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Time window of 3 seconds in cognitive processing reflected as a logistic function

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Chen ZHAO

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Erstes Gutachten:	Prof. Dr. Ernst Pöppel
Zweites Gutachten:	Prof. Dr. Jan Remi
Drittes Gutachten:	Priv. Doz. Dr. Thomas Geyer

Dekan:	Prof. Dr. med. Thomas Gudermann

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Zusammenfassung

„Zeit“ ist eine grundlegende, zugleich jedoch schwer fassbare Dimension der menschlichen Kognition. Obwohl „Zeit“ kein spezifisches Sinnesorgan zugeordnet ist, strukturiert sie Wahrnehmungen und Verhalten in einer umfassenderweise. Diese Dissertation untersucht die Hypothese, dass zeitliche Verarbeitung von Information nicht nur ein Bestandteil der Wahrnehmung, sondern eine fundamentale logistische Funktion ist, die kognitive Prozesse organisiert. Es wurden zwei Experimente durchgeführt, um die Rolle eines niederfrequenten „Zeitfensters“ von etwa drei Sekunden zu untersuchen, das vermutlich als prä-semantische Organisationseinheit zu verstehen ist. In Experiment 1 wurde das Paradigma der Zeitreproduktion angewandt, um das 3-Sekunden-Zeitfenster in einem realitätsnahen Kontext zu testen: Es wurde untersucht, wie visuelle Darstellungen (eine Balken- vs. eine Ring-Anzeige) die subjektive Zeitwahrnehmung bei Intervallen von 3 und 15 Sekunden beeinflussen. Die Ergebnisse zeigten, dass der Einfluss der visuellen Konfiguration nur bei der 15-Sekunden-Bedingung gegeben war. Die Reproduktionen in der 3-Sekunden-Bedingung blieben stabil und unabhängig von den visuellen Reizmerkmalen, was die Annahme eines prä-semantischen 3-Sekunden-Zeitfensters stützt, dass also sensorische Informationen inhaltsunabhängig verarbeitet wird. In Experiment 2 wurde mit Hilfe des MEG untersucht, ob Beta-Oszillationen als neuronale Indikatoren für zeitliche Kontrolle dienen könnten. Die Versuchspersonen führten eine sensomotorische Synchronisationsaufgabe bei fünf unterschiedlichen rhythmischen Tempi aus. Die Analyse zeigte, dass Beta-Oszillationen, insbesondere die Event-Related Synchronization (ERS), systematisch mit der „Stimulus-Onset-Asynchrony“ (SOA) variierten, und das Verhalten signifikant vorhersagten. Der Übergang von antizipatorischem zu reaktivem Verhalten bei der sensomotorische Synchronisationsaufgabe erfolgte etwa bei einer SOA von drei Sekunden, was den Beobachtungen aus Experiment 1 entspricht. Diese Ergebnisse deuten darauf hin, dass Beta-Oszillationen sensitiv für zeitliche Strukturen sind und möglicherweise die neuronale Implementierung des niederfrequenten Zeitfensters widerspiegeln. Sowohl die verhaltensbasierten Befunde wie auch die Beobachtungen über neuronale Oszillationen stützen die Theorie, dass das 3-Sekunden-Zeitfenster ein organisierendes Prinzip kognitiver Verarbeitung repräsentiert. Dieses theoretische Konzept ermöglicht zudem, eine differenzierte Klassifikation kognitiver Funktionen vorzunehmen, wobei zwischen inhaltlichen und logistischen Funktionen unterschieden wird. Diese Taxonomie wird vor allem auch durch physiologische Befunde gestützt, in denen Störungen der zeitlichen Organisation beobachtet wurden. Insgesamt wird nahegelegt, dass „Zeit“ nicht nur ein Inhalt der Wahrnehmung sein kann, sondern als ein organisierendes Gerüst zu verstehen ist, das

wesentlich ist für die Kohärenz von Wahrnehmungen, Handlungen und dem subjektiven Erleben.

Abstract

“Time” is a foundational yet elusive dimension in human cognition, lacking a dedicated sensory organ yet pervasively structuring perception and behavior. This dissertation investigates the hypothesis that temporal processing is not merely a perceptual content but a fundamental logistic function organizing cognitive operations. Two experiments were conducted to examine the role and neural basis of a low-frequency time window of approximately three seconds, proposed to function as a pre-semantic organizational unit. Experiment 1 employed a temporal reproduction paradigm to test the 3-second time window in a realistic setting: how visual representations of progress (bar vs. ring indicators) influence subjective time perception at durations of 3 and 15 seconds. Results revealed that the influence of visual configuration on subjective duration was present only for the 15-second condition. Reproductions in the 3-second condition remained stable and unaffected by visual stimulus features, supporting the idea of a pre-semantic 3-second time window that sensory inputs are processed independently of content. Experiment 2 used magnetoencephalography (MEG) to investigate whether beta-band oscillations could serve as neural indicators of temporal control. Participants performed a sensorimotor synchronization task across five rhythmic tempos. The analysis showed that beta oscillatory activity, particularly event-related synchronization (ERS), varied systematically with stimulus onset asynchrony (SOA) and significantly predicted behavioral asynchrony. Importantly, the transition from predictive to reactive responses occurred around the 3-second SOA, mirroring the behavioral boundary identified in Experiment 1. These results indicate that beta oscillations are sensitive to the temporal structure and may reflect the neural instantiation of the low-frequency time window. By integrating behavioral findings with the oscillatory neural dynamics, the thesis supports a theory that the 3-second time window represents an organizing principle for cognitive processing. This framework further advances a plausible classification of cognitive functions, distinguishing between content and logistic ones. Such taxonomy is also grounded on physiological evidence showing disruptions

in temporal organization. Taken together, this work proposes that time, rather than being merely a content of perception, is an organizing framework essential for the coherence of perception, action, and subjective experiences.

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List of abbreviations

ANOVA: analysis of variance

CV: Coefficient of variance

EEG: Electroencephalography

ERP: Event-related potential

ERD: Event-related desynchronization

ERS: Event-related synchronization

fMRI: functional Magnetic Resonance Imaging

ICA: Independent component analysis

ISI: inter-stimulus interval

MEG: Magnetoencephalography

MEF: Motor-evoked field:

MMN: Mis-match negativity

PET: Positron Emission Tomography

RPD: Reproduction/reproduced duration

SD: Standard deviation

SOA: Stimulus onset asynchrony

Contribution to the publications

This monograph dissertation is based on the content of three publications. Two of them are empirical studies, and one is a theoretical opinion paper, for which I am first author in all cases. As both empirical articles were published open access, I borrow original figures when illustrate methods and results with appropriate citation. Further, disclaimers from the publisher will be provided. Other necessary figures from open publications will also be cited properly. First, I will explain my contribution in the three papers.

The first paper is “Time represented in space: Bar better than ring while waiting” (Zhao et al., 2023). This is an empirical paper, investigating the effect of spatial representation of visual cues on duration perception. As the first author, I led the study from establishing idea to completing the manuscript. I was responsible for the study design, programming, data analysis, and the interpretation of data. The draft of the manuscript was distributed to the co-authors; I revised the whole draft and went through the publication. This work was done during my first year of doctoral program, when I had to stay in Beijing due to the pandemic. Still, the development of research idea, analysis, and interpretation was supervised and advised by Prof. Ernst Pöppel through weekly meetings.

The second paper is “Beta oscillation is an indicator for two patterns of sensorimotor synchronization” (Liu, et al., 2024). This is an empirical study applying Magnetoencephalography (MEG) to compare neural oscillations during sensory-motor synchronization tasks with different tempo. I share the first authorship with Dr. Liu; we contribute equally to different aspects of the publication of this study. We both contributed to the discussion of developing the experiment idea and design. Dr. Liu analyzed the data, wrote and submitted the first version of the manuscript. After getting a request for a major revision, I took the responsibility to check the analysis and add a substantial interpretation of the results. Further, by giving a conceptual framework of the paper, I re-wrote the introduction and discussion while revising the manuscript. And I finished the publication process.

The third paper is “Complementarity of mental content and logistic algorithms in a taxonomy of cognitive functions” (Zhao et al., 2022). This is a theoretical paper proposing a taxonomy in cognition to distinguish between content function (such as perception in different modalities) and logistic function (such as attention and temporal control). As first author, I discussed the framework of the manuscript and the implication of the theory with the coauthors. I wrote the draft, revised it according to the comments from coauthors, and proceeded with submission and revisions of the publication.

1. Introduction

Quid ergo est tempus? Si nemo ex me quaerat, scio;

Si quaerenti explicare velim, nescio."

What then is time? If nobody asks me, I know it.

If I want to explain it to somebody who asks me, I do not know it.

(citation from Augustinus, Confessions, 11th book)

Time is an omnipresent dimension, serving as the foundation for the occurrence of events, the perception of existence, and the phenomena of continuity. Newton (1686) once provided a descriptive definition of physical time, considering it as independent and homogenous: "Absolute, true, and mathematical time by itself and by its own nature flows equably without relation to anything external." For physical time, or what is often referred to as objective time, its measurement and quantification are standardized. But for humans, what is time? The question has many layers. Perhaps the most fundamental one is: how is time represented in human cognition? From the perspective of cognitive science, particularly considering psychophysics, the projection of any physical quantity onto the cognitive level is neither linear nor proportional. This means that when we take time, or in the context of many experiments, durations, as a content of active perception, the subjective estimation is inherently inaccurate. Moreover, existing research indicates that there are systematic biases of subjective estimation and generation of a certain duration.

However, when we reconsider the question of what time is, we realize a key distinction time and other modalities: there is no specialized organ dedicated solely to processing temporal information. For the temporal processing in the brain, whether there is a dedicated or intrinsic system remains a focal point of debate. Taking a different perspective, we recognize that time not only exists as an object of perception but also functions as a fundamental framework underlying perception and cognition. This subtle characteristic of time can be expressed as, "when I feel nothing else, I feel time." Immanuel Kant (1787/1934) implies time to be a priori before contents, suggesting that "time is not an empirical concept. For neither coexistence nor succession would be perceived by us, if the representation of time did not exist as a fundamental a priori."

Therefore, the question of "What is time?" leads us to further explore how time, as an underlying operational framework, constructs cognitive content. We aim to identify the characteristics it imparts to behavior and the corresponding activation pattern in neural activity that align with these overt behavioral features. These research questions are situated within the broader context of temporal perception. Let us first examine how we can measure subjective experiences of time when it is treated as a perceptual content and explore the characteristics of temporal perception revealed through these measurements.

