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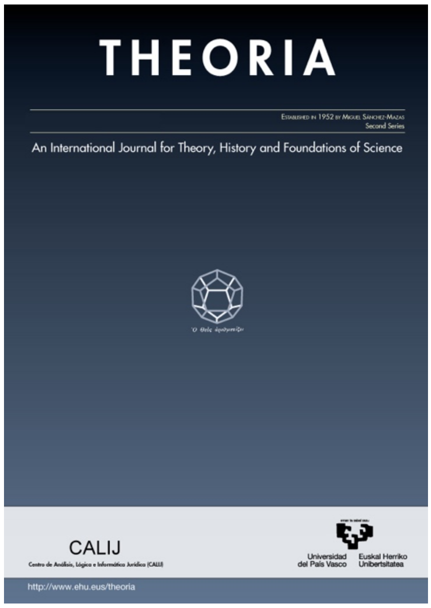

TIME DILATION AND RATES OF THE PASSAGE OF TIME

(Dilatación temporal y ritmo del paso del tiempo)

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ABSTRACT: Debate over the issue of the rate of the passage of time has been persisting in the academic literature for decades without substantial progress. The common explanations of the (empirically well-confirmed) time dilation effects from Special and General Relativity theories requires that there is a physical passage of time which occurs at varying rates. Yet, these theories do not formally posit any passage of time. It is shown that the relativistic time dilation effects strongly imply that the passage of time is not a physical phenomenon.

Keywords: passage of time; rate of time passing; time dilation

RESUMEN: El debate sobre el ritmo del paso del tiempo ha persistido en la literatura académica durante décadas sin progreso sustantivo. La explicación habitual de los (empíricamente confirmados) efectos de dilatación temporal a partir de las teorías de la relatividad especial y general requiere que haya un paso del tiempo que transcurra a ritmos variables. Sin embargo, estas teorías no postulan formalmente ningún paso del tiempo. En este artículo se muestra que los efectos relativistas de dilatación temporal implican con fuerza que el paso del tiempo no es un fenómeno físico.

Palabras clave: paso del tiempo; ritmo del paso del tiempo; dilatación temporal

SHORT SUMMARY: There has not been any substantial progress made on the issue of the rate of the passage of time. This article proposes a way to make such progress and draws a significant conclusion about the nature of time.

1. Introduction

The idea that time has a 'dynamic' nature, i.e. that there is a facet of time characterised by words such as 'passage', 'flow', or 'advance', is very natural for human beings to believe as it seems to be an obvious trait of daily life (Smart 1949, p.484; Tallant 2016, p.35; Callender 2017, p.1). We are all aware, at least intuitively, of this (apparent) 'dynamic' aspect of time. However, a perennial puzzle for philosophers who argue in favour of the existence of an objective passage of time (also called temporal passage) is what should constitute its actual description. Various 'dynamic' models have been proposed over the last hundred years, e.g. Presentism, Moving Spotlight, Growing Block, etc. (for details see: Dainton 2010; Harrington 2015; Dyke 2021; and Forbes 2024) without any consensus being reached by 'dynamic' advocates.

If we do make the general assumption that time does possess a 'dynamic' nature then just this conjecture alone brings forth a host of questions, both philosophical and physical. One of the most persistent and troublesome issues about the passage of time is its *rate*. If there is some kind of temporal passage then it stands to reason that there would have to be a rate at which passage occurs (Price 1996, p.13; Romero 2015, p.136; Boccardi 2016, p.9). Most philosophers of time accept that if time passes, it does so at some rate, as Prosser has stated:

> … a significant number of philosophers, both advocates and opponents of [temporal] passage, have felt that it makes sense to speak of time passing at a rate. (Prosser 2013, p.317)

If time passes then its rate of passage would be an intrinsic trait (i.e. being essential to time's nature) where the value of the rate (i.e. its magnitude) may change depending on physical circumstances (Newman 2021, p.5). This article will examine how Special and General relativistic time dilation effects might influence time's rate of passage in order to draw a conclusion about the existence of a physical passage of time.

