INVARIANCES IN HUMAN INFORMATION PROCESSING

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ROUTLEDGE

Invariances in Human Information Processing

Invariances in Human Information Processing examines and identifies processing universals and how they are implemented in elementary judgmental processes. This edited collection offers evidence that these universals can be extracted and identified from observing lawlike principles in perception, cognition, and action. Addressing memory operations, development, and conceptual learning, this book considers basic and complex meso- and macro-stages of information processing. Chapter authors provide theoretical accounts of cognitive processing that may offer tools for identification of functional components in brain activity in cognitive neuroscience.

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In memoriam Robert Teghtsoonian
(1932–2017)

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Preface

In July 2015, we held a symposium in celebration of Hans-Georg Geissler's eightieth birthday. For this occasion, we invited a number of his former colleagues and travel companions on various stretches of his scientific journey, some of whom have been pioneers in the field of experimental psychology and human information processing. The title of the symposium was "New Stages in Human Information Processing Research". This title hints at the groundbreaking notion of processing stages, which long has been dominant across several fields of research, including visual processing and memory search, both focal to Hans-Georg's research interest. The "new stages" of the title expressed that the topic is still very much alive today, with many recent advances and new key players coming to the fore, several of whom participated in the symposium.

The symposium took place at the campus of the University of Kaiserslautern, as one of the annual symposia of the Center for Cognitive Science at this university. This center was founded a couple of years before in order to provide an interdisciplinary platform for the sharing of resources and the exchange of knowledge and skills beyond the individual disciplines at the university working on cognitive science and experimental psychology. Groups from different fields such as psychology, computer science, psycholinguistics, mathematics, neurobiology, cognitive neuroscience and methods from different departments of the University of Kaiserslautern, the Fraunhofer Institute, and the German Research Institute for Artificial Intelligence are involved. In the spirit of this endeavor, the symposium was interdisciplinary and, as such, made a valuable contribution to the development of the center.

Many of the participants of this symposium were happy to contribute to the present volume, of which the aim is not only to discuss new developments in the field of human information processing research but also to do so in the spirit of Hans-Georg, to look beyond the fences that often separate specific fields of research, and focus on, as the title of the volume says, invariances in human information processing.

Kaiserslautern,
August 2017

Thomas Lachmann
Tina Weis

Part I

Micro-Stages in Information Processing

Identification of Processing Universals

1 Deciphering the Time Code of the Brain

From Psychophysical Invariants to Universals of Neural Organization

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Abstract

Behavioral and brain-based research into perception and cognition are at a point where global principles of dynamic process organization are becoming central. In this state of affairs, it proves to be a serious obstacle that a common theoretical language is missing which would allow translation of statements in terms of psychological concepts into statements referring to neurophysiological concepts, and vice versa. In the present paper an approach is put forth to overcome this obstacle. It is demonstrated that superordinate regularities in temporal performance characteristics surfacing within and across diverse task demands correspond uniquely to the structural composition of the underlying cyclic brain activity. Specifically, it is shown that the fine structures of psychophysically established temporal ranges quantitatively predict the order of EEG bands as well as the potential couplings among their components. In a probabilistic expansion, the same modular architecture is shown to account for Weber's Law in the time domain and for the upper limit of train length in cyclic timing. A particular advantage of the described option of drawing inferences about neural foundations from behavioral evidence is that it brings physiological observations into direct contact with a net of behaviorally established functional denotations that cannot be accessed in the narrow functional context of a specific neuroscientific paradigm. Provisional applications of the proposed rationale are presented to encourage its strategic use.

1.1 Introduction

For many, the mind-body problem of how conscious mind relates to its physical basis in the brain ranks among the last unresolved enigmas of mankind. Brought down to the level of empirical science, the cardinal difficulty is that concepts such as “sensation” or “thought” designate psychological phenomena that differ in qualitative respects from their presumed neural equivalents in the brain. Clearly, this incongruence between psychological and neurophysiological modes of description does not preclude the possibility to establish empirical relations between them. Yet in the absence of a superordinate framework allowing the delineation of one-to-one correspondences on the level of theoretical fundamentals such relations will inevitably remain to be of a correlative nature.

While there is no doubt about progress achieved along the lines of correlative relationships, there is an enduring hope for an overarching integrative approach catalyzing the synthesis of knowledge from behaviorally oriented and brain-related branches of research. Although widely unknown today, by introducing in his "Elements of Psychophysics" the concept of psychophysics as the "Exact Science of Mind-Body Relations," G. T. Fechner (1860) was the first to insist upon the need for a unifying framework. As described in the second volume, this concept embraces "inner psychophysics" as the branch dealing with the inner, neural basis of mind in what he called the "psychophysical process". Even less well known—in a fundamental assertion about the nature of the underlying processes—Fechner located the essence of mental activity in systems of oscillations within the nervous tissue and in their cooperation along principles of "solidarity" (pp. 452– 464). Note that through this hypothesis of a universal spatio-temporal wave code as carrier medium, neural representations of information become, in a specific way, linked back to psychologically described contents. With this proposition, Fechner set the goal of a framework on whose completion and testing behaviorally founded and substrate-oriented disciplines are invited to cooperate.

Yet now—more than 150 years after Fechner's bold proposal and nearly 90 years after the discovery of oscillatory brain waves (Berger, 1929)—the prospects for a unified approach toward mind-body relations still appear rather mixed. True, in exceptional cases near-isomorphic correspondences have already been demonstrated, as in color perception by Izmailov and Sokolov (2004), though not yet on the level of a general representational system. But in the face of mountains of facts calling for a unified explanation, the need for a broad integrative account is appreciated. Also, in current attempts toward that goal there is increasing consent about a central role of general-purpose mechanisms of cyclic timing and synchrony—in agreement with Fechner's vision. However, at the same time, what once was posited to constitute a unique field of inquiry today shows itself fragmented into a multitude of special areas and diverging concepts—with as yet no broadly accepted superordinate framework in sight.

