Paper “as accepted for publication" in Neuroscience & Biobehavioral Reviews, Oxford. Elsevier Ltd., vol 137, 104644, 2022. © 2022 Elsevier Ltd. All rights reserved.
Published version: https://doi.org/10.1016/j.neubiorev.2022.104644

Temporal disorientations and distortions during isolation

Virginie van Wassenhove

CEA, NeuroSpin, Cognitive Neuroimaging Unit, INSERM, CNRS, Université Paris-Saclay, 91191 Gif/Yvette, France

Corresponding Author: Virginie.van.Wassenhove@gmail.com

CEA, DRF/Joliot, NeuroSpin
INSERM Cognitive Neuroimaging Unit
Université Paris-Saclay
Bat 145 PC 156
91191-Cedex Gif-sur-Yvette FRANCE

Abstract

Understanding how the brain maps time is central to neuroscience, behavior, psychology, and cognition. Just as in spatial navigation, self-positioning in a temporal cognitive map depends on numerous factors that are both exogenous and endogenous (e.g. time of day and experienced durations, respectively). The deprivation of external temporal landmarks can greatly reduce the ability of participants to orient in time and to formulate an adequate endogenous representation of time. However, this area of investigation in humans shows a great paucity of empirical data. This article aims at unearthing some of the experimental work that has systematically explored how humans' awareness of time is affected by varying degrees of isolation protocols. The assessment of the literature on the impact of isolation (broadly construed) on human temporalities may contribute to contextualizing the temporal distortions and disorientations reported during the ongoing worldwide pandemic Covid-19.

Keywords

temporal cognition, time perception, human, duration, tapping, rhythm, synchronization

Highlights

- Temporal cognition is central to neuroscience and cognitive science
- Isolation is accompanied by systematic temporal disorientations and distortions
- Factors selectively affecting temporal cognition in isolation are unknown
- Individuals' endogenous biological and behavioral rhythms emerge in isolation
- Timing in the absence of external clocks should be carefully investigated

Psychological time, taken as the set of internal inferences the brain uses to represent the temporal relations (duration, order, sequence, past, future …) between events (Friedman, 1993, p. 199; Michon, 1990), is flexible and adaptive: humans and animals use temporal cognitive maps (Gallistel, 1990) to anticipate their future (Raby et al., 2007) and to adapt their behaviors.

The ability to orient oneself in time has long been recognized as a central feature of psychology (Cottle, 1968) and perspectival (Zimbardo, 1990). Experiencing temporal disorientations can be synonymous with future psychological trauma (Holman & Grisham, 2020) and changes in one's temporal phenomenology can indicate emotional distress (Droit-Volet et al., 2020; Grondin et al., 2020; Yamada et al., 2020), being in a socially deconstructed state (Twenge et al., 2003) and even psychiatric disorders (Mengin et al., 2020). Clinically, temporal disorientation is an indicator of future cognitive impairments and dementia that implicate memory systems (Arzy et al., 2009; Dumurgier et al., 2016). The disorientation experienced by patients with Alzheimer's disease (Dafni-Merom et al., 2019) dramatically impact their personal narratives, and patients with lesions in hippocampal structures show diverse temporal impairments (MacDonald, 2014) such as duration distortions (Richards, 1973) and difficulty to perform mental time travel (Tulving, 1985). H.M., a patient with bilateral hippocampal damage reproduced durations quite accurately up to about 20 seconds of clock time yet estimated 5 minutes of clock time to be equivalent to 40 s (Richards, 1973). Clive Wearing, following massive hippocampal damages extending to his temporal and frontal lobes, lived his life in a perpetual present (Wilson & Wearing, 1995) lasting a few seconds (7 to 30 seconds). His personal notebook shows that his life reads as a series of non-causal snapshots, preventing him to weave a coherent narrative of his conscious life.

A conscious "present" seems to span a few seconds of clock time but it is impervious to the healthy mind bathed in a continuous stream of endogenous thoughts and exogenous stimulations. Mind wandering too is a form of engagement into temporary disorientation, which engages the default-mode network of the brain and has recently been associated with an individual's degree of perceived loneliness and social isolation (Spreng et al., 2020). Yet, temporal disorientation can also be sought after when one deliberately immerses into the narrative of a great novel, at a concert, or even immersing in augmented-to-virtual realities (Wood et al., 2007). What do we know about the effects of isolation on temporal cognition?

In the following, I illustrate how studying the effects of isolation provided insights on how endogenous biological properties eventually shape both temporal perception (the measure of the temporal statistics of events) and cognition (rules and representations used by the brain to compute temporal relations). Human studies focusing on time in isolation have mostly investigated the physiological components of time perception leaving vastly unknown how the construction of temporal cognitive maps may be affected. A short allusion is included, relating changes in time perception and temporal cognition during the lockdown episodes associated with Covid-19.