2. Debate over the rate of time's passage

It is the case that deliberations over the issue of the rate of the passage of time have been appearing in the academic literature for more than 80 years. In 1938, C.D. Broad maintained that the rate of time's passage (or the rate of absolute temporal becoming, as he called it) is a primitive concept which cannot be analysed further (Broad 1938, pp.280-281). Additional discussions followed sporadically throughout the twentieth century (e.g. Smart 1949; Williams 1951; Webb 1960; Prior 1968; Park 1971; Grünbaum 1973; Zwart 1976; Smart 1980; Schlesinger 1982; Kroes 1984; Levison 1987; Markosian 1993; Schlesinger 1994; Dorato 1995; Price 1996) *without agreement* on the issue.

The years since the beginning of the twenty-first century have been witness to greater exploration into (and passionate debate over) definitions of the rate of the passage of time and whether it is a legitimate concept. A survey of the relevant literature verifies this (e.g. see: Lamb 2001; Nerlich 2004; Maudlin 2007; Olson 2009a; Phillips 2009; Raven 2010; Tallant 2010; Price 2011; Skow 2012; Mozersky 2013; Mazzola 2014; Romero 2015; Prosser 2016; Maudlin 2017; Lee 2018; Arthur 2019; Newman 2021; and Gołosz 2022). These arguments will not be revisited. They are cited only to highlight the extent of the continuing debate and its unresolved status.

The unrelenting discussions over the rate of time's passage should not be unexpected as there are many conceptual and empirical difficulties concerning such a rate. The content of the on-going debate over the rate of passage of time shows that questions about time's rate have not been satisfactorily tackled and that there are fiercely held opposing positions. In addition, there has been a tendency of some of the participants in the debate to 'talk past each other' (Callender 2017, p.49). The absence of a shared basis on which to conduct the debate has resulted in there not being any substantial progress achieved.

Whether time does have a 'dynamic' aspect or not holds enormous significance for our understanding of human experience and, more generally, the nature of the physical universe. Barry Dainton has described the extent and bearing of the issue as follows:

> The issue of whether or not time is dynamic may impact on how we think of our lives, but it also has consequences of a less parochial sort … *the ontological ramifications* … are vast in comparison. (Dainton 2010, pp.9-10, italics added)

This significance is a prime motivation for seeking a resolution to the quandary of whether time is or is not ‘dynamic’. An attempt is made below to progress the debate over the passage of time by examining how relativistic time dilation relates to time’s rate of passage.

3. *Relativistic time dilation and time’s passage*

In this section, the concepts and equations which are prerequisites for the material offered in Section 4 will be presented. Our two best theories of space and time are Einstein’s Special and General Theories of Relativity, both of which are highly confirmed. Neither theory posits any passage of time (Penrose 1989, p.393). Many philosophers and physicists have argued for over a century that a passage of time does not mesh with Special Relativity and/or is not necessary for a satisfactory account of physical phenomena (e.g. see: Price 1996, pp.13-15; Mozersky 2000; Dieks 2014; Falk 2016; Turner 2020). Moreover, some commentators forcefully contend that the relativity of simultaneity excludes the possibility of *any* physical passage of time (see: Peterson & Silberstein 2010; Callender 2017, pp.52-57; Baron 2018). Time is indispensable in the description of the physical world, e.g. the minimum specification of any event requires both space coordinates and a time coordinate. Since time is indispensable, if the passage of time is objective then a parameter for it should be found in physical laws at a basic level. However, there is no term corresponding to any passage of time in the fundamental equations of physics (Morris 1985, p.209; Greene 2004, p.130; Callender 2006, p.498; Al-Khalili 2012, p.85).

In spite of these arguments and objections, the reality of a passage of time continues to be an intensely held belief with most people, at least in Western countries, accepting that the (apparent) passage of time is a feature of the physical universe (cf. Dainton 2010, p.28; Prosser 2016, p.22; Callender 2017, p.11). Those philosophers who adhere to this belief insist that we only have an *incomplete* description of the universe as the passage of time is absent from physics (see: Dieks 2012, p.104; Rickles & Kon 2014, p.3). If this is correct and there is a physical passage of time then temporal passage has eluded mainstream physics.

