the seconds-to-minutes scale. Many authors defend the notion of different brain mechanisms for these two-time scales, and there is still some debate over the exact time boundary where these two scales might differ in their neuronal implementation. There is evidence that the time boundary seems to be in the order of 1300 to 2000 ms for perceptual and motor timing tasks that involve one interval or a set of isochronous intervals (see chapters of Simon Grondin, (Grondin, 2012)). However, some researchers maintain that these two-time scales are governed by the same neural clock during complex behaviors, such as the perception and execution of music with a complex hierarchical structure of tempi (see chapter of Sonja Kotz, (Rajendran et al., 2018)).

The classical model of time, often called scalar timing model, proposes a general multicontext clock composed by an internal pacemaker that monitors the passage of time once a gate signal is triggered, and it also includes an integrator that accumulates the pulses of the pacemaker (Treisman, 1963). Many psychophysical studies have successfully used this framework to explain the temporal performance of humans and animals in different perceptual and production timing tasks. At the core of this framework is the *scalar property of time*, showing that the variability of the temporal estimates increases linearly in proportion to total elapsed time (Gibbon, 1977; Gibbon et al., 1997). However, this model uses a black-box approach, in which the possible neural mechanisms behind the clock stage of the model are difficult to identify.

An alternative view emerged in the early 2000s, and it involves the notion of a ubiquitous timing mechanism, that depends on the dynamic properties of the cortical and subcortical recurrent networks of the brain (Karmarkar &

Buonomano, 2007; Buonomano & Laje, 2010). The common clock hypothesis has been supported by fMRI meta-analyses reporting that the neuronal circuit composed of the medial premotor cortex (MPCs; the presupplementary motor area [preSMA], the supplementary motor area [SMA]), and the basal ganglia is engaged in many perceptual and motor timing tasks that span the hundreds of milliseconds range. The notion of a distributed timing mechanism is supported by modeling (Karmarkar & Buonomano, 2007; Zhou et al., 2022), brain slice recordings (Goel & Buonomano, 2014), and psychophysical approaches (Burr et al., 2007; Tonoyan et al., 2022).

A third possibility suggests the existence of a partially distributed timing mechanism, integrated by a main core of interconnected structures, such as the cortico-thalamic-basal ganglia circuit (CTBGc), and cortical areas that are selectively engaged depending on the specific behavioral requirement of a task (Merchant et al., 2013a, 2014a). These task-dependent areas may interact with the core timing system to produce the temporal behavior in a specific task (Merchant et al., 2015b). This recent proposal is based on psychophysical studies (Merchant et al., 2008a, 2008b), functional imaging meta-analysis (Wiener et al., 2010), and fresh neurophysiological observations (Betancourt et al., 2023). Importantly, this corpus of evidence supports neither the existence of either a common timing mechanism that functions equally every time a subject quantifies time, nor a set of timing mechanisms that are specific for each task context.

---

## The Internal Simulation Hypothesis

A recent proposal has been put forward suggesting that the process we call timing is, in fact, an internal re-enactment of the sensory and motor actions that define the timing task to be solved in a particular behavioral context (de Lafuente et al., 2022). For example, under this internal simulation framework, if a subject is asked to time a one-second interval, they would replay the memory associated with a one-second interval.

Importantly, subjects do not make use of a general “one-second” memory, but the specific memory generated during the learning of that task. It is this long-term memory that allows the brain to conduct an internal simulation of the future states of the world.

This is closely related to the often-overlooked fact that each timing task has an almost unique experimental design, a set of very particular sensory stimuli, and, importantly, a set of specific behavioral rules that subjects must follow to solve the task. In this manner, the learning of a timing task generates a unique long-term memory or engram.

Support in favor of the internal simulation hypothesis has come recently from recordings made in nonhuman primates trained in a timing and rhythm perception task (García-Garibay et al., 2016). In this task, subjects must perceive and then internally maintain tempos defined by a visual metronome. Interestingly, when the visual metronome is extinguished and no movements are required from the subjects, the activity of single neurons and of the local field potentials (LFPs) continue to oscillate at the tempo of the metronome. This oscillatory activity was observed in V4, parietal cortices LIP and MIP, SMA, PFC, and the hippocampus (de Lafuente et al., 2022).

Under the internal simulation hypothesis, which we can also call the engram-replay hypothesis, there would be neither dedicated clocks nor specialized mechanism to measure or produce time. Instead, the brain would be using the survival-critical ability to make use of past information to predict the possible future states of the world, make plans, and act accordingly. We consider important to suggest that this new framework might encompass previous important works under a unifying point of view. This new point of view suggests that the brain does not perform “timing” as traditionally has been thought. Instead, to generate well-timed behavior, it re-enacts the sensory-motor engrams related to the task, that we as researchers instruct our subjects to perform (de Lafuente et al., 2022).

