A Brief History of "The Psychology of Time Perception"

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Commentary

A Brief History of "The Psychology of Time Perception"

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Abstract

Basic mechanisms of interval timing and associative learning are shared by many animal species, and develop quickly in early life, particularly across infancy, and childhood. Indeed, John Wearden in his book "*The Psychology of Time Perception*", which is based on decades of his own research with colleagues, and which our commentary serves to primarily review, has been instrumental in implementing animal models and methods in children and adults, and has revealed important similarities (and differences) between human timing (and that of animals) when considered within the context of scalar timing theory. These seminal studies provide a firm foundation upon which the contemporary multifaceted field of timing and time perception has since advanced. The contents of the book are arguably one piece of a larger puzzle, and as Wearden cautions, "The reader is warned that my own contribution to the field has been exaggerated here, but if you are not interested in your own work, why would anyone else be?" Surely there will be many interested readers, however the book is noticeably lacking in it neurobiological perspective. The mind (however it is conceived) needs a brain (even if behaviorists tend to say "the brain behaves", and most neuroscientists currently have a tenuous grasp on the neural mechanisms of temporal cognition), and to truly understand the psychology of time, brain and behavior must go hand in hand regardless of the twists, turns, and detours along the way.

Keywords

Scalar timing theory, striatal beat-frequency model, development, emotion, neurobiology of interval timing

1. Introduction

Typically, over the past 15 years, books dedicated to the scientific investigation of timing and time perception have been edited volumes (e.g., Arstila & Lloyd, 2014; Glickson & Myslobodsky, 2006; Grondin, 2008; Meck, 2003; Merchant & de Lafuente, 2014; Mölder et al., 2016; Nobre & Coull, 2010; Vatakis & Allman, 2015);

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it's unusual to find a single-author book on this topic. In contrast, the current year has brought us two such books dealing with time perception from the perspective of recognized researchers in the field. The first is by Marc Wittmann, "*Felt Time: The Psychology of How We Perceive Time*" (Wittmann, 2016 — 184 pp.). Wittmann argues that the integration of various bodily processes and sensations as a function of time (e.g., heart beat, respiration, digestion, pain, temperature, emotion, etc.) forms a 'Gestalt' of these feelings … which is the essence of 'Felt Time'. Wittmann's noteworthy achievement has been capably reviewed elsewhere (Van Rijn, 2016) and so will scarcely be commented on further. In contrast, John Wearden's "*The Psychology of Time Perception*" (Wearden, 2016 — 261 pp.) presents a historical perspective on the field of timing and time perception from psychophysical and cognitive perspectives. Moreover, Wearden's book is accompanied by a full-throated defense of scalar timing theory presented in a fashion that few other scholars could even imagine.

