# DISCRIMINATION AND SEQUENTIALIZATION OF EVENTS IN PERCEPTION

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## 1. Time Concepts in Fundamental Physics and in Cognitive Science

There are different conceptions of time in different scientific disciplines. Apart from millennia of philosophical discussions of time (cf. [1]), a particularly outstanding discrepancy persists between the concepts of time used in fundamental physical theories on the one hand and psychological theories of perception and cognition on the other.

The prevailing concept of time in physical theories is that of an (abstract) time serving as a continuous background for the representation of events usually conceived as discrete, e.g. in terms of Boolean decisions of alternatives. In the spirit of Newton's absolute time, the evolution of states or observables related to such events is described as a function of a one-dimensional parameter time. A tightly related philosophical conception of time is Kant's notion of time a priori.

Every physical (and other scientific) theory refers to an empirical reality to which measurement and observation provide access. A basic methodological cornerstone of such empirical access is the distinction between observing tools and an observed system. Although this distinction is not universally prescribed in particular instances, observation generally presupposes an outside perspective upon the observed system, which is sometimes called a third person perspective.

By contrast, psychology and cognitive science additionally involve the option of a first person perspective, taking into account experiential aspects of perception and cognition. This includes an internal mode of knowledge acquisition sometimes called introspection. Such a perspective is often disregarded in contemporary research, but emphasized explicitly by phenomenologically oriented philosophers

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such as Bergson, James, Whitehead, and, especially, Husserl. Here the notion of time is primarily derived from a sequence of (concrete) perceived discrete events rather than conceived as a continuous parameter.

From the third person perspective of physical sciences, time is used to parametrize the evolution of systems (e.g. by clock time) and is usually not treated as a property of a system. A well-known example is the problem of introducing a time observable in quantum mechanics. The situation is different in psychology, where temporal properties, such as age, are crucial.

Another key difference concerns the concept of "nowness". In the framework of a one-dimensional parameter time, the now is simply defined as the instant between past and future. By contrast, within an experiential first person account the now is usually referred to as extended, meaning that the present lasts for a finite, non-vanishing interval of parameter time.

As a third important point, fundamental physical theories are generally time-reversal invariant, i.e. the evolution of systems is formalized in reversible terms. The time-reversal symmetry must be broken if an empirically observed time-directed evolution is to be formulated. In psychology and cognitive science, the direction of time from the past to the future is central. The sequence in which events are perceived defines the distinction between "before" and "after" required for the irreversible descriptions of the flow of events.

## 2. Some Temporal Features of Chaotic Systems

The gap between time concepts in physical and cognitive approaches cannot be easily bridged. An apparently inevitable stumbling block is the difference between third person observation and first person experience. Besides this key problem, which we do not consider in the present contribution, there are, however, modern developments in the physics of dynamical systems, which supply quite some insight of how first steps from physical time to psychological time could be made.

The theory of dynamical systems, particularly chaotic systems, was started about a century ago and has gained much popularity since the mid 1970s. It comprises temporal features related to psychological time but based and well understood in a formal physical framework. These features are the breaking of time-reversal symmetry leading to irreversible evolution, the existence of a specific type of time observables characterizing temporal properties of a system, and the concept of a temporal nonlocality resembling the idea of an extended now.

A dynamical system is chaotic (under some fairly unrestrictive conditions), if its so-called Kolmogorov-Sinai entropy

$$h_T = \sum_{i=1}^{d} \begin{cases} \lambda_i & \text{if } \lambda_i > 0 \\ 0 & \text{otherwise} \end{cases}$$

is greater than zero, where $\lambda_i$ denotes the Ljapunov exponents of a $d$-dimensional system, quantifying its stability against perturbations. A positive value of $h_T$ (which has the dimension of an inverse time) indicates a sensitive dependence of the evolution of a chaotic system on initial conditions. For more conceptual and formal details as well as further references see [2].

The stability analysis providing the Ljapunov exponents refers to a pointwise representation of the (ontic) states of the system in an appropriate state space. In this representation, chaotic systems (or, equivalently, K-flows) are time-reversal invariant. The corresponding symmetry can be broken by proceeding to a state representation in terms of probability densities in an associated probability space as a state space.

For the resulting (epistemic) states it is possible to derive a time-directed dynamics [3] from the reversible dynamics generated by the Liouville operator $L$ according to

$$L\rho = i\frac{\partial \rho}{\partial t} \ .$$

In a number of contributions since the 1970s, Misra and coworkers have proven the existence of a time observable $T$ which does not commute with $L$ if $h_T > 0$, i.e. for chaotic systems [4]:

$$i[L, T] = \mathbb{1} \ .$$

For a suitably defined information operator $M = M(T)$, this non-commutativity can be extended to [5]

$$i[L, M] = h_T \mathbb{1} \ ,$$

meaning that the reversible dynamics generated by $L$ and the irreversible dynamics generated by $M$ are complementary. In contrast to the commutation relation between $L$ and $T$, the commutator $h_T$ in the relation between $L$ and $M$ is a quantity which can be theoretically and experimentally determined for a given system.