In this situation, the majority of researchers decided to quietly wait for the multifaceted developments under way to automatically converge into one unified stream. In the present chapter, I oppose this stance by drawing attention to conceptual foundations that need be clarified before a decisive breakthrough can be expected. As will be argued, in order to safeguard free back-and-forth between behaviorally based and substrate-related access routes to cognition, one has to start from relevant global characteristics of the processing system: the brain. A second particularity by which the advocated position differs from common opinion is that in the current state of development, such characteristics can be extracted only as invariants from the task-related variation of perceptual-cognitive performance.

What shall be described in the present chapter, and what appears to be new, are substantial indications that human cognition is governed by a small number of constants and structural invariants in the real-time dynamics of the brain. The role that these universals are supposed to play in the control of performance as a function of task and stimulus conditions can thus be compared to the role that universal physical laws and constants play within the world at large. With the remarkable consequence that, when basing theory on the derived universals of brain activity, predictions of quantitative relations will be rendered possible for mental processes in absolute terms like in physics.

The following presentation falls into two parts. Part I provides a short introduction into conceptual and empirical prerequisites of our approach so far referred to by the mnemonic TQM, for Time Quantum Model—not a model in the usual sense, but a condensed scheme of cross-paradigmatic regularities of temporal organization conceived as an intermediate stage in the development of a dynamic theory. For easier access, primitives of TQM will be presented in a quasi-inductive way proceeding along stages of its stepwise design and revision. Readers interested in more extended reviews are referred to Geissler (2000) or Geissler and Kompass (2003).

Part II of the chapter will address its specific objective: Border-Crossing (BC) predictions, defined as predictions derived from behaviorally based statements of TQM about equivalents in terms of physiological observables. In a first step, this type of prediction will be applied to well-known basic formations of cyclic brain activity in the human electroencephalography (EEG). In a second step, the match attained between predicted and observed structures will then be adopted as an interim validation basis for more complex applications. Examples of such applications are presented in an informal sequence of thematic clusters bringing together general deliberations, testable hypotheses, and pieces of fragmentary evidence accumulated over years. This major and final section of the treatise will hopefully mark the beginning of broader interdisciplinary discussion.

1.2 Part I: Toward Time-Related Universals: A Brief Introduction to TQM

The empirical basis of TQM consists of common regularities in the spacing of preferred points in time characteristics of perceptual-cognitive performance across diverse tasks. Because of approximate integer-ratio relationships among their components, regularities of that kind will be referred to as quantal time structures (QTSs).

A few QTSs in the sense of this definition have over decades become quite popular in the psychological community through nonstandard experiments. As those experiments and the rules proposed for the description of their results played a catalytic role in the emergence of TQM, we start here from a short outline of, in our view, particularly relevant instances.

Precursors of TQM: Early Observations of Quantal Time Structures in Sensory Performance

QTSs whose analysis contributed to the development of TQM had their origin in investigations based on the idea of a privileged epoch or psychological moment, which all other facets of mental timing are derivatives of. The idea was first advanced by the biologist von Baer (1860; cf. 1864). It found its operationalization in identical fusion thresholds at 1/18 Hz, or 55.55 ms, for vision and audition (Lalanne, 1876). More definitely, but only in 1933, the prominent position of an epoch of that duration was established by Brecher (1933) for the modality of touch. In his experiments, which came close to modern standards, Brecher measured tactile time thresholds with the aid of periodic vibrations produced by a needle-shaped stimulator. In a series with 14 participants, he found for period durations presented in descending order a mean fusion threshold of 55.46 ± 0.72 ms. Indicative of a central basis of this epoch in the brain, nearly the same mean and variability (55.87 ± 1.00 ms) were found for threshold measurements across locations on the skin differing in receptor density in proportions of up to 1:10.

Brecher's work was directly referred to by von Békésy (1936, see also 1960) in an experiment on the perception of slow periodic air-pressure fluctuations that yielded the first instance of a QTS to be reported in the literature. In the experiment building on Brecher's findings, absolute thresholds were recorded as a function of frequency for stepwise decreased levels of intensity. In all trials starting from a frequency of 4 Hz, while keeping intensity constant at initially fixed subthreshold levels, frequency was increased until the stimulus was perceived. As illustrated in Figure 1.1A, under these conditions a total of 11 discontinuities, here appearing as vertical leaps, were recorded. Note that among them a particularly prominent one located at 1/18 Hz, or a cycle duration of 55.5 ms, agrees with Brecher's fusion threshold defined as the point of transition from perceived vibration to a smooth tone percept.

