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Consciousness and subjective time: a plausible auditory approach

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ABSTRACT

The perception of time is an indispensable facet of human consciousness, and may in fact be dynamically present in primates and other species, albeit with different manifestations. Moreover, contrary to the physical measures of time, cognitive temporal perception may be subjectively affected by both internal and environmental cues. Here we review the evidence for the potential role of the auditory system in shaping the cortical measures of time, and propose possible auditory methods for studying this aspect of consciousness.

CONSCIOUSNESS AND TIME

Humans are one of the few species which possess an ability to form a rational and highly dynamic relationship with their environment. In doing so, we utilize five input-gathering sensory systems to assay the world around us on an iterative basis that is subject to significant internal 'interpretations' [1]. We possess, for example, very palpable internal notions of space [2]. A unifying factor which underlies these outside-inside perceptions is our purely internal measure of time. The brain is adjusted to a nearly 24-hour cycle, i.e., the circadian rhythm, which is controlled at the suprachiasmatic nucleus (SCN) of the hypothalamus [3]. In this case, 'zeitgebers' or 'time-givers', such as the light-dark cycle, act as exogenous cues [4]. However, short-term time calculations required for sensory processes may not necessarily rely on and/or be under a strict influence of the circadian rhythm system, and may therefore be distributed across the sensory cortices. Furthermore, hormones, such as melatonin, and the light-dark cycle would not be relevant in this concise temporal context. It is therefore conceivable that short-term time processes are not subject to conventional influences and do not follow a naturally 'fluid' course. Given that these processes are inherently tied to the notion of consciousness, some may in fact argue that 'fluidity' would necessitate a loss of consciousness. Moreover, if our temporal perceptions were not subjective and acted as a precise clockwork, a chiasm may be created in the mind of a human observer which some, in the field of robotics, have termed the 'uncanny valley' [5], whereby the exact clockwork mechanism, although very human-like in all aspects, lacks an ultimate 'humanly' essence.

Based on the premise described above, and if subjective time perception may be influenced by mechanisms different than the conventional notions of time, how could one define the relevance of subjective time in day-to-day human behavior? By the time we become conscious of a moment, it has passed. Therefore, consciously living in the moment (i.e., here and now), by definition, is impossible. It follows then that there must be a progression of barely-perceivable moments to attain consciousness. Hence, the mind may possess a temporal landscape and/or a *time of time*. The importance of understanding this aspect of human sensory cognition will affect many disciplines, but since no systematic research has been undertaken in this regard, a number of disparate observations in the neuropsychological and physical fields must be combined to contemplate plausible outcomes and approaches.

To begin with, the most precise temporal processing in mammals is related to sound localization, whereby medial superior olivary (MSO) neurons can determine the time of arrival of low-frequency sound signals at a microsecond scale [6]. Thus, the auditory system, and specifically the signal processing which takes place in the auditory cortex and thalamocortical pathway, may arguably be the most conducive system to allow for an examination of sensory time cognition. It has been determined that virtually two different hearing systems exist in mammalian brains, where low frequency signal processes rely on temporal information and, on the other hand, spectral cues are used for high frequency sounds. Importantly, the anterior insula and subjective time passage have also been variously linked to audition [7, 8]. Moreover, these processes may change significantly as the individual develops from infancy to adulthood [9], and it has been shown that the loss of dopamine in older-age adults suffering from Parkinson's disease may alter the speed and efficiency of signal processing [10]. Hence, developing methods towards this subject may benefit from the utilization of low frequency input signals and sample populations with significant age variation.

If an experimental paradigm based on the auditory system were to be proposed, how could the different facets of (i) the context (external environment), (ii) the internal cognitive processes and (iii) the outputs measured from the test subject by the experimenter be reconciled in an encompassing hypothesis? Here we put forth a model termed the cognitive criticality ring (CCR) **(Figure 1)**, in which each component of the system is critical to the next component, and the circuitry must be closed for a coherent consciousness (by the subject) to be achieved. Based on this model, the context is formed by the five sensory stimuli (of which sound is the most important insofar as the topic concerned) and an embedded perception of the self. In the first tier of cognition, a raw output based on 'default' anatomical computation is produced. Here, the diurnal cycle is dominant, and we can define an anatomically-necessitated time (ANT) to exist at this level. The ANT could be in the range of hundreds of milliseconds, be synonymous with alpha waves in electromagnetic oscillations of the brain and/or be represented by saccades. If the rate of change in the context (dC/dt) is above an unknown threshold (i.e., the context is fast-changing), the raw output immediately becomes the final output of the individual without passing through the filter of the conscious self. However, because the output becomes part of the context of the next moment, the conscious self will become aware of it in the next round of the ring. It follows that if *d*C/*d*t was below the threshold, the raw output would go through the filtering of the self and become more refined. In this tier, the conscious self would have a perception of the ANT which may be quite different than the actual ANT. We define this perception of ANT as consciously-necessitated time (CNT).