1.1 Measuring subjective time

1.1.1 Moments and durations

Research on temporal perception is broadly based on how humans perceive time, which can be categorized into two main aspects: time points and time durations. As early as in the 19th century, Karl Ernst von Baer (1860) proposed that sensory information from different modalities or in different species might require distinct moments in objective time for processing. Corresponding to the subjective experience of time, one question naturally drew attention: "How long is a time point, or a moment?". The Austrian physicist Ernst Mach (1865) discovered, through judgments of auditory stimulus sequences, that when the interval between tones was less than 30ms, subjects reported hearing only a single sound like a time point without any duration, indicating that only one event, "time point" was perceived. Contemporary research has been consistent with this finding, showing that across different sensory modalities, whether auditory, visual, or even tactile, events must be separated by at least some 20 to 30 milliseconds or so to indicate the order (Cellini et al., 2014; Hirsh & Sherrick, 1961). This seemingly simple finding carries two important implications. One is that the continuity of subjective time is an illusion. The other is that there could be central temporal processing units to calibrate inputs from different modalities (Pöppel, 1978;

Schleidt et al., 1987). From a neurophysiological perspective, auditory information transduction time is faster than visual transduction time on the level of the receptors. This implies that the brain must address an organizational problem of cross-modal integration to align sensory inputs from different modalities within a coherent temporal framework, which should be a logistic system of time.

Research on duration perception can also be traced back to the 19th century. Karl von Vierordt, in his work *Der Zeitsinn nach Versuchen* (The sense of time according to experiments, 1868; see also Lejeune & Wearden, 2009), presented numerous pieces of empirical evidence that have been widely cited later. Mainly using the method of reproduction, Vierordt presented duration as the content of perception, asking subjects to experience a standard duration ranging from 0.1 to 8.9s and then reproduce it either immediately or after a delay. The results showed that for shorter durations (less than 2-3s), the reproduction was extended by 15%-25% compared to the standard duration; while for longer durations (over 3-4s), the reproduction was shortened by 10%-20%. In contrast, the reproduction of 2-3s is relatively the most accurate, so it is referred to as the indifference point. In subsequent studies, many factors have been confirmed to influence duration production or reproduction. Although different reproduction paradigms can yield differences, the durations around 3 seconds are the most accurately reproduced (Mioni et al., 2014). This systematic bias, the so-called Vierordt effect, has led the study of time perception focusing on the factors influencing durations. For example, much like other sensory modalities, research examined its interaction with attention and emotion, and Bayesian theories were applied to understand these processes (Shi et al., 2013). However, the indifference point of 3 seconds inspired us to notice the implicit principles unaffected by content or external factors. Thus, when we contemplate time and examine its representation in the brain, we are testing a less conventional but important hypothesis: time is not only a content of perception but should also be understood as a fundamental organizational structure underlying information processing in general.

1.1.2 The temporal reproduction paradigm

Corresponding to the two aspects of temporal perception measurement, i.e., temporal order perception and duration perception, many behavioral experimental paradigms have been developed, including pure estimation, comparison, production, and reproduction (Pöppel, 1971/1972). Here, I focus on the temporal reproduction paradigm, a paradigm commonly used in duration perception, particularly as it has also been employed as a behavioral paradigm in several listed publications. Overall, as the name suggests, this paradigm asks subjects to first experience a standard duration and then reproduce it, which can be easily implemented across various sensory modalities. Specifically, the task can be divided into three phases: presentation of the standard duration, a pause duration, and the reproduction (e.g., Figure 1).

It should be noted that compared to production and estimation, reproduction does not require subjects to use a reference system that they acquired from the social environment, i.e. the units of seconds. The method of reproduction is considered more useful to study the intrinsic temporal organization (Pöppel, 1971/1972). In addition, reproduction does not suffer from the time-order error compared especially to comparison.

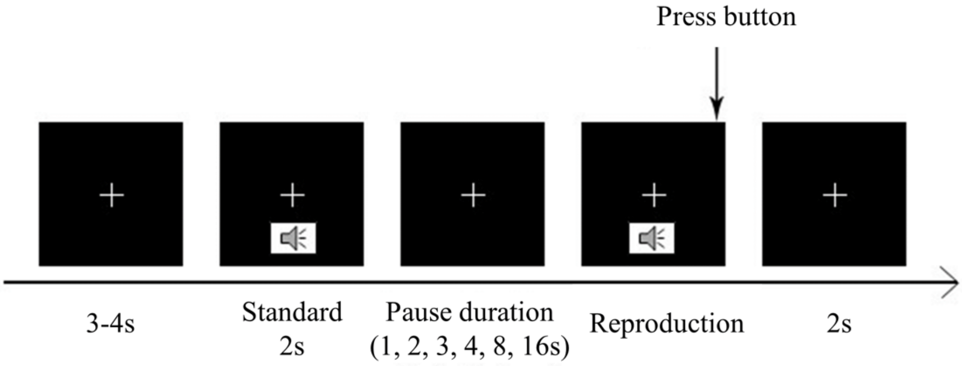

Figure 1 Sample trial in a temporal reproduction task (Zhao et al., 2024)

The variable parameters of the paradigm mainly come from: 1) the way to present the duration, and 2) the method used to achieve reproduction. We can classify durations into empty and filled ones: the former means using sensory stimuli to indicate only the start and the end of a duration, while the latter involves showing sensory stimuli persist through a duration. In most cases, filled stimuli are preferred to present the standard duration to avoid confusion. For reproduction, there are three main implementations: 1) pressing to indicate only the end, 2) pressing to indicate both the start and the end, and 3) maintaining continuous pressing throughout the reproduction. Previous study has shown that these three different methods can affect the accuracy and consistency of reproduction, but for reproduction around 3-4s, there is no difference among the three methods (Mioni et al., 2014). In the experiment 1 below, we used the third implementation as we did not control the pause duration but interested in the subjective reproduction. In all experiments, subjects were instructed not to deliberately measure the duration using any recording methods, such as focusing on breathing, heartbeat, or counting, and they were also told that their performance would not be evaluated based on accuracy. Previous studies suggest that this is a simple and reliable way to ensure the validity of the data (Rattat & Droit-Volet, 2012).

1.2 Temporal structure

As mentioned above, unlike vision or audition, we do not have a specific organ dedicated to processing temporal information. Likewise, the sensory information we perceive cannot exist independently of the temporal dimension, and temporal sequences play a crucial role in perceptions, especially in language. However, mainstream theories of time perception focus on how the perception of durations is generated. For example, in the pacemaker model, a representative of the dedicated models, it is proposed that there is an exclusively dedicated mechanism to measure duration, achieved by accumulating pulses generated by a pacemaker (Grondin, 2010). In contrast, intrinsic models propose that sensory and cognitive processes also play an additional role in timing, like the decay of memory strength is considered an intrinsic timekeeper (Chen et al., 2015; Goel & Buonomano, 2014; Staddon, 2005).

However, these theories seem to imply that time perception is constructed after sensory perception. If we shift our perspective to view time as an underlying organizing structure rather than a cognitive content, we may discover temporal patterns that can be extracted from behavioral and neural phenomena. These patterns could reveal certain organizational challenges and temporal segmentation in the processing of sensory information and the coordination of behaviors.

1.2.1 Hierarchical model of time perception

The review of measuring duration in different modalities already indicates that they may possess qualitatively different mechanisms. The difference in the stimulus transduction in the sensory modalities leads to a temporal challenge in sensorimotor coordination, as on the level of receptor, it takes roughly 20 to 30 ms to transform light into neural signals in vision compared to 1ms or less in audition. Another organizational problem that requires temporal integration is the distributed spatial representation of functions. Thus, it is reasonable to speculate that the construction of temporals structure is apriori to sensory and cognitive contents.

It has been proposed that the realization of such temporal structure is characterized by discrete time sampling (Pöppel, 1997). One is a high-frequency processing system that generates time window of 30-40ms to overcome the organizational problems mentioned above. The other is a complementary low-frequency system of providing a functional window of some 3s, which is believed to be a logistic basis at the behavioral level for subjective present and temporal continuity. It should be noted that neither 30ms nor 3s refers to an exact physical constant, but indicate an operating range (Pöppel, 2009; White, 2017).

One key point of this theory is that temporal structure should be considered as pre-semantic, emphasizing that cognitive experiences and observable phenomena are the results of temporal processing, rather than sensory content determining the temporal structure. In each case of the time windows, entirely different experimental paradigms have yielded similar observations. The following section focuses primarily on the low-frequency time window and will outline representative behavioral results.

1.2.2 The 3 second time window

As mentioned above, Vierordt found that when reproducing durations of approximately 1-8s, reproductions around 2-3s were the most accurate, while shorter durations tended to be overestimated, and longer durations underestimated. This phenomenon was later termed regression to mean, which notably overlooks the unique subjective indifference point around 3s (left panel in Figure 2). A rather simple experiment demonstrated that the accuracy on 2-3s is not the result of sensory adaptation. As shown in the right panel in Figure 2, when the range of standard duration was shifted to 10-15s, reproduction did not exhibit regression to mean, suggesting that the 3s time window may play a significant role in cognitive mechanisms (Pöppel, 1971/1972). This experimental technique was also applied in one temporal reproduction experiment to demonstrate that the consistency observed on 2-3s is not due to sequence effect arising from the experimental design (Zhao et al., 2024).

