Quantum Zeno features of bistable perception

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Abstract. A generalized quantum theoretical framework, not restricted to the validity domain of standard quantum physics, is used to model the dynamics of the bistable perception of ambiguous visual stimuli such as the Necker cube. The central idea is to treat the perception process in terms of the evolution of an unstable two-state system. This gives rise to a "Necker-Zeno" effect, in analogy to the quantum Zeno effect. A quantitative relation between the involved time scales is theoretically derived. This relation is found to be satisfied by empirically obtained cognitive time scales relevant for bistable perception.

1 Introduction

Quantum theory has revolutionized our understanding of the physical world in both scientific and epistemological respects. It was developed in the third decade of the 20th century as a theory describing the behavior of atomic systems. Subsequently, its range of validity turned out to be much wider. Not only are nuclei and elementary particles, more than seven orders of magnitude smaller than atomic systems, governed by quantum theory, but also macroscopic phenomena like superconductivity or superfluidity are successfully described in quantum theoretical terms.

From the present state of knowledge, the broad validity of quantum theory in physics is not surprising. Investigations of its conceptual structure and axiomatic foundations have revealed that quantum theory is a logical consequence of some rather simple and plausible basic assumptions about the nature of observables and states of physical systems. In this framework, classical physics results from basically one additional assumption: the commutativity of the algebra of observables.

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On the other hand, the axiomatic framework has shown how deeply rooted apparently bizarre concepts of quantum theory like complementarity and entanglement really are and that there is no way back to classical concepts on a fundamental level of physical description.

Since the early days of quantum theory, starting with Niels Bohr, the idea has been entertained that quantum theoretical concepts like complementarity and entanglement might be meaningful and important even beyond the realm of the physical world in its strict sense. Concerning such "quantumlike" phenomena, incorporating complementarity or entanglement beyond physics, three different stances, not completely mutually exclusive from a logical point of view, are possible and have found proponents.

1. The application of quantum theoretical concepts to nonphysical situations is merely metaphoric and not elucidated in a precise and general way. The analogies are selected ad hoc and change with the given situation.
2. In the spirit of a strict physicalism, everything can be reduced to physics. There is nothing left beyond the world of physics, and quantumlike phenomena as addressed above are simply physical quantum phenomena.
3. Assuming a nonreductive framework, it might be possible and adequate to describe vital features of parts of the world, physical or nonphysical, by a formalism isomorphic to the formalism of quantum theory. This isomorphy may be total or, more often, partial such that only particular features of the quantum theoretical formalism are realized in a nonphysical context.

An approach within option 3, denoted as weak quantum theory, was recently proposed on an axiomatic basis (Atmanspacher et al. 2002). The starting point in this approach is the algebraic formulation of quantum theory, where the observables of a physical system generate a C^*-algebra $\mathscr{A}$, and the states of the system are positive linear functionals on $\mathscr{A}$. A careful analysis of this formulation shows that its axioms are not equally

fundamental. They can be sifted out into general, indispensable axioms, applying to any (physical or nonphysical) system as long as it is a possible object of meaningful investigation, and more special axioms used in quantum physical applications only.

The most general formal system thus arising, in which concepts like complementarity and entanglement are still meaningful, is a minimal version of weak quantum theory. In short, it can be described in the following way (for details we refer to Atmanspacher et al. 2002):

The notions of system, observables, and states remain unchanged. Observables are identified with functions mapping states to states. This emphasizes the importance of observables as representing active processes with the capacity of changing states, which is vital in quantum theory.

Observables, conceived as functions, can be composed. This composition defines a multiplication of observables endowing the set of all observables with the simple structure of a semigroup. Two observables are incompatible, or complementary with respect to each other, whenever they do not commute. Entanglement can be rephrased as complementarity of a global observable pertaining to a system as a whole and local observables pertaining to its parts. Propositions are special observables related to yes-no questions about the system.