Based on the CCR model, in order to analyze short-term time processing in the auditory system, differences must be observed based on a given pallet of stimuli and therefore complex and nuanced signals should be incorporated in any future experiment. For this purpose, we propose a hierarchy of scrutiny **(Figure 2)** in which each level should be manipulated if an effect on the subjectiveness of time is to be recorded precisely. Normal speech, for example, contains multiple levels of temporal modulation [11] which is subsequently parsed into its components, and it has recently been reported that different neurons are responsible to register the beginning and end of a word or tone [12]. This suggests that separate neuronal activities must be integrated in a temporally-dependent manner to comprehend a sound unit in its entirety. Other investigators have proposed that different neuronal populations cooperate in a multiplicative manner to produce the final unified outcome [13-15]. Based on these findings, in addition to low frequency tones, short sentence and phrase structures which possess suitable gaps could be developed to allow for subtle time difference measurements. However, relying on input variations alone may still be insufficient for real observations to be made [16]. To that end, the whole of the subject's perceptual environment, with the auditory signal acting as an important component, should be considered. For example, it is known that perceptual impression changes even if a sound sequence is constant. Also in speech production, formants, which are based on well-defined time intervals [17], cannot be assumed to invoke an exact mimicry in the auditory perceptual system. A question may arise as to whether any mismatch between the input and the perception is volitional, and if not, whether measuring time processing differences is meaningful in this context. The experiments of B. Libet in measuring conscious intention and the notion of 'free will' may be relevant here [18], whereby he argued that conscious experience is manufactured by the brain after the event and is in essence "retro-inserted … into the stream of consciousness" [19]. This notion is in line with our proposed CCR model and could also be framed in the context of top-down and bottom-up forces, and we could ask how synchronous the processes in these two pathways may be.

An obvious choice related to the subject's environment that could complement the tonally-modulated input signals would be emotion. It is well appreciated that perceptions change due to 'emotional' variations, although it should be noted that no consensual definition of emotion exists across the medical and psychological fields. In fact, the progression of time, in a strict physical sense, may indeed be distantly related to emotion. Specifically, the standard explanation of the advance of time provided by the Austrian physicist L.E. Boltzmann in 1875 correlated the growth of disorder (entropy) and the second law of thermodynamics with the progression of time [20]. His equation, known as Boltzmann's entropy formula, posited that $S = k \log W$ (EQUATION 1), where entropy, S, is related to the logarithm of the number of arrangements of the components of a thermodynamic system, W, and Boltzmann's constant, k. Therefore, the continuous growth of entropy from an initial low point in the Universe up to the present can be thought of as 'time progression'. Although we cannot directly superimpose this image of time to our daily temporal cognitive transactions, it would not be far-fetched to claim that mental processing speeds and temporal perceptions of sensory inputs change as mental load, such as stress and disordered feelings, is varied. In addition to a few reports in the psychology literature pertaining to the general subjectiveness of time perception [21-24], the most relevant and, as far as we are aware, only recent work in this direction has been performed by V.L. Simoens and colleagues who demonstrated that experimentally-induced stress significantly affects the duration of mismatch negativity (MMN) tests, which are a measure of the detection of rare deviant sound stimuli within a series of standard stimuli [25]. As they state in their manuscript, "the amplitudes of the responses to sound duration change, but not to other changes, were smaller during the stressful conditions than during nonstressful conditions." Despite an expectation which may arise from evolutionary hypotheses regarding the effects of stress on sensory acuity, acute stress has been shown to reduce auditory sensitivity [26].

In summary, it seems plausible that developing protocols which utilize believable mental load scenarios to measure temporal perceptual variations to unattended low frequency sound signals and, at later stages, more nuanced auditory inputs, could be fruitful in establishing a new field of study in consciousness and cognitive auditory psychology.