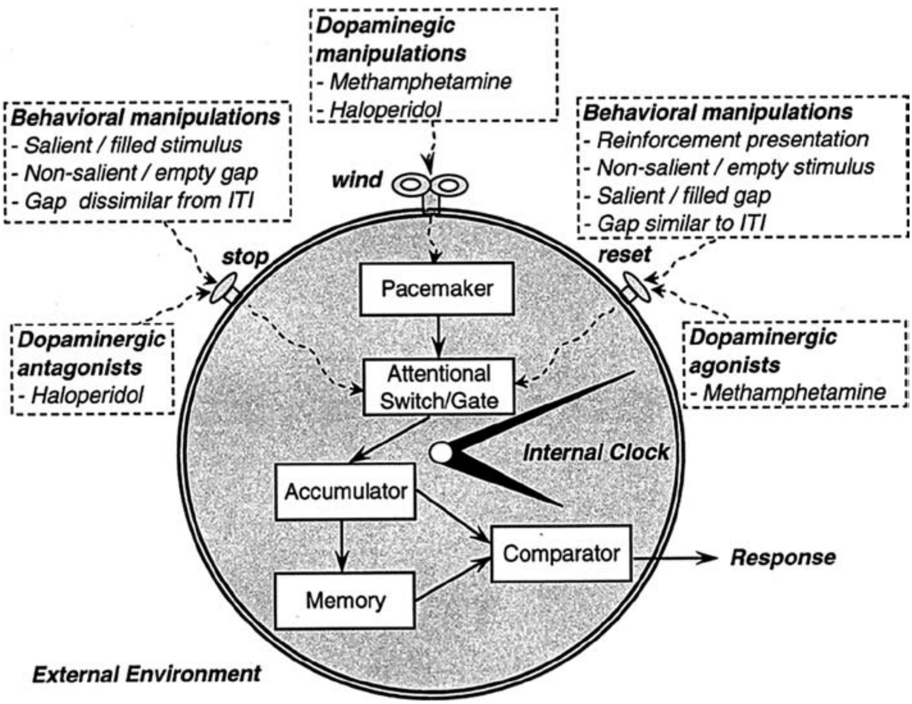

Figure 1. Setting the dials of an internal clock. The 'putative' stopwatch is mapped onto an information-processing (IP) model of interval timing as specified by scalar timing theory (Gibbon et al., 1984). The IP model is comprised of a clock stage with a pacemaker, switch, and accumulator, a memory stage for short and long-term storage, and a decision stage for comparing the current clock reading with a sample taken from memory. Behavioral and pharmacological manipulations tune the stopwatch by winding, stopping, or resetting it (Coull et al., 2011; Meck, 1996). ITI = intertrial interval. Adapted from Buhusi and Meck (2002).

Wearden's position is largely based on his extensive knowledge of the inner workings of Michel Treisman's 'internal clock' model (1963, 2013), John Gibbon's scalar expectancy theory (SET — 1977), and the information-processing (IP) model derived from SET by John Gibbon, Russell Church, and Warren Meck – generally known as scalar timing theory with clock, memory, and decision stages as illustrated in Fig. 1 (e.g., Church, 2003; Church et al., 1994; Gibbon & Church, 1984, 1990, 1992; Gibbon et al., 1984; Meck, 1983; Meck et al., 1985). To use a metaphor, Wearden's vantage point is from a comfortable arm-chair couched within a vast library of journal articles and books related to the control and modeling of the internal clock. At times, however, it almost seems as if that arm-chair has been turned toward a wall, and because of this the book lacks a certain degree of foresight with respect to suggestions for future research, and general coverage of the field of timing and time perception as a whole.

2. Historical Background

For much of his illustrious career at Manchester and later Keele, Wearden enjoyed spatial proximity with Treisman at Oxford and temporal proximity with Gibbon and colleagues at Columbia and Brown — who also share with him an animal learning and conditioning background. As a consequence, John Wearden and his colleague Sylvie Droit-Volet (Blaise Pascal) were able to extend scalar timing theory into the human realm by studying time perception in children and adults (e.g., Droit-Volet & Wearden, 2001; Droit-Volet et al., 2001, 2007). Moreover, Wearden's collaboration with Helga Lejeune in Liege helped to maintain a balance between the animal and human work (Lejeune & Wearden, 2006; Wearden & Lejeune, 2008). In essence, Wearden and his colleagues came to define the intellectual stronghold for scalar timing theory in Europe while Gibbon and his colleagues continued to develop the model in the US and Canada in order to provide both comparative and neurobiological analyses (Gibbon & Allan, 1984; Gibbon et al., 1997; Hinton & Meck, 1997; Malapani et al., 1998; Penney et al., 1996, 1998, 2008).

As Wearden acknowledges in the Preface and Overview, the book largely revolves around his own extensive experimental work with humans which used scalar timing theory to pose the questions studied as well as to provide the interpretation of the results. Although some alternative theories such as Killeen and Fetterman's Behavioral Theory of Timing (BeT — 1988) and Machado and Keen's Learning to Time (LeT — 1999) theory are discussed, the framework of the book remains true to the behavioral instantiation of scalar timing theory (often inaccurately referred to as SET). As Wearden points out, instantiation of the scalar property of interval timing — time-scale invariance exhibited by psychometric functions falling on top of each other when plotted on a relative time scale — is referred to as "superimposition" by Wearden and "superposition" by Gibbon. Meck and others later gravitated to Wearden's usage of "superimposition", which is now the generally accepted term for this important observation — one might say the