The minimal, most general formal system of weak quantum theory can be stepwise supplemented and enriched up to isomorphy with the full quantum theory used in physics. In its minimal form, weak quantum theory, although it implies complementarity and entanglement, is vastly more general and flexible than the full quantum theory. The main differences are:

– In the most general form of weak quantum theory, the sum of observables is not defined in an empirically meaningful way. As a consequence, there is no Hilbert space of states and no way to attribute probabilities to the outcomes of measurements corresponding to the observables.
– Planck's constant h, which determines the amount of noncommutativity and complementarity in quantum physics, enters nowhere. This implies that conspicuous quantumlike phenomena may be effective in situations beyond standard quantum physics.
– Unlike in quantum theory, where Bell's inequalities can be derived, there is in general no way to rule out local realism. As a consequence, indeterminacies and complementarities can be of epistemic rather than ontic origin.

According to the detailed formulation in (Atmanspacher et al. 2002), quantumlike behavior as described by weak quantum theory or its refinements is generically expected for systems with noncommutative properties. This implies the practical impossibility of observation from outside without influencing the state of such systems.

A paradigmatic example for such a situation is the cognitive system and its neural correlates in the brain. This may be one of the reasons why quite a number of approaches have been developed, in greater or lesser detail, to relate conscious activities to quantum theory or describe particular brain operations quantum theoretically. Besides the fairly popular approaches associated with the names of von Neumann, Wigner and Stapp (cf. Stapp 1993) and Penrose (1994), other interesting options have been proposed by Beck and Eccles (1992) and Vitiello (2001).

All these approaches are essentially discussed within the usual quantum physics. This is at variance with the strategy of weak quantum theory; a recently proposed example refers to the perception of temporally subsequent events (Atmanspacher and Filk 2003). This approach proposes a type of temporal entanglement that is not contained in standard quantum physics but can be formulated in the theory of chaotic systems. In the present paper, we intend to apply the framework of weak quantum theory to another scenario of cognitive science: the bistable perception of ambiguous stimuli.[1]

Bistable perception arises whenever a stimulus can be interpreted in two different ways with approximately equal plausibility. A very simple and often investigated example of bistable perception is the so-called Necker cube. (For an overview concerning the current discussion of cognitive and neural features of the perception of the Necker cube see Kornmeier 2002; Kornmeier et al. 2003.) A grid of a cube in two-dimensional representation can be perceived as a three dimensional-object in two different perspectives, as a cube seen from either above or below. The perception of the Necker cube switches back and forth between the two possible interpretations spontaneously and inevitably.

We propose to describe bistable perception with the formalism of a two-state quantum system, where the two basis states correspond to the two different ways to interpret the visual stimulus. Measurement is considered as the mental process determining in which way the figure is perceived. The switching between the different perceptions corresponds to the quantum transition between the two states that are eigenstates of the operator representing a particular perception and unstable under the time evolution of the system.

Such a description of bistable perception employs a nonminimal version of weak quantum theory with a linear structure and a two-dimensional linear state space. This version is fairly close to the structure of the full quantum theory used in physics. This does not imply, however, that we propose to understand bistable perception as a quantum phenomenon in the sense that the related brain processes are usual quantum processes. Rather, we will discuss the quantumlike behavior of bistable perception as a result of the truncation of an extremely complicated system to a two-state system, into which the effect of many uncontrolled variables and influences is lumped in a global way.

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[1] Niels Bohr was familiar with the bistable perception of ambiguous stimuli through his psychologist friend Edgar Rubin. There are indications (Plaum 1992) that this fact, together with Bohr's studies of the writings of Harald Høffding and William James, played an important role in the complicated genesis of his concept of complementarity in quantum physics.

For this purpose, we consider a system with a linear state space spanned by two states ψ_1 and ψ_2, neither of which is an eigenstate of the Hamiltonian H generating the evolution matrix $U(t) = \mathrm{e}^{\mathrm{i}Ht}$. If the system is initially in the state ψ_1 and allowed to evolve freely according to $U(t)$, then its state will oscillate between the states ψ_1 and ψ_2. This oscillation can be slowed down by increasing the frequency at which the system is measured, asking whether it still resides in its initial state. In the limit of continuous measurement, the evolution of the system can be completely suppressed. This phenomenon is known as the quantum Zeno effect.[2] Its possible cognitive significance was indicated previously by Ruhnau (1995), as well as Stapp (1999). In the present contribution, concrete and quantitative predictions for cognitive systems are proposed for the first time.

