Neural Recruitment, Information Processing and the Equation for Subjective Time

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ABSTRACT

Retrospective and Prospective subjective duration estimate experiments reveal that the perceived time duration is in general different from the external objective interval depending on factors such as attention and psychopathological conditions etc. We derive an equation for subjective time to explain its variation with objective time incorporating the role of neural recruitment and the rate of information processing in the brain. The role of attention is included via an attention function defined to have a maximum value one and a minimum zero. A centralized timing resulting from integration of distributed timings in different neural assemblies comes out as a possibility.

Key Words: Neural Recruitment, Neural Information Processing, Subjective Time, Attention, Time Perception, Objective Time

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Introduction

One of the most mysterious ingredients of our experience is that of time. There is nothing physical corresponding to its existence though it is taken as a marker for all physical processes. Kant(Kant, 1998) included time as an a priori precondition of experience along with space. In classical physics time is absolute flowing equably for all observers(Newton, 1999), while in the theory of relativity, it becomes dependent on the motional state of the observer(Einstein, 1922) and it taken as the fourth dimension of the space time continuum. In quantum physics it enters the Schrodinger equation as a parameter conjugate to the Hamiltonian (energy function) of the system (Bauer, 2017). This objective time of physics, which in cosmological sense is taken to have begun with the Big Bang and would continue indefinitely in an open universe while in a closed universe scenario it is supposed to come to an end at the Big crunch(Hawking, 1988). An interval of such objective time, assumed to be made up of a definite number of time units e.g. seconds, is independent of observers and is recorded by instruments such as clocks.

Experience tells us that perception of change is essential for perception of time (Manousakis, 2006) since we find that when no change is perceived (Schlatter, 2013) in a particular mental state as in deep sleep, swoon, coma, deep meditation etc. no temporal flow is perceived by the individual concerned (van Wassenhove *et al.,* 2011). This is the subjective time. An observer's judgment of such a duration of subjective time depends on various factors such as attention, emotion, memory and other pathological conditions, specific diseases or impairments. For example an objective time interval Δt may appear subjectively to be comparatively longer or shorter to an observer depending on these factors. If subjective time passes slowly compared to objective time, we have $\Delta s < \Delta t$ and when it moves

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faster we have Δs>Δt, where Δ s is the corresponding subjective duration.

Psychologists have been dealing with measurement of subjective duration by the study of interval length estimation and subjective passage of time judgments(Sucala *et al.,* 2010). Dyson (Dyson, 1979) proposed to relate subjective time with the information processing rate in terms of the metabolic rate.

In the present study we propose to relate information processing rate to the frequency of neural oscillations and neural recruitment and derive a formula for subjective time incorporating attention as a factor influencing time perception.

Subjective duration and neural oscillations

While change is essential to the perception of passage of time, measurement of time is always done with the help of periodic changes. For example the lunar and the solar calendars are based respectively on the apparent periodic movements of the moon and the sun while modern day clocks use periodic oscillations of quartz crystals for the purpose. The currently accepted definition of the objective time unit (1 second) is taken to be 9192631770 oscillations of the radiation produced by the transition between the two hyperfine levels of the ground state of Cs - 133 atom (Barbour, 2009).

In biological systems different chrono-biological rhythms serve as internal time reckoners for an organism (Hedge, 2013). This could range from the average mitosis period for a unicellular organism like amoeba, to the respiration rate or cardiac cycle for a higher animal. It can even be one of the longer duration cycles like those associated with food, sleep and reproduction etc.

All the above periodicities however, have nothing to do with time perception by an individual; rather they are more associated with the health of the individual. Perception of time can be assumed to be more directly related to neural frequencies rather than to any other biological rhythms (Ivry and Spncer, 2004; Mauk and Buonomano, 2004). Neuronal oscillations corresponding to single neurons at micro scale, local ensembles at the meso-scale and global non-local oscillations across different brain regions at the macro scale have been observed and models have been proposed for them viz. Hudgekin-Huxley (Hudgekin and Huxley, 1952) model for single neuron, Willson-Cowan (Wilson and Cowan, 1973) model for ensembles and Kuramoto (Kuramoto, 1974) model for macro scale binding oscillations respectively and their many variations. The frequency bands primarily observed and classified by Berger(Berger, 1940) are δ-band (1-4 Hz), θ-band (4-8Hz), α-band (8-12 Hz), β-band (12-30 Hz), γ-band (30-70), Γ-band (70-150 Hz) corresponding to different levels and functions of awareness e.g. δ-band for sleep, θ-band for dream and memory, α-band for auditory perception, γ-band for visual perception, Γ-band for cognitive processing etc. (Buzsaki and Draguhn, 2004).