A biological fabric for time

Temporal cognition does not arise through exogenous causes; rather, it is deeply rooted in one's biological endowment and in the endogenous structuring principles that ultimately form our awareness of self in an ever-changing environment. The neurobiological foundations of temporal cognitive maps making up our phenomenology of time remains largely unknown, yet it would be unsurprising that brain rhythms and biological clocks contribute to the shaping of temporal cognition (Buzsáki, 2006; Gallistel, 1990; Jones, 1976; Pöppel, 1971, 1972; van Wassenhove, 2016; F. J. Varela, 1999). Over a large spectrum of scales, biological clocks regulate genes, synchronize individuals to their environment and peers, and endow individuals with the ability for timing. Endogenous dynamics are, after all, constitutive of living systems. Attributing endogenous causes to timing is not as intuitive and accepted as it may first appear. Cognitive neuroscience remains heavily influenced by the idea that behaviors result from external causes and stimulations despite massive controversies at the very origin of cognitive sciences. The explanatory power for "thinking matter" in current brain theories do not readily accommodate how mental representations can be generated in the absence of external stimuli (Barack & Krakauer, 2021; Krakauer et al., 2017). The need to take the perspective of the brain from within, not the perspective of the world from outside, has been vehemently defended by Buzsáki (Buzsaki, 2019). In this context, understanding time in the brain to understand the mind is quite simply primordial (Buonomano, 2017): "*[...] the field of neuroscience will have to further mature and embrace the fact that it will not be possible to understand the human mind without describing how the brain tells, represents, and conceptualizes time. [...]*"

In the mid-nineteenth century, Aschoff and colleagues (Aschoff, 1965) demonstrated that the causes of chronobiology and rhythmic activity in animals (humans included) were endogenous. Biological clocks govern the periodicities of physiological phenomena, independently of external timing cues. The replicable evidence for this assertion is that in the absence of external timing cues (*e.g.* day/night cycles) individuals in many species show undamped self-sustained changes in their physiology and behaviors: the core body temperature will continue its periodic changes, and so will periods of wakefulness and sleepiness. In the absence of external timing cues (or *Zeitgebers*) that synchronize the animals' biological clocks with the external environmental clocks, the animals' physiology will pursue its dynamic variations in *free-running mode*: biological clocks, including neuronal ones (Webb et al., 2009), maintain their inherent periodicities and thus naturally run out of phase with the clocks they cannot entrain to. In full darkness, and in the absence of diel cues, intrinsic rhythms maintain their course but will display distinct, endogenously defined periodicities, and readily de-phase with respect to other clocks (Aschoff et al., 1967). These observations are also demonstrated to be species-specific (Hazlerigg & Tyler, 2019). Additionally, Zeitgebers are not solely defined by universal time constants: they are also driven by social interactions in many species (Aschoff et al., 1971; Bloch, 2010; Eban-Rothschild & Bloch, 2012), thereby higher-order complexity regulates the individual's rhythms, a seed for collective behaviors from insects to humans.

Early chronobiology work reporting time distortions during full isolation

Pioneering studies interested in factors affecting chronobiology were conducted in the 1960's, at a time when physiological factors such as body temperature and arousal were deemed primitives of time estimation. In the developing field of chronobiology, questions regarding the emergence of circadian rhythms motivated the studies of animals and humans under ecological and social conditions that largely differed from their ecological settings. Experiments with human volunteers under free-running schedule (or in "timelessness") isolated individuals from any Zeitgebers in caves or in bunkers. Sometimes, experiments focused on the possible link between biological clocks that regulate the physiology of the body, timing behaviors (such as spontaneous tempo or reaction times) and time perception itself (estimation of a lapse of time).

Vernon and McGill (Vernon & McGill, 1963) conducted two isolation experiments in which they held participants in a dark room from 8 to 96 hours. In the first experiment, a group of participants was asked what day and what time it was before they were released. On average, participants underestimated their confinement time. The authors listed the temporal cues that participants used for their estimation, and a majority of them were food related (eating, hunger) and beard growth (males). In the second experiment, all participants were confined for 96 hours, and they were asked to individually report when one hour had passed. Unfortunately, the report provides data as cumulative time errors without correcting for the fact that participants' changes in sleep patterns (likely misestimated by participants) also contributed to mis-estimations of elapsed time (see (Aschoff, 1992) and below). Such confounds are detrimental for a clear interpretation of the link between chronobiology and time perception.

Around the same time, Michel Siffre, a French speleologist, pioneered the scientific investigation of the effect of confinement in total isolation: in 1962, he isolated himself 58 days, 70 meters underground in the Scaraffon glacier (Italy). In 1972, he repeated this experiment for 205 days (nearly 7 months!) in Deal Rio (Texas, USA). His physiological (ECG, urine), neurophysiological (electroencephalography (EEG)) and behavioral changes were assessed by the NASA. In the total absence of Zeitgebers, Siffre's biological rhythms adjusted to a circabidian or 48 hours cycle instead of a circadian one. These results controversially suggested the existence of individual endogenous rhythms that may differ from the typical circadian ones.

In 1966, Siffre placed a young man for 174 days in a cave (Fraisse, 1973) and tested his spontaneous tempo and reaction times (Oléron et al., 1970). The recordings showed two main effects of isolation on the temporal production measurements: First, during the entire isolation period, the individual's spontaneous tempo accelerated over time whereas his reaction times decelerated over time. The authors interpreted these effects as demonstrating a decrease of vigilance over time akin to a "release from inhibition". The second major observation was that the two measurements showed intra-circadian fluctuations: specifically, during the subjective mid-day, the spontaneous tempo was slowest and the reaction times fastest, whereas at wake time and before sleep time, the spontaneous tempo was fastest and reaction times slowest.

Following these original scientific expeditions, Chouvet and colleagues (Chouvet et al., 1974) tested three more participants in similar cave conditions for 6 months: two were tested according to a free-running schedule, and one was tested using a relative 48 hours controlled schedule. One major question was whether a spontaneous 48 hours cycle would develop (and maintain) in the absence of Zeitgebers. The authors reported a circabidian rhythm, and with it, a lack of proportionality between wake and sleep times. The authors noted that their results differed from the work of Aschoff and colleagues (Aschoff et al., 1967), which argued for the preservation of the circadian rhythm in the absence of external cues although a lengthening of the cycles can be seen on the reported graphs (Aschoff et al., 1967). Chouvet and colleagues (Chouvet et al., 1974) suggested that a major factor may be the temperature during isolation, as core body temperature holds a long albeit partial explanatory function in time estimation research.