The Special and General Relativity theories provide descriptions of physical spacetime, i.e. the union of space and time – ‘flat’ spacetime for the former and curved spacetime for the latter (for an intelligible account of spacetime, see Ellis & Williams 2000, pp.5-11). The metrical structure of spacetime is its most crucial characteristic for the spacetime metric determines intervals and causal relations between events in spacetime (Callender 2017, pp.122-123). These features of spacetime geometry are (quantitatively) summarised in the spacetime metric tensor (Lawrie 1990, p.60) which is prominent in the basic equations of Relativity. Yet, as noted above, neither theory explicitly includes temporal passage. The mathematical formulations of Special and General Relativity together with their wide sphere of applications and high degrees of empirical confirmation suggests that these theories still have more to reveal about the physical universe. If the passage of time is an objective feature of the universe then, given the significance of the metric of spacetime, it may well be the case that metrical aspects of time’s passage might be *inferred* from an (in-principle) examination of situations where both Special and General relativistic time dilation effects are prominent. We shall investigate this possibility below. Let’s first consider these time dilation effects and their equations.

Suppose a ‘moving’ clock (denoted clock 2) in an inertial frame of reference (i.e. a frame where Newton’s First Law holds) measures the time interval between two events to be Δt_2, where the ‘Δ’ symbol indicates an interval. Another clock (denoted clock 1) ‘at rest’ measures the time interval between the same events to be Δt_1. Special relativistic time dilation is the effect when the time interval measured by the ‘moving’ clock is numerically less than the time interval between the same events as measured by the clock 'at rest', i.e. $\Delta t_2 < \Delta t_1$. The equation relating these time intervals as measured by the clocks in their respective (inertial) frames of reference is (Faraoni 2013, p.19):

$$\Delta t_2 = (1 - \mathrm{v}^2 / c^2)^{1/2} \Delta t_1 \qquad (1)$$

where v (≥ 0) is the relative speed of the reference frames and c is the speed of light in vacuum (hereafter referred to as light-speed). Note that light-speed has the same (constant) value in all inertial reference frames and is unreachable by any material body, i.e. v is always strictly less than c (Faraoni 2013, p.36), so that $(\mathrm{v}^2/c^2) < 1$. Relativity textbooks explain why the two time intervals Δt_1 and Δt_2 differ in terms of separate worldlines (i.e. paths in spacetime) between events having unequal time intervals due to the geometrical structure of 'flat' spacetime (Riggs 2022, p.3).

The speed v is typically the speed of one object with respect to another object. Speed is the magnitude of an object's velocity vector so that the object can have an acceleration without its speed changing by there being only a change in the direction of its motion. Both changes in speed and changes in direction are (formally) accelerations as they alter a velocity vector. Contrary to a widespread misunderstanding, Special Relativity has no difficulty in dealing with accelerated motion (Penrose 2004, p.422; Arthur 2010, p.169). The validity of the *Clock Hypothesis* is also accepted which states that the time interval registered on a clock only depends on its speed and not its acceleration (see Arthur 2010 for reasons for acceptance).

It is frequently claimed that the time dilation effect of Special Relativity is explained by there being a physical passage of time which occurs at various rates in different reference frames. This is the common explanation of special relativistic time dilation as found in (print and internet) popularisations of relativity theory. In the common explanation, an actual passage of time with a rate which depends on the relative speed of reference frames is essential. Here is a representative statement of the common explanation of special relativistic time dilation:

> ... if you were in a speeding rocket ship, the passage of time inside that rocket would have to slow down with respect to someone on Earth. Time beats at different rates, depending on how fast you move. (Kaku 2008, p.200)

This slowing of time requires there to be a physical passage of time where its rate has a smaller value than the rate in another reference frame. Moreover, due to the relativity of simultaneity, the physical passage of time would need to be a *local* phenomenon.

Clearly then, in the common explanation, less time would lapse in one frame (e.g. the spacecraft's frame) leading to a shorter time interval between events than in a different frame (e.g. the frame of the Earth). The assumption of a physically slower time thereby accounts for the numerical discrepancy in the time intervals between two events as measured in different reference frames (i.e. (1)). Indeed, it has even been claimed that the slowing of time is the *best explanation* for special relativistic time dilation (Newman 2021, p.1). However, since relativity theory does not formally express anything about time passing, this common explanation is (in essence) a metaphysical 'add-on'.