In Sect. 2, the quantum Zeno effect will be described in as much detail as required for the purpose of this paper. The quantitative relation between different time scales of crucial significance will be emphasized in particular. In Sect. 3, cognitive time scales satisfying this relation will be presented with particular emphasis on the dynamics of bistable perception. Section 4 summarizes the results and concludes the article.

2 Quantum Zeno effect

The quantum Zeno effect was originally discussed as the quantum Zeno "paradox"[3] by Misra and Sudarshan (1977) for the decay of unstable quantum systems. As mentioned above, its key meaning is that repeated observations of the system decelerate the time evolution that it would undergo without observations, e.g., its decay. The metaphor "a watched pot never boils" paraphrases this behavior in the limit of continuous observation.

The situation addressed in the following refers to a quantum system oscillating between two nonstationary states. For this purpose, we consider a system with the following properties:

1. For convenience, a two-state system will be considered. (The results apply to more general systems as well.)
2. An observation is represented by the operator

$$\sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} .$$

Immediately after an observation, the system will be in one of the corresponding eigenstates

$$\psi_1 = |+\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \text{or} \quad \psi_2 = |-\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} .$$

3. Both σ_3-eigenstates may also be represented by their projection operators

$$P_+ = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad \text{and} \quad P_- = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} .$$

4. Without loss of generality, the Hamilton operator giving rise to transitions of the system can be written as

$$H = g\sigma_1 = g \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} ,$$

where g is a coupling constant. Hence, the unitary operator of time evolution is represented by

$$U(t) = \mathrm{e}^{\mathrm{i}Ht} = \begin{pmatrix} \cos gt & \mathrm{i}\sin gt \\ \mathrm{i}\sin gt & \cos gt \end{pmatrix} .$$

Note that σ_1 and σ_3 do not commute, thus motivating the framework of weak quantum theory.

5. In this model, ΔT defines the time interval between two successive observations, and T defines the time scale after which the state has changed with 50% probability. Concerning the cognitive interpretation of ΔT and T we refer to the next section. It is assumed that $T/\Delta T = N \gg 1$.

We now calculate the probability that an eigenstate of the observation operator σ_3 (representing the perception of the Necker cube) remains unchanged after a time $T = N\Delta T$ under the condition that repeated observations (measurements of σ_3) occur in time intervals ΔT. For $t = 0$ we assume the system to be in the eigenstate $|+\rangle$, and this state is confirmed after each observation.

The probability that the system is still in state $|+\rangle$ after time t is

$$w(t) = |\langle +|U(t)|+\rangle|^2 = \cos^2 gt . \tag{1}$$

This oscillation determines a characteristic time scale t_0, given by the requirement that the state of the system contains the eigenstates $|+\rangle$ and $|-\rangle$ with equal probability, corresponding to $1/8$ of a period of the oscillation or $t_0 = \pi/4g$.

By contrast, if the system is observed N times with time step ΔT, the probability that it is still in state $|+\rangle$ after all N observations, each with the result $+$, is given by

$$w(N) = |\langle +|(P_+ U(\Delta T)P_+)^N|+\rangle|^2 = [\cos(g\Delta T)]^{2N} . \tag{2}$$

This is simply the product of the survival probabilities for each individual observation. The number of observations N after which the probability $w(N)$ decreases to $1/2$ is given by

$$w(N) = \frac{1}{2} \rightarrow [\cos(g\Delta T)]^{2N} = \frac{1}{2} \tag{3}$$

or

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[2] See Misra and Antoniou 2003, Fischer et al. 2001 for reviews of theoretical and experimental results concerning the quantum Zeno effect.