A POTENTIAL AUDITORY METHODOLOGY

The auditory system largely decomposes frequency in the cochlea [27], where mechanical Fourier transform takes place. Other decomposition events of the sound wave's envelope and fine structures occur at later stages in the auditory brainstem [28], followed by the basal ganglia, parts of the right prefrontal cortex and the right inferior parietal lobe [29]. If an auditory methodology is to be developed, the interface between the raw anatomical output and the conscious self, before any higher-order cortical processing, should be analyzed. Here, the premises of the auditory middle latency response (MLR), which is a series of auditory evoked potentials occurring between 10 and 80 ms after the onset of an acoustic stimulus [30] could be investigated. This could be put into context with what is known about the entire span of sound duration encoding, which takes place within 250 ms after stimulus onset [31]. Specifically, an implementation of gap detection techniques [29, 31] could be utilized in this regard, whereby detection thresholds of subjects for very short silent gaps (6 to 24 ms) within a pure tone of approximately 500 ms in duration are measured using electroencephalographic (EEG) recording of auditory event-related potentials (ERPs). Various permutations of this test, in the form of a number of different mismatch negativity (MMN) tests, have been used previously to measure an automatic response without conscious attention [32]. It is important to state that synchronization in EEG recordings could be a very interesting phenomenon which may be observed in these tests. Moreover, if study participants are asked to produce an output (e.g., related to eye movement) based on a set of auditory stimuli which would then be used to measure time processing differences, how would the reaction times confound any plausible interpretation? In this realm, i.e., in characterizing a suitable measurable output, the source-filter model of speech production [33] could be used to characterize a feature of speech as an impressionable output which could be measured (interface between cognition and oral motor control).

How could the context of the subject be assayed? Ideally, if the auditory cues could be in the form of language or musical tones on the Pythagorean diatonic scale, for example, the context would be superimposable on the subject's true external milieu. However, these contexts will be too complex to interpret at the beginning. Thus, we have developed a classification system called 'Contextual Indicators' which could initially shape the way in which we include a context in the design of our experiments. For example, we classify the abovementioned contextual variables as 'Layer 2 Contextual Indicators' (L2CI), which will be beyond the scope of preliminary experiments. More subtle contextual variables that may also be essential in the processing of time, such as mental load and stress, spatio-visual indicators in the surrounding environment, noise or hearing of the self, could be classified as 'Layer 1 Contextual Indicators' (L1CI), and in line with this hierarchy, we classify the state of consciousness as a 'Layer 0 Contextual Indicator' (L0CI). The initial focus could be on L0CI (the ground state of contextual indicators) and L1CI in the hope that this classification will bring us closer to an understanding of the importance of and interplays between these two layers, whose features are many folds more comprehensible than the L2CI interactions. More specifically, the Layer 1 context of these experiments may be mental load as exemplified by psychosocial stress. Researchers in the field of stress psychology have identified four recipes for stress, namely (i) novelty, (ii) unpredictability, (iii) threat to the ego and (iv) a sense of loss of control [34]. The neurological effect of these stimuli is mediated by a cascade of molecules starting from corticotropin-releasing hormone (CRH) to adrenocorticotropic hormone (ACTH) and glucocorticoids (GCs), and finally resulting in a stress response in the hippocampus. Nevertheless, many other effects outside of the hippocampus are expected to take place as a result of the stress response, and it is plausible that one such aspect will be related to time cognition. To create stress, one could utilize the Trier Social Stress Test (TSST) developed by Kirschbaum, Pirke and Hellhammer [35] which asks subjects to perform an actual public speech in addition to a demanding mental task in front of a critical jury. Methods should also be developed to accurately quantify acute stress in relation to preattentive temporal auditory processing. The use of salivary cortisol level (unbound fraction of plasma cortisol) by Simoens and colleagues [25] may not necessarily reflect the amount of stress necessary to invoke perceptual time changes, and diurnal cortisol cycles are another layer of complexity which has to be taken into account.

Recent developments of rodent models may be helpful in the initiation of experiments without the need for human subjects. For example, experiments detailing procedures for recording from the left primary auditory cortex of anesthetized rats are highly adaptable [12]. The investigators described generating a tone array of 22 frequencies (logarithmically spaced from 1 to 40 kHz) of 400 ms duration interspersed with 5 ms 10%-90% cosine-squared ramps for gaps, in a free-field configuration, which led to measurable signals in the anesthetized rats. These conditions could be adapted to determine response variation in the context of stress, such as intravenously-injected cortisol.