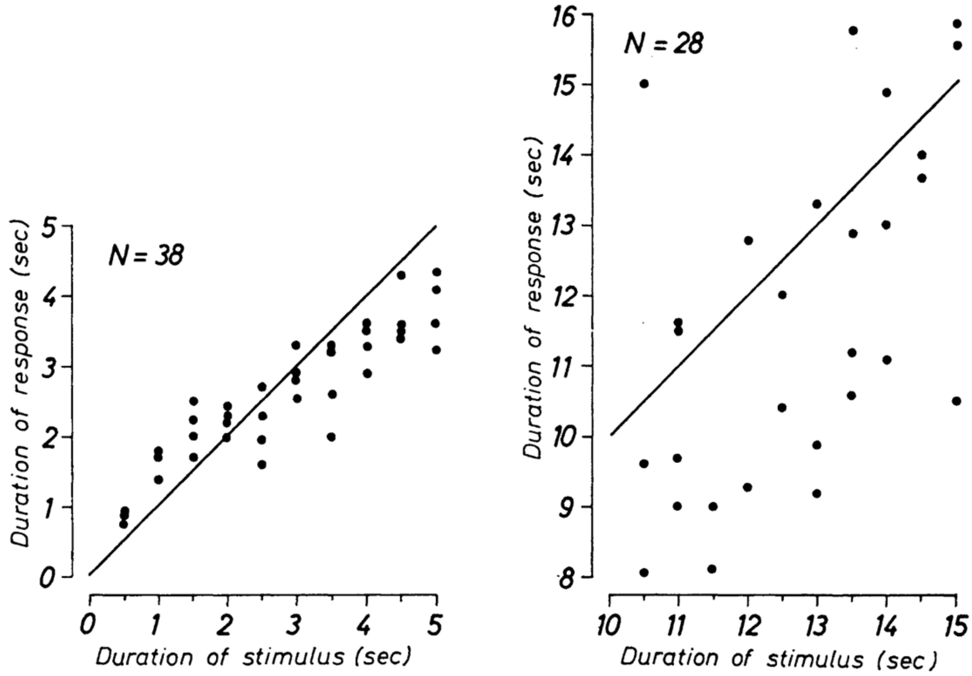

Figure 2 reproduction of stimuli from two different temporal ranges (Pöppel, 1971/1972)

Similar evidence can be collected from distinct behavioral paradigms. For example, in the language domain, neither expression or understanding can be independent of segmentation and organization on the temporal dimension. Vollrath and colleagues (1992) studied German's spontaneous speech and found that singular utterances of 2-3s occurred most frequently, exceeding 25%; while complex combined utterances were most frequently observed in the range of 3-4s, approaching 10%. Studies on other languages have shown similar results. For example, Korean subjects demonstrated a median length of 3.58 seconds when reading prose in their native language (Kien & Kemp, 1994). Recent studies using neurophysiological methods yield similar observations (e.g., Henke & Meyer, 2021). Poetry, as a fusion of language and aesthetics, also involves the significant role of time windows in its construction and appreciation. Turner and Pöppel (1983) found that across many languages, including English, German, Japanese, Chinese, and Latin, the average duration of reading a poetry line is around 3s. They proposed that a poetic verse represents a temporal frame of semantic unit and that poets of all cultures know implicitly about the temporal organization. An empirical study on aesthetic appreciation of Chinese traditional poems shows that for Chinese subjects and German subjects who understand no Chinese, the reciting of a verse in 3s was rated the most beautiful compared in shorter or longer durations (Zhao et al., 2018). Based on the evidence from this field, we may speculate that the 3s time window is not determined by the linguistic content, but it serves as an operational platform for information organization. This characteristic of underlying temporal structure is also examined and confirmed in the experiment 1 with a distinct paradigm.

1.2.3 Sensorimotor synchronization

In nature, the coordination of perception and movement, either automatic or voluntary, is embedded with rhythmic and periodic temporal control. The ability to coordinate motor actions with periodic external stimuli, such as tapping to a metronome, is foundational in daily activities like music performance, dance, and even conversational turn-taking (Repp & Su, 2013). A typical task is to require subjects to synchronize finger taps or other movements with a sequence of stimuli (e.g., auditory tones). A core finding in sensorimotor synchronization research is that the inter-stimulus interval (ISI) – the time between successive stimuli – strongly influences the performance pattern of subjects. Thus, sensorimotor synchronization with innate and fundamental temporal structure has been an essential topic in studies of temporal perception (Bartolo et al., 2014).

By systematically changing ISI, two primary types of responses patterns have been observed. At short ISI (typically <1 second), subjects can anticipate stimulus occurrence by tens of milliseconds and thus show negative asynchronies (von Steinbüchel et al., 1996). The phenomenon was confirmed in later studies, as it is suggested that tapping responses are usually predictive, leading the beats by 20-100ms with ISI less than 2-3 seconds (e.g., Chen et al., 2002); Further, such predictive anticipation with high temporal precision is possible only up to ISI of 3s

(Mates et al.,1994). This indicates predictive timing, in which subjects internalize the tempo and can initiate movements based on the entrained model rather than in passive response to stimulus detection (Repp, 2005). Predictive timing relies on a temporal prediction mechanism and is thought to involve cortical motor areas, the supplementary motor area, and the basal ganglia (Merchant & Honing, 2014).

In contrast, when ISIs are longer (typically > 2 seconds), synchronization performance often deteriorates, and tapping responses become responsive, where subjects respond after perceiving the stimuli (Mates et al., 1994; Miyake et al., 2007). These responses are characterized by positive asynchronies and higher temporal variability, and greater subjective difficulty is usually reported with such reactive tapping (Repp & Su, 2013). This change suggests reduced efficacy of internal temporal prediction and less entrainment, and the reactions rely greater on sensorimotor feedback loops.

Taken these results together, we believe that there are predictive systems operating at different temporal frameworks, and the approximate 3-second time window seem to be a critical operating range that separates the two types of response patterns. It is also suggested that an implicit temporal control can be observed and tested with the sensorimotor synchronization task (Bao et al., 2013; Wittmann, 2013). In this study, we will take advantage of this paradigm to investigate the neural correlates of the temporal control characterized by the low-frequency time window, separating from the motor component.

1.3 Time in the brain

Not only with behavioral paradigms, but empirical studies applying neural recording technologies also provide congruent evidence supporting the low-frequency time window. At the same time, we are aware of the question we cannot evade, how the time windows could be realized based on the neural system. Yet few studies have addressed this directly. By reviewing some insightful previous works, we want to propose that oscillations may be the neural basis of time windows.

1.3.1 Relaxation oscillation

The idea of realizing the time windows by neural oscillations is an exploratory hypothesis under testing, and we still do not fully understand the nature of oscillations, as well as how they are implemented in the neural system. Here I would like to propose a point on the different types of oscillations to simulate further reflections. The types of oscillations are essentially distinguished by the energy exchange between the oscillatory system and the external environment. The examples of two extremes are pendulum oscillation, where system loss and energy exchange are minimal, and relaxation oscillation, where dissipation and exchange are much greater. When describing a self-sustained oscillation with a formula, setting a varying coefficient to represent energy exchange and plotting it reveal the morphological differences between the two types of oscillations. The curve of pendulum oscillation is smooth, resembling the default sin-wave like oscillation. In contrast, relaxation oscillation is characterized by reaching to peak value during a transient duration, completing energy exchange with the external environment. At the same time, because of the characteristic of rapid energy exchange, relaxation oscillation is sensitive to the influences of an external force. Given a periodic force in the external environment, oscillations could be entrained, but the entrainment range is rather limited for self-sustained oscillations. As relaxation oscillations are more sensitive to external force, they have larger entrainment range, being easier to synchronized with an external zeitgeber (Wever, 1965). Taken together, it seems that the oscillations we have encountered in the context of neuroscience more closely align with the characteristics of relaxation oscillation. This aligns with both the all-or-non firing rule of neurons and the entrainment phenomena frequently observed in neural oscillatory studies. Thus, we tend to hypothesize that the oscillations, rhythms, and timing in the brain result from neural activities based on relaxation oscillations, which may be realized through intrinsic interrelated patters.

1.3.2 Neural recording studies

The phenomenon of low-frequency time windows has also been observed in neural signal recording studies using different methods. Mismatch negativity (MMN) is a well-established event-related potential (ERP) component, which is based on the oddball paradigm, presenting odd stimuli in the stream of frequent ones, and the discrepancy of the brain activities elicited by these two kinds of stimuli is defined as MMN. As MMN can be observed when the stimuli are unattended, it is considered to reflect the brain's capability of automatic processing. The innate rhythmic temporal structure makes it a suitable paradigm for temporal perception. In a study using magnetoencephalogram (MEG), the interval between stimuli was manipulated between 1-12 seconds, and it is found that the magnetic component of MMN was greatest when the interval was 3s (Sams et al., 1993; Wang et al., 2015). More importantly, a recent study revealed that the response amplitudes of MMN are positively correlated with their downside slopes, suggesting that an equilibrium shall be reached within a pre-defined time window, and such rubber-band effect was distinct in the left hemisphere (for details, see Wang et al., 2016).

Data from functional neuroimaging studies indicate that the activation of the motor system in the brain is closely related to timing. Specifically, when subjects were asked to time a duration within 3s, the motor systems were more activated than other areas in the brain, while several cortical regions, including medial and frontal areas, were more activated for longer durations (Morillon et al., 2009). An oscillatory component involved in both motor and timing functions is the beta oscillation, and its activity in motor areas can vary with tempo, which is a key temporal structure in sensorimotor synchronization. Similarly, beta oscillations are also correlated with the temporal structure of different tasks such as audio-visual match (Arnal et al., 2011), repetition suppression (Todorovic et al., 2011), and other tasks (Fujioka et al., 2012). It is also discovered to indicate discrete perceptual sampling in the somatosensory domain (Baumgarten et al., 2015).

Specifically, a reduction in beta oscillation amplitude, known as event-related desynchronization (ERD), commonly occurs before the during movement initiation, reflecting the motor system's release from inhibitory control. Conversely, an increase in beta amplitude, event-related synchronization (ERS) typically follows the completion of movement, signifying a re-engagement of motor inhibition (Pollok et al., 2006). Notably, in sensorimotor synchronization tasks with short SOA or fast tempo, beta oscillations tend to remain in a desynchronized state throughout the task (Toma et al., 2002; Yuan et al., 2010). These variations in beta activity have been interpreted as reflecting alterations in movement patters (e.g., Toma et al., 2002). Importantly, beta activity has also been shown to predict subjects' perception of rhythm and duration (Arnal & Giraud, 2012; Kononowicz & van Rijn, 2015).

The aforementioned studies suggest that beta oscillatory activity may serve as a potential marker for the shift in behavioral patterns between sensorimotor synchronization tasks involving short versus long SOAs. Moreover, variations in beta oscillations may reflect the underlying mechanisms of the temporal prediction system involved in motor control. To the best of our knowledge, there is a lack of clear evidence or definitive conclusions concerning the neural markers or mechanisms underlying these distinct behavioral patterns.

2. Research questions

Given the prevalence of observations and empirical studies supporting the 3-second time window, it still needs to be tested whether the effect of temporal organization holds true in a more realistic setting and whether we can locate a neural indicator of temporal control.

Thus, in the first behavioral experiment, we aim to use the temporal reproduction paradigm to investigate if the 3-second time window serves as pre-semantic temporal organization given high-level visual features. Specifically, we apply visual configuration of progress indicators and test how its shape will influence on subjectively perceived time. According to the hierarchical model of temporal perception, we hypothesize that the shape effect may differ between short (3 seconds) and long (15 seconds) durations, aligning with the proposed logistic mechanism around the 3-second threshold.