Supporting this viewpoint on how timed behavior might be achieved, recent electrophysi-

ological evidence has shown that the neuronal activity of the motor cortices is able to oscillate with different time intervals, depending on the tempo that the subjects are holding actively on working memory (Cadena-Valencia et al., 2018). Interestingly, this oscillatory activity is also observed in parietal, V4, frontal, and hippocampal areas, and these patterns of activity are observed in the absence of any motor action or sensory stimuli (de Lafuente et al., 2022).

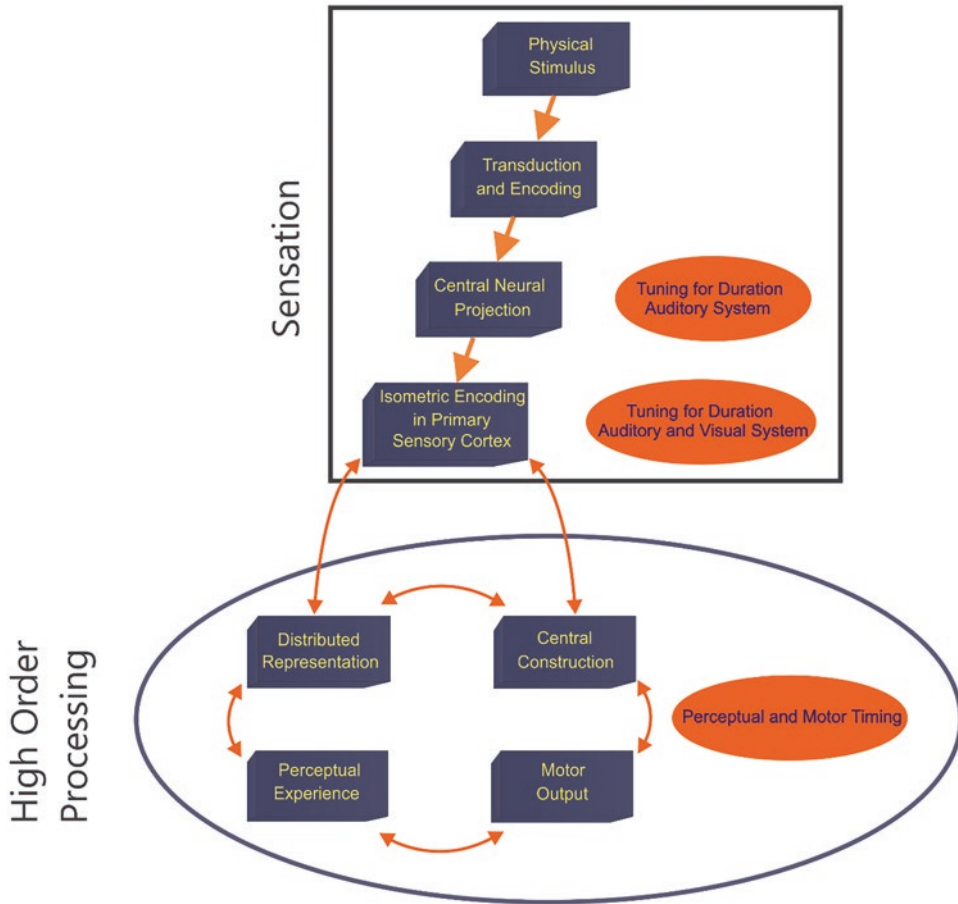
---

## Taxonomy of Timing: A Second Attempt

In the first edition of our book *Neurobiology of Interval Timing*, we suggested an initial scheme for the classification of timing process. The proposal included sensory, perceptual, and motor timing as the pillars for temporal processing classification. Here, we used this scheme as a foundation, and we further suggest a new critical element: the dynamic interaction between sensory, cognitive, and motor areas to flexibly cope with the behavioral demands for time quantification and event prediction.

### Sensory Timing

Organisms can extract temporal information from stimuli of all sensory modalities, even if there is no sensory organ for measuring the passage of time (Fig. 1). We still do not know how time is computed from the activation of different sensory systems or where in the sensory hierarchy is the temporal information computed for perceptual or motor purposes. To answer these fundamental questions, it is important to understand the anatomical and functional relationships that exist between the auditory, visual, and somatosensory systems, which correspond to the most important modalities for temporal information processing, particularly in the hundreds of milliseconds range. These sensory systems share a set of common operations: the sensory transduction of physical information into action potentials in the sensory receptors; the projection



**Fig. 2** A flux diagram for stimulus processing in the auditory, visual, and somatosensory modalities, ranging from sensation (square) to high order processing (ellipse).

The orange ellipses highlight the levels of processing where different aspects of time quantification may occur

of this information (through thalamic nuclei) to the primary sensory areas of the cerebral cortex; the processing of the different aspects of the stimuli in the cortical and subcortical circuits; and finally, the use of high order sensory processing for perception, learning and memory, and voluntary motor action (Fig. 2). Thus, time information could be initially estimated from the transduction of the stimulus and the encoding of its physical properties in the first relays of the sensory systems. Few studies have focused on temporal processing during the transduction and conduction stages of sensation. In this regard, the auditory midbrain of many vertebrates contains cells that are tuned to the duration of stimuli in

the range of tens of milliseconds (10–100 ms) that are also tuned to the stimulus frequency (Alluri et al., 2016). Studies across vertebrates have identified cells with preferred durations and auditory bandwidths for single intervals that mirror the range of species-specific vocalizations (57 for a review). Therefore, the auditory system can efficiently extract temporal information early on within the stimuli processing hierarchy, producing a switch from neural responses driven by the stimulus temporal profile to cells with average rate-tuning to durations.