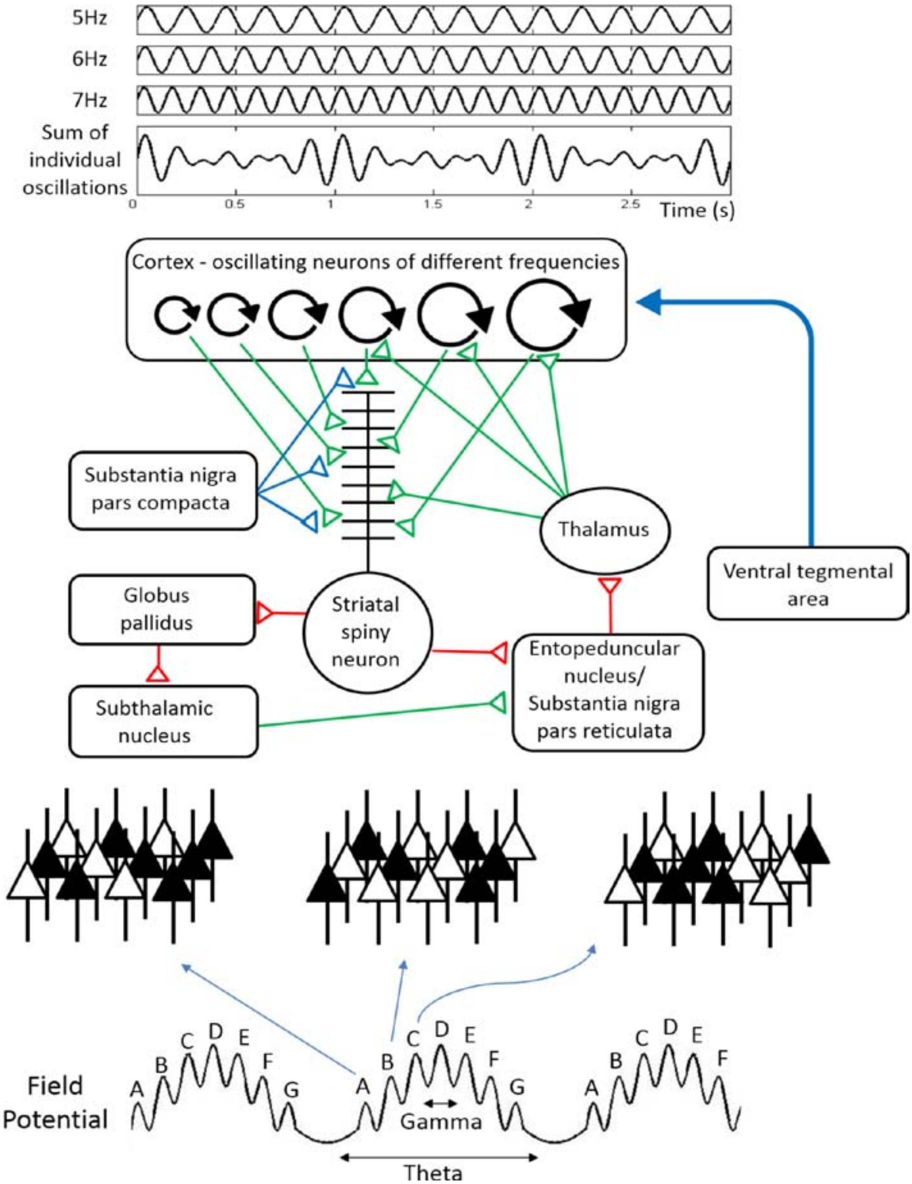

Figure 2. Cortical oscillations as the basis for temporal and identity information. The top panel shows the striatal beat-frequency (SBF) model as specified by Matell and Meck (2000, 2004). Cortical neurons oscillating at different frequencies project on to striatal median spiny neurons. The set of oscillators which are active at the time of a relevant signal (e.g., stimulus offset) provide the code for duration. The lower panel illustrates how theta and gamma cortical oscillations may also underlie the maintenance of stimulus representations in working memory: Individual items are encoded in the spatial pattern of cells firing within a given gamma cycle, with the whole sequence repeated on subsequent theta cycles — and with the capacity of STM dependent on the number of items that can be 'fit' into each theta cycle. Recent modeling has shown that working memory representations and timing can be encoded in a single oscillator-based framework, with different dimensions of the neural oscillations providing the basis for item, order, and duration information. Adapted from Gu et al., (2015). This figure is published in color in the online version.