[3] The Greek philosopher Zeno of Elea proposed the following antinomy: "As long as anything is in space equal to itself, it is at rest. An arrow is in a space equal to itself at every moment in its flight, and therefore also during the whole of its flight. Thus the flying arrow is at rest." (Cajori 1915)

$$\cos(g\Delta T) = \mathrm{e}^{-\frac{1}{2N}\ln 2} \quad .$$

According to $N = T/\Delta T \gg 1$, the right-hand side of this equation is close to unity. Therefore, the argument of the cosine is close to zero and we may expand the cosine function according to

$$\left(1 - \frac{(g\Delta T)^2}{2} + \ldots\right) \approx 1 - \frac{1}{2N}\ln 2 + \ldots \quad (4)$$

or

$$g = \sqrt{\frac{\ln 2}{N\Delta T^2}} = \sqrt{\frac{\ln 2}{T\Delta T}} \quad . \quad (5)$$

In this way, the unknown coupling constant g is expressed by the experimentally accessible quantities ΔT and T.

These quantities can be related to the evolution of the system under the condition that no observations are performed. In this case, the time evolution is given by $U(t)$ and, as mentioned above, the state oscillates between the two eigenstates $|+\rangle$ and $|-\rangle$ with period $t_0 = \pi/4g$. This leads to the relation

$$t_0 = \frac{\pi}{4\sqrt{\ln 2}}\sqrt{T\Delta T} \quad (6)$$

between the three time scales involved. Note that Planck's action h is absent in this relation. If at all, it would enter in g, but g is eliminated in (6).

The derivation of this relation depends on two arbitrary choices: T is determined from the condition that the probability of state flipping is $1/2$ (3), and t_0 is determined from the condition that the oscillating state is a superposition of eigenstates of σ_3 with equal coefficients (6). Even if these conditions are varied, the general result,

$$t_0 = C\sqrt{T\Delta T} \quad , \quad (7)$$

remains unchanged ($C \approx 1$; cf. (6)). It entails the following two predictions:

1. As long as the time interval ΔT between two observations is nonzero, the states will spontaneously switch into each other after an average time T, which is large compared to ΔT and t_0.
2. The relation between the time scales T, ΔT, and t_0 is given by (7).

3 Cognitive time scales

In order to assign significance to the time scales T, ΔT, and t_0 in terms of the process of bistable perception, corresponding cognitive time scales have to be identified with particular respect to bistable perception. In this section, we will argue that there are natural choices for T and ΔT. As a consequence, t_0 can be calculated, and its possible significance will be discussed.

3.1 $T \approx 3\ s$

The perception of ambiguous visual stimuli is a prominent topic of modern research in cognitive science and neurophysiology (Kruse and Stadler 1995). One of the elementary examples is a two-dimensional image of a three-dimensional cube, the so-called Necker cube. The Swiss geologist Necker (1832) first discovered that the front-back orientation of the cube switches spontaneously. Since then, numerous other stimuli have been studied generating the same basic phenomenon. Due to its simplicity and, in comparison with other stimuli, fairly low semantic content, the Necker cube remains one of the most popular objects for investigation.

There are two basically different approaches to studying the perception of ambiguous stimuli. The first one refers to the behavioral response to a stimulus that is (assumed to be) based on psychological (mental) processes. Measuring the frequency of reversals is a typical example. The second perspective is to look for neural correlates of psychological processes triggered by stimuli, using either electrophysiological tools or, more recently, imaging techniques.

One of the fairly invariant patterns that the perception of ambiguous stimuli presents is a remarkably stable rate of reversals for individual subjects, ranging between about 4 and 60 switches per minute for different subjects (Brown 1955). This reversal rate corresponds to a "mean first passage time" of between 1 and 15 s. The duration after which the stimulus orientation spontaneously reverses was found to be gamma-distributed around a maximum of about 3 s (De Marco et al. 1977). This time scale can straightforwardly be attributed as the extended oscillation period T due to observations.