Further, if experiment 1 demonstrated again the approximate 3-second temporal range plays an important role in defining behavioral patterns, we want to further investigate the neural correlates and indicators that distinguish between the patterns. We speculate that tracking oscillations could be a feasible approach given the ground explained in the introduction. To answer the target question, a different but also well-established paradigm must be adopted. Thus, in the second experiment in this study, we aim to investigate the neural activity associated with the transition from predictive to reactive responses in sensorimotor synchronization tasks and if the change of beta oscillation can serve as a neural marker to indicate the modulation of temporal organization in motor control. Specifically, we will test whether beta oscillation will vary with different tempo and compared to other bands of oscillations in conditions involving both motor and temporal components or only one of them.

3. Experiment 1: 3-second time window in behavior

3.1 Method

3.1.1 Subjects

Forty-two healthy right-handed students from Peking University participated in the study, including eleven males, with ages ranging from 17 to 22 years. All subjects provided informed consent and received monetary compensation for their participation. The study was approved by the Ethics Committee of the School of Psychological and Cognitive Sciences, Peking University.

3.1.2 Design

To examine the effect of shape (bar vs. ring) across different duration levels (3 seconds vs. 15 seconds) and its interaction with progress (20% vs. 80%), three factors were manipulated. Shape and progress were treated as within-subject variables, while duration was a between-subject variable. Subjects were randomly assigned to either the 3-second or 15-second condition. As a result, the total experiment duration varied between groups, and subjects received compensation accordingly. For both the 3-second and 15-second groups, the formal experiment consisted of 120 trials in total, with 30 trials per condition across the four combinations: bar20%, bar80%, ring20%, and ring80%.

Subjects performed a temporal reproduction task. Each trial began with a central fixation cross, followed by the presentation of a standard duration (either 3 seconds or 15 seconds) indicated by a dynamic progressing bar or ring, as illustrated in Figure 3. After the stimulus presentation, the fixation cross reappeared. When the fixation turned green, subjects were instructed to press the space bar to reproduce the perceived duration. They were asked to hold the key until they felt the same amount of time had passed and then release it immediately. Detailed display parameters and timing control are presented in Figure 4. The original instruction on the first frame can be translated as: “Formal experiment is about to begin. The task will be the same as in the practice. Please be ready.”

Specifically, the bar measures 628 by 20 pixels, and the ring has a perimeter of 628 pixels and a width of 20 pixels. The gray color is defined as RGB [200, 200, 200], and the green as RGB [147, 230, 95]. Progress advances at a constant velocity—from left to right for the bar, and clockwise for the ring. Moreover, the fixation duration and inter-trial interval were jittered to prevent motion prediction arising from trial repetition.

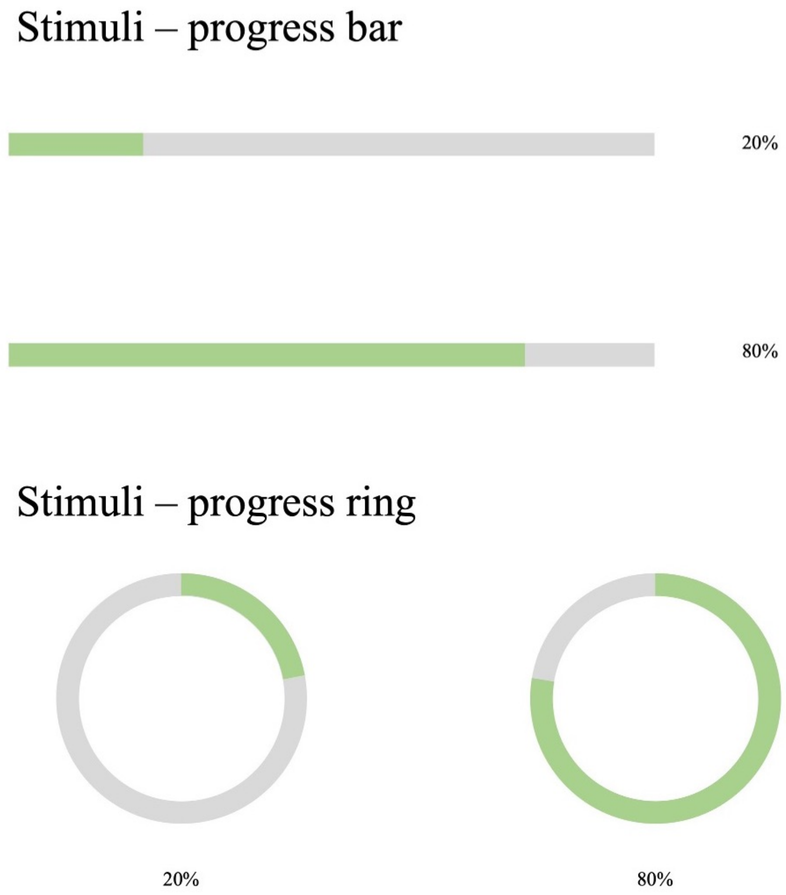

Figure 3 The completed states of the bar and ring indicators at two progress levels (Zhao et al., 2023)

3.1.3 Procedure

All subjects first received identical, detailed instructions originally in Chinese. They were explicitly instructed not to engage in intentional timing strategies such as counting, tapping, or relying on any external cues. Instead, they were encouraged to focus on their subjective sense of time rather than aiming for precise reproduction.

The experiment began with four practice trials, followed by the formal session including three interleaved breaks. Throughout the experiment, subjects sat comfortably in a chair with their chin supported by a rest positioned 60 cm from the screen. Stimuli were presented on a 20-inch ViewSonic monitor with a resolution of 1366×768 and a refresh rate of 60 Hz. The experimental program was implemented using MATLAB 2017b.

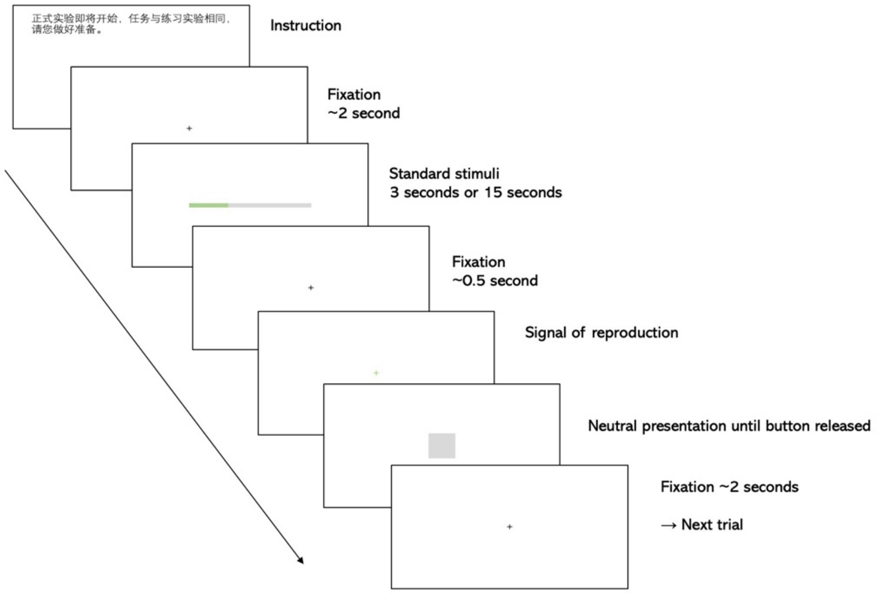

Figure 4 The temporal reproduction task (Zhao et al., 2023)

3.1.4 Data analysis

During data preprocessing, trials were excluded if the reproduction reaction time was less than 100ms, as such responses likely indicated that subjects had initiated the reproduction before the green signal appeared, resulting in invalid measurements. Additionally, trials identified as outliers for each subject based on boxplot criteria were also removed.

For each of the eight experimental conditions, the mean reproduced duration (RPD) and its standard deviation (SD(r)) were calculated separately for each participant. The coefficient of variation (CV) was then computed as the ratio of RPD to SD(r). In addition to classic statistic approach, we also rendered the data to Bayesian statistic in JASP (JASP Team, 2022). The employment of Bayesian approach can provide a more nuanced interpretation of the data. Unlike traditional p-values, which only indicate whether to reject the null hypothesis, Bayesian methods quantify the relative evidence for both the null and alternative hypotheses using Bayes Factors (BF) by incorporating prior distributions and updating them with observed data (Wagenmakers et al., 2018).

3.2 Results

3.2.1 Accuracy of temporal reproduction

At the 3-second duration level, the average reproduced time across all conditions was significantly longer than the standard duration of three seconds (mean = 3.196, t(75) = 2.511, p < 0.050, Cohen's d = 0.288). In contrast, at the 15-second level, the mean reproduced duration did not significantly differ from the standard (mean = 15.241, t(91) = 0.625, p = 0.534).

In terms of variability, the 3-second reproductions exhibited a significantly lower CV (mean = 0.171) compared to the 15-second reproductions (mean = 0.250; F(1,40) = 20.579, p < 0.001, η_p^2 = 0.340) as in Figure 5.

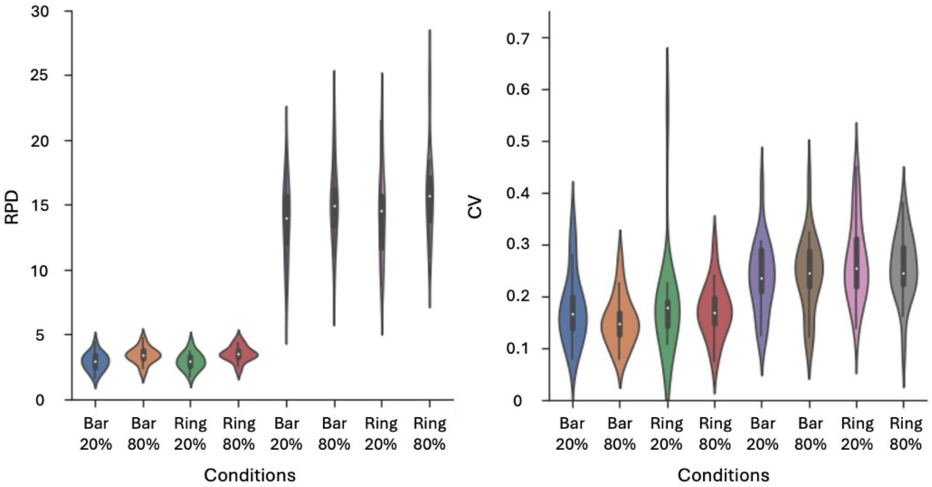

Figure 5 Distribution plot of the RPD and CV across all conditions

3.2.2 Shape effect

A three-way repeated-measures ANOVA was conducted to analyze the effects of duration, shape, and progress. For the absolute reproduced duration (RPD), no significant three-way interaction among the three variables was observed. However, at the two-way level, a significant interaction emerged between duration and shape (F(1,40) = 5.012, $p < 0.050$, $\eta_p^2 = 0.112$).