Body temperature

François (1927) reported that diurnal changes in body temperature were accompanied by changes of time perception. Following this work, Hoagland constructed the chemical clock hypothesis according to which the body temperature would predict the passage of time felt by individuals. Famously testing his own feverish wife on her perception of time passing, Hoagland replicated the original observation of François in that the higher his wife's bodily temperature was, the faster her counting of time was (Wearden, 2005): one minute of clock time was about 2 minutes of his wife's perceived time. According to the chemical clock hypothesis, an increased arousal and body temperature would result in an increased cellular metabolic rate, which would speed up the internal clock. Subsequent experiments replicated the effect of body temperature on time perception (Fox et al., 1967; Kuriyama et al., 2003, 2005; Pande et al., 2014; Pexirra, n.d.; van Maanen et al., 2019) but the reported relation between body temperature and time perception did not follow the Arrhenius equation strongly suggesting that a direct thermodynamics account of time perception was unsupported. Additionally, large inter-individual differences were observed despite comparable body temperatures and the effect of temperature affected only fast time scales, not the longer time scales at which orientation to time evolves (Aschoff, 1998). More recent work showed that the performance of individuals tested on three tasks (motor tapping, duration reproduction and duration discrimination) within a day was stable despite endogenous fluctuations in body temperature(Mioni et al., 2016). Hence, while core body temperature appears to affect time perception, the exact nature of this relation remains uncertain and could be parsimoniously accounted for by domain-general modulations of cognitive functions (e.g. decision-making (Monteiro et al., 2021)) affected by homeostatic instabilities.

Temporal disorientations in isolation studies

Independently of the chronobiology research program, the first empirical study of temporal disorientation was realized by Macleod and Roff (Macleod & Roff, 1936) who gravitated away from the folk psychology notion of "time sense". Instead, they wished to assess the problem as follows: *"Rather than postulate a mysterious "time sense" the experimental scientist has chosen to assume that orientation in time is a mediate process, resting upon inferences (possibly unconscious in character) from non-temporal sense-data."* To test their working hypothesis, they isolated two individuals, one for 48 hours, the other for 86 hours in a soundproof booth and on a free-running schedule. One participant was asked to indicate every time 30 minutes or 1 hour had passed; the other participant was prompted at irregular intervals to provide his time estimation. No other time cues were accessible to the participants. The report provides insights on the participants' experienced awareness of temporal distortions, which interestingly echoed Siffre's own personal diary. For instance, "*11:30 a.m. – I am just as much at a loss about the time as I ever was. When I got up I hardly knew what time to report, but when I considered the matter I concluded that ordinarily after a good night's sleep like that I would be likely to wake up first at 7:00 a.m., and then if I turned over and slept far quite a while I probably would wake up again about 8:30. Since that hour would do as well as any other I reported it to you."*

There are several observations, which are quite remarkable in these early reports. The *first* is that there was a general trend towards the underestimation of elapsed time, consistent with the subsequent bulk of studies on time in isolation. The *second* observation was that the participant irregularly prompted to report elapsed time showed no major disturbances of time estimation compared with the participant who self-initiated his time estimates. A *third* observation was that general orientation to time was a more reliable measure than duration estimation. According to the reported data, the pattern of results obtained by the participants regularly providing their duration estimates seemed consistent with the later reports of Thor & Crawford (Crawford & Thor, 1964, 1967) in that morning durations tended to be underestimated. Morning estimations were also consistent with the positive temporal errors reported in MacLeod and Roff (Macleod & Roff, 1936), which indicated that the individual tended to think that it was later than the actual clock time in the morning hours. To the contrary, in the evening, durations were overestimated (Crawford & Thor, 1964, 1967) and individuals in (Macleod & Roff, 1936) reported that it was earlier than the actual clock time.

The study of Thor & Crawford (Crawford & Thor, 1964) confined a group of 30 adults and children in a simulated fallout shelter for 304.6 hours. Participants had no beds, no bathing water, no coffee and no change clothing. They were provided with a restrictive 912 calories a day and drinking water. The light was turned on when more than half of the group awakened, and turned off when the group retired for the night. They reported that morning hours tended to be estimated as being earlier than they actually were, and that evening hours tended to be estimated later than they actually were. However, a major confounding factor in this experiment was that participants' time estimations were regularly checked twice a day at 9 am and 9 pm (+/- 1 hour), effectively pacing the experimental design over the twelve days period and providing participants with regular (even if implicit) Zeitgebers. A similar observation was found in a more recent case study (Bonmati-Carrion et al., 2020), in which a participant isolated in a bunker for 10 days was prompted to report what time of day it was in the course of the study. The authors reported a systematic delay in the participant's reported clock time as compared to actual clock time: the difference was most pronounced during a constant dim light protocol (up to 5 hours of differences) and least pronounced under a circadian schedule with early wake time (less than 1 hour). The difference between clock time and estimated time was also more pronounced late in the circadian days as compared to early mornings. The authors suggested that this time estimation pattern was dependent on the midpoint sleep duration, which is a marker of individuals' chronotype i.e. endogenous circadian clock properties (Roenneberg, 2012; Roenneberg et al., 2003).

