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ON THE PASSAGE OF SUBJECTIVE TIME IN TEMPORAL ISOLATION

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Data were collected in 48 experiments from subjects who lived singly in an underground isolation unit without any temporal cues. By recording the sleep-wake cycle and rectal temperature, two states of the circadian system could be distinguished: internal synchronization with equal periods for the sleep-wake cycle and the rhythm of temperature (n = 33), and internal desynchronization either by a lengthening of the sleep-wake cycle to more than 28 h (n = 12) or by a shortening to less than 22 h (n = 3). Due to desynchronization, the duration of wake time varied within the limits from about 10 to more than 30 h. The subjects were asked to press a button whenever they thought that one hour had passed. The intervals produced in this manner were longer than 1 h, and varied in strong proportionality to the duration of wake time. This relationship held intraindividually as well as between subjects. It is concluded that the passage of subjective time is closely coupled to the sleep-wake cycle.

The passage of subjective time has mainly been studied by experiments in which subjects were asked to estimate short time intervals in the range of seconds (for surveys of the literature cf. Pöppel, 1971; Zakay, 1989). In contrast, only a few studies deal with the perception of time intervals in the range of hours (Aschoff, 1985a) and days (Wulfften-Palte, 1968), or with the estimation of the time of day in isolation (cf. Table 1 in Campbell, 1990). The perception of such long stretches of time has been shown to be closely coupled to the sleep-wake cycle which in itself is part of a clock-like biological periodicity, the circadian system (Aschoff, 1989). The analysis of this system, and the search for its control mechanisms, has a long history (Aschoff, 1990a). One of the earliest allusions that the sleep-wake cycle may not be controlled by external cues only but could be due to an endogenous property of the organism, has been published at Brussels in 1806: "Le phénomène périodique le plus remarquable parmi les fonctions physiologiques, et qui coïncide le mieux avec la succession du jour et de la nuit, c'est le retour alternatif du sommeil et de la veille;

cette fonction n'appartient pas aux phénomènes du périodisme physique, mais elle s'en rapproche, si la cause qui la fait naître ne réside point en nous" (Murat, 1806). This was written 8 years prior to Virey (1814) who, in discussing the rhythmic functions of the organism as "une périodicité habituelle et comme innée", coined the term "l'horloge vivante". As will be shown below, it is the speed of this "living clock" which determines the passage of subjective time.

METHODS

All experiments were carried out in two underground units, especially designed for long lasting isolation studies (Wever, 1979). Each unit consisted of a bed-sitting room, a kitchen, and a toilet with shower. The subjects stayed singly in either unit for time spans of at least 7 days up to more than a month. They had no information on time of day, had to prepare their own meals, and were allowed to turn the lights in the unit on and off as desired or were exposed to continuous illumination; in three experiments, the sleep-wake cycles were entrained to 24 h by externally controlled light-dark cycles complemented by acoustical signals. Body temperature was recorded continuously by means of a rectal probe. By pressing a button, the subjects indicated when they took a meal. The duration of wake time (α) and of sleep (ρ) was derived from signals given by the subjects when waking up and when going to sleep (turning on or off their bedside reading lamp).

Altogether 42 subjects were studied, six of whom participated in the experiments twice. With the exception of the three experiments with controlled light-dark cycles, all subjects developed free-running circadian rhythms. In 30 experiments, the rhythms remained internally synchronized, i.e. the sleep-wake cycle and the rhythm of body temperature kept the same period τ with an overall mean of $25.0 \,^{+}/_{-}\, 0.95$ h. In 12 experiments, the sleep-wake cycle (SW) was lengthened to more than 28 h (mean $\tau_{SW} = 29.64 \,^{+}/_{-}\, 1.97$ h) while the rhythm of temperature continued to free-run with a period close to 25 h; such a state of the circadian system has been designated as "long internal desynchronisation" (Aschoff & Wever, 1976). In three experiments, the sleep-wake cycle was shortened to less than 22 h (mean $\tau_{SW} = 21.04 \,^{+}/_{-}\, 0.71$ h), resulting in a state of "short internal desynchronisation".

For testing the passage of subjective time, the subjects were asked to press a button whenever they thought that one hour had passed;

this task had to be performed every "day" from wake-up to bedtime throughout the entire experiment. The total amount of "1-h" intervals produced in this manner comes close to 10.000. In analyzing the data, the possibility had to be taken into account that occasionally a subject could forget to press the button. Such "missing" estimates should result in intervals of about double length. To test this hypothesis, frequency histograms of all estimates were made for each subject. In most cases, these histograms were unimodal, with a narrow distribution of data around the individual mean in internally synchronized rhythms, and a somewhat larger distribution in desynchronized rhythms. Only in a few subjects with long desynchronized rhythms, a secondary peak appeared in the histogram at twice the individual mean interval, indicating "missing" estimates. Such data were excluded from the analysis.