Specifically, in the 3-second condition, RPD did not significantly differ between the bar and ring shapes (mean difference = -0.077, t = -0.43, *p*_bonf = 1.000). In contrast, in the 15-second condition, RPD was significantly shorter with the bar compared to the ring (mean difference = -0.622, t = -3.806, *p*_bonf < 0.010). These findings are visualized in a raincloud plot showing the distribution patterns (Figure 6).

The main effect of shape also reached significance, indicating that overall, reproduced durations were shorter with the bar (mean = 9.258) than with the ring (mean = 9.613; F(1,40) = 8.284, $p < 0.010$, $\eta_p^2 = 0.172$).

Regarding temporal variability, as measured by the coefficient of variation (CV), the ANOVA revealed no significant interactions at any level. The only significant main effect was that of shape: reproductions using the bar exhibited significantly lower variability (mean CV = 0.205) than those using the ring (mean CV = 0.223; F(1,40) = 4.178, $p < 0.050$, $\eta_p^2 = 0.095$).

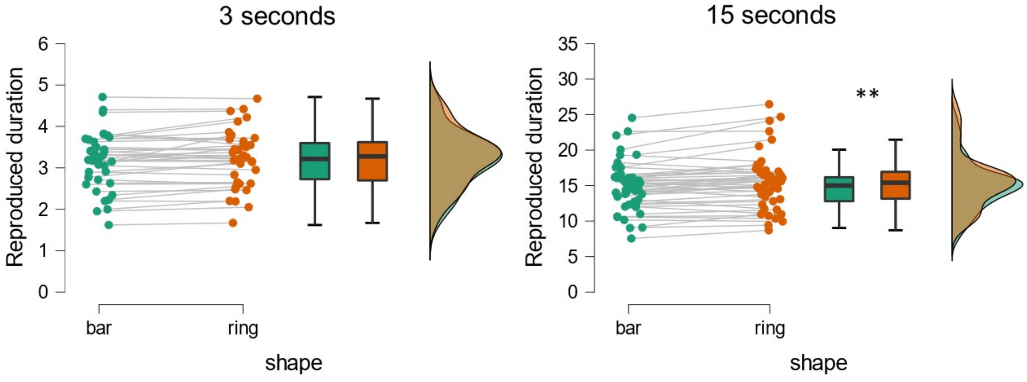

Figure 6 RPD with the bar and ring at the 3-s level and the 15-s level (Zhao et al., 2023)

3.2.3 Progress effect

For the absolute reproduced duration (RPD), a significant two-way interaction was also observed between duration and progress (F(1,40) = 10.692, $p < 0.050$, $\eta_p^2 = 0.186$). Like the interaction with shape, this effect was specific to the 15-second condition, where a significant difference was found between the 20% and 80% progress levels (mean difference = -1.541, t = -6.835, *p*_bonf < 0.001). In contrast, no significant difference was observed between progress conditions at the 3-second level (mean difference = -0.527, t = -2.126, *p*_bonf = 0.238). The distribution of the data is visualized in Figure 7.

The main effect of progress also reached significance, showing that overall, durations were reproduced significantly shorter under the 20% progress condition (mean RPD = 8.900) compared to the 80% condition (mean RPD = 9.971; F(1,40) = 38.069, $p < 0.001$, $\eta_p^2 = 0.488$).

Overall, Bayesian repeated-measures ANOVA supported the model that included the main effects of shape, progress, and duration, as well as the interactions shape × duration and progress × duration. This model had the highest posterior probability (P(M|data) = 0.404) and a Bayes Factor for model comparison (BFM) of 12.196, consistent with the findings from the classical repeated-measures ANOVA.

3.3 Discussion

In this study, we employed a temporal reproduction paradigm to further investigate how the visual representation of progress indicators affects the subjective experience of waiting time. Our findings highlight the advantage of bar-shaped indicators and brief progress cues; however, this effect was observed only at the longer duration level (15 seconds) and not at the shorter duration level (3 seconds).

3.3.1 Effect of visual configuration

We observed a clear advantage of the bar-shaped progress indicator at the longer duration of 15 seconds. This finding offers practical value as empirical support for interface design in industry settings: when representing extended waiting times, using a bar-shaped indicator may help reduce users' perceived duration. But why does this advantage appear only with the bar?

We propose that the explanation lies in the spatial layout of the progress indicators, and more specifically, in the framework of the A Theory of Magnitude (ATOM). According to ATOM, time, space, and numbers are processed by a shared analog magnitude system, with these dimensions mutually influencing one another (Walsh, 2003). In particular, a well-documented phenomenon known as the Spatial–Temporal Association of Response Codes (STEARC) effect suggests that temporal information is mentally mapped along a horizontal axis from left to right. This effect has been observed across various tasks involving time judgments, including time-based responses, temporal estimation, and duration reproduction (Ishihara et al., 2008; Fabbri et al., 2012).

In our stimulus design, the bar progressed horizontally from left to right, spanning up to 8 degrees of visual angle, whereas the ring progressed clockwise starting from the vertical meridian. Since we set progress levels at either 20% or 80%, most of the bar's visual representation remained within the left visual field—an area associated with shorter perceived durations according to the STEARC effect. In contrast, the ring's clockwise progression placed the majority of its filled area in the right visual field, which may be associated with longer perceived time. A testable prediction arising from this account is that a counterclockwise ring might produce shorter reproduction durations, similar to the bar.

Within the same theoretical framework, we can also interpret the observed progress effect: across conditions, 80% progress consistently led to longer reproduced durations, despite both the 20% and 80% indicators lasting for the same objective duration. Prior research has shown that larger spatial extents can result in longer perceived time (DeLong, 1981), and our findings suggest that this principle also applies in dynamic visual contexts.

We also speculate that the difference between the bar and ring shapes during longer waiting periods may stem from distinct subjective experiences. The bar presents a one-dimensional, linear spatial representation that aligns directly with the passage of time, whereas the ring incorporates a two-dimensional spatial structure. This linear format may facilitate easier evaluation of ongoing progress and support temporal prediction. Such predictability could enhance the user's sense of control, which in turn may contribute to a reduced perception of waiting time.

3.3.2 Temporal mechanism

Interpreting the observed interactions presents a key challenge. One interaction occurred between duration and shape, indicating that shape had no significant effect at the 3-second level, whereas the bar indicator led to shorter reproduced durations at the 15-second level. The other interaction was between duration and progress, showing that the effect of 20% progress in reducing reproduced time emerged only at the 15-second level.

These findings clearly extend beyond individual differences or user preferences. Instead, they suggest that both the shape and progress features of the indicator exert temporally dependent influences on time perception. We propose that these results offer valuable insight into potentially distinct underlying temporal mechanisms operating at shorter (3-second) versus longer (15-second) durations.

This observation aligns with the phenomenon of low-frequency temporal organization. It has been proposed that sequential events are integrated into perceptual units within a temporal window of approximately three seconds (Pöppel, 1997). This integration period is thought to form the foundation for cognitive representations of the subjective present—the “now.” Within this temporal boundary, sensory information is grouped into a coherent unit and retains a distinct identity. In the context of the current study, when the waiting time is around three seconds, its temporal structure is perceived and maintained independently of other sensory input. However, when the waiting period extends to 15 seconds, differences in reproduced duration emerge depending on the visual characteristics of the progress indicator.

We argue that these behavioral findings support the notion that the three-second window represents a fundamental temporal structure that is both logistic and pre-semantic. That is, within this window, the subjectively experienced duration is not influenced by the sensory attributes of the stimulus—whether the indicator is a bar or a ring. At this short duration, temporal organization takes precedence over visual differences. In contrast, once the duration exceeds this temporal limit—as in the 15-second condition—higher-order cognitive processes become engaged, allowing stimulus features to influence the encoding and retrieval of temporal information.

While we emphasize the potential significance of the three-second time window, we acknowledge that three seconds may not represent a precise transition point, and our categorization of short versus long durations is to some extent arbitrary. Future research incorporating additional intermediate durations between three and fifteen seconds could help refine this distinction and empirically test the proposed prediction.

4. Experiment 2: beta oscillation as an indicator

4.1 Methods

4.1.1 Subjects

Fourteen young, right-handed subjects with no neurological conditions participated in the study. All reported normal hearing and no formal musical training. Prior to the experiment, subjects received detailed instructions and provided informed consent. Compensation was given upon completion of the experiment. This study has received ethics approval by the ethical board of the Ludwig Maximilian University of Munich.

4.1.2 Procedure

The experiment consisted of five blocks, each comprising three sequential tasks: a listening task, a synchronization task, and a continuation task (see Figure 7). The task order was fixed across blocks. First, in the listening task, subjects passively listened to 40 isochronous clicks without making any movements. Next, in the synchronization task, they tapped their right index finger in synchrony with another 40 clicks at the same tempo. Finally, in the continuation task, the auditory pacing was removed, and subjects continued tapping at the established tempo for an additional 40 taps. Transitions between tasks were indicated by a higher frequency click marking the end of each phase.

The stimulus onset asynchrony (SOA) was manipulated as different tempos and varied across blocks as 0.60, 1.20, 1.80, 3.00, and 4.20 seconds. For each SOA, the click duration was scaled proportionally as 16, 32, 48, 84, and 112ms, respectively. Block order was randomized across subjects, and a 2-minute break separated each block.

Prior to the experimental session, a 3-minute resting-state recording was conducted while subjects remained relaxed with eyes open. Subjects also completed a practice session before entering the experimental chamber and were instructed to tap as accurately as possible while minimizing movement in other body parts.