In order to make a quantitative analysis of the metrical implications of the passage of time in a relativistic context, we need to employ a frame independent quantity. The apt quantity to use in a *physical* account is proper time (denoted τ) not coordinate time t (Nerlich 2004, p.23; Peacock 2006, p.250). A proper time interval is defined between two events which have a timelike separation, i.e. the relativistic spacetime separation applying to material objects, and is reference frame invariant. The proper time interval between two timelike related events (e.g. the reception of two successive pulses of light) can be measured by a clock which shares the worldline joining these events (Adler et al. 1975, pp.122-123; Ferraro 2014, p.18; Woodhouse 2014, p.52; Newman 2021, p.3).

Suppose we have a clock flying past an identical clock which is at rest with respect to a suitable inertial frame with a relative constant speed v close to light-speed. If two successive events which have a timelike separation occur then the time difference between these events measured by the clocks will be their respective proper time intervals, denoted $\Delta \tau_2$ for the 'moving' clock and $\Delta \tau_1$ for the 'stationary' clock. We can relate these proper time intervals by replacing the coordinate time intervals Δt_1 and Δt_2 in (1) with $\Delta \tau_1$ and $\Delta \tau_2$ respectively (Kroes 1985, pp.78-80; Nerlich 2004, p.28):

$$\Delta \tau_2 = (1 - v^2 / c^2)^{1/2} \Delta \tau_1 \tag{2}$$

It must be stressed that proper time intervals are those which have physical significance in both Special and General Relativity.

In General Relativity, gravitational time dilation is where the time interval between two (timelike) events has unequal values at different distances from a source of gravity. A clock further away from the source (i.e. at a 'higher' gravitational potential) will record a larger proper time interval than a clock closer to the source. Suppose we have two clocks at rest relative to each other and the gravitational source which are at different distances from the source. Let the radial coordinates of the clocks be r_1 and r_2 from the source of gravity and the proper time intervals registered between two events be $\Delta \tau_1$ at r_1 and $\Delta \tau_2$ at r_2. The equation relating the proper time intervals measured by these clocks is (Adler et al. 1975, p.136):

$$\Delta \tau_2 = [g_{00}(r_2) / g_{00}(r_1)]^{1/2} \Delta \tau_1 \tag{3}$$

where $g_{00}(r_2)$ and $g_{00}(r_1)$ are the time components of the spacetime metric tensor (i.e. functions of the gravitational potentials) at positions r_2 and r_1 respectively. If $r_2 > r_1$ then $\Delta \tau_2 > \Delta \tau_1$. Relativity textbooks explain these unequal proper time intervals in terms of the geometrical structure of curved spacetime (Riggs 2023, p.3). However, if it is accepted that a physical passage of time occurs at various rates then the explanation of gravitational time dilation is that gravity slows the passage of time as a source of gravity is approached. This is the common explanation of gravitational time dilation which (again) is to be found in print and internet popularisations.

We should also acknowledge that special relativistic and gravitational time dilation effects are so extremely well-confirmed that they must be viewed as being beyond *practical* doubt (see: Hafele & Keating 1972; Bailey et al. 1977; Williams 2002, pp. 126-128; NPL 2005; Reinhardt et al. 2007; Chou et al. 2010; NPL 2011; Bertolami & Páramos 2014; Botermann et al. 2014). Such confirmation continues on a daily basis by the operation of the Global Positioning System (see: Ashby 2003; Pascual-Sánchez 2007; Taylor et al. 2018, chap.4) It is worth emphasising again that these time dilation effects are thoroughly explained within the two theories of relativity without any need to postulate a physical passage of time.

4. Quantified rates of time's passage

If one maintains that the passage of time is physically objective and is a local phenomenon, it would also follow that different rates of passage are local characteristics of time (see: Dieks 2006; Newman 2021). Both special relativistic and gravitational time dilation being localised effects is not incompatible with this conclusion. What might these local rates inform us about the nature of time?

In order to pursue this question, it might be expected that a prerequisite is to have a concept of the passage of time that is coherent and a definition of its rate that is consistent. Yet, these are long-standing, unresolved problems in the philosophy of time which remain a primary challenge for passage advocates.