Observations converge on the interpretation that in free-running schedule, and in the absence of Zeitgebers, an intradiurnal effect of duration estimation and passage of time can be found during isolation so that time in the morning may be felt to pass faster than in the evening. Yet, while more recent work imposing a free-running schedule in isolation (Pöppel & Giedke, 1970) or a 30 hours schedule (Kuriyama et al., 2003, 2005; Pande et al., 2014) confirmed diurnal variations in participants' duration estimations, the pattern of temporal productions do not fully fit a unitary description of time distortions. In these studies, temporal reproductions in the circadian mornings were longer than temporal reproductions in the circadian afternoons and evenings, observing linear (Kuriyama et al., 2003, 2005) or non-linear patterns (Pande et al., 2014; Pöppel & Giedke, 1970).

In a series of experiments dedicated to the study of diurnal variations of time perception (Pöppel & Giedke, 1970), Pöppel & Giedke trained participants outside a bunker to produce a 10 seconds interval through motor action. The training of participants stopped after a set criterion and participants were subsequently tested during a free-running isolation protocol that lasted several weeks. Among the different tasks, one asked participants to produce the learned 10s interval about 6 to 8 times a day. As a side observation (Pöppel, 1971), the authors reported that each participant slowly drifted away from the set point while in the bunker and in the total absence of Zeitgebers. Most importantly, each individual displayed a different drift so that while two participants produced durations much longer than 10 seconds, the others produced shorter estimates. This observation strongly favored the hypothesis of a coordinate system for time that is individually defined (Gallistel, 1990; Pöppel, 1971), echoing early observations in chronobiology and crucially emphasizing the need to take an individual perspective to timing.

Early on, Macleod and Roff (Macleod & Roff, 1936) formulated very modern theoretical parallels between one's orientation in space and time, and discussed how duration estimation may be a subordinate function of a temporal orientation system. This point is particularly relevant with respect to current considerations on how the brain may map time building on the computational machinery and neural systems dedicated to mapping space (Buzsáki & Moser, 2013; Gallistel, 1990; Issa et al., 2020; MacDonald, 2014). The authors otherwise legitimately and critically assessed the major limitations of their initial work with the nascent discussions, at their times, on the physiological bases of an internal clock and the developing field of chronobiology.

Siffre (Siffre, 1963) too had largely underestimated the time he spent isolated underground. He underestimated the 58 days isolated on a free-running schedule and thought he had spent 33 days as if 25 days had gone unregistered. However, the major reason accounting for this gross underestimation was that his sleep-wake cycle elongated to a 48 hours rhythm. In a subsequent experiment testing Mairetet, who was aware of such phenomenon, the researchers agreed to dissociate night sleep from nap sleep, and asked Mairetet to count "sleep-wakefulness cycles" as opposed to days. Due to the development of a circabidian rhythm and the lengthening of his naps, which Mairetet himself did not seem to be aware of, the count also resulted in a gross underestimation of his stay underground: 86 days when he effectively spent 174 days in isolation. Fraisse (Fraisse, 1973) further described the duration estimates that were provided by Mairetet for hours and minutes long durations. For the hours-long durations, Mairetet estimated the time elapsing between temporal landmarks such as waking time and lunch time, or between nap time and diner: there again, they reported a nearly 50% underestimation of clock durations. The puzzled experimenters reasoned that Mairetet provided duration estimates based on his typical routines outside the cave as opposed to keeping track of time *per se*. In other words, reports may have been made inferential.

For the estimation of shorter durations, three types of tests were used: a verbal estimation of elapsed time between two auditory clicks played over the phone, a temporal reproduction of that same click-to-click duration by pressing on a button for the same amount of time, and a temporal production task in which Mairetet was provided with a verbal duration, which he had to produce by pressing on a button. Fraisse (Fraisse, 1973) reports the ratio of the verbal or motor production over the provided clock time: while the estimation task revealed a nearly perfect score, the production and reproduction tasks systematically lengthened in the course of isolation going from a roughly good performance to a 2.5 fold overestimation. Fraisse (Fraisse, 1973) does not provide a clear interpretation of these results, beyond concluding that Mairetet did experience temporal distortions that cannot be accounted for by mere learning, vigilance or arousal effects. In agreement with these, a series of experiments concluded that neither the sleep-wake cycle, nor the circadian rhythms of body temperature can fully account for the changes observed in time estimations tested in bunkers in full or partial isolations and in total darkness (Pöppel & Giedke, 1970).

Time perception *vs.* cognition?

Isolation in controlled laboratory conditions and over short periods of time have been performed by modulating the severity of a participant's sensory deprivation. Sensory deprivation differs from bodily inactivity in that the arousal system, under an increased degree of isolation (as controlled by the amount of delivered stimulation) increases participants' stress and arousal (Leiderman, 1962; Zuckerman et al., 1964). Schwartz (Schwartz, 1967) used the "Iron maiden", a water-immersion g-capsule, to deprive participants sensorily for up to 3 hours. While recorded physiological parameters such as heart-rate and skin temperatures showed visible changes in his experiments, no robust changes in time estimations were found as a function of sensory deprivation. The author concluded that short experimental isolations were insufficient to affect timing in a way that is effective in full isolation in caves or bunkers. Still, in total isolation and in sensory deprivation studies, a great majority of participants systematically report experiencing "temporal disorientations". This phenomenon is not solely attributable to perceptual distortions of elapsed time but possibly fed by cognitive distortions of time perspective.

The setting up of temporal orientation requires that an individual be aware of distinct temporalities (in Westerners referred to as past, present, and future) and of their associated chronology (ordinal sequencing of past to present to future). Time perspective builds on the notion that time is personal and subjective (Kastenbaum, 1966) and modern psychology embraced the notion of an individual's belief system about his past, present, and future and their interrelations (Rokeach, 1960). In its initial inception, an individual could display a narrow focus on past, present or future independently of their interconnections and alternatively, the interconnections may prevail to the detriment of one's temporal positioning. Given the importance of assessing future perspectival, Lewin

(Lewin, 1951) coined the term “time perspective” as “*the totality of the individual’s views of his psychological future and his psychological past existing at a given time”*.