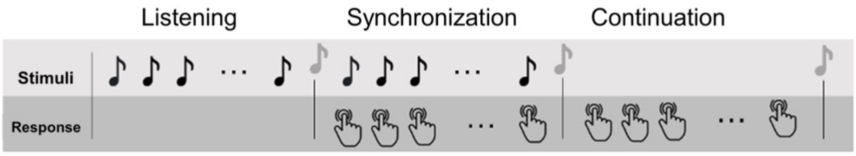

Figure 7 Task demonstration (Liu, Zhao et al., 2024)

4.1.3 Data acquisition

MEG data were recorded at a sampling rate of 500 Hz using a Yokogawa MEG system (Yokogawa Electric Corporation, Japan) housed in a dimly lit, sound-attenuated, and magnetically shielded chamber (Ak3b, Vakuumschmelze, Hanau, Germany). The system consisted of 125 axial gradiometers and three reference magnetometers. Head position relative to the sensor helmet was tracked using localization coils attached to anatomical landmarks on the scalp (nasion and preauricular points), with coil positions digitized via a 3D digitizer (Zebris, Isny, Germany).

Auditory stimuli—clicks at approximately 75 dB SPL—were delivered binaurally through MEG-compatible tube earphones (Etymotic Research, Elk Grove Village, USA). All stimuli were presented using Presentation software (Neurobehavioral Systems). During recording, subjects lay horizontally with their arms crossed over their chest, holding a computer mouse in their right hand, which they used to respond by pressing a button.

4.1.4 Data analysis

Due to excessive noise in their MEG data, three subjects were excluded from the analysis. Additionally, for all the rest subjects, the first three taps of each trial were discarded to allow analysis only on stabilized synchronization and continuation. The final tap was also excluded to avoid potential interference from the transition between tasks.

Behavioral results analysis

For behavioral data, an initial analysis was conducted to examine whether behavioral patterns in sensorimotor synchronization tasks varied with tempo. The proportion of predictive taps during the synchronization task was used as the performance index. Predictive taps were defined as those occurring before a reaction time threshold of 150ms following click onset. The SOA served as the independent variable, with five levels: 0.60, 1.20, 1.80, 3.00, and 4.20 seconds. Post-hoc t-tests were conducted with Bonferroni correction to adjust for multiple comparisons.

Preprocessing of MEG data

The preprocessing was performed using MATLAB R2018b with custom-written scripts in combination with the FieldTrip toolbox (Oostenveld et al., 2011). Line noise was removed using band-stop Butterworth filters (49–51 Hz, 99–101 Hz, and 149–151 Hz; filter order 4). Low-frequency noise was eliminated using a high-pass Butterworth filter at 0.5 Hz (filter order 4). Noisy or malfunctioning sensors were identified through visual inspection and subsequently interpolated using data from surrounding sensors (1 to 3 sensors interpolated per participant). Eye movement and cardiac artifacts were removed using independent component analysis (ICA), with 3 to 7 components discarded per participant. The cleaned data were then segmented into epochs ranging from 2000ms before to 2000ms after stimulus or response onset. Finally, trials containing excessive artifacts were manually identified and excluded from further analysis, with 0 to 11 trials removed per participant.

Functional localization of sensors

Due to the absence of individual anatomical MRI data, the spatial accuracy of source-level analysis was significantly limited (Gross et al., 2013). To address this, we used the first motor-evoked field (MEF1) as a functional localizer to identify motor cortex–related areas at the topographical level. MEF1 is a characteristic movement-evoked response that typically peaks around 50ms following a keystroke (Joliot et al., 1998). The analysis proceeded as follows: first, sensors located near the edge of the helmet were excluded. Next, trials from the continuation task were averaged for each sensor. For each participant, the five sensors exhibiting the highest absolute MEF1 peak amplitudes were selected. To determine the absolute peak amplitude, we first identified the signal maximum within a time window of -30 to 70ms around the tap. We then averaged the absolute event-related field values within a ±6ms window centered on this peak. This average was used as the sensor's peak amplitude.

Time-frequency analysis

To perform time-frequency analysis, the MEG time series were transformed into time-frequency representations spanning 5 to 80 Hz in 1 Hz increments using 7-cycle Morlet wavelets. To mitigate edge artifacts, the first and last 300ms of each epoch were discarded. The remaining data were normalized using decibel (dB) conversion to reduce variability arising from individual differences and the 1/f spectral characteristic. For each participant, trial-averaged power values were computed separately for sensors associated with the motor cortex across three frequency bands: mu (10–12 Hz), beta (14–28 Hz), and gamma (30–50 Hz).

We began by analyzing the event-related desynchronization (ERD) and event-related synchronization (ERS) peaks of beta oscillations. For the ERD peak, the minimum power was identified within a time window of -400 to 200ms relative to tap or sound onset. The peak amplitude was then computed as the average power within a ±6ms window centered on this minimum. For the ERS peak, the maximum power was located within 0 to 1000ms following tap or sound onset, and the corresponding peak amplitude was similarly calculated using a ±6ms window around the maximum. To assess the effects of task and stimulus onset asynchrony (SOA, or tempo) on ERD and ERS peak amplitudes, we conducted a two-way repeated-measures ANOVA. The independent variables were task (listening, synchronization, and continuation) and SOA (0.60, 1.20, 1.80, 3.00, and 4.20 seconds).

Next, we analyzed activity in the mu and gamma frequency bands. Since it remains unclear whether these oscillations contribute to temporal processing in the absence of overt movement, we first assessed whether mu and gamma power changed during the listening task. For each SOA condition, data from 500ms before to 200ms after the click onset were extracted. One-sample t-tests were performed to determine whether mu and gamma power significantly differed from zero, with p-values corrected using the Benjamini-Hochberg false discovery rate method. If significant effects were detected in the listening condition, a two-way ANOVA was then conducted across all three task conditions (listening, synchronization, and continuation). Otherwise, the analysis included only the synchronization and continuation tasks. The independent variables were task and SOA (0.60, 1.20, 1.80, 3.00, and 4.20 seconds), and the dependent variables were the mu ERD peak and gamma ERS peak, respectively. Peaks were calculated within a time window from 500ms before to 200ms after either click onset or movement onset, using the same procedure applied for detecting beta oscillation peaks.

Prediction of oscillatory features on response asynchrony

We then examined whether neural activity could predict performance in the synchronization task. Using single-trial data, we constructed a mixed-effects linear regression model. The dependent variable was behavioral asynchrony, while the independent variables were neural measures that showed significant differences across SOA conditions during synchronization. Variable of subject was included as a random effect with a random intercept to account for individual variability. The analysis was conducted using the *lme4* and *lmerTest* packages in R (Kuznetsova et al., 2017).

4.2 Results

4.2.1 Behavioral results

The proportion of predictive taps significantly decreased as SOA increased (F(4,40) = 26.087, $p < .001$, $\eta^2 = .723$; see Figure 8). Post-hoc comparisons revealed that the longer SOAs (3.00 and 4.20 seconds) differed significantly from the shorter SOAs: *p*(3.0 vs. 0.6) = .015, *p*(3.0 vs. 1.2) = .001, *p*(3.0 vs. 1.8) = .051; *p*(4.2 vs. 0.6) = .002, *p*(4.2 vs. 1.2) < .001, and *p*(4.2 vs. 1.8) = .001.

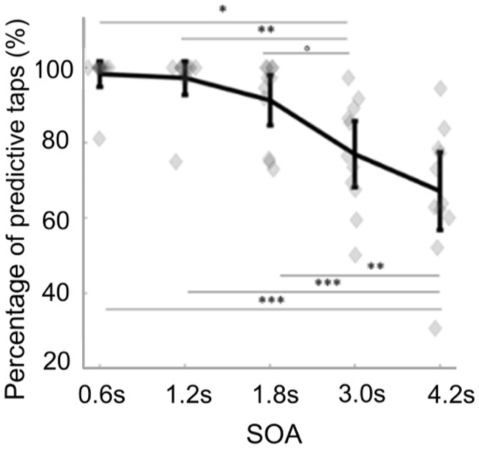

Figure 8 Percentage of predictive taps with different SOAs (Liu, Zhao et al., 2024)

4.2.2 Neural recording results

The selected motor-related sensors were primarily located in the frontoparietal region with a dominant distribution over the left hemisphere (Figure 9). The number of subjects indicates the selected sensors are shared by how many subjects.

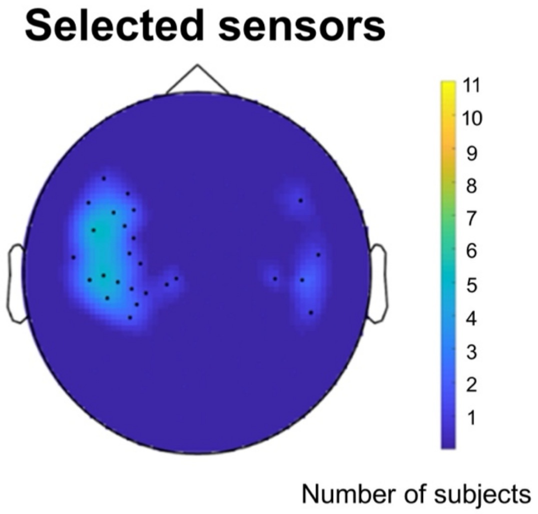

Figure 9 The selected sensors for analysis (Liu, Zhao et al., 2024)

In the Figure 10 below shows the amplitude of beta-band oscillation before and after a tap in three conditions. A clear pattern of beta ERD (decrease in the amplitude before a tap) followed by ERS (increase in the amplitude after a tap) can be observed. The pattern is also visually consistent with different SOAs, supporting the following analysis results.

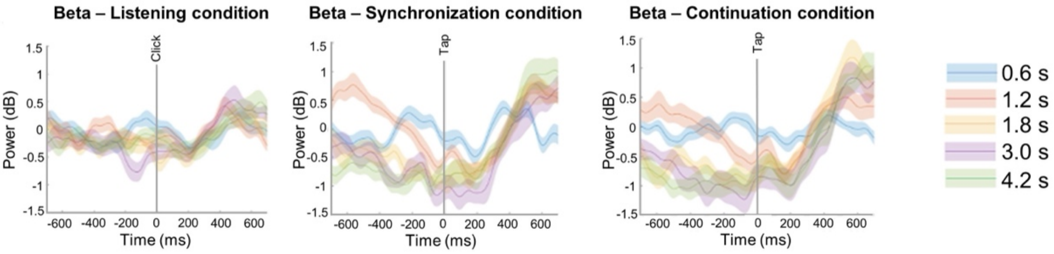

Figure 10 Amplitudes of beta-band oscillation across conditions
(modified from Liu, Zhao et al., 2024)

For the beta ERD peak, a significant main effect of task was found (F(2,20) = 16.061, *p* < .001, η² = .616). The ERD peak was significantly smaller during the listening task compared to both the synchronization (*p* = .012) and continuation tasks (*p* = .007). Additionally, there was a significant main effect of SOA (F(4,40) = 19.541, *p* < .001, η² = .661). Specifically, the ERD peak magnitude was reduced at the shortest SOA (0.6 s) compared to 1.2 s (*p* = .031), 1.8 s (*p* = .001), 2.4 s (*p* = .008), and 3.0 s (*p* = .004). Results are shown in Figure 11A.

