Experimental and Computational Investigation of the Effect of Caffeine on Human Time Perception

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Abstract

Perception of time is an active process that takes place continually. However, we are yet to learn its exact mechanisms conclusively. The temporal bisection task is ideal to investigate the circuitry underlying time perception. Caffeine, a commonly used stimulant, has been known to play a role in modulation of time perception. The objective of this article is to explore the role of caffeine, a neuromodulator, in the perception of time in human beings by conducting suitable experiments. The experiment shows that an expansion of time is perceived by subjects after caffeine ingestion and that caffeine has an accelerating effect on our time perception system. Additionally, we present a preliminary 2-step decision model that fits the results of the experiment and potentially gives insights into the mechanisms of caffeine. We conclude by pointing out future directions towards a more biologically realistic computational model.

Keywords: Caffeine; Timing; Perception; Temporal bisection; Computational modeling; Decision making

Introduction

Time perception is essential for human survival. It is a multilayered process which covers a wide range of timescales, from microsecond estimation to the maintaining of the circadian rhythm. However, there is still a lack of consensus on the mechanisms behind temporal perception.

Researchers have proposed several qualitative and quantitative models to explain the data obtained in various temporal judgement experiments (Jeffress, 1948; Machado, Malheiro, & Erlhagen, 2009; Oprisan & Buhusi, 2011), with Internal Clock Theory being one of the most widely accepted ones. It suggests that our perception of time highly relies on the clock speed. Akin to an internal clock, the theory of scalar expectancy postulates that a group of oscillating neurons would work as a pacemaker and help in the judgement of durations (Gibbon, 1977; Gibbon, Church, & Meck, 1984; Wearden, 1991). As described in the information processing model in Figure 1, a pacemaker oscillates at a mean frequency and produces regular clock pulses, which are gated to an accumulator in working memory via a switch. The accumulator records and stores the number of pulses from the onset of the stimulus. A comparator decides if the current record in the working memory is close enough to the reference memory and responds accordingly. If the response is reinforced, the time value recorded in the working memory is stored in the permanent reference memory for reinforced values.

In the previous findings, it has been argued that the nuclei involved in the circadian rhythm in the brain participate in our perception of time (Cheng, Meck, & Williams, 2006). Findings from psychopharmacological studies also suggest that caffeine and other psychoactive drugs affect these nuclei (Dunlap, 1999). Further, literature also shows that dopaminergic drugs influence the speed of internal pacemaker (Buhusi & Meck, 2002). In general, caffeine has been known to have effects on other cognitive processes like vigilance, attention, memory and other cognitive functions (McLellan, Caldwell, & Lieberman, 2016). There have been a wide range of studies that have investigated the role of caffeine in time perception. However, the findings are still largely inconclusive (Hussain & Cole, 2015; Favila & Kuhl, 2014; Borota et al., 2014).

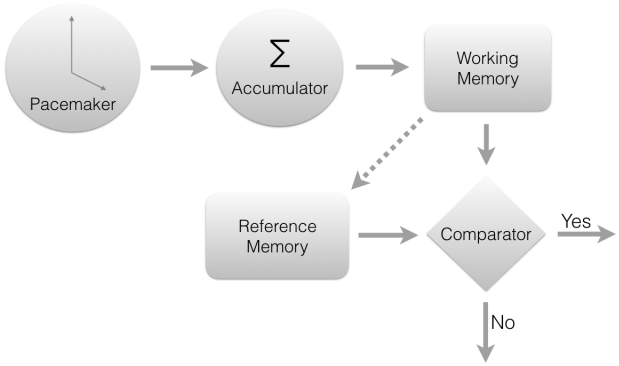

Figure 1: Information-processing model for Scalar Expectancy Theory (adapted from SET, Gibbon (Gibbon et al., 1984)).

Given the above theoretical basis, we hypothesized that the administration of caffeine would cause a difference in perception of duration by influencing the speed of the internal pacemaker. The aim of the current experiment is to explore the role of caffeine, a neuromodulator, on time judgement via suitable experiments and to design a computational model, based on decision-making, to investigate the possible mechanisms underlying the perception of duration.