The first attempt to capture regularities in Békésy's results was made in an influential paper titled "The Fine Structure of Psychological Time" by Stroud (1956). According to the rule he stated, significant discontinuities are either integer fractions L/n or integer multiples $m * L$ of a basic reference period L of $\sim$110 ms duration, which in the Baer tradition he called "Moment". Two weaknesses in Stroud's formulation are immediately apparent: First, while it covers a series of four particularly salient discontinuities, it ignores

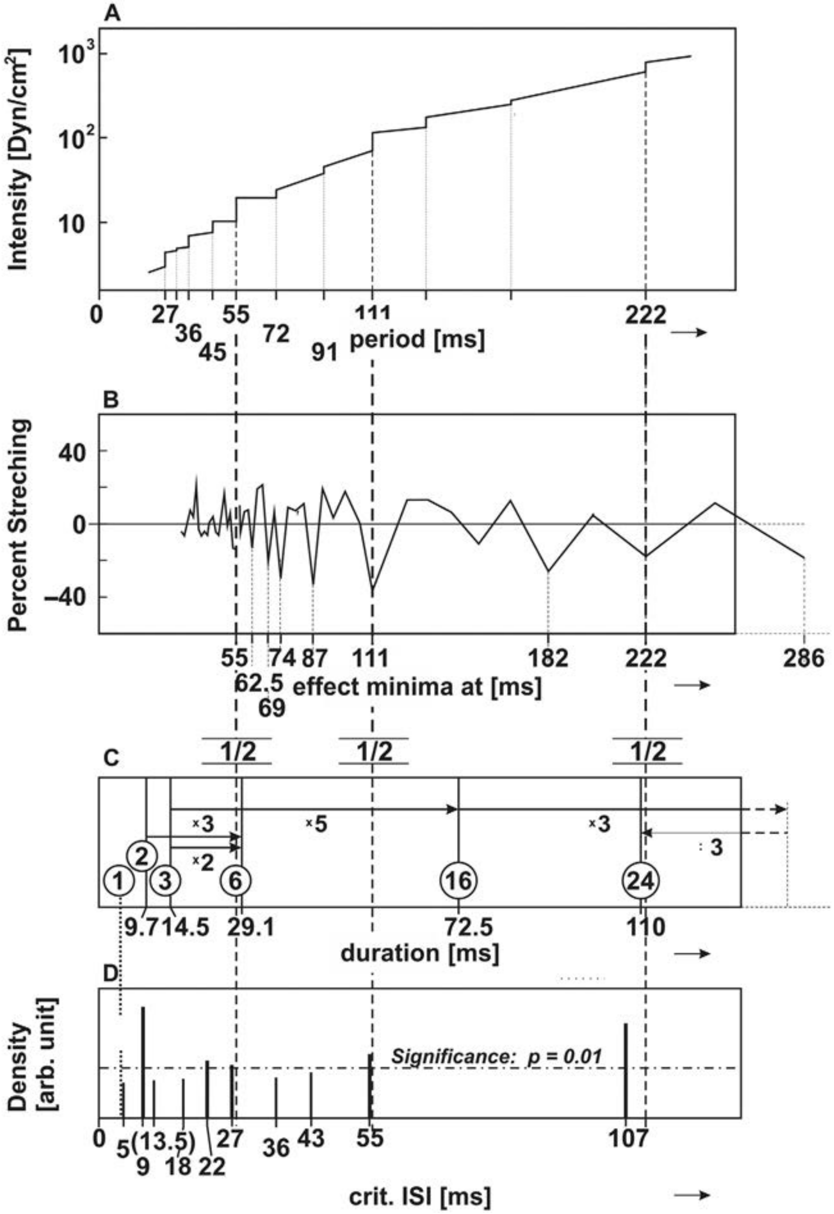

Figure 1.1 Four empirical structures defined as QTSs exhibiting superordinate regularities across diverse stimulus situations and task demands. Dashed vertical lines indicate doubling relations among preferred points in common to all four empirical characteristics that approximately follow a rule suggested by Stroud (1956). In panel C, numbers in circles denote integer multiples of an assumed smallest time epoch of ~4.5 ms. Further explanations in the text.

two further sets of less pronounced discontinuities mentioned by Békésy as distinct "harmonic" series. Second, due to the uniform nature of the doubling rule, L is actually not preferred as the central element, but Brecher's Moment of half the size of L yields the same predictions as L.

Empirically and formally, a further important step was made by Latour (1967) in a study that along with behavioral epochs (eye-movement latencies) included cycles of EEG activity recorded before and during his experiment. In that manner, a direct relation between behaviorally and physiologically measurable cycle durations was first established.[1] The scheme depicted in Figure 1.1C agrees with Stroud's rule in that it attributes a preferred role to cycles of ~110 ms and ~220 ms duration. It deviates from it, however, in two respects. Instead of one series defining a uniform QTS, three different series of hierarchically related epochs are presumed. Additionally, the 220-ms cycle is included as a purely computational figure, apparently in order to maintain the assumption of a common basis of timing in the sense of the Moment concept.

Figure 1.1B stands for another source of evidence often called driving paradigms, which account for a growing stock of QTSs. In the corresponding experimental situations, modulations of perceived stimulus attributes are induced by periodic stimulation applied in addition to the task-related focal stimuli. As a rule, QTSs of this "induced" type are more robust and easier to replicate than spontaneously surfacing structures. However, the related procedures also exhibit disadvantages. In general, the observed modulations reflect complex mixtures of task and driving-related effects that only in subsequent analyses can be disentangled. Our figure displays one of the earliest examples: alterations of perceived duration induced by periodic flicker as reported by Treisman and coworkers (e.g., Treisman, Faulkner, Naish, & Brogan, 1990). Note that the graph includes effect minima at the preferred cycle durations of 222, 111, and 55 ms in close agreement with Stroud's rule. The model put forward by the authors for the relative positioning of minima assumes an internal clock whose ticks the induced modulations are harmonically related to.

Preferred epochs may also appear in the form of relative maxima in distributions of perceptual changes occurring as functions of time parameters of stimulus presentation. As an example, in Figure 1.1D, a schematic representation of data is provided from a later experiment by Geissler, Schebera, and Kompass (1999) on Beta Motion. Apparent motion was induced by sequential presentation of light stimuli at different positions. In the figure, vertical bars denote relative maxima in the distribution of ISIs at sudden transitions from the percept of seen motion to stationary flickering as recorded for 12 different stimulus-exposure durations. Note that three of the five significant peaks are found at inter-stimulus intervals (ISIs) of 107, 55, and 27 ms. Except for a deviation of 3 ms of the largest one, which is to be attributed to overshoots in ISI downward adjustment, these data again agree closely with Stroud's rule.