'hallmark' of scalar timing theory (e.g., Buhusi et al. 2009; Cheng & Meck, 2007; Church et al., 1994; Gibbon, 1991; Rakitin et al., 1998). Moreover, this realization of the scalar property of interval timing (e.g., superimposition) inspired Meck and Malapani (2004) to reanalyze the human neuroimaging data of Hinton and Meck (2004) with respect to the time course of the hemodynamic response in a fMRI study using the peak-interval timing procedure with target durations of 11 and 17 s. This analysis showed that the only brain region that displayed superimposition of the hemodynamic response as a function of its activation during timing trials (compared to non-timing control trials) was the putamen — the brain area designated as performing the 'detection' of target durations in coincidence-detection models of interval timing such as the striatal beat-frequency (SBF) model illustrated in Fig. 2 (Allman & Meck, 2012; Lustig et al., 2005; Matell & Meck, 2000, 2004; Meck et al., 2008).

3. Neurobiological Considerations

Wearden's "anti-neurobiological" position — best captured in his words: "none of the topics treated in the book would be significantly illuminated in any way by the neuroscience of timing in it's present state, at least in my view" (p. vi) is most unfortunate and closes the door on many promising lines of research similar to the way that radical behaviorism shunned the cognitive processes (e.g., clock, memory, and decision stages — see Gibbon et al., 1997; Merchant & de Lafuente, 2014; Shi et al., 2013; Van Rijn, 2014). These concepts, as well as the use of the term 'internal clock', were hard fought for in the early days of scalar timing theory when its proponents were trying to make the transition from SET which was purely mathematical and descriptive and included none of this 'cognitive architecture' ... not even a clock (see Church, 1978, 1984, 2003; Van Rijn et al., 2014). Interestingly, Wearden has found himself capable of embracing these unobservable constructs in the face of heavy criticism from behaviorists. This historical trend of enlightenment should provide encouragement to many chronobiologists as well as cognitive and computational neuroscientists now advocating the SBF model of interval timing which has its origins in scalar timing theory (e.g., Agostino et al., 2011; Allman et al., 2014a; Gu et al., 2015; Hashimoto & Yotsumoto, 2015, Kononowicz et al., 2016; Kononowicz & Van Wassenhove, 2016; Matthews & Meck, 2014, 2016; Oprisan & Buhusi, 2011, 2014; Terhune et al., 2016; Van Rijn et al., 2011, 2014; Yin et al., 2016).

There are similarities between non-temporal environmental factors (e.g., stimulus intensity, modality, and patterning) and neurobiological (e.g., dopaminergic activation of cortico-striatal circuits) effects on timing functions (Buhusi, 2003; Buhusi & Meck, 2000, 2002; Coull et al., 2011), including their analysis, with respect to encoding efficiency (Matthews et al., 2014) and specific components of the IP model (Cheng et al., 2008; Church, 1984; Meck, 1996; Van Rijn et al., 2014). Nevertheless, Wearden has chosen to distance himself from the synergism that neuroscience could provide in spite of the obvious anatomical differences between auditory and visual modalities that contribute to one of the findings that he finds the most fascinating, namely that auditory signals are judged to be proportionally longer that visual signals of the same duration (e.g., Allman et al., 2014a; Droit-Volet et al., 2004a; Kanai et al., 2011; Penney, 1997; Penney et al., 2000; Wearden et al., 1998; Yuasa & Yotsumoto, 2015). Wearden exploits this well-known auditory/visual difference in order to determine where in the IP model the rate of temporal integration for auditory signals might be able to surpass the rate of temporal integration for visual signals. A certain fondness is also expressed for the 'classic' experiment where the temperature of a patient with fever is correlated with duration estimates (Hoagland, 1933). Despite being fraught with difficulties, this experiment clearly points toward a neurobiological mechanism whose activity is modulated by temperature (but see a recent study by Mioni et al., 2016 questioning this effect).