The time scale of approximately 3 s was found in the bistable perception of not only visual stimuli but also of ambiguous auditory stimuli. For instance, the phoneme sequence BA-CU-BA-CU-...switches into CU-BA-CU-BA-...after a corresponding time interval (Radilova et al. 1990). In addition, there are other features in perception, cognition, memory, and movement control for which the 3-s interval is crucial. Here are some of the most conspicuous observations, discussed in more detail in Pöppel (1997):

- Length of lines in classical verse in different languages (Kien and Kemp 1994, Turner and Pöppel 1983), also of melody phrases;
- Segmentation of spontaneous speech acts, i.e., closed verbal utterances (Kowal et al. 1975);
- Rhythmic accentuation of successive beats within 3 second windows (Szelag et al. 1996);
- Length of spontaneous motor activity (e.g., scratching) in different mammalian species (Gerstner and Fazio 1995);
- Information retrieval by short-time (working) memory within 3-s windows (Peterson and Peterson 1959)
- The reproduction of time intervals is overestimated for time intervals less than 3 s and underestimated for intervals greater than 3 s; the "indifference point" is at 3 s (Pöppel 1978).

All these observations and more indicate that temporal segmentation into 3-s windows is a basic principle of many aspects of conscious activity. Therefore Pöppel refers to single 3-s intervals as "states of being conscious" and emphasizes that the segmentation mechanism itself is automatic and presemantic (Pöppel 1997). Such discrete successive states are semantically linked with their predecessor and successor. The resulting subjective experience of the continuity of consciousness is thus intimately related to the assignment of meaning.

The ubiquity and the basic significance of the time scale of approximately 3 s suggests that $T \approx 3$ s is also significant for cognitive processes beyond the bistable perception of ambiguous stimuli. In the context of the present article, however, the focus remains bistable perception of Necker-type stimuli since it offers a scenario that is conceptually better defined and experimentally more controllable than transitions between other mental representations.

3.2 $\Delta T \approx 30$ ms

A reasonable estimate for the time between observations in the sense of the Zeno effect, ΔT, is difficult to obtain from the phenomenology of bistable perception. It has to satisfy at least one condition: the perceptual system must be able to assign a temporal sequence to successive events, i.e., observations.

Experiments concerning the capabilities of discriminating and sequentializing temporally separate perceptual events have been carried out for a long time (Pöppel 1978). A particular version of such experiments was reported by Pöppel (1968). Exposing subjects to two successive separable (e.g., by frequency) stimuli and varying the time interval Δt between them, three regimes of different kinds of perception of the stimuli were observed.

For $\Delta t \gg 30$ ms, two different individual events are clearly separable, and their sequence can be correctly assigned. For $\Delta t < 3$ ms (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 ms $< \Delta t <$ 30 ms. Here, two different individual 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 (Pöppel 1997; Ruhnau 1995), 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 perceived events. This threshold is modality dependent. While the mentioned value of approximately 3 ms refers to auditory perception, the fusion threshold in visual and tactile perception is of the order of 10 ms (Pöppel 1997).
2. A so-called order threshold of approximately 30 ms that can be interpreted as an elementary integration interval for the ability to assign sequential order to perceived events. This modality-independent threshold is often characterized as an extended period of simultaneity.

While the fusion threshold can be explained by transduction properties of signals in the brain, a proper understanding of the order threshold remains a topic of lively discussion. Since its size ($\approx$30 ms) is the same for different modalities, it was speculated that the order threshold might be related to the problem of how pieces of information from an external event that 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 ms with $\approx$30–50 Hz (γ-band) brain activity suggests that the order threshold could be related to collective neural oscillations as first reported in Eckhorn and Reitböck (1989) and Gray and Singer (1989). For a recent approach to understanding the relation between the order threshold and collective oscillations, see Atmanspacher and Filk (2003).

The nature of the order threshold as an elementary integration interval prevents the sequentialization of successive stimuli with a temporal interval smaller than approximately 30 ms. This strongly suggests the idea of using it as a generic lower bound of the time ΔT between successive observations in the Zeno effect. Observations with smaller temporal distance cannot be perceptually time-ordered. The fact that the order threshold is modality independent and its fundamental significance for the binding problem add to the plausibility of this suggestion.

