BRILL KronoScope 7 (2007) 1-12 www.brill.nl/kron

On the Nature of Time in Conceptual and Computational Nervous Systems

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Abstract

The central premise of the present paper is that the spectacular failure to create a fully functional artificial intelligence results from a fundamental misunderstanding of the nature of time in relation to living systems. Unlike the sterile and purely chronometric conception that is subsumed in the central, clock referent system of most current computational machines, intelligence and especially human intelligence is erected on a tri-level, integrated system of temporal processing capacities. Here, I present the fundamental nature and manner of integration of these three, evolution-driven mechanisms which help life cope with the vagaries of uncertain but not totally unpredictable environments. The implications for the development of effective artificially-intelligent machines are discussed.

Keywords

time, nervous system, computation, brain, artificial intelligence

The Challenge

Many of the early hopes and expectations for machine-based intelligence remain, to the present, fundamentally unfulfilled. While there have been obvious gains in computer technology and some notable breakthroughs in terms of replicating some rudimentary cognitive capacities, we still do not yet possess the fully cognizant entities promised in the visions of the earlier pioneers of artificial intelligence. Indeed, despite the continuing growth in computational capacity as expressed in Moore's law (Moore, 1965), and possibly even because of this increase in the speed of serial event processing, we have seen only limited progress toward our aspiration for an independently functioning, artificial intelligence; one that is fully adaptable to the needs of its human partners (Hoffman, Hancock, Ford, & Hayes, 2002). Why is this so? It is my contention that this disappointing situation stems, at least in part, from a

DOI: 10.1163/156852407X249034

fundamental misconception as to the nature of time as it must necessarily be expressed in conceptual and computational nervous systems.

Disputation Premise

The need to understand and recognize duration, which represents the continuity of temporal experience, is older than the human species itself. Arguably, such a capacity is a necessary condition for life (Schrodinger, 1944). The instrument that humans have created to deal with the accurate parsing of duration is the clock. It is almost certainly true that the clock is the most ubiquitous tool in the world today. This is a supportable generalization since clocks are essential for virtually all current computer systems, both those with which humans interact and those which are of a more autonomous nature. The nature of clocks is rarely questioned (although for example, in a fundamental sense, any clock is more fundamentally spatial in character than it is temporal). Clocks are the quintessential technical expression of determinism and their evolution has been marked by the ever-increasing degree of accuracy and their independence from external environmental influences (see Cippola, 1967; Sobel, 1996). Across history, the accuracy of time-keeping has increased exponentially, starting with the revolution in understanding celestial mechanics to the contemporary needs for extraordinarily accurate event timing. One fundamental problem has been that the nature of time itself is often confused with the accuracy of timing so that now we accept a view of time that is itself very mechanistic in nature. In making this equation, we confuse the intrinsic phenomena itself with its quantification and confound the embedded relationship between object/object and subject/object relations in the physical world (Russell, 1915; Treisman, 1999). Despite this crucial confusion, and Einstein's subsequent observations on dimensional relativity, the traditional mechanical conception of time as a linear and equi-potential (each second is exactly equivalent to the previous second and the next one to come) flow persists. However, this embodiment of time is very misdirected as far as intelligent systems are concerned. For the clock, simultaneity, succession, duration, and memory essentially have no meaning, but for living intelligences, they are the very stuff of life (Hancock, 2002). Problematically, time has also become to be regarded as the *sine qua non* of causality. The philosopher David Hume saw through this facile assumption (Hume, 1739), and argued that causation is fundamentally a property of the habits of perception, which turn propinquity and sequentiality into cause and effect. This view however failed to percolate into a general scientific understanding of time and it is Newton's mathematical and utilitarian notion of time as a separable and metrical dimension which has dominated western thinking ever since.