As mentioned previously, in addition to selecting a sensory system and defining the appropriate context for the system to be measured for cognition of time, a third related variable must be considered, namely the level of consciousness at which the measurements are performed. Generally speaking, two levels of consciousness could be defined: primary, which includes simple awareness, perception and emotion; and secondary, which depends on higher (self-reflective) awareness, abstract thinking, volition, language and metacognition [36]. At the cortical level, three objectively identifiable states can be defined: waking, non-rapid eye movement (NREM) sleep and rapid eye movement (REM) sleep, with REM sleep having features of primary consciousness. However, it may be difficult to rely solely on these classifications, since it is well-understood that a basal level of consciousness can be detected even in so-called ‘vegetative state’ patients [37, 38]. At a neuronal level, brain activity ranges from low-frequency slow cortical potentials (SCP), with groups of neurons activated every 10 seconds, to neurons firing at more than 100 cycles per second. The latter group of neurons is in synchrony with the phases of SCP, and it may be a shifting of the activity balance between these groups of neurons that may determine the state of consciousness, attention and concentration [39].

An analytical tool which may be beneficial to complement the above experimental procedures, and that may be expected of studies of this nature to be funded, would be the use of functional magnetic resonance imaging (fMRI), possibly coupled to a clustered-sparse temporal acquisition (CTA) design [40]. Using this tool it may be possible to connect consciously-necessitated time (CNT) with the newly evolving field in cognitive neuroscience of the brain's default mode network (DMN), which consists of a collaborating group of brain regions which provide background activity and processing at times of inattentiveness and mental drift [39, 41]. Uncovering these connections may bring us closer to the inherent internal notion of time, and whether the mental time-scale is already predetermined prior to an actual sensory perception in its anticipation. However, there is a fundamental assumption in the use of fMRI which should not go unexplored. Namely, as fMRI techniques rely on deoxygenated and oxygenated blood as a measure of neuronal activity, it would be a leap of theory to assume that neuronal activity and firing are directly correlated to the internal notion of time. Furthermore, we cannot provide any answer at present as to whether neuronal signalling and oscillation are the underlying mechanism for short-term cognitive timekeeping.

In summary, if we imagine the auditory system at the center of a cognitive ring in order to achieve a better understanding of time cognition, observing subtle variations in the system initially using gap detection and MMN techniques in a suitably-selected cohort, using the L0 and L1 contextual indicators as the penumbra of the system, could represent the general framework with which to begin an investigation into this facet of consciousness.

CONCLUDING REMARKS

It is evident that the development of a research protocol towards the elucidation of time cognition will require (1) the careful analysis of the features of a suitable sensory system, (2) the selection of appropriate contexts leading to different manifestations of sensory cognition, and (3) the attentive and conscious state of the study subjects, which in itself is the ground state of other contextual features. Here we have proposed that cognitive load, which varies with internal and external stimuli, may influence the inherent cortical measures of time, which in turn may affect immediate dependent inputs and outputs, such as audition and speech production **(Figure 3)**.

The significance of the subject of consciousness and time is manifold. To begin with, it would bring us one step closer to understanding the nature of the conscious self and its perception of the environment around it, and may shed light on whether the notion of time in the brain could be viewed as an emergent property. Not only would a better understanding of time cognition lead to the decipherment of some aspects of higher mental faculties in humans [42], but it is anticipated that it could lead to new thinking regarding different speech conditions and their inherent components of auditory temporal perception and subsequent impressionable outputs [43, 44].

Nevertheless, many challenges still remain. For example, multisensory integration mechanisms in mental load pretexts are known to exist [45], and it would be necessary to determine different control conditions if the perception of time is to be studied from the perspective of a single sensory system. Furthermore, we should acknowledge that a research path towards the understanding of an elusive feature of cognition may indeed prove 'fruitless' upon the exhaustion of various avenues of investigation. However, such a search in and of itself will be greatly beneficial to the fields of neuroscience and psychology in defining the limits of existent methods in probing certain scientific questions. Such endpoints could be exemplified by the following passage stipulated by N. Chomsky: "We might think of the natural sciences as a kind of chance convergence between our cognitive capacities and what is more or less true of the natural world. There is no reason to believe that humans can solve every problem they pose or even that they can formulate the right questions; they may simply lack the conceptual tools, just as rats cannot deal with a prime number maze" [46]. In the same line, we could ask to what extent consciousness (i.e., the experimenter) can be introspective of itself (i.e., of another conscious being or the subject). A review by P. Gloor as to why a satisfactory explanation of consciousness may never be possible [47] is relevant in this case. Overall, although it is difficult to predict whether or not the proposed and similar research areas would lead to an ambiguous eventuality, we believe it is important to recognize the significance of the question and the quest even in the absence of the predicted results, and to frame the individual questions in such a way that they could be unambiguously accepted or refuted.