Interestingly, it is also at the same historical period that the notion of (temporal) cognitive map was put forward (Tolman, 1935, 1948). Indeed, the ability to map time is central to daily decision-making and future planning while being subjected to various cognitive biases (Sanna & Schwarz, 2004) such as the planning fallacy or the tendency to underestimate the time necessary to finish a task (Kahneman & Tversky, 1977). In extreme cases of confinement, inmates’ emotional states are influenced by their future temporal horizon: men with an indefinite time sentence overall suffer more than those with timed sentences yet inmates with two years sentences suffered more than those with sentences longer than 5 years (Farber et al., 1944). In short, one’s lived past and experienced present shape one’s well-being, but so do the ability to build future possibilities.

Lockdowns, isolation and the covid pandemic

In recent years, the spread of Covid-19 have forced exceptional worldwide sanitary measures to limit the spread of viral infection: lockdowns became the rule for weeks at a time. Physical and social distancing imposed new rhythms to the world population. As the length and severity of the pandemic could not be anticipated, citizens were also unprepared for the future months to come. Many reported feeling disorientated in time with days seemingly melting into one another, a phenomenon popularly referred to as “blursday”. These phenomenological reports converge with some of the empirical work reviewed above that report temporal disorientations in different kinds of isolation protocols in humans. However, and as summarized above, our current knowledge on the effects of isolation on human psychology and (neuro)physiology is quite scarce and largely insufficient to provide clear-cut causal explanations for the temporal distortions reported in the kind of partial isolation we lived through in these historical times.

The precise understanding of factors affecting individuals’ awareness of time has been ongoing in concerted international efforts (Chaumon et al., 2021; Cravo et al., 2021; Droit-Volet et al., 2020; Grondin et al., 2020; Loose et al., 2021; Martinelli et al., 2020; R. Ogden, 2021; R. S. Ogden, 2020) suggesting that lockdowns too induced temporal distortions and disorientations. Reports during the pandemic went from self-reported difficulties with keeping track of the time of day and of the days themselves to quantitative descriptions of subjective duration expanding and time slowing down (Cellini et al., 2020; Cravo et al., 2021; Droit-Volet et al., 2020, 2021; Loose et al., 2021; Martinelli et al., 2020; Ogden, 2021; Ogden, 2020). All surveys confirmed self-reported temporal distortions during lockdowns but did not necessarily converge on their underlying explanatory causes. Changes in felt passage of time during the pandemic appeared to be dependent on how lonely participants felt and no as much on the objective stringency index undergone by participants: the more isolated one felt, the slower time seemed to pass (Chaumon et al., 2021). This rating and phenomenological measurement of felt time during the pandemic converged with more cognitive measures of temporal distance assessing how far in past or future particular life events seem to be: individuals who felt isolated evaluated events to be further away in both their past and future orientations (Chaumon et al., 2021).

Conclusions

In lab settings, we design experiments to control for, and separate, confounding factors to single out variable of interests. In this process, we reduce the problem to its basic constituents: the scientific method identifies which variables are necessary and sufficient to replicate a behavioral, perceptual or cognitive effect. Factors affecting a single behavior can be exogenous (stimuli) and arguably easiest to control for in an experiment. Others are endogenous, sometimes oblivious to the participants' own awareness ("unconscious", "implicit") or not easily intelligible to consciousness ("qualia"): these constitute the hard problem of cognition to which psychological time and temporal cognition belong.

Empirical work on the impact of isolation (broadly construed) on subjective temporalities is scarce, but temporal disorientations often evidenced with the deprivation of temporal cues clearly reducing one's ability to orient in time. The study of time in biology is integrative: chronobiology focuses on automatic physiological responses of the body; time perception mostly focuses on the lived present, whether implicit (in the form of temporal expectations (Nobre & Van Ede, 2018)) or intelligible to consciousness (as magnitude estimation or decision-making); memory research focuses on mapping the temporal relations between events stored for future use. Whether this compartmentalization should be regarded as theoretically grounded and operant for understanding temporal cognition and its biological implementation remains largely unexplored even if alluded to (Laje et al., 2018; Tucci et al., 2014).

That sharing meaningful information through a symbolic system (from bees to humans) can affect chronobiology and the coding of events in a temporal cognitive map highlights the remarkable importance of a top-down approach to temporal cognition. For us humans, sharing future plans using clocks, calendars and agendas (all sophisticated counters and timelines directed towards a quantification of time that is meaningful to the observer) indicate that neither chronobiology nor temporal cognition are fully reducible to the automatisms of well-clocked physical systems. This uniqueness should be a strong driving force for our understanding of minds and behaviors in biological systems.

Acknowledgments: V.vW. received funding from La Diagonale Paris-Saclay and AAP Arts-Sciences-Technologies "Expérimentation 2020" for the project ÆON and EXPERIENCE project of the European Commission H2020 Framework Program, Grant No. 101017727.

References

Arzy, S., Bick, A., & Blanke, O. (2009). Mental time in amnesia: Evidence from bilateral medial temporal damage before and after recovery. *Cognitive Neuropsychology*, *26*(6), 503–510. https://doi.org/10.1080/02643290903439178

Aschoff, J. (1965). Circadian rhythms in man. *Science*, *148*(3676), 1427–1432.

Aschoff, J. (1992). Estimates on the duration of sleep and wakefulness made in isolation. *Chronobiology International*, *9*(1), 1–10.