Beginnings of TQM: The Discovery of QTSs in Recognition Performance

While QTS regularities such as the ones described attracted considerable attention at the time of their discovery, none of the formal descriptions yielded a plausible explanation of their likely relation to underlying procedures of task-specific information processing. In this perspective, it can be considered a stroke of good fortune that TQM in its incubation phase developed in the context of a then novel experimental paradigm: Sternberg's (1966) item-recognition task. Set forth in conjunction with his serial-search model of memory scanning, its processing logic provided for a straightforward data interpretation in terms of operation times. Just to recall, in the original version of Sternberg's task, participants are asked to indicate whether or not an item presented is a member of a set of items memorized before. Under standard conditions, mean reaction times yield near-linear functions of the number of items kept in memory, whose slopes are equal for positive and negative responses. The time required to process in memory a set of items of size s can thus by linear regression be separated from the time consumed by preceding stages of stimulus encoding and subsequent stages of response organization and execution. Given uniform processing, the slopes calculated can be interpreted as mean operation times (OTs) per item required in a random process of exhaustive serial comparison. OT differences between uniform materials can readily be attributed to differences in item complexity.

While not as obvious at the beginning of our investigations, given uniform item materials, mean scanning times per item, as a function of item complexity, seem to vary in near-integer proportions. First suspicions of such "quantized" timing arose from the occasional observation of fixed integer proportions between OT estimates obtained for "perceptual" versus "conceptual" tasks. The impetus to further study such QTS-type relations came from a striking near-exact, integer-ratio relation between the mean OT for digits of 36.81 ± 0.71 ms, calculated from Sternberg (1966, 1967a, 1967b, 1969a, 1969b), and from estimates very close to 220 ms of a macro period found in concept-picture verification experiments of Klix and coworkers (e.g., Klix & van der Meer, 1978). According to $6 \times 36.81 = 220.86$, the Klix et al. period amounts to almost exactly six times the mean of Sternberg's estimates. The reliability of Sternberg's estimates was confirmed by a later replication in a 25-day training series of Marianne W. Kristofferson (1972) that yielded an average OT of 36.2 ± 0.7 ms. When dropping an outlier of 34.6 ms from one session, we obtain 36.50 ± 0.35 ms.

The decisive push to step forward along this line of reasoning came from a study by Vanagas, Balkelite, Bartusjavicus, and Kirvialis (1976), who employed another familiar paradigm to study pattern recognition. In the experiment, complex visual patterns were briefly presented, and stimulus exposure was interrupted by presenting the completely masking prototype pattern of which all the patterns employed were parts. Participants had to reproduce the patterns presented. For presentation times spaced in uncommonly small intervals of 1 ms and after extensive training of participants, steplike courses were found to emerge in the percentage-correct functions. While numbers of steps increase with the logarithm dualis of the size of the trained pattern set (the "alphabet"), step widths of, on average, about 9 ms turned out to be approximately constant under set-size variation, thus strongly suggesting that the interval reflects an invariant elementary processing epoch or "time quantum". Reanalysis by Geissler and Buffart of data from eight participants in the Vanagas et al. study (cf. Geissler, 1985b) revealed an estimate of the alleged quantum size of 9.13 ms, in the following referred to by Q^+. According to 9.13 × 4 = 36.52 and 36.52 × 6 = 219.12, the estimate forms with the two aforementioned longer epochs found by Sternberg and Klix et al., with surprising precision, a tripartite integer-ratio sequence. The assumption that Q^+ is a basic unit of which larger time intervals are integer multiples constituted for us a preliminary form of the "time quantum" hypothesis that will be stated further below.

To explore its range of validity, the hypothesis was tested against a sample of data available at the time from item-recognition experiments (Geissler, 1985a). In Figure 1.2, OT estimates from altogether 14 experiments are plotted against the integer multiples 3, 4, 5, 6, 9, and 12 of an assumed common unit. Best fit was obtained for the greatest common

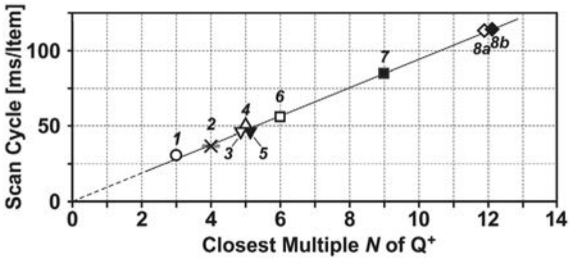

Figure 1.2 OTs as estimated from rates of memory scanning per item plotted against integer multiples of the best-fitting GCD of 9.38 ms. In the following, references and types of items are listed in the order of the italics in the figure: 1) Clifton and Birenbaum (1970), negative responses for digits, for subjects pursuing a self-terminating strategy. 2) Sternberg (1966, 1967a, 1967b, 1969a, 1969b), mean rates of exhaustive search for digits from seven experiments. Horizontal bars indicate confidence margins. 3) Sternberg (1969b), rates for nonsense forms. 4) Clifton and Birenbaum (1970), rate for negative responses to digits for subjects pursuing an exhaustive strategy. 5) Sternberg (1969b), rates of exhaustive search for nonsense forms. 6) Sternberg (1969b), rates for photographs of faces. 7) Keating, Keniston, Manis, and Bobbitt (1980), search rates for digits for children at age 9. 8) Sternberg (1969b), 8a and 8b, rates for digits in context recognition for same and reversed-order pairs, respectively. Note that entries 3 and 5 as well as 8a and 8b are horizontally displaced for better readability.[2]

denominator (GCD) of 9.4 ms, some 3% larger than the estimate from the Vanagas et al. experiment.