RESULTS

To give an idea of the patterns of free-running circadian rhythms, the data from three subjects are presented in Figure 1. Consecutive days are plotted beneath each other, and the 24-h scale at the abscissa is repeated several times to render possible a continuous plot. In each of the three diagrams, the five lines connect, from left to right, the times of wake-up, of the three meals, and of bedtime. The data from subject No.228 (A) represent the state of internal synchronization, with a mean τ of 24.8 h. Subject No.112 (B) remained internally synchronized for the first six cycles (with a rather short τ of only 24.0 h), was internally short desynchronized for the following 10 cycles (τ_{SW} = 17.6 h), and regained internal synchronization for the rest of the experiment. Subject No.111 (C) began internally synchronized with a τ of 25.1 h, and changed after 8 cycles into long internal desynchronization (τ_{SW} = 34.1 h). From these diagrams it is evident that the subjects adhered to a sequence of three meals per "day", irrespective of for how long they had been awake. Instead of increasing the number of meals, as one could expect, on unusually long "days" (C) or of omitting a meal on short "days" (B), they stretched or compressed the intervals between meals. A detailed analysis reveals that the intervals between meals, as well as the intervals from wake-up to breakfast and from dinner to bedtime, were proportional to the duration of wake time. This relationship is valid for internally synchronized as well as for short and long desynchronized rhythms, and it holds intra- as well as interindividually (cf. Figures 4, 5 and 7 in Aschoff, von Goetz, Wildgruber, & Wever, 1986).

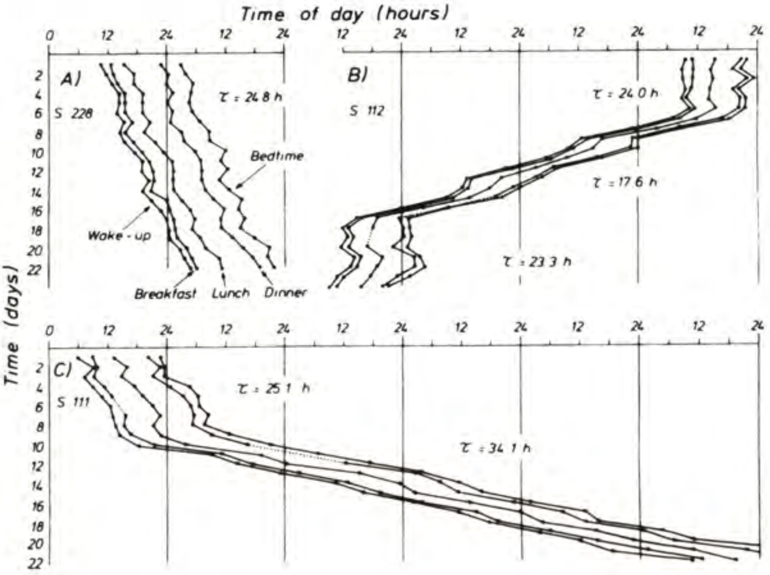

Figure 1. Circadian rhythms of three subjects who lived singly in an isolation unit under conditions of self-selected light-dark cycles (A, female) or of constant illumination (B, female; C, male). Lines connect the times of wake-up, of the three main meals, and of bedtime as recorded on consecutive days. The three records represent internal synchronization (A), short desynchronization (B), and long desynchronization (C). The rhythms of rectal temperature (not shown) had a mean period of 24.8 h (A), 24.0 h (B), and 24.2 h (C). τ = period of the sleep-wake cycle (from Aschoff et al., 1986).

In Figure 2, the 1-h estimates made by four subjects are plotted for three consecutive cycles before, and for three cycles after the occurrence of long internal desynchronization. The single estimates show a large variability between 0.4 and more than 2.0 h, and the "daily" means (dashed horizontal lines) are all longer than 1 h. There is furthermore a conspicuous increase in the means with the beginning of long internal desynchronization. A closer inspection of such data reveals that the "daily" means of produced intervals are proportional to the duration of wake time α in internally synchronized as well as in long desynchronized rhythms (Figure 3). The three subjects who became internally short desynchronized produced intervals that were, on the average, shorter than those of all other subjects. The overall means of intervals were: 1.20 h during short desynchronization, 1.36 h during entrainment to 24 h, 1.42 h in free-running internally synchronized rhythms, and 1.65 h in the long desynchronized rhythms.