3.3 The significance of t_0

In the quantum Zeno scenario, t_0 is the oscillation period of the transition process between the considered nonstationary states, under the assumption that there is no observation and the evolution of the system is governed by $U(t)$. According to (7) and setting $C = 1$, observation leads to an increase of the effective oscillation time from t_0 to

$$T = \frac{t_0^2}{\Delta T} \ . \tag{8}$$

With $T \approx 3$ s and $\Delta T \approx 30$ ms, this provides $t_0 \approx 300$ ms. Under the influence of observations at a temporal distance of 30 ms, the observation-free oscillation period of 300 ms due to $U(t)$ is increased to an oscillation period of 3 s. It has to be understood, though, that the value of t_0 is as approximate as those of T and ΔT. A cognitive time scale corresponding to t_0 should thus be of the order of some hundred milliseconds.

Roughly speaking, this is the order of magnitude that is most often discussed as the time required for a stimulus to become "conscious". It essentially consists of the time required for signal transduction from sensory input to the relevant parts of the cortex plus "unconscious" preprocessing. Neurophysiological studies with event-related potentials show a distinctive universal signature after approximately 300 ms, the so-called P300 component, sometimes referring to additional features up to 900 ms (Sutton et al. 1993; Donchin et al. 1983). It is independent of the specific stimulus and has been attributed to the fact that the perception of a stimulus is a process demanding conscious attention (see Kornmeier 2002 and references therein). From another perspective, it has been proposed that any cognitive processing requires about 100 ms to lead to a consciously available result (Lehmann et al. 1986), e.g., in terms of a representation.

The significance of the hundred millisecond time scale with respect to the conscious availability of a mental representation offers an intuitive understanding of t_0 in the cognitive context. In contrast to T, which represents the "lifetime" (or mean first passage time) of each of the perceptual representations, t_0 can be regarded as the transition time between those representations. The relaxation into each one of the representations is much faster than the lifetime in each representation due to the Zeno effect. Without the Zeno effect, the lifetime T would be more or less identical to the transition time t_0.

It has been observed that the lifetime T, i.e., the inverse switching rate, for bistable Necker cube perception changes considerably if the stimulus is presented in a noncontinuous way (Orbach et al. 1966). Particular combinations of on- and off-time intervals lead to a significantly enhanced value of T. Recent observations (Kornmeier 2002) show that T depends essentially on off-times rather than on on-times. T is maximal for long off-times (on the order of a second).

The relation between ΔT, T, and t_0 implies that T increases if ΔT is decreased or t_0 is increased. Is it possible to interpret the situation for noncontinuous presentation in such a way that either ΔT or t_0 is effectively changed due to the discrete on- and off-times and thus leads to an increase in T?

Let us first consider the time scale $\Delta T \approx 30$ ms. It represents an intrinsically (due to the operation of the cognitive system) given lower bound to the time between observations. Therefore, it would be implausible to consider significantly smaller values of ΔT. Moreover, there is no empirical evidence at hand that an increase in ΔT could be forced by long off-times in noncontinuous presentation.

On the other hand, long off-times obviously increase the interval after which a reversal of the Necker cube perception becomes possible at all. From the theoretical point of view outlined in Sect. 2, noncontinuous presentation of the Necker cube with considerable off-times effectively modifies the Hamiltonian of the system, leading to an increased oscillation time t_0. More specifically, this argument applies if off-times are greater than the value of t_0 under continuous presentation (with

vanishing off-time). For noncontinuous presentation, off-times (provided they are long enough) can therefore be identified with t_0 and utilized for an experimentally well-controlled variation of its numerical value. For such a situation, Fig. 1 shows experimental results for $T = f(t_0)$ from Kornmeier (2002) and Orbach et al. (1966), together with a theoretically obtained curve according to (8) and with $\Delta T = 70$ ms. The theoretical curve fits the empirical results perfectly well. Using $\Delta T = 70$ ms to estimate t_0 for continuous presentation provides $t_0 \approx 460$ ms.