The temporal bisection task was initially used in 1977 to study temporal discrimination in rats (Church & Deluty, 1977). As the task requires several time-dependent cognitive functions, such as the comparison of durations, it is

an ideal technique to study perception and processing of time (Wearden, 1991; Allan & Gibbon, 1991). We have thus chosen the temporal bisection task as the paradigm to investigate the modulation of judgement of duration by caffeine.

Experiment

Participants

The study sample consisted of 24 adults (8 females and 16 males, mean age = 21 years, SD=0.89), who were students of the International Institute of Information Technology, Hyderabad, India. All participants gave informed consent prior to the experiment. A Python script was used to randomly assign each subject to either the control group (0mg caffeine) or the experimental group (200mg caffeine). All participants were right-handed and had normal or corrected-to-normal vision.

Materials and apparatus

Each participant was tested individually in a quiet room in the institute. The experiment was presented on a Macintosh laptop, which controlled the presentation of the experimental stimuli and recorded the participants' responses with Psychopy (Peirce, 2009). The participants were asked to convey their response using the 'S' and 'L' keys on the keyboard, for 'short' and 'long', respectively. The stimuli used for representation of duration in the bisection task were a white rectangle (during the training phase) and a white triangle (during the testing phase) on a black background, presented in the center of the screen. During the training phase, post-response feedback was presented as white text on a black background. The feedback was presented for 2s in the center of the laptop screen (Droit-Volet, Brunot, & Niedenthal, 2004).

The participants were administered plain or caffeinated milk orally, in the control or experimental group, respectively. The participants in the group were administered a moderate dose of 200mg caffeine since it has been observed that caffeine enhances performance in several cognitive tasks with minimal side effects, in doses up to approximately 300 mg (Lieberman, Tharion, Shukitt-Hale, Speckman, & Tulley, 2002).

Peak plasma levels of caffeine are found in the body about 30 minutes after ingestion (Blanchard & Sawers, 1983), following which the effects are felt substantially for approximately 30 minutes (Barry, Clarke, Johnstone, & Rushby, 2008). Hence, the experiment was conducted 20 to 25 minutes after the administration of plain or ceffeinated milk. One session of the experiment lasted for a duration of about 35 minutes.

Experimental Procedure

The temporal bisection task comprises duration judgement between two reference durations. The task involves subjects classifying various probe durations as either 'short' or 'long'. The conscious realm of time perception occurs in the range of seconds and minutes (Mauk & Buonomano, 2004). Effects of emotion, age, etc. on time perception have been studied via temporal bisection tasks in this time range (Droit-Volet et al., 2004). In order to see the effects of caffeine on this time range and to investigate conscious time estimation, we have chosen 400ms (short standard) and 1600ms (long standard), as the reference durations for our experiment.

The temporal bisection task consisted of two phases: training and testing. The training phase, in itself, was composed of three sections. In the first section, participants were presented with the short(S) and long(L) standard stimulus durations. Each standard was initially presented five times each and the subjects were asked to observe carefully. In section two of the training phase, the participants were presented with 5 trials each for S and L, in randomised order. In each trial, after the presentation of stimulus, the participants were asked to decide if the given stimulus was short or long by pressing the 'S' or 'L' keys, respectively. On responding, they were presented with a feedback, informing them if their response was accurate or not. The feedback message lasted on the screen for a duration of 2s. In section three of the training phase, the participants were again presented with 5 trials each of S and L in randomised order, similar to section 2 and asked to respond if they perceived the duration as short or long. However, this time, they were provided with no feedback. The inter-stimulus interval (ISI) in this phase was fixed at 1s. After the completion of section three, participants with a score higher than 7 correct trials out of 10 (in section three) were selected for the testing phase. The testing phase was conducted after a break of 1 minute.

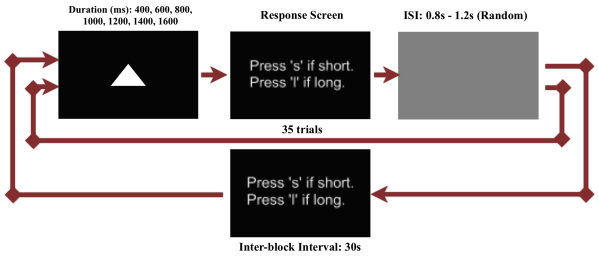

Figure 2: Schematic diagram of the testing phase.