These results are particularly interesting insofar as they show that chaotic systems can be characterized by a non-commutative algebra of observables. This entails features usually known as consequences of the non-commutativity of the algebra of observables of quantum systems, such as entanglement and nonlocality [6]. In chaotic systems, one of these features is a kind of temporal nonlocality first addressed in [7]. This nonlocality is epistemic: It means that different ontic states are epistemically indistinguishable if they are roughly separated by a time interval less than the inverse of $h_T$.

## 3. Discriminating and Sequentializing Events in Perception

### 3.1. EXPERIMENTAL EVIDENCE

Experiments concerning the capabilities of discriminating and sequentializing temporally separate perceptual events have been carried out for a long time [8] (see also both Binder and Vicario, this volume). A particular version of such experiments was reported by Pöppel [9]. Exposing subjects to two successive separable (e.g. by frequency) stimuli and varying the time interval $\Delta t$ between them, three regimes of different kinds of perception of the stimuli were observed.

For $\Delta t \gg 30$ msec, two different individual events are clearly separable, and their sequence can be correctly assigned. For $\Delta t < 3$ msec (in the auditory modality), the two different events remain unresolved and, as a consequence, a sequential order cannot be assigned to them. Most interesting is the result for the regime 3 msec $< \Delta t <$ 30 msec. Here, two individual different events can be discriminated, but their temporal sequence cannot be assigned correctly (rather, the sequence assignment is more or less at random). This implies that the discrimination of temporally distinct events and their sequentialization are different perceptual capabilities.

These results, which were found for different sensory modalities [10,11], suggest the existence of two different kinds of temporal thresholds for the discrimination and sequentialization of perceived events:
(1) a so-called *fusion threshold* (or transduction threshold) which can be interpreted as an elementary integration interval for discriminating ($d$) perceived events. This threshold represents an extended $d$-now and is modality-dependent. While the mentioned value of approximately 3 msec refers to auditory perception, the fusion threshold in visual and tactile perception is of the order of 10 msec [10].
(2) a so-called *order threshold* of approximately 30 msec which can be interpreted as an elementary integration interval for the capability to assign sequential ($s$) order to perceived events. This threshold represents an extended $s$-now and is modality-independent.

While the $d$-now can be explained by transduction properties of signals in the brain, a proper understanding of the $s$-now remains a topic of vivid discussion. Since its size ($\approx$ 30 msec) is the same for different modalities, it was speculated that the $s$-now might be related to the problem of how pieces of information from an external event, which are received in terms of different sensory modalities, are bound together such that the external event is perceived as a whole (binding problem). In addition, the approximate equivalence of $\approx$ 20–40 msec with $\approx$ 30–50 Hz ($\gamma$-band) brain activity suggests that the $s$-now could be related to collective neuronal oscillations as first reported in [12,13].

## 3.2. PROPOSED EXPLANATIVE APPROACH

As an explanative approach concerning the threshold behavior of temporal perception we propose a interpretive framework ultimately based on the non-commutativity of the algebra of observables associated with chaotic systems. In particular, this approach focuses on the existence of a non-commuting time observable and its ramifications. Chaotic behavior of the brain has been empirically found and theoretically described in numerous investigations [14,15], but the quantum-like features arising from such behavior have remained unexplored so far.

It should be stressed that the features we will outline in the following are embedded in a *generalized* (axiomatic) quantum theory [6] which relaxes particular assumptions underlying ordinary quantum physics. In contrast to approaches by Beck, Penrose, Stapp and others, we do not intend to use results of ordinary quantum physics to describe brain behavior. Our approach also differs from the proposal by Ruhnau and Pöppel [16], which is based on an analogy with delayed choice experiments.

The key idea is to understand the $s$-now due to a temporal analogue of the well-known double-slit experiment (cf. [17]), in which the non-commutativity of a time observable $T$ is the formal cornerstone. In recent years, double-slit experiments have received renewed attention in terms of so-called "which-way" experiments concerning the conceptual relation of uncertainty and complementarity (cf. [18]) in quantum physics.

In an ordinary double slit experiment, a beam of particles (say electrons) of well-defined momentum is directed toward a screen with two slits. Somewhat behind the screen, the electrons can be detected on a photographic plate. If one slit is closed, the electrons produce a broad Gaussian distribution on the plate (neglecting diffraction effects). If both slits are open, the distribution on the plate shows an interference pattern well known from wave-like systems. This is different from the sum of two single slit distributions which would be expected for particle-like systems.

The interference pattern can be explained by the wave-like nature of the state function, also called wavefunction, of the electrons propagating through the two slits like a wave. The superposition of the contributions due to the two slits behind the screen provides the characteristic interference pattern, which indicates that both slits were open. Any attempt to identify the slit through which electrons have passed destroys the interference pattern. In other words, information about the spatial position of the electron at the screen and information about its momentum (well-defined wavelength but nonlocal wavefunction) mutually exclude each other.