Aschoff, J. (1998). Human perception of short and long time intervals: Its correlation with body temperature and the duration of wake time. *Journal of Biological Rhythms*, *13*(5), 437–442.

Aschoff, J., Fatranska, M., Giedke, H., Doerr, P., Stamm, D., & Wisser, H. (1971). Human circadian rhythms in continuous darkness: Entrainment by social cues. *Science*, *171*(3967), 213–215.

Aschoff, J., GERECKE, U., & Wever, R. (1967). Desynchronization of human circadian rhythms. *The Japanese Journal of Physiology*, *17*(4), 450–457.

Barack, D. L., & Krakauer, J. W. (2021). Two views on the cognitive brain. *Nature Reviews Neuroscience*, *22*(6), 359–371.

Bloch, G. (2010). The Social Clock of the Honeybee. *Journal of Biological Rhythms*, *25*(5), 307–317. https://doi.org/10.1177/0748730410380149

Bonmati-Carrion, M.-A., Revell, V. L., Cook, T. J., Welch, T. R., Rol, M.-A., Skene, D. J., & Madrid, J. A. (2020). Living Without Temporal Cues: A Case Study. *Frontiers in Physiology*, *11*, 11.

Buonomano, D. (2017). *Your brain is a time machine: The neuroscience and physics of time*. WW Norton & Company.

Buzsáki, G. (2006). *Rhythms of the brain*. Oxford University Press.

Buzsaki, G. (2019). *The Brain from Inside Out*. Oxford University Press, USA.

Buzsáki, G., & Moser, E. I. (2013). Memory, navigation and theta rhythm in the hippocampal-entorhinal system. *Nature Neuroscience*, *16*(2), 130–138. https://doi.org/10.1038/nn.3304

Cellini, N., Canale, N., Mioni, G., & Costa, S. (2020). Changes in sleep pattern, sense of time and digital media use during COVID-19 lockdown in Italy. *Journal of Sleep Research*, e13074.

Chaumon, M., Rioux, P.-A., Herbst, S., Spiousas, I., Kübel, S., Hiroyasu, E. G., Runyun, S., Micillo, L., Thanopoulos, V., Mendoza-Durán, E., Wagelmans, A., Mudumba, R., Tachmatzidou, R., Cellini, N., D'Argembeau, A., Giersch, A., Grondin, S., Gronfier, C., Igarzábal, F. A., … Wassenhove, V. van. (2021). *The Blursday Database: Individuals' Temporalities in Covid Times*. https://doi.org/10.21203/rs.3.rs-1098637/v1

Chouvet, G., Mouret, J., Coindet, J., Siffre, M., & Jouvet, M. (1974). Periodicite bicircadienne du cycle veille-sommeil dans des conditions hors du temps. Etude polygraphique. *Electroencephalography and Clinical Neurophysiology*, *37*(4), 367–380.

Cottle, T. J. (1968). The location of experience: A manifest time orientation. *Acta Psychologica*, *28*, 129–149.

Cravo, A. M., de Azevedo, G. B., Azarias, C. M. B., Barne, L. C., Bueno, F. D., de Camargo, R. Y., Morita, V. C., Sirius, E., Recio, R. S., & Silvestrin, M. (2021). *Time experience in social isolation: A longitudinal study during the first months of COVID-19 pandemic in Brazil*.

Crawford, M. L. J., & Thor, D. H. (1964). Circadian activity and noise comparisons of two confined groups with and without reference to clock time. *Perceptual and Motor Skills*, *19*(1), 211–216.

Crawford, M. L. J., & Thor, D. H. (1967). Time perception in children in the absence of external temporal synchronizers. *Acta Psychologica*, *26*, 182–188.

Dafni-Merom, A., Peters-Founshtein, G., Kahana-Merhavi, S., & Arzy, S. (2019). A unified brain system of orientation and its disruption in Alzheimer's disease. *Annals of Clinical and Translational Neurology*, *6*(12), 2468–2478.

Droit-Volet, S., Gil, S., Martinelli, N., Andant, N., Clinchamps, M., Parreira, L., Rouffiac, K., Dambrun, M., Huguet, P., & Dubuis, B. (2020). Time and Covid-19 stress in the lockdown situation: Time free,«Dying» of boredom and sadness. *PloS One*, *15*(8), e0236465.

Droit-Volet, S., Martinelli, N., Chevalère, J., Belletier, C., Dezecache, G., Gil, S., & Huguet, P. (2021). The persistence of slowed time experience during the COVID-19 pandemic: Two longitudinal studies in France. *Frontiers in Psychology*, *12*.

Dumurgier, J., Dartigues, J.-F., Gabelle, A., Paquet, C., Prevot, M., Hugon, J., & Tzourio, C. (2016). Time Orientation and 10 Years Risk of Dementia in Elderly Adults: The Three-City Study. *Journal of Alzheimer's Disease*, *53*(4), 1411–1418. https://doi.org/10.3233/JAD-160295

Eban-Rothschild, A., & Bloch, G. (2012). Social influences on circadian rhythms and sleep in insects. *Advances in Genetics*, *77*, 1–32.

Farber, M. L., Lewin, K., & Sears, R. R. (1944). *Suffering and time perspective of the prisoner*. University of Iowa Press.

Fox, R. H., Bradbury, P. A., & Hampton, I. F. G. (1967). Time judgment and body temperature. *Journal of Experimental Psychology*, *75*(1), 88–96. https://doi.org/10.1037/h0024888

Fraisse, P. (1973). Temporal isolation, activity rhythms, and time estimation. *Man in Isolation and Confinement*, 85–98.