Chronometric Explorations of Mind

As well as being the hidden well-spring of technology, the clock metaphor of time lies at the very heart of psychological information-processing theory as it applies to human cognitive capacities. The idea that the human brain contains such a clock subsumes the pure chronometric analyses of cognition (Posner, 1978). For example, much of the understanding of fundamental neuropsychological processes, such as memory retrieval, has been derived by determining timelines for "short-term memory" processes down to the level of milliseconds (e.g., Card, Moran, & Newell, 1983; John, Vera, & Newell, 1994; Wilson, Bernard, Green, & MacLean, 1988). While it is undeniable that the clock metaphor has proved its utility in the psychological domain and beyond, the underlying assumption is that every 'processing' millisecond is equal in value to all of its peers and therefore ensures that equal 'processing' to occur in each unit of 'clock' time. Predicated upon this assumption, the various stages of information-processing can thus be assessed relative to each other by comparing their respective processing 'times'. Known as the 'additive factors' approach, empirical manipulations serve to change facets of demand placed on particular stages and then examine the resulting change in processing time in order to derive conclusions about the architecture of and the nature of the processes themselves. For example, in choice reaction time, an individual's processing speed increases as a log-linear function of the number of binary choices that have to be accomplished (Hick, 1952: Hyman, 1953). By changing the visual character of a stimulus, the temporal difference between responses in a baseline condition can be compared with responses in a manipulated condition to assess the impact of the manipulation on the capability of early processing stages. Similarly, to test response processes, one can manipulate response complexity and compare the outcome temporal values under controlled conditions respectively.

While there have, and continue to be, arguments over the serial versus parallel nature of such processes (e.g., McClelland, 1979; Schweickert, 1984), the critical issue here is to illuminate the underlying temporal assumption upon which such conceptions are founded. From early researchers such as Franciscus Donders (1859; 1969) to more recent luminaries such as Saul Sternberg (1966; 1969), the additive factors methodology has proved an important window through which to examine intelligent micro-scale behavior. However, it may well be that the crucial assumption which underlies it is fundamentally flawed. The extensive literature on time distortion under stressful conditions (see Hancock & Weaver, 2005) confirms that the perceived passage of time is certainly non-linear, contingent upon the nature of the events themselves. This observation is intrinsic to Einstein's comment on relatively when he remarked that:

> *When a man sits with a pretty girl for an hour, it seems like a minute. But let him sit on a hot stove for a minute-and it's longer than any hour.*

There are also findings in the psychological literature (see Block, 1990) and results from neuro-imaging and neuroscience studies (e.g., Coull, Vidal, Nazarian, & Macar, 2004; Harrington, Haaland, & Knight, 1998) that indicate the general fragility of the clock metaphor as a veridical representation of temporal processing in living nervous systems. This finds significant support in studies that show arousal, drug stimulants, and body temperature (Hancock, 1984) all influence estimates of brief intervals of duration. Recent neuro-imaging studies have shown that there are different cortical and sub-cortical loops involved with different timing functions (e.g., encoding, comparison, execution) (Matell & Meck, 2000; Meck & Malapani, 2004; Rao, Mayer, & Harrington, 2001), while there is substantive EEG data that support a model showing several van der Pol oscillators that register duration and coordinate perceptions and actions (Treisman, Cook, Naish, & MacCrone, 1994). In other words, there is this no one single unique or master clock in the brain that is used to control processing or to tick off events in subjective awareness (Hancock, Szalma, & Oron-Gilad, 2005; Lewis & Walsh, 2002). It also affirms that there is no single privileged observational site within the brain as there is no privileged observational site in the Universe (see Hancock, 2005). One can only wonder then whether one should seek to build intelligent systems predicated upon this limited assumption of mono-temporality. This mono-temporal view is misguided at best and at worst appears to doom to failure efforts to create intelligent entities based upon this limitation. However, it is this form of temporal assumption that still underlies much of the present efforts to fabricate artificial intelligence.