Later studies carried out in order to more systematically test the hypothesis revealed an even better match with the earlier estimate of 9.13 ms. Special mention should be made here of the matching-task experiment by Schmidt and Ackermann (1990), a reanalysis by Martina Puffe (1990) of data from 11 group studies using word lists, training experiments by Bredenkamp and Klein (1998), and Bredenkamp and Hamm (2001). Bredenkamp and coworkers investigated the time-quantum assumption in the context of interrelated invariance hypotheses (cf. Bredenkamp, 2004, for a survey). With groups of 75 and 105 participants, and items consisting of carefully constructed vowel-consonant sequences of definite information content, both studies met strong procedural and statistical requirements. Findings in social judgment of Petzold and Edeler (1995; cf. 2018, this volume) are of special relevance, since their results demonstrated that temporal quantization may also be found in latencies obtained in decisions about verbal statements on social features provided that response generation is triggered in strict separation from the intake of task-related text information.

In Table 1.1, estimates of Q^+ from ten independent studies are put together that underpin the assumption of a quantal processing epoch of somewhat more than 9 ms operative in recognition tasks for diverse materials ranging from meaningless visual patterns through word lists to inventories of features for person description.

The Relative Upper Limit of Multiples: The Quantal-Range Hypothesis

Evidence of a smallest unit of time operative in recognition situations established as a GCD of reaction-time-based OT estimates next raised the question for the upper limit of the range of possible multiples N of Q^+. Results from complex recognition tasks explored by Geissler and Buffart (1985) suggested for N an upper limit between 24 and about 30. Referring to $T_c = 243$ ms as estimate of the time required to scan a full short-term memory as obtained by Cavanagh (1972) from data in the literature, Geissler (1985a) discussed the option of the multiple $N = 24$ as inclusive upper bound. However, subsequent analyses (Geissler, 1987, 1990, 2000) converged at $M = 30$. The most precise estimate stems from the earlier quoted study by Petzold and Edeler. The data from nine participants revealed 274.4 ± 3.7 ms (cf. Geissler, 2000) corresponding to a time quantum value of 274.5/30 = 9.15 ms.

From recognition data alone, reliable conclusions on an upper range limit are difficult to draw, primarily because in most instances, graining of the data does not support GCDs up to a level of resolution corresponding to Q^+. For this reason, at that stage of development, complementary evidence was of importance, indicating that a constraint analogous to that for recognition times also holds for the perception of temporal

Table 1.1 Eleven estimates of Q^+ .* indicates correction according to Bredenkamp (1993).

EstimateQ^+ *(ms)*	*References*	*Material, task/indicators & Ss*	*Calculation*
9.13 ± 0.59	Vanagas et al. (1976)	geometric patterns; recognition/step widths in perc. correct; 8 trained Ss	-
9.14 ± 0.09	Staude (1985)	digits; item recogn./OTs per item; 18 Ss	2 GCD
9.04* (8.8)	Puffe (1990)	item recognition for long lists; group data from 11 exp.	Performance for first branch
8.83/8.84	Schmidt and Ackermann (1990)	"Garner patterns"; same-different decisions; OTs from pred. steps; 17 Ss	-
9.24	Bredenkamp (1993)	mental arithmetic; OTs calculated from presumed algorithm; one expert subject	-
9.15 ± 0.18	Petzold and Edeler (1995)	judgments about person features; OTs like in item recognition; from 9 Ss	1/30 largest OTs
9.25	Bredenkamp and Klein (1998)	items of controlled information content; item recognition; 75 Ss	1/3 OT
8.99	Bredenkamp and Hamm (2001)	items of controlled information content; item recognition; 105 Ss	1/3 OT
9.05 ± 0.18	Sternberg (1967a, 1967b, 1969a, 1969b)	digits; item recognition; mean/confid. Seven OTs from different experiments	1/4 OT
9.20 ± 0.18	M. W. Kristofferson (1972)	digits; item recognition; mean/confid. for OTs across training sessions	1/4 OT
9.10 ± 0.08	Grand Mean & 0.05 conf.		

relationships. Relevant information came from a small pilot study by Foster and Kristofferson (see Kristofferson, 1990). They employed the so-called pulse-train paradigm where participants had to decide whether or not single auditory pulses presented after a series of equally spaced pulses deviated from the temporal order in which the pulses were presented. For each of the two participants in the experiment, performance was almost constant up to 278 ms and 286 ms, respectively. For standard deviations (SDs) of 3.5 ms and 4.2 ms, respectively, the adopted model yielded quantal resolutions of 8.6 ms and 10.3 ms amounting to an average of 9.45 ms. With the mean of the upper limits of 282 ms, one gets the rough estimate of a relative upper bound of 282/9.45 = 29.84, which is in fair agreement with the hypothesized value of 30.

Together with the evidence reviewed in the previous section, the results outlined supported the view that OTs in recognition tasks constitute a range of admissible integer multiples N of a quantal epoch Q^+ of a mean duration of 9.13 ms, with N varying within $1 \leq N \leq M = 30$. This statement represents the first version of what we later referred to as Quantal-Range Hypothesis.