Experiments done on albino rats(Gibbon and Russel, 1981) for durations of less than one minute support linear variation of subjective time with objective time:

$$ds \propto dt \tag{1}$$

Different areas of brain such as the frontal cortex, basal ganglia, parietal cortex, cerebellum and hippocampus (Fontes *et al.,* 2016) have been found to be involved (Ivry and Spencer, 2004; Gibbon and Russel, 1981) in the temporal perception by interpretation of the information processed in the interval from milli seconds to minutes (Buhusi and Meck, 2005).

Time is perceived by decoding the time varying activity of large number of neurons distributed over different neural assemblies (Matell *et al.,* 2003). If in a particular neural assembly N neurons are oscillating at frequency F during the objective time interval dt, the subjective interval ds will be proportional to $r(t)$, the rate of neural information processing (Dyson, 1979):

$$ds \propto r(t) \tag{2}$$

Pradhan(Pradhan, 2017) has proposed that the decoding of the neural correlates for perception occurs via the Fechner logarithmic Law(Fechner, 1980). Thus the rate of neural information processing can be written as :

$$r(t) \propto f \ln \frac{N(t)}{N_0} \tag{3}$$

Thus,

$$ds \propto f \ln \frac{N(t)}{N_0} \tag{4}$$

Where $N(t)$ is the instantaneous neural recruitment and N_0 is the minimal neural recruitment for that perception.

Combining (1), (2) and (4), we get the expression for the subjective time interval :

$$ds = K\, f \ln \frac{N(t)}{N_0} dt \qquad (5)$$

Where K is a proportionality constant having dimensions of time and can be identified as the time constant for neural assembly (Treisman *et al.,* 1990).

Role of Attention in time perception

To judge duration we need to pay attention to that duration when we are directly required to respond to a duration estimate experiment. Prospective and retrospective duration judgments have yielded different variations of subjective duration with objective duration (Gruber *et al.,* 2000).

Psychological disorders like ADHD (Attention Deficit Hyper Activity Disorder) and schizophrenia lead to attention deficits and thus affect time perception (Droit-Volet, 2013). The neural systems responsible for spatial and temporal attention have been studied using PET (Positron Emission Tomography) and fMRI (functional magnetic resonance imaging) techniques (Coull and Nobre, 2008) which show activity in different brain regions corresponding to the neural correlates of attention.

This means that attention is a key factor in temporal judgment and has to be taken into account in finding the expression for subjective duration in terms objective time. Since, definite neural correlate have been identified in attention tasks(Coull *et al.,* 2004), the total number of neurons activated during a period of attention must be different from that in the period of no attention or comparatively less attention. What kind of a function $N(t)$ can be of attention which itself is a time dependent function?

To explain psychophysical interactions observed experimentally by Radin *et al* (Radin *et al.,* 2012) and Pradhan (Pradhan, 2015) has proposed an attention function $a(t)$ defined by:

$$a(t) = \begin{Bmatrix} 1, full\ attention = a_{max} \\ 0, \ \ no\ attention = a_{min} \end{Bmatrix} \qquad (6)$$

which can be any appropriate function of time during the interval concerned obeying these two extrema e.g. $sin^2 \omega t, cos^2 \omega t, \omega = 2\pi f$ $=$ angular frequency) or a square wave or triangular wave of unit height etc.

It is common experience that when attention is perfectly directed $(a(t) = 1)$ towards an object, event or a process, the subjective time seems to pass extremely slowly compared to the objective time (Tse, 2004), but when attention is less or sporadic $(0 \leq a(t) < 1)$ during an interval, the subjective time seems to pass faster compared to the objective time. These facts can be incorporated into eq. (5) by writing

$$N(t) = N_0 + N'(t) \qquad (7)$$

where $N'(t)$ is the attention dependent contribution to $N(t)$ and is given by

$$N'(t) = -N_0' \ ln\,\{a(t)\} \qquad (8)$$

where N_0' is the basic neural recruitment for attention and $0 \leq a(t) \leq 1$.