Discrete Event Timing

One of the primary limitations in understanding intelligent human behavior which emanates from the use of the simple clock metaphor is the expectation that one can specify the discrete onset of events. This in turn promulgates the notion that time and duration are separable phenomena. Such misconception results in fallacious notions such as the 'ultimate command neuron' (see Kupfermann & Weiss, 1978) since with the idea of a 'start' stimulus and an 'end' response, there must be a spatial location in the brain which represents the putative 'now.' (and see the critique by Hancock, 2005). Pineal glands and Descartes notwithstanding, and however phenomenologically appealing the idea might appear, there is no unique and discrete 'now' in the brain. In terms of neuro-anatomical architecture, there is no discrete, spatial location 'where it all comes together.' (Dennett & Kinsbourne, 1992).

Up to the present, with computational surrogates that seek to express intelligent behavior, or a veridical replication of human intelligence, there is always an ever-present 'now' represented by the clock referent. Human beings do have to register duration. That is, they inevitably have a sense of the present moment or what William James (1890) referred to as the 'specious present.' However, this experience is derived from their perception of self-continuity, i.e., I am the same entity that perceived the previous 'now' that is presently experiencing the current 'now.' This sense of self-continuity emanates from a thermally-mediated mechanism (Hancock, 1984; 1993). However, evidence suggests that this thermal effect has a distributed influence across the cortex and acts in a very different fashion from the clock in a computer system (and see Buzsaki & Draghun, 2004). Specifically, the moment to moment control of perception and action need have only very infrequent intercourse with this continuity function and then probably only as a general form of calibration interchange (Hancock, 2005). To identify these various timing effects in the brain, there have been extensive efforts to relate facets of the electroencephalographic (EEG) trace to time perception down to the millisecond level. Despite prolonged and dedicated efforts, the outcome of this search has, in general, been frustrating and disappointing (see Surwillo, 1966; Treisman, 1984). This failure may well derive from the same sort of category error that is proposed here (i.e., continuity generation cannot be parsed into discrete temporal units except by forcing it to do so, in which case an answer is inevitably forthcoming but inevitably turns out to be both wrong and misleading, e.g., see Vroon, 1974). Virtually all physiological and neuro-physiological processes have, at one time or another been identified as the potential master clocking system. Evidence for each of these has, in its turn, proved in its turn, similarly disappointing. The only neuro-physiological attribute that relates in any consistent way with temporal perception is body temperature. However, body temperature is itself is a distributed parameter and thus a search for a single location, or indeed single brain mechanism influenced by such a parameter is a search with little hope of success (see Hancock, 1993).

In the step toward a solution to the conundrum of time in the brain itself, I propose that human beings possess a tripartite division of timing mechanisms that each sequentially build upon each other in a manner consistent with evolutionary development.

- The first, primary level of temporal processing is a *continuity mechanism*, often incorrectly referred to as the "internal clock." This allows for the persistence of self and is expressed phenomenologically as the continuous flow of experience. Its primary use in consciousness and intelligent activity is as a referent against which upper level systems can periodically match and calibrate their own activities. Failure of, or damage to, this capacity results in the disturbance to the sense of self which is manifest in a number of psychological disorders.
- At the second, sensory level, a *timing mechanism* largely concerns an immediate response to the demands of the immediate present. Fast inter and intra-sensory modality comparisons permit actions such as localization of stimuli and the coordination of motor responses to effect action and change within the world (and see Child & Wendt, 1938). I have previously suggested that these sensory level activities need have no necessary access to any absolute, external frame of reference (Hancock, 2005). That is, they occur within a local region of influence and do not necessarily require reference to any form of socially agreed time-keeping mechanism.
- The final, cognitive level of temporal processing involves an *internal calibration mechanism* that accumulates information derived from a confluence of top-down expectation/goal setting and bottom-up confirmation derived from sensory processing of environmental events. The parsing of this information accumulation into coherent units provides us with our experience of time-in-passing. Previous experience (e.g., goal fulfillment) helps us to construct "what-if" scenarios so that this highest level "cognitive clock" permits us to process situations 'faster than time.' The only vital function of memory is therefore to provide information for the creation of these 'what if' scenarios. It is this anticipatory capacity which largely characterizes complex intelligent behavior.
- Thus, there are three levels of timing in the brain. The first simply assures a sense of individual continuity and consistent with all of life. It is primitive and limited but an essential facet of any organism that has to distinguish self from non-self (environment). The second level, erected by evolution on top of this initial mechanism deals with the demands of the moment. It is responsible for orchestrating and coordinating the sequence of perception to action that characterizes the adaptive response of many