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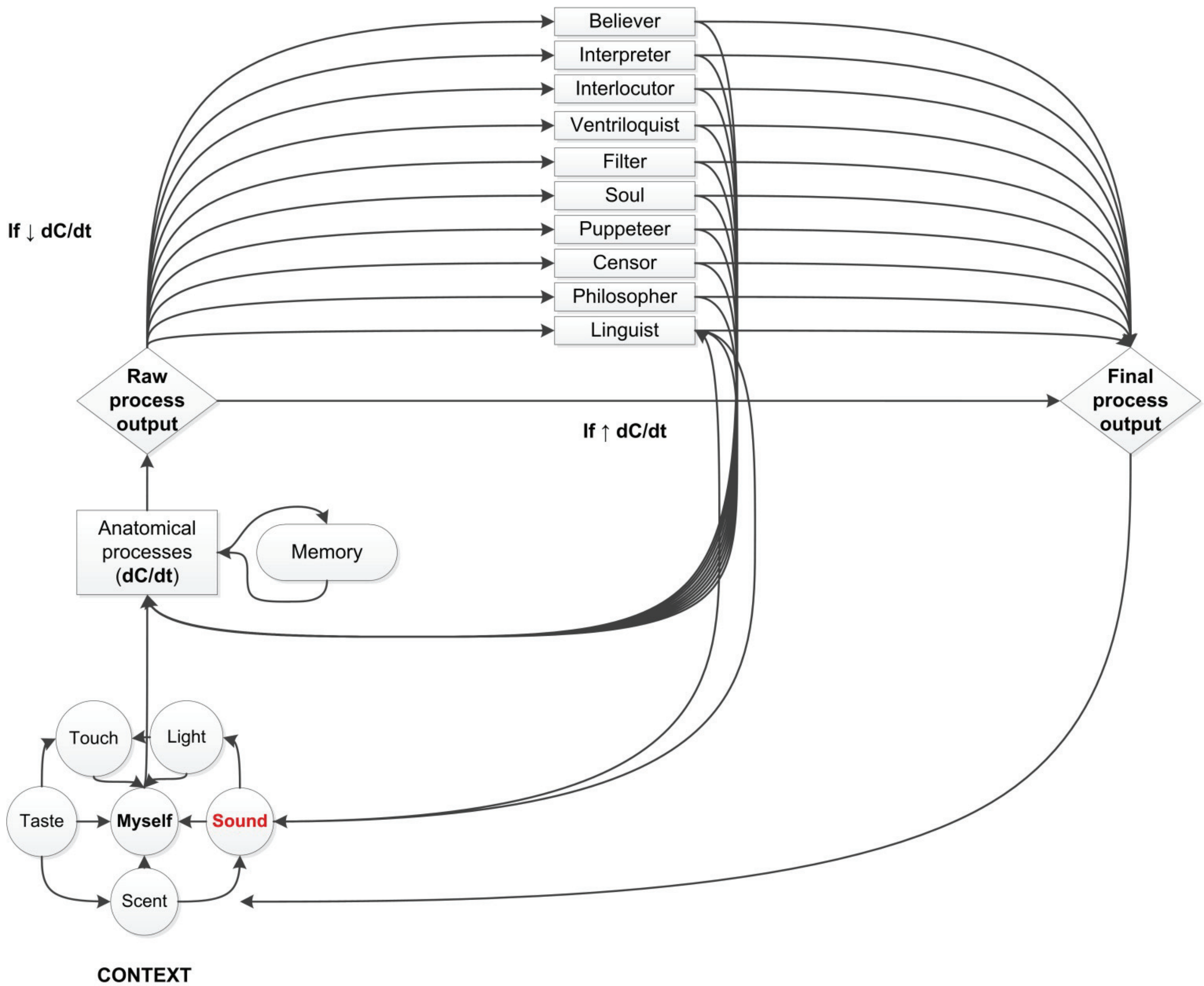

Figure 1. Cognitive Criticality Ring (CCR) model. Based on this model, the rate of change of the context (*d*C/*d*t) would determine the level of involvement of the conscious self in producing the individual's final outputs. The anatomical processes could be defined to code for an anatomically-necessitated time (ANT), whereas the conscious self (i.e., ventriloquist, interlocutor, etc.) may determine the 'subjective' consciously-necessitated time (CNT).