Putting this in eq. (5) we get the final expression for subjective time interval

$$ds = Kf \ln[1 - \frac{N_0'}{N^0} \ln\{a(t)\}]dt \qquad (9)$$

Attention as a function of neural recruitment

It is seen that when neural recruitment is minimum(N_0), it corresponds to $a(t) = 1$ and hence to maximum attention. But at the other extreme, zero attention to a task renders it meaningless whether it is time perception or anything else. This means that meaningful attention values can only tend to zero but cannot be exactly zero.

Inverting eq. (8) we get for $a(t)$

$$a(t) = \exp\left[-\left(\frac{N(t)-N_0}{N_0}\right)\right] \qquad (10)$$

Thus zero attention would correspond to a large value of $N(t)$ such that there is exceptionally large neural recruitment but lack of attention leads to no perception.

Centralized verses distributed timing mechanisms

Because of the involvement of neuronal assemblies in different brain areas in the time perception (Muller and Nobre, 2014), it has been proposed that timing mechanism may be different for different assemblies such as the hippocampal, cortical, basal ganglia and so on. Depending on the modality the assemblies may be having different frequencies of neuronal oscillations as well as different recruitments. However, when a duration judgment is made it is neither hippocampal nor striatal nor cortical but is a unique subjective estimate, which may be taken to be the mean of all these distributed estimates.

If f_i, N_i and a_i are respectively the frequency, recruitment, attention corresponding to the *ith* neural assembly out of a total of n assemblies then, the subjective estimate ds becomes

$$ds = \frac{1}{n}\sum_{i=1}^{n} ds_i \tag{11}$$

$$\Rightarrow ds = \frac{1}{n}\sum_{i=1}^{n} K_i f_i \ln\left[1 - \frac{N'_{io}}{N_{io}}\ln\{a_i(t)\}\right] dt \tag{12}$$

Where K_i is the time constant for the *ith* neuronal assembly.

A finite duration running into minutes to hours may, in general, have time varying frequencies $f_i = f_i(t)$ can be obtained by integration:

$$s(t) = \int_0^{s(t)} ds = \frac{1}{n}\sum_{i=1}^{n}\int_0^{t} \mathrm{dt}\ K_i f_i(t) \ln\left[1 - \frac{N'_{io}}{N_{io}}\right] \tag{13}$$

Thus, from this final form of the equation for subjective duration, it is possible that all the distributed timing mechanisms finally lead to giving a single subjective estimate of the as if to finally favor a centralized timing (Treisman, 1990). This of course leaves open the binding problem (Feldman, 2013) and begs the question: what agency does this averaging and in which area, if any, of the nervous system?

Conclusions

We have derived a formula for subjective time incorporating the neural recruitment and attention as factors influencing time perception. The flow rate of subjective time increases or decreases depending on the decrease or increase in attention. The neural processing rate which has been proposed to be responsible for time perception through metabolic rates (Dyson, 1979; Gruber *et al.,* 2000) has been expressed here in terms of the frequency of neuronal oscillations and the neural recruitment in an assembly. These oscillation frequencies are the frequencies of the different bands, which have already been established experimentally.

Emotional states such as anger, fear and sadness etc. have been known to affect time perception as also neurological and physiological disorders like schizophrenia, ADHD (Teixeira *et al.,* 2013; Fontes *et al.,* 2016; Droit-volet, 2013). These factors can be accommodated in the proposed formulation as long as the appropriate choice of $a(t)$ and $N(t)$ suffice for the purpose.

We note that the approach taken here deals with the total neural recruitment without any detailed neural network analysis but the formula arrived at (eq. 13) can be verified by determination of $K_i, f_i,$ and $N_i,$ for different assemblies in any specific experiment.

Further the linear variation (eq. 1) of subjective duration with objective duration in the interval from $10^{-3}s$ to $10^{-2}\ s$. Hence eq. 13 may take different form for larger time intervals.

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