> higher-level organisms. It is a real-time system but is largely limited to reactive response. Nature is then faced with the challenge of making organisms which go 'faster than time.' Nature's solution, embodied in human capacities (among other higher order mammals), is to provide a 'theater' largely within the frontal cortex of the brain (and see Meck & Benson, 2002), in which to run a series of 'what if' simulations. When sensory patterns confirm the antecedent conditions to one of these scenarios, the individual can run off the prepared strategy and thus exceed real-time constraints. The fact that such a temporal capacity inevitably provides human beings with the certain knowledge of their own demise is a central human characteristic. For, after all, time is the punishment for consciousness.

Thus a single, central, mechanistically-fashioned clock cannot lie at the heart of biological intelligence as we know it. If we are seeking to use biological intelligence as a template for artificial intelligence then and it is most probably the case that such a line of progress with such an inherent structure must inevitable end in disappointment. Indeed, one can argue that it is this very failure of biologically intelligent systems to march in step with a simple 'Newtonian' clock that lies at the heart of their survivability and adaptability in the world. Of course, this does not rule out solutions to the creation of artificial intelligence based upon radically different assumptions and principles. However, the putative existence proof of human intelligence encourages the hope and expectation that success made be hard based upon knowledge of brain architecture. The efforts to create artificial intelligence which are not based largely upon the knowledge of human capacities has no such assurance that success is eventually achievable.

Potential Solution Paths

If humans possess a this tri-level synchronization and timing system, what would a computational system look like if it were not dependent on access to a single, central clock for a representation of 'now' but rather possessed the timing characteristics of such human (biological) systems? To understand how such systems might function, we must return briefly to some of the basic assumptions concerning the character of our present computational systems (e.g., Turing, 1950). The Turing Machine is an important mathematical conception. With a relatively simple set of components and actions, limitless input data and limitless instructions can be read and followed serially for writing limitless output data. Using this freedom, Turing was able to conclude that any computation that can be carried out by a rote method could be performed on such a machine (and see also Wells, 1998). The length of the tape and the size of the output in our present systems is represented by the fight for ever increasing memory. This system requires a simple clock to coordinate the execution of instructions. The speed with which an output or goal can be achieved is contingent upon how many instructions per second can be undertaken. In essence, this is the equivalent of how fast we can set clock speed. The problem here is the nature of time and contemporary computational devices. In some of the very first forms of calculating machine (e.g., Jacquard's Loom, Babbage's computational engine, the Argo clock, etc), the problem of time was finessed by leaving the rate control to the requisite human operator as well as the intrinsic limitations in the speed with which mechanical parts could move, or be moved (although this is not to say these systems may have benefited from a linkage to some sort of metronomic device). A critical question in current computational systems is the degree to which the clock per se is either a necessary, sufficient, or, exclusive element. It could be argued that because duration is necessarily ubiquitous, then the clock is simply one necessary component. Of course, I have argued here that the clock is the exclusive identifier of such systems and its regularity and equi-potentiality is indeed the fundamental character that needs to be re-evaluated.