The auditory cortex also shows duration selectivity for single intervals. In both cats and monkeys, cells show selectivity for the duration of

auditory stimuli (He et al., 1997; Brosch et al., 1999), with preferred durations that are distributed over a wider range and for longer durations (50–350 ms) as compared to the inferior colliculus (Aubie et al., 2012).

The migration of time interval selectivity toward longer durations in the auditory cortex can be explained by the integration of duration selectivity from inferior colliculus inputs or from the stimulus temporal integration, where both temporal summation and suppression of responses within the circuits of the auditory cortex are taking place (He et al., 1997; Brosch et al., 1999). A key aspect of duration tuning implies the existence of different populations of cells encoding different intervals, filtering the continuous passage of time in subpopulations for short, medium, and long intervals. Thus, the fast identification of sounds would allow animal communication, echolocation, and even human language perception though funneling elapsed time into subpopulations of duration-tuned cells that act as feature detectors. Importantly, these feature detectors are hardwired in the inferior colliculus and auditory cortex as labeled lines for fast temporal processing (Zarco & Merchant, 2009). Overall, these studies suggest that the auditory modality has an outstanding ability to extract temporal information for single intervals in the range of early hundreds of milliseconds across the first relays of sensory processing. This indicates that the auditory modality is shaped for temporal processing.

For rhythmic auditory stimuli, recent neurophysiological studies have shown that sensory adaptation in the inferior colliculus and the auditory cortex of the rat is a critical mechanism for beat extraction. Importantly, the duration tuning of auditory cortex defines a response asymmetry that can detect stimuli that are on- or off-beat for real music excerpts, and this beat contrast selectivity aligns well with the beat tapping preference that human subjects produce in response to the same musical excerpts (Rajendran et al., 2017, 2018). Therefore, these findings suggest that the precision of the temporal coding in the inferior colliculus and auditory cortex predisposes the

reliability of the estimated beat, even in the case of real music (Rajendran et al., 2020).

For vision, the first node in the visual pathway that shows duration-tuned cells for single intervals is the primary visual cortex (V1; Fig. 2). These cells show an orderly change in response magnitude to a visual stimulus that is presented in their receptive field (Duysens et al., 1996). The range of durations represented in V1 spans 50–400 ms. Interestingly, no such tuned cells have been found in the lateral geniculate nucleus of the thalamus (Duysens et al., 1996), suggesting that time selectivity is a property arising from local processing in V1. Psychophysical studies have investigated the sensory adaptation for the temporal properties of stimuli, an effect that probably depends on the primary sensory cortical areas. For instance, the apparent duration of a visual stimulus can be modified in a local region of the visual field by adaptation to oscillatory motion or flicker, suggesting that there is a spatially localized temporal mechanism for the sensation of time of visual events in the first nodes of the cortical hierarchy of visual processing (Tonoyan et al., 2022). As far as we know, there are no studies documenting neuronal responses to periodic or nonperiodic stimuli in V1.

The tactile system possesses three receptors to transduce mechanical stimuli: the rapidly adapting Pacinian, the rapidly adapting Meissner, and the slowly adapting Merkel (Romo et al., 1998). The primary somatosensory cortex contains a columnar organization that faithfully encodes the properties of these three mechanoreceptors (Romo et al., 1995; Mountcastle et al., 1969). Interestingly, rapidly adapting cells in the somatosensory cortex increase their discharge rate as a function of the duration of a moving probe in their finger receptive field (Romo et al., 1995, 1996). Thus, the primary somatosensory cortex also has a finely tuned machinery to extract temporal information (Luna et al., 2005).

Neurophysiological studies of time processing have provided evidence in favor of the idea that the auditory modality has a privileged capability for time quantification. Indeed, the precision of temporal estimations, measured in psychophysi-

cal tasks on humans, is more accurate and less variable when the intervals are defined by auditory as compared to visual or tactile stimuli. This increased precision has been observed during the perception of single and multiple intervals, as well as in the production time intervals. Interestingly, the time intervals marked by auditory signals are judged to be longer than those defined by visual stimuli (Wearden et al., 1998; Grondin & Rousseau, 1991; Grondin et al., 1998).