Progress in the debate over the issue of the passage of time can be achieved by *sidestepping* the definitional problems whilst still making the minimal assumptions that time does have a physical passage and that there are precise (positive, real-valued) rates of passage, regardless of how the rates might be (consistently) defined. Positive, real-valued rates are necessary otherwise the passage of time could either cease or 'go backwards'. We will also need to specify how rates of passage relate to time intervals between events. This proposed (sidestepping) approach would be compatible with a range of different concepts of time's passage. Since no concept of the passage of time has withstood sustained criticism *and* been found acceptable in both physics and philosophy of time, the proposed approach offers a means to move the debate forward. Let's accept these assumptions and see how far this approach can reach.

We shall begin by (generally) specifying rates of passage of time whilst still not having to define them explicitly. In intergalactic space (where gravitational time dilation is completely negligible), we shall assign the magnitude of the rate of passage to have the value α. Consider the case of a clock (denoted clock 1) which sits in intergalactic space (i.e. zero gravitational time dilation) and is at rest relative to say, the cosmic microwave background (i.e. zero special relativistic time dilation). An identical clock (denoted clock 2) on a spacecraft travelling at constant speed v with respect to clock 1 has previously been synchronised with clock 1. When the spacecraft goes past the position of clock 1, two successive radio or laser pulses are directed at the spacecraft from the location of clock 1 such that the pulses travel the same distance. Let the proper time interval between the pulses recorded on clock 1 be $\Delta \tau_1$ and $\Delta \tau_2$ on clock 2. These proper time intervals are related by (2). The size of the rate of the passage of time at the location of clock 1 has the value α. Given that $\Delta \tau_2 < \Delta \tau_1$, it is the case that time's passage is slowed on the spacecraft and therefore its rate would be reduced by an amount which depends on speed v, as a lower rate yields a shorter time interval and vice-versa. If we denote this variable amount as f then the rate of passage on the spacecraft will have the value $(\alpha - f)$ with $0 \leq f < \alpha$ for $0 \leq v < c$. The quantity f gets larger with increases in speed v such that the rate on the spacecraft tends to zero as its speed advances towards light-speed. The rate cannot be zero as this would require $v = c$.

The common explanation of gravitational time dilation is that the rate of the passage of time *reduces* with decreasing distance to a source of gravity. It would then follow that, as we approach a sizeable gravitational source (e.g. the Earth), time's local passage will slow and its rate will get smaller and smaller. Set the size of the rate at a specified height h above the Earth's surface (where the rate will be determined by the gravitational potential at this height) to have the value $(\alpha - \varepsilon_2)$ where ε_2 is a fixed amount by which time's passage is slowed at height h, with $0 < \varepsilon_2 < \alpha$. The rate on the Earth's surface will have an even lower value. We can likewise set the size of this rate to be: $(\alpha - \varepsilon_1)$ where ε_1 is a fixed amount by which time's passage is slowed on the Earth's surface, with $\varepsilon_2 < \varepsilon_1 < \alpha$. Note that ε_1 and ε_2 must be strictly less than α or the passage of time would cease.

Let's move to a situation where both special relativistic and gravitational time dilation are concurrent. In this circumstance, we choose to have our spacecraft travelling at a speed v which is a large fraction of light-speed whilst in a circular, equatorial orbit around the Earth so that the value of the gravitational potential for the spacecraft is constant. Such an orbit can be maintained by use of suitably directed thrust from the spacecraft's engines. Clock 1 is on the Earth's surface and clock 2 is on the spacecraft. The equation which relates the proper time intervals between two suitable events for an object travelling in a circular orbit and for an object on the Earth (respectively $\Delta\ \tau_2$ and $\Delta\ \tau_1$) has been derived to be (Matolcsi & Matolcsi 2008, pp.1147-1150):

$$\Delta\ \tau_2 = [1 + (2\Phi/c^2) - (v^2/c^2)]^{1/2}\ \Delta\ \tau_1 \qquad (4)$$

where Φ (> 0) is the gravitational potential at the altitude of the orbit. Notice in (4) that the term $[1 + (2\Phi/c^2) - (v^2/c^2)]$ is greater than unity for $(2\Phi/c^2) > (v^2/c^2)$ and less than unity for $(2\Phi/c^2) < (v^2/c^2)$ but is always positive.