Inferring a Doubling Cascade of Quantal Ranges

This interim Quantal-Range Hypothesis was obviously incomplete insofar as relevant processing periods may exceed the upper range limit of some 280 ms. However, there have also been many indications that time epochs smaller than Q^+ must play a role. To maintain consistency with the range so far introduced, an assumed smaller unit needs to be an integer fraction of Q^+. A reanalysis by Geissler (1987) of data from various sources including the aforementioned early findings suggested an elementary unit Q_0 of half the size of Q^+, of which all other quantal units are integer multiples. The suggestion resulted, for example, from two discontinuities in Békésy's profile (see Figure 1.1) at 7.5 and 32 Hz that correspond to cycle durations of 14.6 and 3.4 times Q^+, respectively. The factor 14.6 is located approximately in the middle between 14 and 15, and 3.4 between 3 and 4. In addition, from a reanalysis of data from an experiment by Staude (1985, cf. Geissler, 1987), it turned out that even in item recognition, some participants must have performed in accordance with a quantal unit of half the size of Q^+. In her experiment with 18 participants, for three different materials and one replication, a total of 108 slopes were obtained. Analysis of the entire data set revealed nine sharp clusters standing out from among the nearly uniform remainder with centers of which three were inconsistent with a quantal-lattice distance of Q^+, but close to multiples of 5-, 7-, and 9-times $\sim 9/2$ ms. Least-square analysis across clusters revealed a GCD of $Q_0 = 4.57$ ms with a confidence of ± 0.04.[3]

Relying on these and other pieces of evidence (cf. Geissler, 1990), the components of QTSs of different extensions seem to form a sequence of overlapping ranges whose elements are multiples $N \times Q_q$ of range-specific units Q_q that in turn are integer multiples $q \times Q_0$ of the assumed smallest unit Q_0. While empirical demonstration of such a structural arrangement in multiples of Q_0 constitutes an extremely laborious task, it is worthwhile reflecting about possible constraints that could help to further delimit the scope of possibilities. It appears, for instance, reasonable to postulate that the total manifold of ranges forms a dense and uniform structure of maximum compatibility within subranges of overlap between neighboring ranges. As one readily realizes, this implies that the additional condition $q = 2^n$ with $n = 0$, or a positive integer must hold – i.e., any larger range is of twice the size of the preceding one. Putting it differently, all ranges form a doubling cascade.

Empirical indications in favor of this conception arose from a reexamination of Cavanagh's hypothesis (1972) according to which a constant period of time is required to scan a full short-term memory, independent of the item material involved. In the rank-order plot of Figure 1.3, empty diamonds represent estimates put together by Puffe (1990) from 11 item-recognition experiments. Filled symbols stand for data of an earlier experiment with 20 participants of Puckett and Kausler (1984). The resulting clusters, separated by gaps, contradict the assumption of a single constant. Instead, both data sets together form the clear picture of a doubling cascade composed of three substructures, two of which terminate in close vicinity to the upper limits at 137 ms and 274 ms predicted for $n = 0$ and 1, respectively[4]. The third branch ends some 20 ms below the predicted termination at 548 ms, but fits otherwise pretty well into the doubling structure.

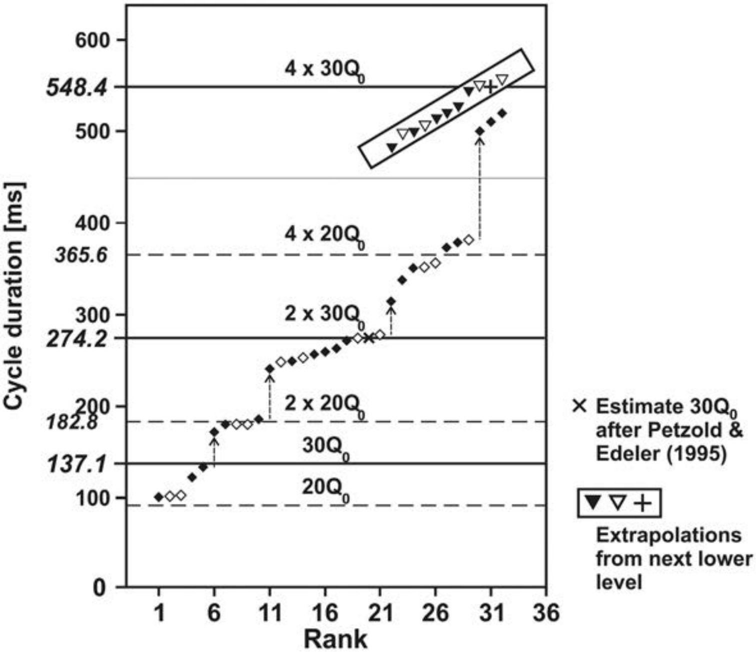

Figure 1.3 Estimates of the time required for scanning a full short-term memory. Note that the cascade structure of the entries contradicts the notion that this time is a constant (Cavanagh, 1972). Filled diamonds denote data for 20 individuals after Puckett and Kausler (1984); empty diamonds group data from 11 experiments reported by Martina Puffe (1990).

The Base-Level Status of Q_0: Evidence From Apparent Motion

The numerical value of the time quantum Q_0 is of the order of magnitude of the smallest observed neuronal transmission times. This suggests that Q_0 is the smallest time unit of information processes in the brain. However, from a psychological point of view, determination of the value of ~4.5 ms on the basis of GCDs from empirical distributions is insufficient to demonstrate its functional significance. It therefore appears important to strengthen the assumed status of an elementary processing unit relying on evidence from local response distributions rather than just GCDs.