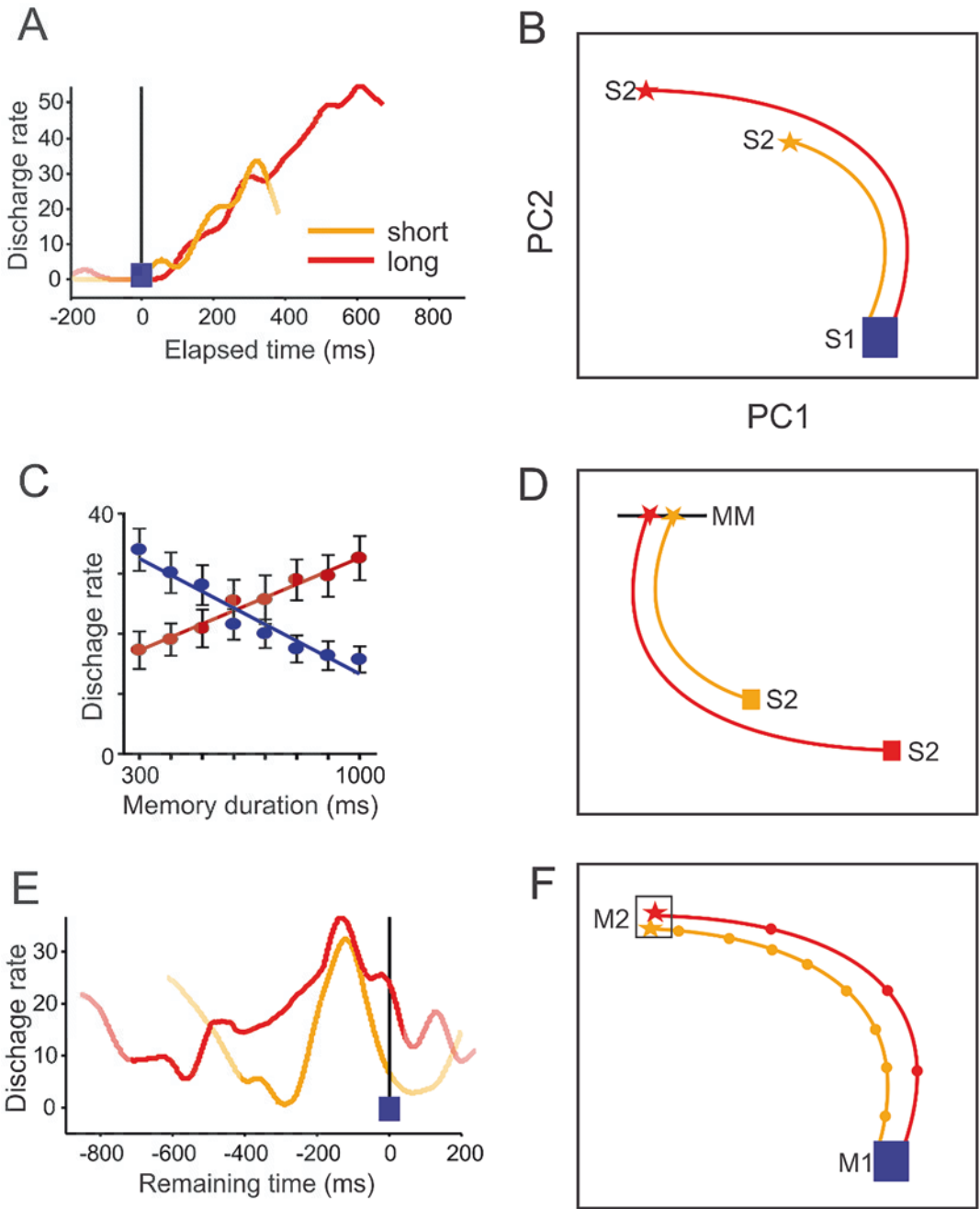
Thus, the perception of time passage seems to depend on specialized groups of cells in early nodes of the sensory processing which contain neurons that are tuned to the duration of auditory and visual stimuli (Fig. 3). Consequently, it is evident that how we perceive the passage of time in the tens to hundreds of milliseconds, is highly influenced by the sensory modality, and depends on the anatomofunctional properties of each sensory system, where feature detectors are hardwired and where hearing has a clear advantage in temporal processing.

## The Perception of Time

Once the sensory information is encoded as brief events or as a pattern of populations' neural activity tuned to the duration of the input stimuli, the neural system needs to translate sensation into a subjective sense of time, within the context of a specific behavior or task (Fig. 2). The most used tasks to measure time perception are the categorization and discrimination of time intervals (Merchant et al., 2008a, 2008b, 2008c). The former comes with two flavors: time bisection where subjects keep in memory the short and long prototypes to categorize intermediate probes (Wearden, 1991; Ng et al., 2011; Mendez et al., 2011), and time generalization where subjects keep in memory the boundary between the short and long categories and use it to decide on each trial which intervals are short or long (Wearden, 1992). The latter implies the comparison between the working memory trace of the first interval with the duration of a second interval to determine which one is the longer and produces a

response that expresses that decision. Therefore, time perception tasks demand not only the encoding of an interval defined by an empty or filled stimulus duration, but also maintaining in memory this quantity and to categorize it or discriminate the memory trace with a second interval using specific decision rules and learned movements to express the decision (Merchant et al., 2008a, 2008b). Consequently, the representation of elapsed time needs to be dissociated from the memory trace of an interval (Chiba et al., 2015), the decision making (Merchant et al., 2011a, 2014b), and the voluntary motor signals to communicate the decision (Hernández et al., 2010; Méndez et al., 2014). This is not a trivial analytical problem, since the brain areas engaged in timing, such as the medial premotor areas, the putamen and motor thalamus, and the prefrontal and parietal areas, are also deeply involved in executive functions, working memory, and voluntary motor control (Mendoza & Merchant, 2014; Romo & Rossi-Pool, 2020; Caminiti et al., 2010; Miller & Cohen, 2001).