In adopting Turing's basic architecture (although elaborated and instantiated by von Neumann and others), the large majority of current computational systems fight to reduce the unit time/cost for each sequential, serial operational step. In this, technology has been magnificently successful in increasing from millions, to billions and even potentially trillions of operations per second (Moore, 1965). The combination of greater memory storage and higher processing speed is essentially the battle to develop an infinite tape and to move it through the reader at the highest possible speed, but still in a uniform step-wise manner. However, in the battle to generate intelligence, as I have noted, this approach may well be literally sending us down the wrong path at an ever increasing speed. There are two assumptions in the Turing architecture which, while mathematically justified, are biologically flawed. Although the Turing architecture is mathematically capable of replicating any computational machine, the fundamental problem is that it can take an infinite amount of time to do so. While this is mathematically satisfactory (and hence the fight to increase processing speed), under the driving force of biological evolution, the concept of unbound computational time is simply untenable.[1] If we accept the Turing test for machine intelligence (and not all

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[1] There is a potential problem with the argument here which certainly needs to be resolved. If the tape reader is activated by completion of the reading act then there is no necessary reason which this needs to be timed at all! In actuality, this looks much more like the 'cognitive clock'

of us would do so, see Hoffman, Hancock, Ford, & Hayes, 2002), then the human is the only viable comparator against which to assess intelligence (Turing, 1950). Given there is no unique 'now' in the human brain that provides the equivalent of the momentary, tape reading 'window,' and given that the human system has been evolved through a series of incarnations that have each had to solve highly timed-limited problems, it should not be unexpected that present computer systems, founded upon such an architecture, have vast problems replicating human intelligence. In essence, we are seeking to fabricate machines which are progressively better able to deal with the specious present and the issues of input (perception) and output (action) and our success here is seductive. But true intelligence requires adaptation through anticipation and it is this constraint that cannot be surmounted by systems incapable of non-linear temporal processing.

The facile answer to this conundrum is that since brains appear to be massively parallel, they are amenable to replication on massively parallel machines. Again, this assumes a structural and functional isomorphism between brain and machine architecture which simply is not so. For example, most parallel architectures are actually erected on extremely fast, serial machines. However, even were this so, there is still the question of qualitative differences in units of time. All human beings, after even a moment's perusal, become acutely aware that time is not a simple linear dimension. For anyone who has been involved in life-threatening situations, the evident distortions of time that are involved are some of the most vivid of all life experiences (cf., Hancock & Weaver, 2005). Those readers who have felt the hand of age on their shoulder will be very familiar with the increasing speed of perceived time as the years pass (Hancock, 2002). Even memory, which we have traditionally taken to be a flawed chronometric record of past events, is highly influenced by the content of specific epochs which make some actions literally unforgettable, while consigning the vast majority of others to the halls of forgetfulness.

While it may also be argued that these neuro-psychological constructs are themselves erected on much more mechanistic neuro-physiological substrates, it can equally well be argued that intelligence is exactly the same order of construct. In computing, we are not unhappy with spatial diffusion that permits various functions to be accomplished by discrete subsystems that then

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notion that we have proposed elsewhere (see Hancock, Szalma, & Oron-Gilad 2005), in which the storage mechanism proceeds at an unregulated temporal pace and completes each step in the sequence of actions at the maximal rate at which it can be achieved. This, of course, does not need to be constrained or controlled by any clock-like mechanism. While the analogy to present day computational systems is still reasonable we need to focus beyond the Turing Machine as the modal example.

integrated with the outcome of other, spatially distributed functions. Perhaps now is the time to begin to explore temporal diffusion in exactly the same manner (and see Angelini, 2005; Burdick, 2006; Werner & Akella, 1997). Of course, any radically new hardware architecture that fails to specify a unique 'now' will have to spawn software that matches this novel incarnation of temporality. We might be able to use a threshold-initiated mechanism in which the accumulation of commands to a certain value initiates a marker of epoch length. This 'saw-toothed' morphology in which information would be accumulated in a store until a threshold value was reached would be functionally equivalent to a metronomic clock if and only if the accumulation rate was uniform, or at least specifiable. However, as soon as differential rates of information accumulation were introduced or encountered, the counting mechanism would vary according to this local accumulation rate and a non-linear temporal effect would become evident, which would appear similar to a metronomic system with a continually varying frequency. Software for such a variable accumulator-modeled architecture would be radically different from our present conceptions. If we can construct computer systems that use duration not as a single unifying (and stultifying) referent, but rather as an integrated multi-level system that deals respectively with continuity, with momentary response, and with the planning of future actions, then perhaps machine intelligence may be closer than we think.