François, M. (1927). VI. Contribution à l'étude du sens du Temps. La température interne comme facteur de variation de l'appréciation subjective des durées. *L'Année Psychologique*, *28*(1), 186–204.

Friedman, W. J. (1993). Memory for the time of past events. *Psychological Bulletin*, *113*(1), 44.

Gallistel, C. R. (1990). *The organization of learning.* The MIT Press.

Grondin, S., Mendoza-Duran, E., & Rioux, P.-A. (2020). Pandemic, Quarantine, and Psychological Time. *Frontiers in Psychology*, *11*, 581036. https://doi.org/10.3389/fpsyg.2020.581036

Hazlerigg, D. G., & Tyler, N. J. (2019). Activity patterns in mammals: Circadian dominance challenged. *PLoS Biology*, *17*(7), e3000360.

Holman, E. A., & Grisham, E. L. (2020). When time falls apart: The public health implications of distorted time perception in the age of COVID-19. *Psychological Trauma: Theory, Research, Practice, and Policy*, *12*(S1), S63. https://doi.org/10.1037/tra0000756

Issa, J. B., Tocker, G., Hasselmo, M. E., Heys, J. G., & Dombeck, D. A. (2020). Navigating through time: A spatial navigation perspective on how the brain may encode time. *Annual Review of Neuroscience*, *43*.

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review*, *83*(5), 323–355. https://doi.org/doi:10.1037/0033-295X.83.5.323

Kahneman, D., & Tversky, A. (1977). *Intuitive prediction: Biases and corrective procedures*. Decisions and Designs Inc Mclean Va.

Kastenbaum, R. (1966). On the meaning of time in later life. *The Journal of Genetic Psychology*, *109*(1), 9–25.

Krakauer, J. W., Ghazanfar, A. A., Gomez-Marin, A., MacIver, M. A., & Poeppel, D. (2017). Neuroscience needs behavior: Correcting a reductionist bias. *Neuron*, *93*(3), 480–490.

Kuriyama, K., Uchiyama, M., Suzuki, H., Tagaya, H., Ozaki, A., Aritake, S., Kamei, Y., Nishikawa, T., & Takahashi, K. (2003). Circadian fluctuation of time perception in healthy human subjects. *Neuroscience Research*, *46*(1), 23–31.

Kuriyama, K., Uchiyama, M., Suzuki, H., Tagaya, H., Ozaki, A., Aritake, S., Shibui, K., Xin, T., Lan, L., & Kamei, Y. (2005). Diurnal fluctuation of time perception under 30-h sustained wakefulness. *Neuroscience Research*, *53*(2), 123–128.

Laje, R., Agostino, P. V., & Golombek, D. A. (2018). The times of our lives: Interaction among different biological periodicities. *Frontiers in Integrative Neuroscience*, *12*, 10.

Leiderman, P. H. (1962). *Imagery and sensory deprivation, an experimental study*. HARVARD MEDICAL SCHOOL BOSTON MASS.

Lewin, K. (1951). *Intention, will and need.*

Loose, T., Wittmann, M., & Vásquez-Echeverría, A. (2021). Disrupting times in the wake of the pandemic: Dispositional time attitudes, time perception and temporal focus. *Time & Society*, 0961463X211027420.

MacDonald, C. J. (2014). Prospective and retrospective duration memory in the hippocampus: Is time in the foreground or background? *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1637), 20120463.

Macleod, R. B., & Roff, M. F. (1936). An experiment in temporal disorientation. *Acta Psychologica*, *1*, 381–423.

Martinelli, N., Gil, S., Belletier, C., Chevalère, J., Dezecache, G., Huguet, P., & Droit-Volet, S. (2020). Time and Emotion in the lockdown for the Covid-19 epidemic: The determinants of our experience of time? *Frontiers in Psychology*, *11*, 3738.

Mengin, A., Allé, M. C., Rolling, J., Ligier, F., Schroder, C., Lalanne, L., Berna, F., Jardri, R., Vaiva, G., Geoffroy, P. A., Brunault, P., Thibaut, F., Chevance, A., & Giersch, A. (2020). [Psychopathological consequences of confinement]. *L'Encephale*, *46*(3S), S43–S52. https://doi.org/10.1016/j.encep.2020.04.007

Michon, J. A. (1990). Implicit and explicit representations of time. *Cognitive Models of Psychological Time*, 37–58.

Mioni, G., Labonté, K., Cellini, N., & Grondin, S. (2016). Relationship between daily fluctuations of body temperature and the processing of sub-second intervals. *Physiology & Behavior*, *164*, 220–226.

Monteiro, T., Rodrigues, F. S., Pexirra, M., Cruz, B. F., Gonçalves, A. I., Rueda-Orozco, P. E., & Paton, J. J. (2021). *Using temperature to analyse the neural basis of a latent temporal decision* (p. 2020.08.24.251827). https://doi.org/10.1101/2020.08.24.251827

Nobre, A. C., & Van Ede, F. (2018). Anticipated moments: Temporal structure in attention. *Nature Reviews Neuroscience*, *19*(1), 34.

Ogden, R. (2021). Distortions to the passage of time during England's second national lockdown: A role for depression. *Plos One*, *16*(4), e0250412.

Ogden, R. S. (2020). The passage of time during the UK Covid-19 lockdown. *Plos One*, *15*(7), e0235871.

Oléron, G., Fraisse, P., Siffre, M., & Zuili, N. (1970). Les variations circadiennes du temps de réaction et du tempo spontané au cours d'une expérience «hors du temps». *L'année Psychologique*, *70*(2), 347–356.