A recent neurophysiological study from our lab showed that the primate presupplementary cortex (preSMA) shows a boundary signal for interval categorization. These neurons showed an up-down profile of activation with a time peak that corresponded to the subjective limit between the short and long category. Notably, the time at which this peak is reached changes according to the categorical boundary of the current block, predicting the monkeys' categorical decision on a trial-by-trial basis (Mendoza et al., 2018). In addition, preSMA shows strong neural signals for the categorical choice made by the monkey and for the outcome of the categorization (Romo et al., 1993, 1997). Paradoxically, this internal prediction signal was not preceded by neurons encoding the elapsed time between the beginning and end of the intervals to be categorized. This could be due to the overtraining of the monkeys in this task (Mendez et al., 2011), which could favor the neural representation of boundary prediction than of elapsed time, while promoting the migration of time encoding to the basal ganglia (Merchant et al., 1997), where elapsed time is represented during a categorization task (Gouvêa



**Fig. 3** (a) Ramping activity of a cell whose discharge rate increases with elapsed time. (b) Neural trajectories of a cell population starting at the same state space position at the first stimulus (S1) and encoding elapsed time in the final position of the trajectory at the time of the second stimulus (S2). (c) Two neurons show an increase (red) or decrease (blue) in discharge rate as a function of the mem-

orized interval. (d) Neural trajectories reaching an attractor (MM during the memory delay). (e) Cell with a ramping activity that reaches a peak few milliseconds before the predicted event, with a larger activation slope for the shorter interval. (f) Neural trajectories that follow the same path but with larger speed for the shorter interval, generating temporal scaling

et al., 2015). Accordingly, recordings in monkeys performing a duration discrimination task showed single cell activity related with the encoding of elapsed time for the first interval in the striatum (Chiba et al., 2015) but not in dorsolateral prefrontal cortex, where the neurons might encode either the memory trace of the first duration, the decision rule, or the decision choice (Oshio et al., 2006; Genovesio et al., 2009).

Elapsed time can be encoded in the ramping activity of cells whose firing rates increase as a function of time and peak at preferred times (sand clock neurons); or can also be encoded by increments or decrements in firing activity that covers the length of the times interval (Merchant et al., 2011b; Knudsen et al., 2014; Henke et al., 2021) (Fig. 3a). Importantly, it is likely that thousands of ramping neurons might constitute a population clock (Merchant & Averbeck, 2017). Thus, the elapsed time between two stimuli can be represented by the dynamic interactions across the neural populations that display neural sequences (Merchant et al., 2015b; Crowe et al., 2014; Zhou et al., 2022).

This recent proposal of encoding time through dynamic neuronal activity uses dimensional reduction techniques to project the high-dimensional individual neural activity of a network into a low-dimensional state space to study the underlying computational principles of timing. This approach has been used to show that the elapsed time between events could be encoded by the final position of the neural population trajectory. Given that the trajectories triggered by the first event follow a stereotypic path for all durations, a simple linear decoder can determine time as the position of the trajectory at the second event (Fig. 3b) (Gouvêa et al., 2015; Kim et al., 2013; Sohn et al., 2019; Merchant & Pérez, 2020). Therefore, this neural population clock, observed in SMA, the striatum, and prefrontal cortex, can be started and stopped flexibly. However, this coding scheme is less efficient than the feature detectors in the midbrain or the sensory cortex that are tuned to durations. In fact, it is not yet clear whether primary sensory areas use the population mechanism for encoding elapsed time.

An important question in the encoding–decoding of time by neuronal activity is the nature of the clock reader. The final position of the neural trajectories could be used to generate a working memory representation of time for discrimination or for action triggering. Recurrent network modeling and monkey neurophysiology have shown that interval working memory might be represented as a manifold in the space generated by the neural trajectories (Fig. 3d), while at the single cell level, neurons show an increase or decrease in discharge rate as a function of the memorized duration (Chiba et al., 2015; Bi & Zhou, 2020) (Fig. 3c).