Along the same lines, Wearden also uses the rapid flickering of a stimulus (click trains) prior to the steady, continuous presentation of the 'to-be-timed' signal to try and drive the internal clock at a faster rate, either due to general arousal or to selective entrainment (e.g., Penton-Voak et al., 1996; Schirmer et al., 2016a; Treisman et al., 1990 – but see Cheng et al., 2016; Herbst et al., 2014; Repp et al., 2013).

Taken together, "*The Psychology of Time Perception*" Wearden is able to take the interested reader on a journey through time exploring the nuances of interval timing through the lens of scalar timing theory. From the position of his arm-chair and language issues aside, Wearden gives his view of the success of scalar timing theory while also pointing out its weaknesses and limitations. As an advocate of the theory, he never really challenges it in any systematic way and is more or less committed to adapting it as necessary to accommodate the data obtained in various situations. To this end, throughout his career he developed human analogs of the animal timing procedures first used by Gibbon, Church, and colleagues, such as the time left (Gibbon and Church, 1981), temporal bisection (Church & Deluty, 1977; Meck et al., 1985), temporal generalization (Church & Gibbon, 1982; Meck & Church, 1982), and peak-interval procedures (Church et al., 1994; Meck & Church, 1984). The findings were typically in accord with the rat and pigeon data and consistent with scalar timing theory. The behavioral data were subsequently fit with computer-simulation models by which to interpret them [a hardware of sorts, insofar as components of simulated models have the potential to be 'lesioned/manipulated' (by increasing noise) to predict and accommodate obtained findings from young, old, and clinical populations].

4. Developmental Considerations

Similarly, in collaboration with Sylvie Droit-Volet and colleagues, developmental studies revealed that temporal precision increases with age, and these data have been modeled to produce inferences on the content and 'fuzziness' of memory, and fluctuations in attention. Wearden's comment and stance on the utility of neuroscience to advance our understanding of time perception is unfortunate as this body of child studies serves as an important foundation and reference for related studies in children with disorders of the mind and brain such as autism and attention deficit hyperactivity disorder (e.g., Allman, 2011; Allman et al., 2012; Allman & Falter, 2015). For example, in another study, Wearden and colleagues (Allman et al., 2011) modeled the timing functions of children with and without autism ($M = 9$ yrs), and made comparisons to previously published (and derived) data with children at different ages (3, 5, 8 yrs). The best fitting model was able to capture the obtained autism timing data reasonably well, and revealed the possibility of a developmental delay in temporal processing (~3 and 5 yrs, comparing across studies by Droit-Volet; but see Gil et al., 2012). However such IP theories and models are not so readily able to capture a characteristic feature of the data from this study (unless they suppose a difference in the strategy by which children with autism performed the task), which was a flattening of the functions around 5 s, nor do they accommodate the theoretical possibility that (at least in humans) different breaths of time (i.e., within an event lasting seconds to minutes) might be experienced differently (i.e., in all such accounts a stimulus is assumed to be timed without error). The integration of numerous sensations argued for in the other single-author book (Wittmann, 2016), as well as the co-development of time and space (McCormack, 2015) might provide a framework to accommodate these observations by providing alternative sources and forms of variance affecting attention as well as the clock, memory, and decision stages.