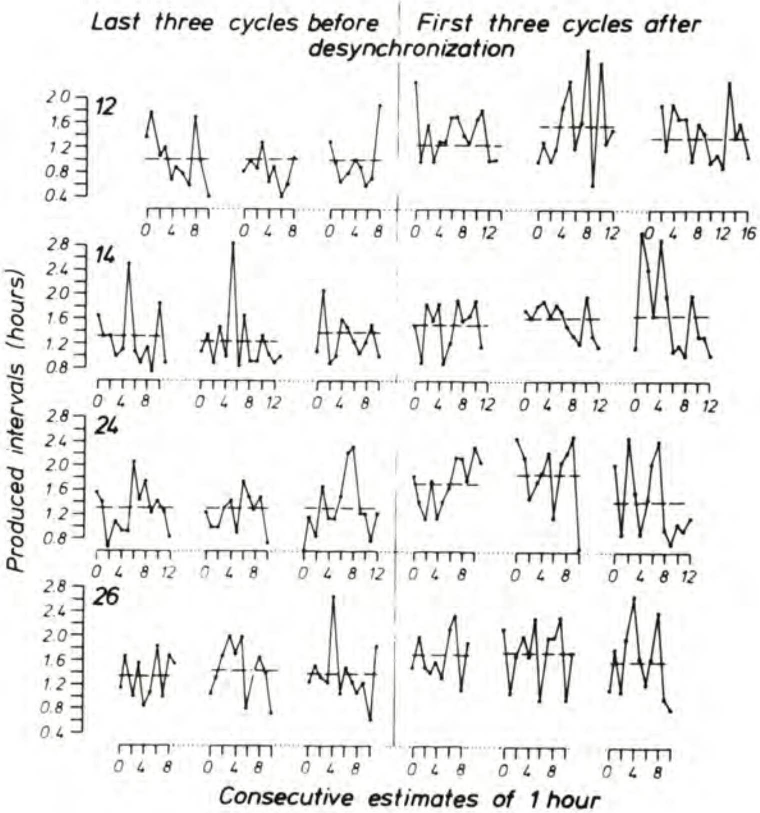

Figure 2. Consecutive productions of 1-h intervals, made by four subjects during the last three cycles before and the first three cycles after the occurrence of long internal desynchronization. Dashed lines: means of produced intervals (from Aschoff, 1985a).

From the result presented in Figure 3 it is evident that a subject experiences about the same number of subjective hours when he or she is awake for only 12 or for as much as 40 h. Hence, it is not surprising that, in temporal isolation, the subjects consider their "days" to be of about equal (normal) length. One might further assume that a subject, when changing from internal synchronization to long desynchronization, just continues to stretch the intervals as the "days" grow longer. The records from three subjects shown on the left side of Figure 4 seem to agree with this hypothesis in general. However, the regression lines indicate that the data fall slightly short of being proportional to α. This deviation disappears, and the coefficients of correlation become larger, if the regressions are computed separately for the data points recorded during internal synchronization, and for those recorded during desynchronization (Figure 4, right side). During both these states of the circadian system, the produced intervals are proportional to α, but the change from internal synchronization to desynchronization results in a shift of the coordinate grid. It seems as if, due to desynchronization, the system has been set at a slightly different level. Consequently, the frequency of estimates within a given α is somewhat higher in desynchronized than in synchronized subjects (cf. Figure 10 in Aschoff, 1987).

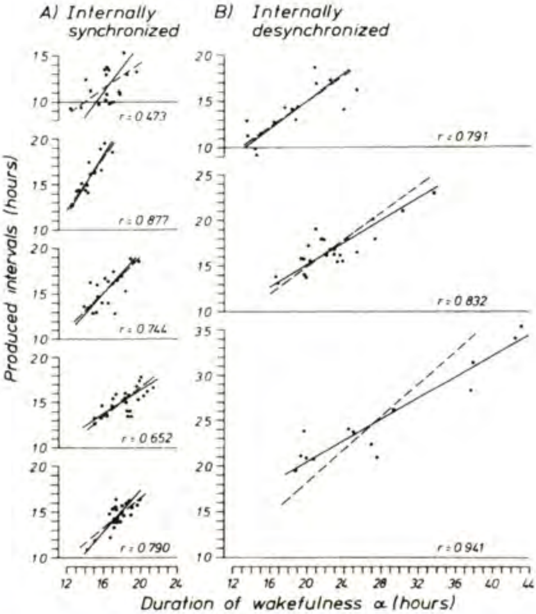

Figure 3. "Daily" means of 1-h productions, drawn as a function of the duration of wake time α. Data from five subjects who remained internally synchronized (left) and from three subjects who became long desynchronized (right). Solid lines: regression. Dashed lines: proportionality between intervals and α. r: coefficient of correlation.