On the other hand, the study of perceptual interval learning and the generalization properties of such learning has provided important insights into the neural underpinnings of multimodal temporal information processing. For example, using interval discrimination, it has been shown that intensive learning can generalize across untrained auditory frequencies (Wright et al., 1997; Karmarkar & Buonomano, 2003), sensory modalities (Nagarajan et al., 1998; Westheimer, 1999), stimulus locations (Nagarajan et al., 1998), and even from sensory to motor timing tasks (Meegan et al., 2000; Sánchez-Moncada et al., 2020). However, none of these studies found generalization toward untrained interval durations. In addition, it has been suggested that the learning transfer depends on the improvement of temporal processing and not on more efficient memory or decision processes, at least for auditory interval discrimination (Wright et al., 1997). Therefore, these findings not only support the notion of a centralized or a partially overlapping distributed timing mechanism, but they also introduce the concept of duration-specific circuits. Regarding the first point, we can speculate that the timing signals sent from the primary sensory cortical areas to the large and distributed core timing network during the learning period may increase the global efficiency of the temporal information processing. Thus, an efficient core timing network will transfer its improved timing abilities across senses and between perceptual and motor contexts. A recent investigation found that only the subjects that can learn to



efficiently discriminate visual intervals, and that show a generalization gain in tapping performance after learning, show a concomitant increase in activity in SMA, putamen, and the cerebellum (Sánchez-Moncada et al., 2020).

Another crucial aspect is that subjective time is prompt to distortions and generally does not have a one-to-one relation with physical time. As mentioned above, many factors can affect timing, and it is evident that temporal distortions can happen at different processing levels. For example, adaptation to fast visual motion strongly reduces the duration estimation of a subsequent stimulus, using a nonretinotopic reference frame. In addition, the duration of larger, brighter, or more numerous stimuli (Xuan et al., 2007; Togoli et al., 2021) is perceived to be longer than stimuli with the same duration but smaller magnitudes. Subjective time is dilated by the temporal frequency of moving flickering displays (Kanai et al., 2006) and affected by the contexts in which the stimuli are presented (Fornaciai et al., 2018; Karmarkar & Buonomano, 2007). Notably, time perception is also affected by movement (Merchant & Yarrow 2016). For example, when making a saccade to a target, a temporal expansion is produced (Yarrow et al., 2004).

Overall, the study of the neural mechanisms behind time perception would be greatly advanced by making use of experimental designs where time distortions are induced in a controlled fashion to determine their origins in the dynamics of neural population clocks across the timing circuits (De Kock et al., 2021). As a complement, studies using different modalities or contexts that share temporal resources can shed light into the properties of a core timing circuit and its interaction with context-dependent areas.

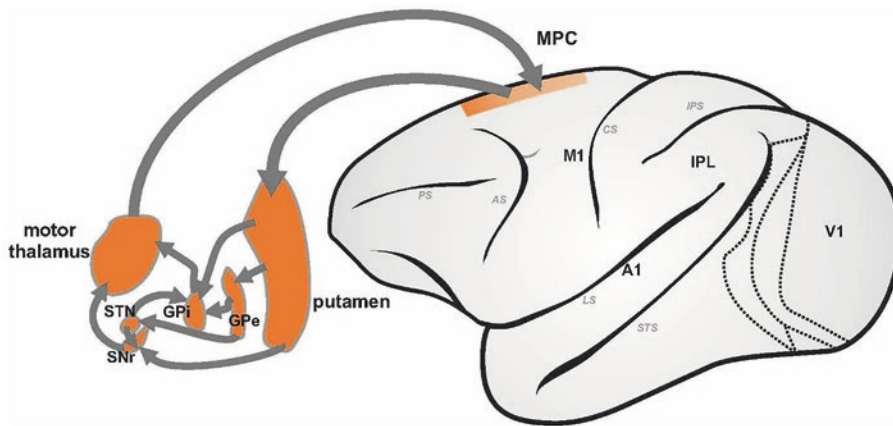
## Motor Timing

Instead of reacting to sensory stimuli, the motor system can anticipate the appearance of future events. As we mentioned before, interval timing within the milliseconds range is a prerequisite for many complex behaviors, such as perception and production of speech (Kotz & Schwartze, 2010;

Poeppl & Assaneo, 2020), the execution and appreciation of music and dance (Merchant et al., 2015a), and the performance of sports (Merchant & Georgopoulos, 2006). During single interval production tasks, the activity of neural populations evolves with similar trajectories across durations, reaching a common terminal state when the movement is triggered. Crucially, the trajectories are temporally scaled stretching for short and compressing for long intervals (Bi & Zhou, 2020; Wang et al., 2018; Merchant et al., 2011b).

At the single cell level, neurons encode the time to an event as ramping activity that reaches a peak shortly before the estimated time of the interval (Fig. 3c). This mechanism has been described in SMA, prefrontal cortex, and the striatum (Merchant et al., 2011b; Henke et al., 2021; Merchant & Bartolo, 2018; Kunitatsu et al., 2018). On the other hand, when monkeys produce rhythmic taps in synchrony with a metronome, neural trajectories show three main properties. First, they have circular dynamics that form a regenerating loop for every produced interval. Second, they converge to a similar state space right at the tapping time, resetting the beat-based clock at this point. Finally, the periodic trajectories increase in amplitude as a function of the length of the isochronous beat (Balasubramaniam et al., 2021; Gámez et al., 2019; Lenc et al., 2021) but also are temporally scaled (Betancourt et al., 2022). Hence, single interval and beat-based timing seem to have partially shared neural mechanisms (see chapter “Cognition of Time and Thinking Beyond”).