For the beta ERS peak, a significant main effect of task was observed (F(2,20) = 10.204, *p* < .001, η² = .505). The ERS peak was significantly lower during the listening task compared to both the synchronization (*p* = .028) and continuation tasks (*p* = .007). A significant main effect of SOA was also found (F(4,40) = 13.179, *p* < .001, η² = .569). Specifically, the ERS peak was reduced at an SOA of 0.6 s compared to 1.2 s (*p* = .002), 1.8 s (*p* = .001), 2.4 s (*p* = .024), and 3.0 s (*p* = .001). Additionally, the ERS peak at 1.2 s was significantly smaller than that at 4.2 s (*p* = .032). Details can be found in Figure 11B.

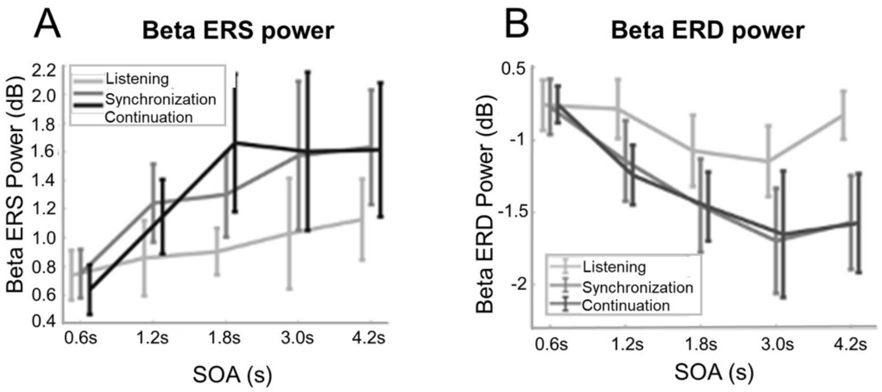

Figure 11 Beta ERS and ERD power change across SOAs
(modified from Liu, Zhao et al., 2024)

In contrast, for gamma-band oscillations, the amplitude did not exhibit trend of ERD or ERS around a tap; while mu-band oscillation showed a trend of ERD and ERS as illustrated in Figure 12 below. And the pattern is also visually consistent with different SOAs, supporting the following analysis results.

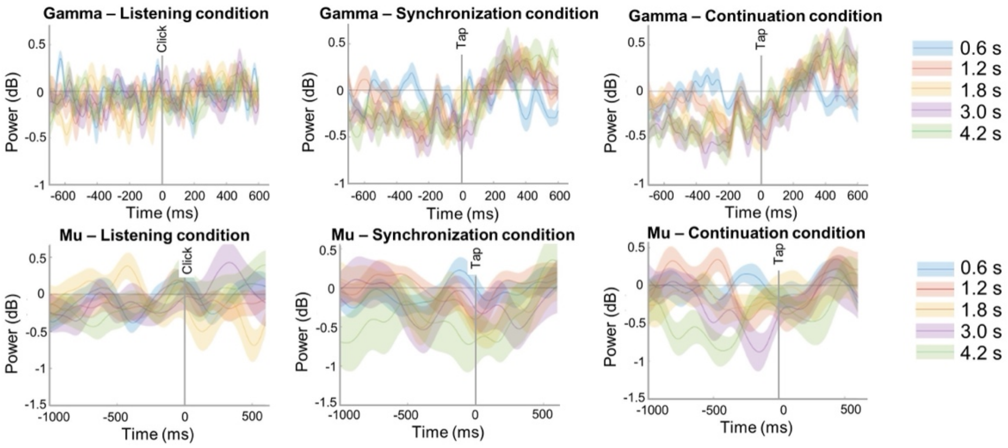

Figure 12 Amplitudes of gamma- and mu-band oscillations across conditions
(modified from Liu, Zhao et al., 2024)

Again, for analysis of ERD and ERS with different SOAs, mu oscillation activity showed greater desynchronization at longer SOAs during tasks involving overt movement. Specifically, no significant changes in mu power were observed during the listening task. However, in the synchronization and continuation tasks, mu

ERD peaks significantly decreased as SOA increased (F(4,40) = 5.875, *p* < .001, $\eta^2 = .370$; Figure 13A).

For gamma oscillations, no significant modulation was found in the listening task. Additionally, gamma ERS peaks did not show significant variation across SOA conditions or task types (Figure 13B).

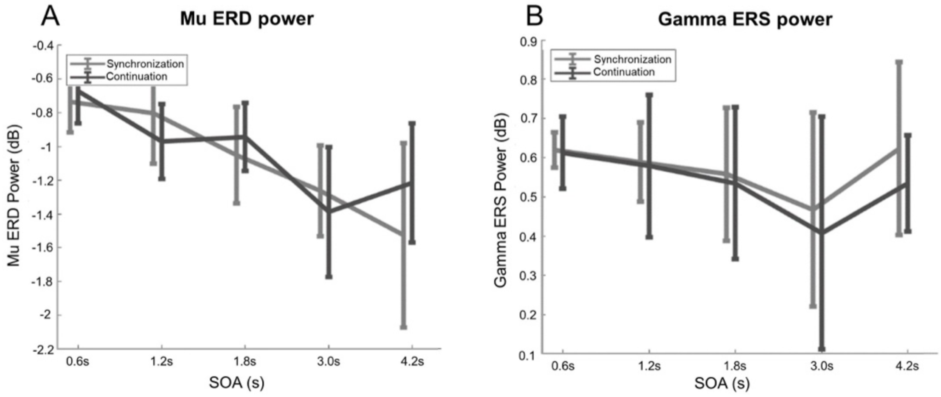

Figure 13 Mu and gamma ERS and ERD power change across SOAs (modified from Liu, Zhao et al., 2024)

Based on the results above, we identified that mu ERD, beta ERD, and beta ERS peaks varied with SOA during the synchronization task. These three neural measures were then included as predictors in a linear mixed-effects regression model. The analysis revealed that only the beta ERS peak significantly predicted behavioral asynchrony ($\beta = -5.590$, F(1, 1977.2) = 7.413, *p* = .007; Figure 14). Specifically, higher beta ERS peak values were associated with more positive asynchronies, as illustrated in Figure 14.

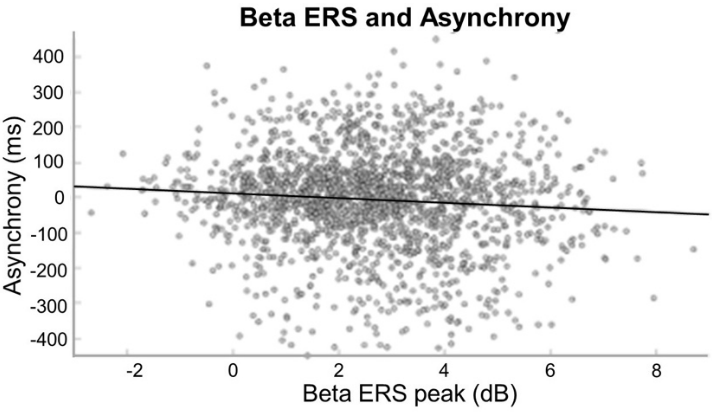

Figure 14 Regression line with scattered plot between beta ERS and behavioral asynchrony (modified from Liu, Zhao et al., 2024)

4.3 Discussion

The present study yielded three key findings. First, beta oscillatory activity in the motor system varies with rhythmic tempo, both in the presence and absence of overt movement. Second, the beta ERS peak significantly predicts behavioral asynchrony during the synchronization task. Third, during synchronization, mu oscillations are modulated by tempo, whereas gamma oscillations remain unaffected.

In line with previous studies, we found that both beta ERD and ERS increased with longer SOAs (e.g., Toma et al., 2002; Seeber et al., 2016). In conditions with short SOAs, desynchronized beta oscillations may serve as active motor inhibitors, helping to sustain rapid, continuous movements. The observed reduction in both ERS and ERD peak amplitudes may reflect the involvement of smaller cortical populations during fast-paced synchronization (Buzsáki, 2006). This supports the notion that faster movements are easier to sustain and may demand fewer cognitive resources (Park et al., 2017; Van der Wel et al., 2009). Notably, this modulation of beta activity by SOA was also evident during passive listening, suggesting that beta oscillations may be involved in two distinct functions: not only in motor inhibition but also in temporal prediction.

As part of the temporal prediction system, beta oscillations may contribute to actively anticipating the timing of movements by modulating ERD and ERS peak magnitudes. Given that the tempo in the passive listening task matched that of the synchronization task, subjects may have engaged in covert motor simulation, leading to changes in beta activity. This activity could reflect simulated motor efference signals transmitted to sensory cortices to support temporal encoding (Patel & Iversen, 2014). Thus, the modulation of beta oscillations by SOA during passive listening may represent the neural signature of this simulation process.

A negative correlation was found between beta ERS amplitude and behavioral asynchrony in the synchronization task. This aligns with previous findings using a time reproduction paradigm, where beta ERS amplitude was shown to predict the length of reproduced durations (Kononowicz et al., 2015). Similarly, Fujioka et al. (2012) reported that beta ERS amplitudes over auditory and motor-related cortices correlated with tempo information across SOAs ranging from 300 to 1200ms. These results collectively support the view that beta ERS reflects a process of temporal information integration, representing internally generated timing signals (Tan et al., 2014; Torrecillos et al., 2015).

In our study, the negative correlation may reflect differences in subjective timing between predictive and reactive tapping. Predictive taps are likely to occur when subjects perceived elapsed time aligns with the SOA—particularly for shorter SOAs, typically under three seconds. In contrast, for longer SOAs, reactive taps may occur in response to the click onset before subjects feel the SOA has subjectively elapsed. We propose that the observed variation in beta ERS magnitude may result from differences in perceptual feedback and timing integration following these two types of responses.