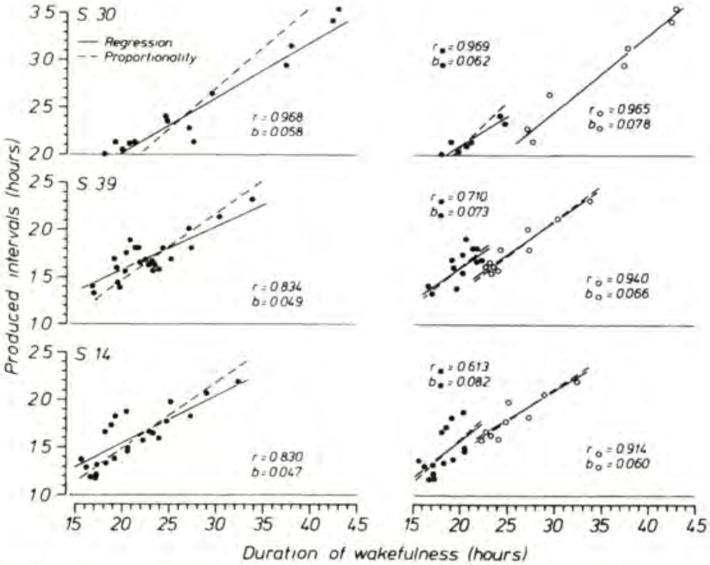

Figure 4. Dependence of 1-h productions on the duration on wake time. Data from three subjects who, in the course of the experiment, changed from internal synchronization to long desynchronization. Left: regressions computed through all data points. Right: data treated separately for internal synchronized cycles (closed circles) and for desynchronized cycles (open circles). r: coefficient of correlation; b: coefficient of regression.

So far, the analysis has been made intraindividually. In a next step, data from different subjects shall be compared. To this end, individual means were computed for all 1-h productions, and these means were then related to the mean duration of α of each subject. The results of those computations, summarized in Figure 5, demonstrate that also among individuals the intervals come close to being proportional to α. In other words: each subject seems to have its own "preferred" duration of wake time, and a corresponding perception of long time intervals. Again, there is a difference in "set-point" between the internally synchronized subjects and the desynchronized subjects.

DISCUSSION

The occurrence of internal desynchronization in human circadian rhythms has been considered as evidence for the existence of two

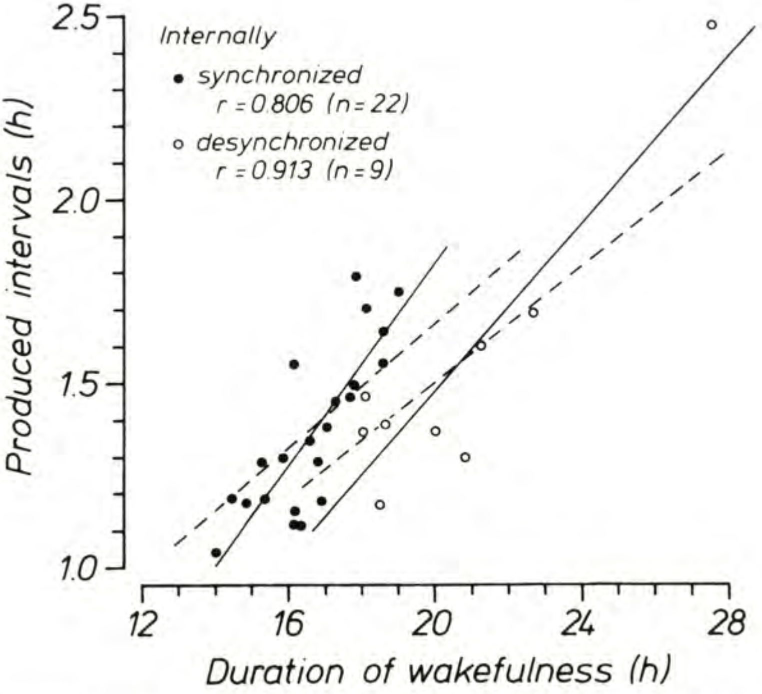

Figure 5. Individual means of 1-h productions, drawn as a function of the individual mean duration of wake time. Data from 22 subjects who remained internally synchronized (closed circles), and from 9 subjects who became long desynchronized (open circles). Solid lines: regression; dashed lines: proportionality between intervals and wake time. r: coefficient of correlation.