Music and dance are behaviors that depend on intricate loops of perception and action, where temporal processing can be involved during the synchronization of movements with sensory information or during the internal generation of movement sequences (Rajendran et al., 2018). Many functional imaging studies have demonstrated that the circuits engaged in the perception of time are the same that are activated during motor timing (Coull et al., 2008; Wiener et al., 2010; Schubotz et al., 2000; Merchant et al., 2013a). The cortico-basal ganglia-thalamo-cortical circuit (CBGT), that includes the medial



**Fig. 4** The core timing network in the monkey brain is highlighted as orange structures. This core timing network is constituted by the skeleton-motor cortico-basalganglia-thalamo-cortical circuit, which includes the medial premotor areas (MPC: SMA and preSMA), as well as the putamen, the globus pallidus, and the motor thalamus. A1

primary auditory area, AS arcuate sulcus, CS central sulcus, GPe globus pallidus externus, GPi globus pallidus internus, IPL inferior parietal lobe, IPS intraparietal sulcus, LS lateral sulcus, MPC medial premotor cortex, PS principal sulcus, SNr substantia nigra pars reticulata, STN subthalamic nucleus, STS superior temporal sulcus

premotor areas (Supplementary (SMA) and Presupplementary motor areas (preSMA), as well as the neostriatum, the globus pallidus, and the motor thalamus), is a network that is strongly engaged by interval perception and by time-constrained movements. These studies support the notion that the CBGT circuit is a key element of the core timing network, and that it is activated during the categorization and discrimination of time intervals, as well as during the perception and production of rhythms (Fig. 4). Accordingly, the neural population trajectories have now been characterized within the core timing network during perceptual and motor timing tasks for single intervals, as well as for rhythmic tapping tasks. Nevertheless, further studies are needed to determine whether the rules of time processing change in the core timing circuit when the same subjects perform perceptual and motor timing tasks, or when they perform single interval and rhythmic timing tasks. Another critical unanswered question relates to the role of the output of the basal ganglia in shaping the geometry and dynamics of the medial premotor neural trajectories during all these tasks.

In addition to the neural dynamics in population trajectories, different laboratories have shown that different core timing areas contain

neurons that show duration tuning during motor timing tasks. Interval tuning during single interval and beat-based timing has been reported in medial premotor areas (Merchant et al., 2013b; Mita et al., 2009), prefrontal cortex (Henke et al., 2021), the putamen (Bartolo et al., 2014; Bartolo & Merchant, 2015), the caudate (Kameda et al., 2019; Kunitatsu et al., 2018), and the cerebellum (Ohmae et al., 2017; Okada et al., 2022). In addition, a chronomap in the medial premotor cortex has been described in humans using functional imaging, where interval-specific circuits show a topography with short preferred intervals in the anterior and long preferred intervals in the posterior portion of SMA/preSMA (Protopapa et al., 2019). Therefore, motor timing depends on distinct timing circuits composed by duration specific neurons. Each of these circuits quantify the time remaining for an event by contracting or expanding their activity patterns using temporal scaling (Merchant & Bartolo, 2018; Bartolo & Merchant, 2009). In fact, tuning and modularity are mechanisms for division of labor that are widely used in cortical and subcortical circuits to represent sensory, cognitive, and motor information (Mountcastle, 1998; Goldman-Rakic, 1984; Georgopoulos et al., 2007; Merchant et al., 2008d; Naselaris et al., 2006). Interval tuning can

provide large flexibility to encode the passage of time and to predict events across many behaviors that require temporal processing by integrating timing with other task-dependent parameters with different mapping frameworks (Merchant & Bartolo, 2018; Zhou et al., 2022).

A set of functional imaging studies have revealed the neural and functional overlap between perceptual and motor timing, and the conclusion is that the motor network of the CBGT is activated across a wide range of timing contexts. A critical question, then, is what is the meaning of this anatomofunctional overlap? One possibility is that the increase in the BOLD signal in the motor areas across timing tasks reflects the presence of confounding cognitive processes, such as effector selection and motor preparation, or working memory and decision processes (Sánchez-Moncada et al., 2020). This is unlikely, however, since SMA, the CBGT circuit, and the prefrontal cortex are selectively activated even when duration estimates are registered with a perceptual discrimination (Wiener et al., 2010), or after motor preparation and/or execution processes have been rigorously controlled for (Coull et al., 2008; Schubotz et al., 2000) (see Chapter 11 of Coull and Morillon). Another possibility is that core timing network shares the neural circuitry with motor function because our general sense of time has been developed through action since childhood (Fraisse, 1982; Levin, 1992). This proposal is similar in principle to other embodied theories of time perception (Wittmann, 2013). Developmental studies have demonstrated that young children appear to represent time in motor terms (Droit-Volet & Rattat, 1999). Their duration estimates are more accurate when the duration is filled with an action than when it is empty (Fraisse, 1982), and they find it difficult to dissociate an estimate of duration from the motor act itself (Droit-Volet et al., 2006). Hence, it is possible that the motor circuits are engaged early in development to build up and acquire representations of time, forming a core timing network inside the motor system.