We again choose the suitable events to be two successive radio or laser pulses directed at the spacecraft from the location of clock 1 such that the pulses travel the same distance. Note that the proper time interval $\Delta\ \tau_2$ (measured on the spacecraft) in this situation arises from the competing effects of gravitational and special relativistic time dilation. Gravitational time dilation would lead to a longer time interval between the pulses as measured on the spacecraft than on the Earth's surface and special relativistic time dilation would lead to a shorter time interval. Which effect dominates will depend on the speed of the spacecraft and its altitude (i.e. orbital radius). What might this scenario reveal about time's rate of passage?

Given that the rate at which time passes would have to determine the corresponding time interval between events, there must be a definite quantitative relation which holds between the local rate of time's passage and the proper time interval which results from this passage. What is this relation likely to be? The most straight-forward relation is direct proportionality. If time does pass then there are sound reasons for accepting the relation between time's local rate and the resulting proper time interval to be that of direct proportionality. There are at least three justifications for accepting this relation:

- Harmony with basic natural processes.

The relation of direct proportionality is in harmony with the tendency for all basic natural processes to have the simplest quantitative expression (other things being equal).

- Non-linear changes in the rate of passage are not experienced.

If the human experience of the passage of time is accepted as veridical then the relation of direct proportionality would need to hold as disjointed, discontinuous, or other non-linear changes in the perceived rate of passage are never experienced (by mentally stable people).

- Time shares some characteristics with a smoothly flowing river.

Many philosophers who accept that time passes insist that time shares some (but obviously not all) characteristics with a smoothly flowing river (or similar water course). On this basis, the relevant traits of time would be having a physical passage with a fixed direction and rates that can vary. (A few theoretical physicists also embrace this view of time and use it in concert with the common explanations of time dilation, e.g. Novikov 1998; Kaku 2008). Now it is the case that, in an unrestricted channel of (non-turbulent) flowing water, the amount of water flowing depends directly on the rate of flow (Serway & Jewett 2008, 400). Accepting this as a trait in common with time leads to granting that the passage of time would have a rate which is directly proportional to the resulting proper time interval.

In light of these reasons, it is entirely rational to accept that the relation of direct proportionality holds between the local rate of passage and the resulting proper time interval. If we apply this then we will have the following quantitative relationship for clock 1 (on the Earth's surface):

$$\Delta \tau_1 = \mathrm{K}\,(\alpha - \varepsilon_1) \tag{5}$$

where $\Delta \tau_1$ is the proper time interval between the pulses measured on clock 1, K (> 0) is the constant of proportionality whose magnitude is determined by the relativistic spacetime separation between the two pulses and whose units are determined by the units of α (with $\varepsilon_1 < \alpha$ or the passage of time would cease). Note that timelike spacetime separations have invariant (positive) values.

If the extent of a proper time interval between two events arises from both special relativistic and gravitational time dilation effects then the net rate of time's passage on the spacecraft will equal the size of the rate at height h minus the variable quantity f, i.e. $(\alpha - \varepsilon_2 - f)$ where f depends on speed v of the spacecraft (relative to the Earth). This net rate will be directly proportional to the proper time interval between the two successive pulses as measured on the spacecraft ($\Delta \tau_2$), so that for clock 2:

$$\Delta \tau_2 = \mathrm{K}\,(\alpha - \varepsilon_2 - f) \tag{6}$$

where $f < (\alpha - \varepsilon_2)$ or the passage of time would cease. Note that (6) only applies when both time dilation effects are concurrent.

If we square the left-hand and right-hand sides of the equal sign in (4), we get:

$$(\Delta \tau_2)^2 = [1 + (2\Phi/c^2) - (\mathrm{v}^2/c^2)]\,(\Delta \tau_1)^2 \tag{7}$$

Substituting (5) & (6) into (7) allows a quantitative relationship involving the numerical difference of the squares of the proper time intervals between the two pulses and the numerical difference of the squares of the respective rates of time's passage involved to be derived:

$$(\Delta \tau_2)^2 - (\Delta \tau_1)^2 = [(2\Phi/c^2) - (\mathrm{v}^2/c^2)]\,(\Delta \tau_1)^2 = \mathrm{K}^2\,[(\alpha - \varepsilon_2 - f)^2 - (\alpha - \varepsilon_1)^2] \tag{8}$$

In (8), we have:

$$(\alpha - \varepsilon_2 - f)^2 - (\alpha - \varepsilon_1)^2 = (\varepsilon_2^2 - \varepsilon_1^2) - 2\alpha(\varepsilon_2 - \varepsilon_1) - 2f(\alpha - \varepsilon_2) + f^2 \tag{9}$$

Although we will avoid explicitly defining rates of passage, we can choose the option of taking rates of passage to be dimensionless. The constant of proportionality K will then have units of time. We may also normalise the rate α to a base value of unity.