Pande, B., Parganiha, A., Patra, P. K., & Pati, A. K. (2014). *Short-duration judgment in young Indian subjects under 30 h constant wakefulness*.

Pexirra, M. (n.d.). *Manipulation of striatal population dynamics using temperature warps judgment of time*. 61.

Pöppel, E. (1971). Oscillations as possible basis for time perception. *Stud Gen (Berl)*, *24*(1), 85–107.

Pöppel, E. (1972). Oscillations as possible basis for time perception. In *The study of time* (pp. 219–241). Springer.

Pöppel, E., & Giedke, H. (1970). Diurnal variation of time perception. *Psychologische Forschung*, *34*(2), 182–198.

Raby, C. R., Alexis, D. M., Dickinson, A., & Clayton, N. S. (2007). Planning for the future by western scrub-jays. *Nature*, *445*(7130), 919–921.

Richards, W. (1973). Time reproductions by HM. *Acta Psychologica*, *37*(4), 279–282.

Roenneberg, T. (2012). What is chronotype? *Sleep and Biological Rhythms*, *10*(2), 75–76.

Roenneberg, T., Wirz-Justice, A., & Merrow, M. (2003). Life between clocks: Daily temporal patterns of human chronotypes. *Journal of Biological Rhythms*, *18*(1), 80–90.

Rokeach, M. (1960). *The open and closed mind: Investigations into the nature of belief systems and personality systems.*

Sanna, L. J., & Schwarz, N. (2004). Integrating temporal biases: The interplay of focal thoughts and accessibility experiences. *Psychological Science*, *15*(7), 474–481.

Schwartz, B. K. (1967). *An Investigation of the Effects of Isolation on Time Perception and Its Physiological Correlates*. US Naval Air Development Center.

Siffre, M. (1963). *Hors du temps: L'expérience du 16 juillet 1962 au fond du gouffre de Scarasson par celui qui l'a vécue*. FeniXX.

Spreng, R. N., Dimas, E., Mwilambwe-Tshilobo, L., Dagher, A., Koellinger, P., Nave, G., Ong, A., Kernbach, J. M., Wiecki, T. V., Ge, T., Li, Y., Holmes, A. J., Yeo, B. T. T., Turner, G. R., Dunbar, R. I. M., & Bzdok, D. (2020). The default network of the human brain is associated with perceived social isolation. *Nature Communications*, *11*(1), 6393. https://doi.org/10.1038/s41467-020-20039-w

Tolman, E. C. (1935). Psychology versus immediate experience. *Philosophy of Science*, *2*(3), 356–380.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, *55*(4), 189–208. https://doi.org/10.1037/h0061626

Tucci, V., Buhusi, C. V., Gallistel, R., & Meck, W. H. (2014). Towards an integrated understanding of the biology of timing. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1637), 20120470. https://doi.org/10.1098/rstb.2012.0470

Tulving, E. (1985). *Elements of episodic memory*.

Twenge, J. M., Catanese, K. R., & Baumeister, R. F. (2003). Social exclusion and the deconstructed state: Time perception, meaninglessness, lethargy, lack of emotion, and self-awareness. *Journal of Personality and Social Psychology*, 409–423.

van Maanen, L., van der Mijn, R., van Beurden, M. H. P. H., Roijendijk, L. M. M., Kingma, B. R. M., Miletić, S., & van Rijn, H. (2019). Core body temperature speeds up temporal processing and choice behavior under deadlines. *Scientific Reports*, *9*(1), 10053. https://doi.org/10.1038/s41598-019-46073-3

van Wassenhove, V. (2016). Temporal cognition and neural oscillations. *Current Opinion in Behavioral Sciences*, *8*, 124–130.

Varela, F. J. (1999). Present-time consciousness. In F. K. Varela & J. Shear (Eds.), *The view from within: Dirst-person approaches to the study of consciousness*. Imprint Academic.

Vernon, J. A., & McGill, T. E. (1963). Time estimations during sensory deprivation. *The Journal of General Psychology*, *69*(1), 11–18.

Wearden, J. H. (2005). Origins and development of internal clock theories of time. *Psychologie Française*. http://www.academia.edu/download/45315873/Origins_and_development_of_internal_cloc20160503-53089-wxfqr0.pdf

Webb, A. B., Angelo, N., Huettner, J. E., & Herzog, E. D. (2009). Intrinsic, nondeterministic circadian rhythm generation in identified mammalian neurons. *Proceedings of the National Academy of Sciences*, *106*(38), 16493–16498. https://doi.org/10.1073/pnas.0902768106

Wilson, B. A., & Wearing, D. (1995). Prisoner of consciousness: A state of just awakening following herpes simplex encephalitis. In *Broken memories: Case studies in memory impairment* (pp. 14–30). Blackwell Publishing.

Wood, R. T., Griffiths, M. D., & Parke, A. (2007). Experiences of time loss among videogame players: An empirical study. *Cyberpsychology & Behavior*, *10*(1), 38–44.

Yamada, Y., Ćepulić, D.-B., Coll-Martín, T., Debove, S., Gautreau, G., Han, H., Rasmussen, J., Tran, T., Travaglino, G. A., & Lieberoth, A. (2020). *COVIDiSTRESS Global Survey dataset on psychological and behavioural consequences of the COVID-19 outbreak*.

Zimbardo, P. G. (1990). *The Stanford time perspective inventory*. Stanford, CA: Stanford University.

Zuckerman, M., Levine, S., & Biase, V. D. (1964). Stress response in total and partial perceptual isolation. *Psychosomatic Medicine*, *26*(3), 250–260.