As has been proposed before, different cognitive functions may share the same neural representations and circuits for action and perception

(Merchant et al., 2015a; Mendoza & Merchant, 2014). In the case of temporal processing, it is possible that the learned associations between particular actions and their durations have been engrained in the dynamics of the cortical and subcortical motor networks (Mendoza et al., 2016, 2018; Merchant & Averbeck, 2017; Méndez et al., 2014). Thus, the dynamic representation of time in the activity of cell populations could become a generalized temporal representation, which is independent of the motor output, and can be used for motor and perceptual acts that require a strict temporal control (Fig. 4). Longitudinal experiments recording the activity of the core timing network and context-dependent structures during learning a timing skill are required to test these ideas.

### Sensory-Motor Loops

The strong correlation between fluctuations in the speed of the trajectories with trial-by-trial changes in movement times supports the notion of a robust predictive signal that triggers behavior within the core timing network. This motor top-down prediction should dynamically interact with the sensory bottom-up input to generate calibration loops of the timing system for both single interval and beat-based timing. In fact, it has been shown that predictive signals associated with a rhythmic motor behavior are fed back to the sensory areas through a corollary discharge that enhances processing of incoming auditory signals at a particular cyclic phase (Morillon et al., 2014). During beat-based timing, the motor system routinely produces dynamic signals in order to internally represent time, predict movements, enhance sensory events, and coordinate all these parameters (Merchant et al., 2015a; Merchant & Yarrow, 2016). Regarding the coordination process, two error signals must be computed: the time difference between the motor corollary discharge, and the proprioceptive reafference and the time difference between the internal beat signal and the sensory input (Repp, 2005). Both error signals could be used to calibrate the prediction of interval length (Betancourt

et al., 2023). There is a large knowledge gap about how the motor and sensory timing areas accomplish these processes.

---

## Bayesian Timing

As a final comment, the study of the neural basis of timing has been recently enriched using Bayesian approaches that can successfully account for behavioral performance across different timing tasks. This approach has also been used to dissociate the neural signals involved in tracking time, from those related to the acquired knowledge of the task parameters to optimize behavior. Bayesian estimators compute the posterior probability as the product of the likelihood function and the prior probability distribution. It has been shown that, across timing tasks, subjects tend to overestimate short intervals and overestimate long intervals, an effect described by the Vierderord's Law, and now have been recently called regression toward the mean or bias effect (Jones & McAuley, 2005; Pérez & Merchant, 2018). The prior distribution explains the bias effect by mapping the history of sample intervals that the observer has encountered during a block of trials with a mean that is close to the intermediate interval in the input distribution. Larger bias effects are captured as narrower prior distributions, reflecting more weight for previous knowledge of task conditions than the actual trial information. In addition, the likelihood function captures the scalar property of timing (Jazayeri & Shadlen, 2010; Merchant & Pérez, 2020; Perez et al., 2023). Notably, the curvature of the neural trajectories in SMA-preSMA reflects the effect of the prior on the bias effect (Sohn et al., 2019), while the variability of the neural trajectories is linked to the scalar property of timing (Betancourt et al., 2023; Gámez et al., 2019).

---

## Book Overview

It is with great pride and excitement that we present the second edition of the book *Neurobiology of Interval Timing*. A great deal of new and

encouraging findings have been uncovered since the first edition 10 years ago. In this updated edition, we had the fortune to count among the contributions one of the finest researchers in the field of timing.

First, authors Vatakis and Teki provide us with a detailed recapitulation of the meetings and events that have now coalesced into a mature timing research field. From the first TIMELY meeting back in 2007, up until last year, these meetings brought together a highly interdisciplinary group of researchers, often with conflicting views about the future of field, which makes it more interesting for students and scientists alike.

In his excellent chapter, Prof. Grondin clearly exposes how the precision and accuracy of time estimates depend on a number of critical factors, such as the sensory stimuli utilized to define time intervals and whether the intervals are filled or empty, and importantly, the chapter provides a balanced view of the conflicting evidence pointing to the existence of a single universal Weber Fraction for time estimation, or, instead, to the fairly common observation that different time scales might result in different estimations of the value of Weber's Fraction.

Prof. Buonomano's chapter provides a very thorough and precise account of previous and current mechanistic models that have been put forward to account for the timing abilities of the brain. A remarkable observation that the authors point out is that across species and behavioral tasks, a pattern of sequential activation of neurons arises when the subjects are timing intervals. From this pattern, time can be decoded by looking at the different times at which neurons peak in their activity. Importantly, the authors make the argument that with such population clocks, the activity of each individual neuron is highly independent of the rest of the population. Hence, timing is in the neural sequences, oscillatory or ramping activity might not be sufficient to produce the flexible chronometers that are needed to account for our complex timing behavior.

Regarding electrophysiological findings in nonhuman primates, Prof. Tanaka and colleagues present and discuss an outstanding body of experimental results that strongly suggest that the