Acknowledgement

I am very happy to offer my grateful thanks to Dr. Robert Hoffman whose illuminating comments on an earlier version of this work were exceptionally helpful. I also wish to acknowledge the comments of my colleagues Drs. Jim Szalma and Tal Oron-Gilad on an early draft of this paper. The comments of Dr. James Allen are also very much appreciated. As always, he has given freely of his time and insight and I remain deeply, in his debt. This work was prepared under Grant #NBCH 1030012 from the Defense Advanced Research Projects Agency, (DARPA) via the Department of the Interior. The Grant Monitors for this work were CDR (Sel.), Dr. Dylan Schmorrow and Lt. Cmdr, Dr. Russell D. Shilling. The report itself is under the direction of Dr Dennis McBride of the Potomac Institute. The view expressed here is that of the author and does not necessarily represent those of any named individual or agency.

References

Angelini, C. (May 2005). Asynchronous logic: Who let the clocks out? *Computer Power User, 5* (5), 46-48.

Block, R.A. (1990). (Ed.). *Cognitive models of psychological time*. Hillsdale, New Jersey: Erlbaum.

Burdick, A. (2006). The mind in overdrive. *Discover, 27* (4), 21-22.

Buzsaki, G., & Draghun, A. (2004). Neuronal oscillators in cortical networks. *Science, 304*, 1926-1929.

Card, S., Moran, T., & Newell, A. (1983). *The psychology of human-computer interaction*. Hillsdale, NJ: Lawrence Erlbaum.

Child, I.L., & Wendt, G.R. (1938). The temporal course of the influence of visual stimulation upon the auditory threshold. *Journal of Experimental Psychology, 23* (2), 109-127.

Cippola, C.M. (1967). *Clocks and culture 1300-1700.* NY: W.W Norton & Company.

Coull, J.T., Vidal, F., Nazarian, B., & Macar, F. (2004). Functional anatomy of the attentional modulation of time estimation. *Science, 303*, 1506-1508.

Dennett, D.C., & Kinsbourne, M. (1992). Time and the observer: The where and when of consciousness in the brain. *Behavioural and Brain Sciences, 15*, 183-247.

Donders, F.C. (1859). *Physiologie des menschen*. Hirzel: Leipzig.

—— (1969). On the speed of mental processes. *Acta Psychologia, 30*, 412-431.

Hancock, P.A. (1984). An endogenous metric for the control of perception of brief temporal intervals. *Annals of the New York Academy of Sciences, 423*, 594-596.

—— (1993). Body temperature influences on duration estimation. *Journal of General Psychology, 120*, 197-216.

—— (2002). The time of your life. *Kronoscope, 2*, 135-165.

—— (2005). Time and the privileged observer. *Kronoscope, 5*, 176-191.

Hancock, P.A., Szalma, J.L., & Oron-Gilad, T. (2005). Time, emotion, and the limits to human information processing. In: D. McBride and D. Schmorrow (Eds.). *Quantifying human information processing*. (pp. 157-175), Lexington Books: Boulder, CO.

Hancock, P.A. & Weaver, J.L. (2005). Temporal distortions under extreme stress. *Theoretical Issues in Ergonomics Science, 6*, 193-211.

Harrington, D.L., Haaland, K.Y., & Knight, R.T. (1998). Cortical networks underlying mechanisms of time perception. *The Journal of Neuroscience, 18* (3), 1085-1095.

Hick, W. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology, 4*, 11-26

Hoffman, R., Hancock, P.A., Ford, K., & Hayes, P. (2002). The triples rule. *IEEE Intelligent Systems, 17*, 62-65.