For nonscientific reasons, systematic studies intended for this purpose had to wait until the mid-1990s. Leaping ahead of a more detailed discussion to follow, we will therefore here refer to findings from a later experiment on Beta Motion first published in Geissler et al. (1999). In three series with 46 participants, ISI values critical for the breakdown of seen motion were determined by ISI downward adjustment for 12 different stimulus exposure durations (EDs) kept constant during each trial.

Due to the sheer number of data collected in the experiment, trial replications could be exploited to check on the role of the assumed quantum in the emergence of single responses. A first attempt was prompted by the observation of tiny periodic modulations in the ISIs critical for breakdown of seen motion critical ISIs (cISIs) in individual participants obtained for one and the same value of the independent variable ED. Note that it is such periodicities that are to be expected when variation in discrete quantal steps occurs in the presence of random contributions that play the role of background "noise". As illustrated in Figure 1.4A, an evaluation based on data fitting for each participant separately indeed revealed a quantal epoch of ~4.5 ms. Later, Kompass (2004) showed that confinement to trial replications is not necessary in order to demonstrate quantal variation with a period of that duration. In a reevaluation of the same data for individual

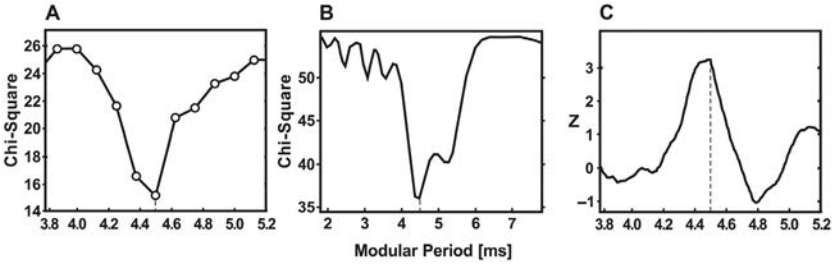

Figure 1.4 Panel A: chi-square distribution for individuals of differences between ISIs at motion breakdown in trials with identical EDs according to Geissler et al. (1999). B: the same if including neighboring EDs (Kompass, 2004). C: tentative results for reaction times recorded for near-asymptotic performance (cf. Geissler, Kompass, & Lachmann, 1998). Details in the text.

participants based on cISI differences for neighboring EDs, he found the distribution shown in Figure 1.4B, which exhibits a minimum at nearly precisely one half of the estimate of $Q^+ = 9.13$ ms from the Vanagas et al. experiment.

The results raised the question of whether an analogous demonstration of the assumed quantal epoch might also be possible for reaction time (RT) paradigms. In general, the degree to which single response times vary in identical conditions seems to exclude such a possibility. Yet there remains the option of gathering indications of a preferred elementary epoch after excessive training. An attempt of that kind relied on RTs from a same-different experiment using regularly structured five-point patterns (cf. Geissler et al., 1998). In order to separate quantized from unordered random variation, the analysis focused on near-asymptotic performance and was restricted to neighboring trials in sequences indicative of a near-stationary regime. In fact, the result depicted in Figure 1.4C suggests preference of a cycle of about 4.5 ms. Unfortunately, replication studies or an expansion of this type of analysis to larger sets of conditions are still lacking.

Interim Summary and Prospects

The developments described earlier amount to the claim that QTSs of different origins can be reduced to configurations of discrete epochs forming a self-similar cascade of quantal ranges. From a functional perspective, that structure is, however, not an end in itself. Its significance as a superordinate regularity, valid across modalities and task-specific performance characteristics, strongly suggests the significance of the invariants Q_0 and M in the function of universals of processing in the brain. In a dynamic view, this résumé opens a wider prospect—namely, the option of process modeling based on the assumed universals as canonic parameters—an until now unexplored type of modeling that differs from standard methodologies in that it optimally ensures a unified representation of behaviorally established relations and their neural equivalents.

Vital for progress in this direction are conceptual links that mediate between primitives of TQM and quasi-neural interpretations in terms of cyclic carriers and their temporal coordination. As a basis for applications in the second part of this chapter, we conclude this introduction to TQM with a brief outline of two hypotheses that have proved to be instrumental in the function of such links.

Links to Process Organization in the Brain: The Prominence and Limited-Coherence Hypotheses

H1: The Prominence Hypothesis

In a preliminary version, both hypotheses were put forward together with the first draft of TQM in Geissler (1985a). The first of the hypotheses includes two elements: (A) an interpretation of QTSs in terms of underlying cyclic carriers and (B) a hypothesis that explains the preferred occurrences of certain QTSs relative to other possible options. Interpretation (A) maintains that QTSs reflect the cooperation of carriers of cyclic activity in the form of synchrony hierarchies (SHs)—i.e., configurations of carriers of hierarchically related cycle durations integrated by phase synchrony. Hypothesis (B) explains the preferred occurrence of certain QTSs by comparison with others as a consequence of their different chances to be encoded as components of SHs. The simplest measure of the likelihood to be encoded is the prominence function $\Pi(N)$. It is defined as the number of possible hierarchies in which multiple N of a given quantal time unit is contained. To illustrate, what we here call "prominence hypothesis" explains the observed prominence of discontinuities at 110 ms according to Stroud's rule by the fact that this cycle duration agrees with the multiple $N = 24$ of Q_0 for which $\Pi(N)$ assumes its maximum value, or, what is equivalent, the multiple is part of 20 different SHs, which is the highest number possible for any multiple N within the range from $N = 1$ to $N = 30$.