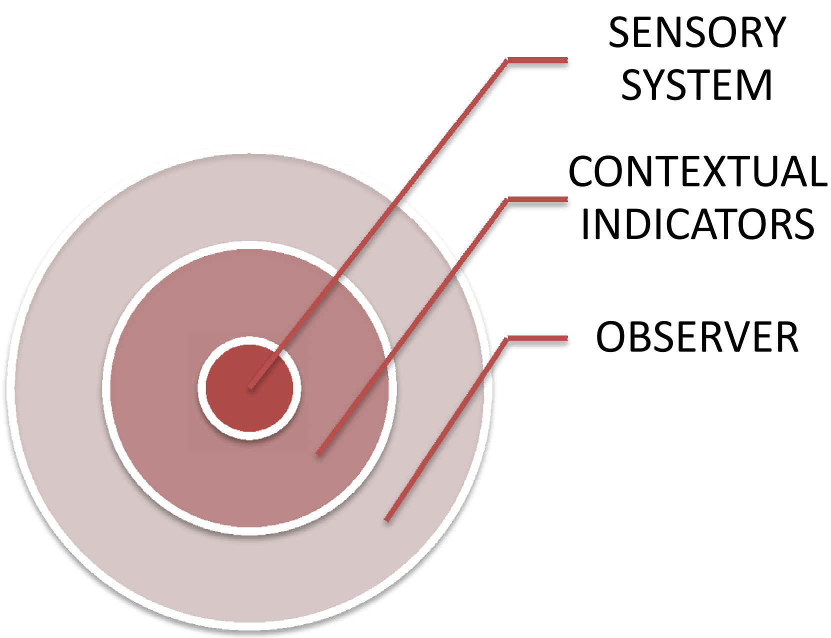

Figure 2. Hierarchy of scrutiny. To measure any aspect of the sensory (auditory) system, we can define the perceptual and cognitive facets of the participants as a core property, which cannot be directly measured by the experimenter (observer). Sets of 'contextual indicators' can be considered which shape the operation of the system and should be included in the design of any experiment.

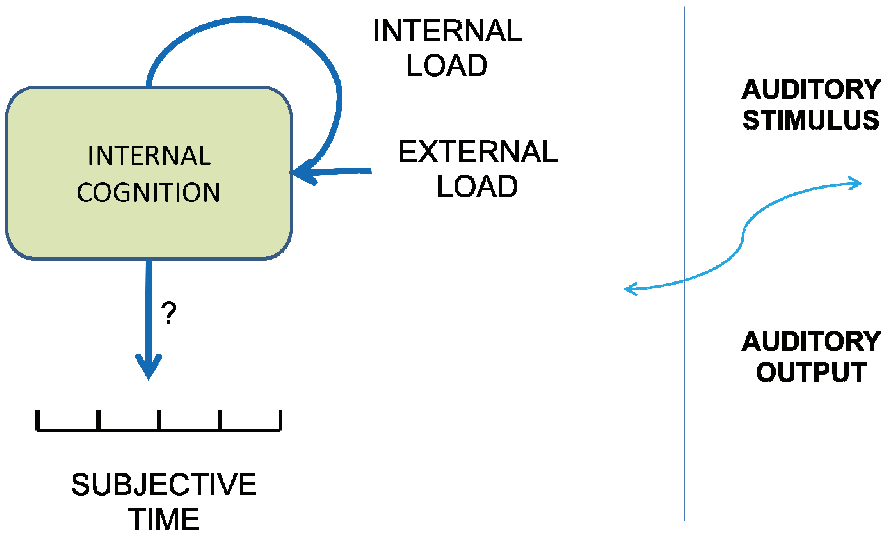

Figure 3. Time cognition hypothesis. Auditory stimuli encounter higher cognitive processes after passing through the initial stages of the sensory perceptual system, at which point mental load could alter the eventual perception of the stimuli. This may in turn render the perceived time interval of the stimuli variable depending on the context of the conscious self, which may subsequently alter a reactionary output to the stimuli.