A collection of developmental studies by other researchers (e.g., Brannon et al., 2004, 2008) has suggested a fully functional internal clock is present and makes considerable gains in the first year of life. That the brain invests valuable resources into developing areas and early cognitive skills that serve timing abilities during infancy supports the idea that basic mechanisms of time perception are a phylogenic and ontogenic foundational building block for other cognitive abilities (Allman & Mareschal, 2016; Matthews & Meck, 2016); which might reasonably include causal learning and counterfactual thinking, episodic (and future episodic memory) and theory of mind. In infants, proportionality (and the scalar property) has been observed at both the behavioral and electrophysiological levels (in passive listening paradigms; e.g., Brannon et al., 2004). Although he largely rejects cognitive neuroscience, Wearden's book is focused on associative and cognitive aspects of timing and time perception, and in the chapter on development, he provides an illuminating account of a few early cognitive studies of time, highlighting those that are difficult to 'get hold of' either through the experimental methodologies of the past; or language and accessibility. As Wearden notes, studies such as those by Piaget (1969) have an important place in psychology and despite some limitations, provide conceptual insights as to how children begin to process relations among dimensions of magnitude, such as time, space (size, distance) and number when performing certain tasks. Included is a summary of the work of Levin (1992), who separately examined judgments of time with dolls that were either static, rotationally or linearly moving through space, generally observing that linear motion (i.e., distance through space) interfered with temporal judgments (as do other factors, such as intensity). This type of result has generally been interpreted by Piaget and others, as suggestive of dominance of space over time, and the existence of some form of generalized 'more' estimator (see also Allman et al., 2012, 2014a, b). A shared analog and cross-dimensional mapping system (but see Dallal et al., 2015) might be particularly effective in providing a mechanism for abstract extrapolation to other modalities (i.e., more time = more space/number/force/distance, etc.) for example, during processes of past or future episodic memory and counterfactual thinking (Brown et al., 2014). However, much like the remainder of the book, Wearden does not discuss the implications of the cognitive studies he includes, nor does he attempt to relate them to his own studies of time perception in children with Sylvie Droit-Volet. While he has helped demonstrate that attention and memory processes mature and improve the accuracy and precision of time perception in children up until 8–9 years (at which point adult-level performance is typically achieved; Droit-Volet, 2016); this is by no means a complete account, nor developmental theory of how a child develops a perception of time, and becomes able to adapt to and predict events and contingencies based in time (e.g., of the type provided by Allman & DeLeon, 2009; Boucher, 2001; McCormack, 2015).

With regard to other chapters, the book provides an excellent starting point for appreciating additional current work being done on aging, emotion, and IQ (e.g., Bartholomew et al., 2015; Cheng et al., 2016; Droit-Volet & Meck, 2007; Lake et al., 2016a, b; Schirmer et al., 2016b; Turgeon et al., 2016 — inspired, in part, by the pioneering work of Droit-Volet et al., 2004b and Wearden et al., 1997) while also allowing for a comparison between prospective timing and retrospective timing, i.e., mentally traveling back in time in order to determine how long something has lasted after the fact (e.g., Addyman et al., 2016; French et al., 2014; MacDonald, 2014; Wearden, 2005). Such estimates have been referred to as "timing without a clock" (Ivry & Hazeltine, 1992) because participants are unaware that time will be a relevant factor when first exposed to the events in question. Comparisons between prospective and retrospective timing, and potentially the temporal discounting of events in the future, help to determine which properties (e.g., accuracy and precision vis-à-vis the scalar property) are general and which are specific to a particular domain (e.g., cerebellar and striatal 'time cells' in the case of prospective timing and hippocampal "time cells" in the case of retrospective timing — Lusk et al., 2016; MacDonald, 2014; MacDonald et al., 2014).

5. Summary

All in all, the book is a magnificent achievement, a compendium of information that all serious students of timing and time perception should consider when contemplating the historical roots of the field and celebrating the "Golden Anniversary of Timing" (Wearden, 2013). Exhibiting a type of 'mental time travel', the book conveys one man's journey through time as he studies the interval-timing abilities of others in a controlled and systematic fashion. No new doors to perception are opened during the journey and no guidance for the future is provided at its conclusion. Throughout the book Wearden remains true to himself and his particular version of scientific inquiry. As a consequence, the book is more about one person's attempt at understanding time perception during his academic career than about providing an integrated view of the scientific enterprise comprised of researchers from diverse and varied fields over the course of multiple generations. This, of course, reminds one about the story of a group of blind men trying to touch an elephant in order to get some idea of what it is. One person trained in a single discipline (e.g., psychology) without significant computational, engineering, genomic, and neurobiological knowledge is unlikely to grasp enough of the elephant to make a difference no matter how hard they try (Meck & Ivry, 2016; Meck et al., 2014). Just as the mechanisms of timing and time perception in the sub- and supra-second ranges are likely to be diverse and distributed throughout the brain (Buhusi & Meck, 2005; Merchant et al., 2013) so must the scientific team or community be that cracks the 'Morse code' (Hardy & Buonomano, 2016) to find the 'Holy Grail' (Matell, 2014), thereby discovering the brain's 'internal clock' (Allman et al., 2014a) and/or "dynamic network states" (Leje & Buonomano, 2013).

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