The basis of the corresponding complementarity, leading to an associated uncertainty relation, is the commutation relation

$$i[P,Q] = \hbar \mathbb{1} \ ,$$

where $P$ is the momentum observable, $Q$ is the position observable, and $\hbar = h/2\pi$ with $h$ as Planck's action. It can be rephrased as a complementarity of the distinguishability $D$ of the electron path and the fringe visibility $V$ of the interference pattern by $D^2 + V^2 = 1$ [18]. Both complementarities indicate that the state $\psi_b$ of the electron beam is entangled with the state $\psi_d$ of a detector determining which slit the electrons passed.

It is possible to map the spatial features of the ordinary double slit experiment to the temporal domain, thus introducing a "temporal double slit" scenario (cf. [19]). In recent years, this idea has been used for various versions of quantum state tomography (for an overview, see [20]), mainly with respect to optical pulses, e.g., represented by distributions of intensity as a function of time. The core feature of such a temporal double slit scenario is that information about the temporal location of a measured intensity within the pulse is complementary to the interference or coherence properties of the pulse. Assigning temporal locations (and their sequence) within the pulse is precluded by observing the interference.

The thresholds of temporal perception discussed above can be interpreted according to such a temporal double slit scenario. In perception, the pulses are represented by the stimulus-induced signals in the brain, and the measuring instrument can be conceived as a neural assembly responsible for the discrimination or sequentialization task. An entanglement analogous to the double slit scenario would refer to the state $\rho_s$ of the stimulus-induced signal and the state $\rho_a$ of the neuronal assembly "detecting" the signal.

As mentioned above, temporal features of chaotic systems are used to relate this analogy to formal arguments. The non-commutativity of $T$ and $L$ is a general feature of chaotic behavior, which in turn seems to be generic for numerous brain functions. Using this non-commutativity, the capability of discriminating temporally distinct perceived events on the one hand and the capability to assign temporal sequence to them on the other can be understood as complementary. The discrimination of two events is based on information from temporal interference in the same manner as spatial interference implies that both slits are open. Sequentialization is based on specifying the temporal location of an event, analogous to the spatial location of the slit through which the electrons passed. As a consequence, discriminating two events precludes their sequentialization.

An important difference between the ordinary spatial and the proposed temporal scenario is that the ordinary case is based on ordinary quantum physics where entangled states $\psi$ are represented pointwise. For the temporal double slit, statistical states $\rho$, i.e. probability distributions or density matrices, are relevant (recall that the definition of $T$ refers to statistical states). Such a state concept is highly appropriate for (many-particle) brain states. Although this situation is different from ordinary quantum physics, it can entail entanglement in the generalized sense addressed in [6].

Assuming that the temporal nonlocality corresponding to an $s$-now is due to chaotic dynamics, its extension would be of the order of $h_T^{-1} \approx 30$ msec. Using the notations $D$ and $V$ introduced above for ordinary double slit scenarios, the experimental evidence described in Sec. 3.1 is reflected by $D = 1$ and $V = 0$ for 3 msec $< \Delta t <$ 30 msec. Outside this interval, $D$ and $V$ are either both 1 or both 0, and a temporal double slit scenario does not apply. Within the interval between the two thresholds, the proposed approach would predict that $D$ and $V$ change as a function of $\Delta t$.

Finally, there is the question of how to decide whether observed correlations are due to entanglement or not. In ordinary quantum physics, this is possible by Bell's theorem. In more general cases of entanglement, Bell's theorem cannot be presupposed, so other options must be developed. Concerning temporal perception, the proposed approach suggests focusing on an observable not commuting with $T$, e.g. $L$. Since $L\rho = i[H, \rho]$ (for a Hamiltonian $H$), $L$ can be interpreted as an observable corresponding to an energy difference. What could the neurophysiological significance of such an energy difference be? One speculation might be to consider the numerical coincidence of the $\approx 30$ msec order threshold and the $\approx 40$ Hz ($\gamma$-band) neuronal oscillations in terms of a generalized time-energy uncertainty relation. The distribution of measured order thresholds should therefore change if the distribution of $\gamma$-band oscillations is varied.

## 4. Summary

The time concepts used in traditional fields of fundamental physics and in the study of cognitive systems are quite distinct. The theory of chaotic systems, which can be related to both areas, provides viable links between them. Two key issues are the breaking of time-reversal symmetry (irreversibility) and the emergence of temporal properties (time observables) rather than time as a parameter.

A third important issue is a specific kind of temporal entanglement or temporal nonlocality which can be interpreted in terms of an extended now. Since the algebra of observables, among them time observables, of chaotic systems is non-commutative, those observables exhibit complementarity and indicate the possibility of entanglement in a generalized sense, applicable beyond ordinary quantum theory. Extended nowness can be addressed from this perspective.

Experimental evidence suggests that discriminating two temporally distant events excludes the proper assignment of their sequence under particular circumstances. It is proposed to understand this result in terms of quantum-like properties of chaotic brain processes arising from their non-commutative algebra of observables. A "temporal double slit" scenario is outlined, where the discrimination of two events is complementary to their sequentialization. This proposal is different from ordinary double slit schemes in some respects. Moreover, it has ramifications which might be experimentally accessible.

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## 6. References

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