At this point, it is worth mentioning that $\Pi(N)$ is of strategic significance not only because it predicts prominent components of empirical response characteristics but also because it forecasts components of low prominence. For judgments on the validity of the approach it was, for example, important that gaps were found in response distributions at predicted positions corresponding to quantal multiples that are prime numbers (see, e.g., Geissler, 1990). Another significant feature of Π is that, for mathematical reasons, highly prominent multiples are surrounded by low-value multiples. Quite in accordance, in comparable QTS patterns, no further components were found in the proximity of predicted prominent components across diverse paradigms. Note that due to this unambiguous relation between quantal multiples and empirically preferred epochs, the interpretation of several multiple-componential structures within limits is rendered immune against measurement errors. For illustration, again consider Figure 1.1 and the example of Stroud's rule, in the picture indicated by dashed vertical lines.

H2: The Limited-Coherence Hypothesis

A long-term goal of the TQM approach is a theoretical framework that incorporates the stochastic variability of mental timing. The limited-coherence hypothesis contributes to achieving that goal by providing an explanation for the most widely applying law of stochastic variation, Weber's Law. The reason for its significance in the time domain became apparent from a dynamic reinterpretation of range limit M (Geissler, 1985a). The model adopted there attributes the presence of M to a fundamental fuzziness of cycle boundaries described as a consequence of superposition of carriers of slightly differing cycle durations. After initial synchrony, a Weber Law–type gradual increase in the dispersion of phase positions occurs that terminates in a complete smoothing out of any residual overall periodicity. In analogy to the propagation of coherent light, the boundary thus predicted was referred to as "coherence limit", and the number of cyclic undulations until the boundary is reached equated with *M*. Note that this explanation of *M* by inner, representational, factors rather than relying on an independent, externally enforced constraint involves conceptual resources that would otherwise be missing. Specifically, it predicts a testable relation between *M* and a suitably chosen measure of cycle fuzziness. Also, as will be seen below, instead of posing a rigid limitation, boundary *M* acquires the meaning of a barrier that may become permeable, for instance, through switching from a given cycle to a cycle of longer duration.

A major problem with the limited-coherence hypothesis had been that for more than a decade, none of the available data sets had been large enough for a sufficiently safe assessment of Weber-type regularities of random variation in quantal time structures (note, however, Part II of this chapter).

1.3 Part II: From Psychology to Brain Sciences: "Border-Crossing" Predictions as a Tool to Bridge the Gap

Basic Policy

The primary aim in this second part of the present chapter is to study the possibility of using behavioral evidence of quantal regularities in the temporal architecture of perception and cognition in order to derive predictions about their equivalents in the underlying brain processes. This type of forecast will be referred to as "BC" prediction. We will proceed in three steps, each corresponding to a separate section.

In Section 1.3.1, we focus on indications of a close quantitative agreement between substructures at the bottom of the assumed quantal-range cascade and broadly accepted traditional EEG band definitions. More specifically, it will be shown that the sizes of the three upper subranges of R_1, converted into frequencies, closely match the widths of the alpha, the beta and the (classical) gamma frequency band, whereas the only subrange of R_2 that does not overlap with R_1 closely agrees with the theta band.

In Section 1.3.2, the congruence of TQM constructs with empirically established EEG bands, thus suggested, will be taken as heuristic justification for BC predictions about equivalents of most basic behaviorally established regularities in the organization of cyclic brain activity. The section falls into three subsections, 1.3.2.1, 1.3.2.2, and 1.3.2.3. In 1.3.2.1, predictions about band-like formations of cyclic brain activity will be expanded to slower frequencies and to so far unknown higher-order structures. Subsection 1.3.2.2 deals with predicted neural equivalents of the hierarchical organization of quantal epochs in phase-coupling relations between different EEG bands. In subsection 1.3.2.3, the deterministic TQM constructs are amended by incorporation of a most fundamental determinant of randomness in neural functioning that accounts for Weber's Law and the limitation of EEG bands to longer cycle durations. The common message of the three subsections is that the band-like composition of cyclic brain activity can be traced back to TQM universals: the time quantum Q_0, an inherent relative cycle fuzziness c that determines the upper range bound M, and the order parameter q of quantum-package size.

Closer examination of the related BC predictions constitutes a research program of its own. However, TQM constructs can even be useful as tools in many situations without any ambitious goals of theorizing. To illustrate this is the purpose of the final Section 1.3.3. Not more than a list of options, the examples presented will be flanked by short comments on their assumed significance.

1.3.1 Pinpointing a Fundamental Congruence: BC Predictions Match EEG Band Definitions

A Historical Note

The idea that the basic postulates of TQM might reveal a theoretical underpinning of EEG band definitions was pushed ahead when we learned about early findings of Livanov on discrete fine structures in the analogue of the human alpha band in rabbits (cf. Livanov, 1972). Reasoning along that line was further encouraged through studies by Lebedev and coworkers in humans that built upon a hypothesis by Lebedev and Lutzky (1973, see also Lebedev, 1990; also Geissler, 1992, for further references). It claims that spindle-shaped undulations in human alpha activity reflect superposition effects of waves whose cycle durations differ by integer multiples of a basic discrete unit (cf. Geissler, 1991b, 1997).

For the EEG Band Structure as a whole, the possibility of a near-isomorphic congruence with the quantal TQM cascade was variously articulated in psychological progress reports (e.g., Geissler, 1987, 1990, 1992, 1994, 2000; Geissler & Kompass, 1999, 2003; Geissler et al., 1998, among others).

In the following, we go beyond those accounts by dissecting the comparison of the TQM constructs with their assumed physiological equivalents into logically independent steps and basing it on a more representative collection of operative definitions of the alpha band that have been in practical use in psychophysiological research.

Specifying a Base-Level Congruence: The "Theoretical" Alpha Band

As long as the comparison between psychological and physiological structures is limited to series of predicted and empirical bands forming analogous