Hume, D. (1739). *A treatise of human nature*. Noon: Cheapside, London.

Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology, 45*, 188-196.

James, W. (1989). *Principles of psychology*. New York: Holt.

John, B., Vera, A., & Newell, A. (1994). Towards real-time GOMS: A model of expert behaviour in a highly interactive task. *Behavior and Information Technology, 13*, 255-267.

Kupfermann, I., & Weiss, K.R. (1978). The command neuron concept. *Behavioral & Brain Sciences, 1* (1), 3-39.

Lewis, P.A., & Walsh, V. (2002). Neuropsychology: Time out of mind. *Current Biology, 12*, R9-R11.

Matell, M.S., & Meck, W.H. (2000). Neuropsychological mechanisms of interval timing behavior. *Bioessays, 22*, 94-103.

McClelland, J.L. (1979). On the time relations of mental processes: An examination of processes in cascade. *Psychological .Review, 86*, 287-330.

Meck, W.H., & Benson, A.M. (2002). Dissecting the brain's internal clock: How frontal-striatal circuitry keeps time and shifts attention. *Brain and Cognition, 48*, 195-211.

Meck, W. & Malapani, C. (2004). Neuroimaging of interval timing. *Cognitive Brain Research, 21*, 133-137.

Moore, G.E. (1965). Cramming more components onto integrated circuits. *Electronics, 38* (8), April, 19.

Posner, M. (1978). *Chronometric explorations of mind.* Erlbaum: Hillsdale, New Jersey.

Rao, S., Mayer, A., & Harrington, D. (2001). The evolution of brain activation during temporal processing. *Nature Neuroscience, 4*, 317-323.

Russell, B. (1915). On the experience of time. *Monist, 25*, 212-233.

Schrodinger, E (1944/1967). What is life? Cambridge: Cambridge University Press.

Schweickert, R.J. (1984). The representation of mental activities in critical path networks. In J. Gibbon and L. Allan (Eds.), *Timing and time perception* (pp. 82-95), New York Academy of Sciences: New York.

Sobel, D. (1996). *Longitude.* London: Penguin.

Sternberg, S. (1966). High speed scanning in human memory. *Science, 153*, 652-654.

—— (1969). The discovery of processing stages: Extensions of Donders' method. In W.G. Koster (Ed.), *Attention and performance II.* Amsterdam: North-Holland.

Surwillo, W.W. (1966). Time perception and the 'internal clock': Some observations on the role of the electroencephalogram. *Brain Research, 2*, 390-392.

Treisman, M. (1984). Temporal rhythms and cerebral rhythms. In J.Gibbon and L. Allan (Eds.), *Timing and time perception* (pp. 542-565), New York Academy of Sciences: New York.

—— (1999). The perception of time: Philosophical views and psychological evidence. In: J.N. Butterfield (Ed.), *The arguments of time.* (pp. 217-246). Oxford: Oxford University Press.

Treisman, M., Cook, N., Naish, P., & MacCrone, J. (1994). The internal clock: Electroencephalographic evidence for oscillatory processes underlying time perception. *Quarterly Journal of Experimental Psychology, 47A*, 241-289.

Turing, A.M. (1950). Computing machinery and intelligence. *Mind, 59*, 433-460.

Vroon, P.A. (1974). is there a quantum in duration experience? *American Journal of Psychology, 87*, 237-245.

Wells, A.J. (1998). Turing's analysis of computation and theories of cognition. *Cognitive Science, 22* (3), 269-294.

Werner, T., & Akella, V. (1997). Asynchronous processor survey. *IEEE Computer, 30* (11), 67-76.

Wilson, M., Bernard, P., Green, T., & MacLean, A. (1988). Knowledge-based task analysis for human computer systems. In G. van de Veer, T. Green, J. Hoc, and D. Murray (Eds.), *Working with computers: Theory versus outcome.* (pp. 47-87). London: Academic Press.