central pacemakers, one controlling the sleep-wake cycle, and the other one the rhythms of autonomic functions such as body temperature (Wever, 1975; Aschoff & Wever, 1976). It must be noted, however, that a more recent model of sleep that supposes only one pacemaker in combination with a homeostatic process (Daan, Beersma, & Borbély, 1984), is capable of simulating all characteristics known from human circadian rhythms, including internal desynchronization. Whatever the final explanation for the phenomenon may be, it remains astounding that subjects can be awake continuously for more than 30 h, or for only 10 h, without being aware of it. In those instances the intervals between meals may become more than twice as long as they are normally, or only half as long. Despite of these large variations, the caloric intake per meal does not change, and body weight remains constant (Green, Pollack & Smith, 1987; Aschoff, 1989). Hence, energy expenditure (per unit of time) ought to be reduced during long, or increased during short internal desynchronization. To some extent, this is achieved by systematic changes in locomotor activity: the means of hourly movements across the unit are negatively correlated with the duration of α in such a way that the total amount of activity per "day" remains constant (Aschoff, 1993). This saving of energy, however, does not suffice to explain the constancy of body weight; it seems likely that basal metabolic rate as well is adjusted to the duration of wake time (Aschoff, 1985b).

It is not yet clear what the mechanisms are that determine the apparent passage of subjective time (Aschoff, 1992), but the participation of metabolic processes and of body temperature seems likely. There is little doubt that body temperature plays a role in the estimation of short time intervals in the range of seconds (for a survey of experimental results cf. Figure 10 in Daan, 1986). On the other hand, such estimates represent a "personal tempo" which, apart from variations *within* the circadian cycle (Aschoff, 1984), is *independent of the duration of wake time*; the production of short time intervals remains completely unaffected by internal desynchronization (cf. Figures 14 and 17 in Aschoff, 1985a). In 7 of our subjects, a strict independence from α could be demonstrated even for intervals of (estimated) 120 sec. This observation is at variance with estimates made by Siffre (1963) who was staying in a cave for two months (cf. Halberg, Siffre, Engeli, Hillman, & Reinberg, 1965). Siffre was asked to count from 1 to 120 at the pace of 1 sec, and he produced 142 sec at the beginning of the experiment but 215 at his end (when, most likely, he had become long desynchronized; cf. Figure 1.16 in Aschoff, 1990b). At present, no explanation can be given for this discrepancy in results, though one has to keep in mind that Siffre made one estimate per "day" while our subjects had a mean frequency of 11.7 estimates per "day" (cf. Figure 18 in Aschoff, 1985a), and were not asked to count (and presumably did not count). It remains to be seen wether 2-min estimates are just at the border where independence from changes into dependence on α.

In contrast with the short time estimates, the perception of long time intervals is strongly coupled to the sleep-wake cycle, and it may well be affected by changes in metabolic rate as they occur concurrently with changes in the duration of α. Such changes in metabolic rate do not necessarily affect body temperature. In free-running rhythms, wether internally synchronized or desynchronized, the *amplitude* of the rhythm in body temperature is modified, but there are no indications for systematic changes in its mean *level* (Wever, 1992). The conclusion suggests itself that the subjects adjusted heat loss to the changes in heat production; unfortunately, no data are available from mean skin temperature. The possibility of differences in the effects of temperature and metabolic rate on short and long time estimates certainly deserves further attention. Apart from this problem, it remains noteworthy that the proportionality between 1-h productions and α applies not only intraindividually but also if a comparison is made among subjects (Figure 5). This is the time that "travels in diverse paces with diverse persons" (Shakespeare, 1831).

REFERENCES

Aschoff, J. (1984). Circadian timing. In J. Gibbon & L. Allan (Eds.), *Timing and time perception* (pp. 442-448). New York: Annals of the New York Academy of Sciences, 423.

Aschoff, J. (1985a). On the perception of time during prolonged temporal isolation. *Human Neurobiology, 4*, 41-52.