Therefore, beta oscillations could serve as a reliable neural marker distinguishing predictive tapping under short SOAs from reactive tapping under longer SOAs. Additionally, the modulation of beta activity by SOA highlights its role in the temporal organization of motor control. Notably, the dividing line between short and long SOAs appears to center around three seconds—a duration widely regarded as a fundamental temporal boundary in human cognition, supported by converging evidence from multiple disciplines (Zhao et al., 2022).

Additionally, we observed that SOA influenced mu oscillations during sensorimotor synchronization, but not during the listening task, where no movement was required. This suggests that mu oscillations are likely associated with motor-related components—such as changes in movement speed—rather than with the temporal processing of rhythmic auditory input. In contrast, gamma oscillations showed no significant modulation by SOA. This finding aligns with previous research indicating that gamma activity is more closely tied to local information processing (Muthukumaraswamy, 2010).

Taken together, the findings of this study support the active functional role of beta oscillations—particularly beta ERS—in the motor cortex during temporal anticipation. In answering the target question, we believe that beta oscillation serves as an important neural indicator of temporal control, and this contributes to future studies to investigate the dynamic process during the 3-second time window through beta oscillations.

5. General discussion

5.1 Implications from the behavioral and neural results

Based on the results of the two experiments, we not only confirmed the role of the 3-second time window in distinguishing behavioral patterns, but also identified, through MEG, that features of beta oscillations can serve as indicators of temporal control across different rhythmic tempos. Notably, in both experiments—which employed different paradigms—time emerged as a structural framework rather than mere content; it provided the foundational scaffold for information processing.

In Experiment 1, although participants were instructed to perceive and reproduce durations, the results showed that subjective perception was influenced not only by the content presented within those durations, but also by the temporal structure used to convey that content. In other words, the framework itself shaped how time was experienced. In Experiment 2, by comparing the listening condition with the synchronization condition, we found that the two temporal response patterns distinguished by beta oscillations were not solely driven by motor control. Even in the absence of movement, as in the listening condition, beta oscillation features varied systematically with changes in tempo. This suggests that beta oscillations are more likely involved in encoding temporal structure and supporting entrainment, which in turn modulates motor control.

These findings are consistent with phenomena previously identified and summarized in earlier research. Temporal processing in neural systems is characterized by a time window of approximately 3 seconds. This temporal segmentation is reflected in cognitive processes such as sensorimotor synchronization, intentional movements, temporal perception, verbal communication, attentional modulation, and, at the neural level, in the temporal modulation of cortical sensitivity (Wang et al., 2015; for an overview and mechanisms involved, see Bao et al., 2015; Pöppel & Bao, 2014)

The observation of similar patterns across different domains and experimental methods leads us to propose that the importance of time perception lies not only in how individuals subjectively experience duration, but more critically, in how the brain organizes information along the temporal dimension. At a low-frequency level, we suggest that the 3-second interval may represent an important operating system. As noted in the introduction, the “3 seconds” referenced here is not a fixed physical value, nor does it refer to a specific duration in physical time. Rather, we argue that the 3-second time window reflects a content-independent processing mechanism determined by how the brain handles information. The brain inherently requires a temporal window to process sequentially unfolding information—such as integrating cross-modal inputs, making comparisons, establishing order, and forming unified perceptual experiences. It is precisely because this underlying temporal rule exists that we can observe consistent behavioral patterns across different tasks. This characteristic of the time window is what we refer to as pre-semantic—a temporal structure that is not defined by the content it contains.

From this perspective, we hope to propose a new way of understanding time perception and psychological functions by offering a classification of cognitive processes that differs from previous views. At the same time, we also consider time and temporal perception with its biological roots, giving predictions based on previous physiological studies on malfunctions related to disrupted logistic functions.

5.2 Beyond the results: time as a logistic function

As argued several times above, in various cognitive activities, the activation of specific neural modules introduces the challenge: how to organize these states of activation coherently over time. Specifically, the idea that distinct cognitive functions are localized in different brain areas or implemented via different algorithms raises the critical question of how these disparate activities are temporally synchronized. This issue of temporal organization was already addressed by Lashley (1951), who proposed that behavioral sequences are typically governed by hierarchical central plans (see Rosenbaum et al., 2007, for a contemporary overview). This gives rise to further questions: How can a unified subjective experience emerge when multiple modules are active across different brain regions? What mechanisms ensure that the neural representation of an event is correctly linked to a particular perceptual stimulus? We suggest that the challenge necessitates the involvement of support functions—logistic mechanisms that manage coordination. The logistic functions (the “how”) can be analogically defined as automatic programs running in the background, which is determined by the infrastructure of the neural circuits. These functions make conscious content possible, including for example activation modulated by the circadian rhythm, attention mechanisms, and the temporal organization.

It has been proposed that the temporal organization is achieved through neural synchronization mechanisms, which manifest as oscillatory activity within neural populations (e.g., Pöppel, 1997). These neural oscillations provide distinct temporal states that help organize cognitive processes. It is suggested that within a single cycle of neural oscillation, all events—despite being physically non-simultaneous—are processed as if they occur simultaneously. This concept is supported by various physiological and psychophysical findings pointing to the existence of such oscillatory dynamics, referred to as a high-frequency time window in the range of 30 to 40 Hz (Bao et al., 2013, 2015, 2016). More importantly, in the current study, we found that the features of oscillations at the higher frequency band, such as the beta oscillation, can also indicate behavioral transitions embedded in the low frequency 3s time window.

The 3s time window also represents temporal integration—a phenomenon that extends beyond seconds and refers to cognitive and behavioral processes that unfold over several seconds, capturing a broader timescale of information processing not accounted for by fast neural rhythms alone. The cognitive representation of the three-second interval can be understood as the subjective present, the “now”, or the contents of consciousness at a given moment (Pöppel et al., 1991; Zhou et al., 2014). Initially, this “now” may appear as a discrete mental island within the ongoing stream of time. However, the subjective experience of time is shaped by the way these islands of “now” are linked together. It is through the integration of these temporal segments that we perceive time as flowing and continuous.

It is important to recognize that, although the semantic linkage between discrete temporal windows creates the subjective experience of continuity in conscious content, we remain unaware that each act or moment of conscious experience is confined to only a few seconds. In our subjective reality, we focus on the “what” (the content of experience), rather than the “how” (the underlying logistic processes). As a result, the temporal structure of consciousness functions as a hidden logistic framework—an essential but unnoticed foundation that supports conscious content. This temporal structure is not itself part of conscious content and, therefore, should not be defined by it. As previously emphasized, the classification of cognitive functions is governed by a principle of complementarity. This principle suggests that maintaining the integrity of both content and logistic domains is essential for supporting a full range of cognitive and behavioral capacities (Bao et al., 2017).

The taxonomy of cognitive functions proposed here is grounded in a biologically oriented framework. It assumes that the loss of a specific neural module results in the loss of its associated function—meaning that functions relying on discrete neural circuits or algorithms become inaccessible when those modules are impaired. However, the scope of logistic functions extends beyond temporal organization alone. We propose, without asserting an exhaustive list, that logistic functions encompass various systemic processes necessary for maintaining information processing. These include temporal organization, arousal (involving patterns of activation and energy regulation), emotional regulation, and attention. Disruptions or damage in these logistic domains can lead to a range of pathological outcomes. For example, disturbances in the activation system can result in severe states such as coma or reduced vigilance. Chronic degeneration of this system may lead to depression, characterized by slowed reasoning, sleep disturbances, impaired concentration, psychomotor lethargy, and general inhibition. Some psychiatric theories suggest that disruptions in circadian regulation contribute to depression, while manic symptoms may reflect excessive activation due to a dysregulated circadian oscillator (Walker et al., 2020; Wulff et al., 2010).

5.3 Summary and future perspectives

More detailed speculations on how brain works with time would go beyond far from the scope of the current studies. Though we have contributed to shedding more light on the 3-second time window, limitations and potential improvements exist and shall be addresses in future studies. And as the spiral of research goes on, trying to answer a target question always bring up more ideas and directions.

A behavioral experiment and an MEG-recording study were performed to test the low-frequency 3s time window in a realistic setting and further target oscillation features as indicator of this temporal boundary. It should be noted that because of the focusing on the research questions and the perspective of a broader framework, the second experiment employed a distinct paradigm but provided complementary evidence. Nevertheless, current results are far from providing the whole picture of the underlying neural mechanisms of the time windows, and it will be the focus of our future studies.

Specifically, the finding with beta-band oscillation in the second experiment is limited with signals from motor areas. One reason is the sensorimotor synchronization task, and the other reason is due to the property of MEG recording. The outstanding temporal resolution permits the signal to show oscillatory activities, but it lacks spatial resolution. And we need to investigate also where in the brain is involved in temporal organization in answering the long-debated question of dedicated or distributed neural system in temporal perception. Beyond this dissertation, one of my on-going projects is to apply functional magnetic resonance imaging (fMRI) track the change of activation pattern during the time window of approximate 3 seconds. And one may also consider combining the strength of different neural recording methods (like EEG or MEG with fMRI, PET) to yield more constructive results.

Finally, I would like to emphasize again that a new perspective regarding the role of time is necessary, as it suggests a different mindset in viewing cognitive phenomena. Logistic functions shall work in a complementary way with content functions to generate subject experiences.

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Affidavit

LMU

LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

Promotionsbüro
Medizinische Fakultät

MMRS

Affidavit

Zhao, Chen

Surname, first name

Goethestrasse 31/I

Street

80336, Munich, Germany

Zip code, town, country

I hereby declare that the submitted thesis entitled:

Time window of 3 seconds in cognitive processing reflected as a logistic function

……………………………………………………………………………………………………

is my own work. I have only used the sources indicated and have not made unauthorized use of services of a third party. Where the work of others has been quoted or reproduced, the source is always given.

I further declare that the dissertation presented here has not been submitted in the same or similar form to any other institution for the purpose of obtaining an academic degree.

Munich, 22/09/2025

place, date

Chen ZHAO

Signature doctoral candidate

Erklärung zur Übereinstimmung

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MÜNCHEN

Dekanat Medizinische Fakultät
Promotionsbüro

Erklärung zur Übereinstimmung der gebundenen Ausgabe der Dissertation mit der elektronischen Fassung

Zhao, Chen

Name, Vorname

Hiermit erkläre ich, dass die elektronische Version der eingereichten Dissertation mit dem Titel:

Time window of 3 seconds in cognitive processing reflected as a logistic function

in Inhalt und Formatierung mit den gedruckten und gebundenen Exemplaren übereinstimmt.

Munich, 22/09/2025	Chen ZHAO
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