Using (8) & (9) and setting the rate α to unity (i.e. $\alpha = 1$), we get the equation:

$$[(2\Phi/c^2) - (\mathrm{v}^2/c^2)]\,(\Delta \tau_1)^2 = \mathrm{K}^2\,\{(\varepsilon_2 - \varepsilon_1)\,[(\varepsilon_2 + \varepsilon_1) - 2] - 2f(1 - \varepsilon_2) + f^2\} \tag{10}$$

Substituting for $(\Delta \tau_1)^2$ from (5) into (10) yields:

$$[(2\Phi/c^2) - (\mathrm{v}^2/c^2)]\,\mathrm{K}^2\,(1 - \varepsilon_1)^2 = \mathrm{K}^2\,\{(\varepsilon_2 - \varepsilon_1)\,[(\varepsilon_2 + \varepsilon_1) - 2] - [2f(1 - \varepsilon_2) - f^2]\} \tag{11}$$

Note that ε_1 and ε_2 have fixed values with $0 < \varepsilon_1, \varepsilon_2 < 1$ (as $\alpha = 1$) and $\varepsilon_1 > \varepsilon_2$. It then follows that $(\varepsilon_2 - \varepsilon_1) < 0$ and $(\varepsilon_2 + \varepsilon_1) < 2$ so that $(\varepsilon_2 - \varepsilon_1)\,[(\varepsilon_2 + \varepsilon_1) - 2] > 0$. Also, as $f < (1 - \varepsilon_2)$, $[2f(1 - \varepsilon_2) - f^2] > 0$. Since $(2\Phi/c^2) > 0$, $(\mathrm{v}^2/c^2) > 0$, and f is a function of speed v with $f = 0$ when $\mathrm{v} = 0$, it can be seen from (11) that:

$$(2\Phi/c^2) = (\varepsilon_2 - \varepsilon_1)\,[(\varepsilon_2 + \varepsilon_1) - 2] \,/\, (1 - \varepsilon_1)^2 \tag{12}$$

which is a positive quantity (as required); and

$$2f\,(1-\varepsilon_2) - f^2 = (1-\varepsilon_1)^2\,(v^2/c^2) \qquad (13)$$

Equation (13) is a quadratic equation in f with the solution:

$$f = (1-\varepsilon_2) - [(1-\varepsilon_2)^2 - (1-\varepsilon_1)^2\,(v^2/c^2)]^{1/2} \qquad (14)$$

where the minus sign between the two main terms has been chosen to meet the condition that $f = 0$ when $v = 0$. We can see that the variable f is not only dependent on speed v but also on ε_1 and ε_2. We have arrived at two equations (i.e. (12) & (14)) which can be used to describe time's local rates of passage when both time dilation effects are concurrent. So far – so good!

Using (14), the rate of time's passage on the spacecraft may now be expressed in terms of v, ε_1 and ε_2:

$$(1-\varepsilon_2-f) = 1-\varepsilon_2 - \{(1-\varepsilon_2) - [(1-\varepsilon_2)^2 - (1-\varepsilon_1)^2\,(v^2/c^2)]^{1/2}\}$$

$$= [(1-\varepsilon_2)^2 - (1-\varepsilon_1)^2\,(v^2/c^2)]^{1/2} \qquad (15)$$

which (taking the plus square-root) gives a positive value (as required for rates of passage) since $(1-\varepsilon_2) > (1-\varepsilon_1)$ and $(v^2/c^2) < 1$. We can rearrange (12) to provide the following expression for the quantity $(1-\varepsilon_1)^2$:

$$(1-\varepsilon_1)^2 = (\varepsilon_2-\varepsilon_1)\,[(\varepsilon_2+\varepsilon_1)-2]\,/\,(2\Phi/c^2) \qquad (16)$$

and by substitution of (16) into (15), we find:

$$(1-\varepsilon_2-f) = \{(1-\varepsilon_2)^2 - (v^2/2\Phi)\,(\varepsilon_2-\varepsilon_1)\,[(\varepsilon_2+\varepsilon_1)-2]\}^{1/2} \qquad (17)$$