Aschoff, J. (1985b). Time perception and timing of meals during temporal isolation. In T. Hiroshige & K. Honma (Eds.), *Circadian clocks and zeitgebers* (pp. 3-18). Sapporo: Hokkaido University Press.

Aschoff, J. (1987). Circadiane Zeitordnung und Zeitwahrnehmung beim Menschen. In M. Amelang (Ed.), *Bericht über den 35. Kongress der deutschen Gesellschaft für Psychologie in Heidelberg 1986* (pp. 83-93). Göttingen: Verlag für Psychologie Dr. C. J. Hogrefe.

Aschoff, J. (1989). Temporal orientation: Circadian clocks in animals and humans. *Animal Behaviour, 37*, 881-896.

Aschoff, J. (1990a). From temperature regulation to rhythm research. *Chronobiology International, 7*, 179-186.

Aschoff, J. (1990b). Circadian temporal orientation. In D. E. Blackman & H. Lejeune (Eds.), *Behaviour analysis in theory and practice: Contributions and controversies* (pp. 3-31). Hove, East Sussex: Erlbaum.

Aschoff, J. (1992). On the dilatability of subjective time. *Perspectives in Biology and Medicine, 35*, 276-280.

Aschoff, J. (1993). On the relationship between motor activity and the sleep-wake cycle in humans during temporal isolation. *Journal of Biological Rhythms, 8*, 33-46.

Aschoff, J., von Goetz, Ch., Wildgruber, Ch., & Wever, R. A. (1986). Meal timing in man during isolation without time cues. *Journal of Biological Rhythms, 1*, 154-162.

Aschoff, J., & Wever R. A. (1976). Human circadian rhythms: A multioscillatory system. *Federation Proceedings, 35*, 2326-2332.

Campbell, S. S. (1990). Circadian rhythms and human temporal experience. In R. A. Block (Ed.), *Cognitive models of psychological time* (pp. 101-118). Hillsdale, NJ: Erlbaum.

Daan, S. (1986). Tijd en gedrag: het raderwerk van biologische klokken. *Vakblad voor Biologen, 66*, 143-148.

Daan, S., Beersma, D. G. M., & Borbély, A. A. (1984). Timing of human sleep: recovery process gated by a circadian pacemaker. *American Journal of Physiology (Regulatory, Integrative and Comparative Physiology), 246*, R161-R178.

Green, J., Pollack, C. P., & Smith, G. P. (1987). Meal size and intermeal interval in human subjects in time isolation. *Physiology and Behavior, 41*, 141-147.

Halberg, F., Siffre, M., Engeli, M., Hillman, D., & Reinberg, A. (1965). Etude en libre-cours des rythmes circadiens du pouls, de l'alternance veille-sommeil et de l'estimation du temps pendant les deux mois de séjour souterrain d'un homme adulte jeune. *Comptes Rendus de l'Académie des Sciences, Paris, 260*, 1259-1252.

Murat, J. A., (1806). Mémoire No. VII, seconde partie. In *De l'Influence de la nuit sur les malades. Recueils des mémoires couronnés par la Société de Médecine de Bruxelles* (pp. 192-266). L'Imprimerie de Weissenbruch.

Pöppel, E. (1971). Oscillations as a possible basis for time perception. *Studium Generale, 24*, 85-107.

Shakespeare, W. (1831). *As you like it.* In The Dramatic Works of Shakespeare (pp. 237). London: Young and Young.

Siffre, M. (1963). *Hors du temps.* Paris: René Juillard.

Virey, J. J. (1814). *Ephémérides de la vie humaine, ou recherches sur la révolution journalière, et la périodicité de ses phénomènes dans la santé et les maladies* (pp. 33). Med. Thesis. Paris: L'Imprimerie de Didot Jeune.

Wever, R. (1975). The circadian multi-oscillator system of man. *International Journal of Chronobiology, 3*, 19-55.

Wever, R. (1979). *The Circadian system of man.* Berlin: Springer Verlag.

Wever, R. A. (1992). Basic principles of human circadian rhythms. In T. F. H. Schmidt, B. T. Engel, & G. Blümchen (Eds.), *Temporal variations of the cardiovascular system* (pp. 15-84). Berlin: Springer Verlag.

Wulfften-Palte, P. M. (1968). Time sense in isolation. *Psychiatria, Neurologia, Neurochirurgia, 71*, 221-241.

Zakay, D. (1989). The evasive art of subjective time measurement: some methodological dilemmas. In R. Block (Ed.), *Cognitive models of psychological time* (pp. 59-84). Hillsdale, NJ: Erlbaum.

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