4 Summary and conclusions

In the framework of a generalized, "weak" quantum theory, the formalism of the quantum Zeno effect was applied to the bistable perception of ambiguous stimuli such as the Necker cube. In this application to a phenomenon of cognitive science, which obviously exceeds the domain of standard quantum physics, the quantum feature of measurement corresponds to the act of perception. The main result of this paper is the derivation and cognitive interpretation of three crucial time scales:

ΔT: the time between successive observations; as a lower bound for ΔT in cognitive operations, the so-called order threshold of ≈ 30 ms is proposed.

t_0: the oscillation period for the switching process between two nonstationary states under the unperturbed evolution of the system; t_0 will be increased to T if measurements are carried out.

T: the increased switching period for the case that measurements are carried out; cognitively this
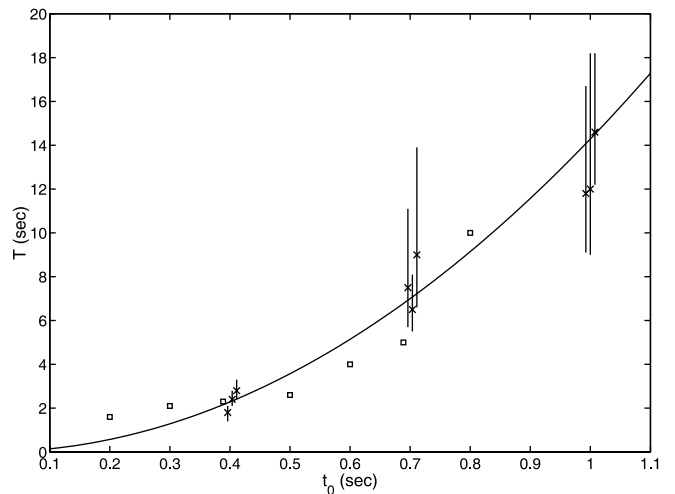

Fig. 1. Experimentally obtained lifetimes T (inverse switching rates) for the bistable perception of a noncontinuously presented Necker cube. *Crosses* mark results from Kornmeier (2002): for each off-time t_0, T (including standard errors) is plotted for three on-times of 0.05 s, 0.1 s, and 0.4 s. *Squares* mark results from Orbach et al. (1966) for an on-time of 0.3 s (no errors indicated in Orbach et al. 1966). The plotted *curve* shows T as a function of off-times t_0 according to (8) with $\Delta T = 70$ ms

corresponds to the switching period of ≈ 3 s for bistable perception under continuous presentation of the stimulus.

The presented "Necker-Zeno" model establishes a relation between these three time scales, yielding $t_0 \approx 300$ ms for $\Delta T \approx 30$ ms, and $T \approx 3$ s under the condition of continuous stimulus presentation. Such a value of t_0 is often discussed as the approximate size of the time interval after which the processing of sensory inputs leads to a consciously available result, i.e., a mental representation of the stimulus.

Noncontinuous presentation of the Necker cube provides the possibility of varying t_0 in an experimentally controlled manner in terms of off-times between stimulus presentation. Empirical results for T as a function of t_0 support the relation between the three times scales with respect to their cognitive significance. However, further experimental material will be needed to firmly establish the cognitive relevance of the Necker-Zeno time scales.

Another prediction of the Necker-Zeno effect is the existence of superpositions $c_1\psi_1 + c_2\psi_2$ of the individual well-defined perception states ψ_1 and ψ_2. It is presumably not easy to prepare and observe such superposition states. Nevertheless, they should appear at least as unstable, transitional states between ψ_1 and ψ_2. Elsewhere (Atmanspacher 1992) such states were tentatively described as "acategoreal" states, indicating that they do not encode categoreal representations in the usual sense of cognitive science. In Kornmeier et al. (2003), a specific neural correlate of such states was for the first time reported in terms of an early (250 ms) component in event-related potentials.

An interesting option for the preparation of superposition states is the perception of paradoxical rather than ambiguous figures. In this case, the key idea is that both alternatives of perception operate as repellors rather than attractors, thus pushing the state of the system toward the unstable superposition in between them. So far, no experimental material is available concerning such a scenario.

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