In the circumstances where the spacecraft closely approaches light-speed, the value of $\{(1-\varepsilon_2)^2 - (v^2/2\Phi)\,(\varepsilon_2-\varepsilon_1)\,[(\varepsilon_2+\varepsilon_1)-2]\}$ in (17) will become negative as $0 < (1-\varepsilon_2)^2 < 1$ and $(v^2/2\Phi)$ will have a very large positive value (e.g. $\approx 10^9$ for high Earth orbit). This will result in the rate of the passage of time on the spacecraft becoming equal to an *imaginary* number as light-speed is approached (i.e. right-hand side of (17)) which *contradicts* the requirement that the rate of time's passage must be positive and real-valued. This is a significant outcome. What then follows? Given that the argument presented is based on there being a physical passage of time with a variable rate (which is an intrinsic attribute), the demonstrated inconsistency implies that the passage of time cannot be an element of physical reality (although time itself, being a part of spacetime, has an objective existence).

5. Physical indicators

It is also appropriate to consider relevant physical indicators in respect to the existence of any physical passage of time as such indicators should have some primacy in the assessment of issues about time:

- The fundamental laws of physics do not contain a term corresponding to a physical passage of time.

If the passage of time was an aspect of physical reality, then there would be a variable term in the fundamental equations of physics for time's passage, which is not the case (as already noted in Section 3).

- Clocks do not measure rates of time passing.

Philosophers who advocate the existence of temporal passage contend that clocks explicitly measure time passing. This assertion is incorrect. What a clock does measure is *intervals of time* (Newton-Smith 1980, p.156; Kroes 1985, p.39; Nerlich 2004, p.24; Olson 2009b, p.447; Franck 2012, p.95; Davies 2024, p.139) — conventionally from midnight for standard clocks or from when started for stopwatches, egg-timers and other timing devices.

- No physical passage of time has been experimentally established.

Any regular, repetitive physical process can be used as a type of clock but, as noted above, clocks do not measure the passage of time. Nor has the passage of time been demonstrated to be a physical quantity which can be measured. Consequently, the passage of time is *not experimentally established.* Indeed, if the passage of time had been so established then we would no longer be debating the issue of whether time passes or not as it would have been shown to be an empirical fact (Riggs 2024, p.461).

These physical indicators also lead to the conclusion that there is no physical passage of time and so provide additional support for accepting this conclusion.

6. Awareness of time passing

The human awareness of the passage of time has always been a compelling reason for believing time's passage to be an objective phenomenon. It is for this reason that the conclusion that there is not a physical passage of time conjures up the obvious question – how is the awareness of passage to be accounted for without invoking temporal passage? Note that the only way that human beings are aware of time passing is through its (apparent) conscious perception (Davies 2002, p.43; Greene 2004, pp.139-140; Prosser 2007, p.77). This being the case, it is *not necessary* for there to be a physical passage of time in order to explain human awareness of time passing as this is explicable by mechanisms which do not require the existence of any (objective) physical passage.

Discussion of the details of these mechanisms of the awareness of passage is beyond the scope of the current article. Indeed, this is an area of on-going research where aspects of physics, philosophy, psychology, and neuroscience intersect and which is still in an early stage of development (e.g. see: Prosser 2016; Riggs 2017; Callender 2017; Gruber et al. 2022; Droit-Volet et al. 2023; and Binder 2024).

7. Final remarks

The assumptions that time does have a physical passage, that there are precise, positive, real-valued rates of time's passage, and this rate being directly proportional to a resulting proper time interval has led to the conclusion that there is no physical passage of time. In accepting this conclusion, we recall the statement quoted in Section 2 that the ontological ramifications of whether or not time is 'dynamic' are vast. A full analysis of these ramifications will have to wait for another occasion. Nevertheless, there are two implications of relevance to issues raised in this article which follow immediately from the conclusion that there is no physical passage of time:

(i) the common explanations of special relativistic and gravitational time dilation are both incorrect; and
(ii) the human awareness of time's passage must originate from processes other than a physical passage of time.

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