In the testing phase, as depicted in Figure 2, the participants were presented with 5 intermediate probe durations, 600ms, 800ms, 1000ms, 1200ms, 1400ms in addition to the 400ms (S) and 1600ms (L) reference durations, in a randomised order and asked to respond if they perceived the given duration as short or long (Droit-Volet et al., 2004). The inter-stimulus interval was randomly chosen between 0.8s and 1.2s. No accuracy feedback was presented in the testing phase. Each block consisted of 35 trials, i.e. each probe duration occurred 5 times in a block in a random order. After each block, the participants were asked to take a 30s break. The participants were presented with 10 such blocks.

Results and Analysis: Experiment

For each participant, the proportion of 'long' responses was calculated for each probe duration. In Figure 3, the proportion of 'long' responses from all participants in both groups has been plotted against the probe durations. The point of subjective equality (PSE) is the stimulus duration for which a subject recorded a response of 'long' with a 50% probability. The PSE was calculated for each participant by fitting a Weibull curve to the plot of proportion of 'long' responses vs probe duration. The PSEs for the 12 participants in the control group ($M = 1.137s, SD = 0.118$) was found to be generally higher than in the experimental group ($M = 0.929s, SD = 0.140$). An independent samples t-test revealed that there was a statistically significant difference between the two groups, $t(22) = 3.76, p = 0.001$.

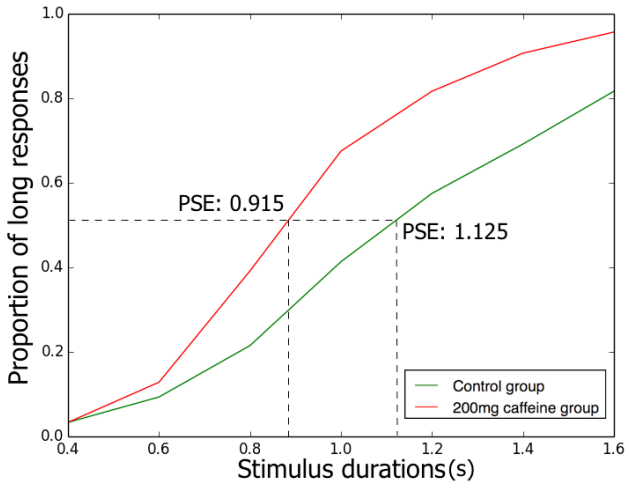

Figure 3: Proportion of 'long' responses as a function of stimulus duration, by subjects from the control and experimental groups. Also, the PSEs of both groups are depicted (not to scale).

Discussion: Experiment

An independent samples t-test showed that the PSE for the participants in the two groups remarkably varied from each other. This allows us to conclude that the administration of caffeine leads to a notable change in the perception of duration. The mean PSE of the 12 participants in the control group is higher than the mean PSE of the participants in the experimental group. Moreover, as shown in Figure 3, a clear shift in the PSE of the experimental group towards the shorter reference duration is observed. This shift in PSE implies that for a given stimulus duration, there is a higher probability that a participant responds 'long' in the experimental group than in the control group. In other words, a given probe duration is perceived as longer by participants under the influence of caffeine. These results lead us to conclude that caffeine produces a perception of expansion of time in humans.

The scalar expectancy theory postulates that a pacemaker sends pulses at a mean frequency from the onset of stimulus, gated by a switch, to the accumulator. In the working memory, a comparator judges if the number of pulses accumulated is closer to a reference memory value of the short or the long standard and responds accordingly (Gibbon et al., 1984). In accordance with this information processing model, we can infer that caffeine could influence discrimination of temporal durations in one or more of the following ways.

- By increasing the frequency with which pulses are generated by the pacemaker. This would lead to a higher number of pulses getting accumulated for a given duration, due to which the comparator would associate it to be closer to the long reference duration.
- By causing distortion in the memory of the reference durations. Since the recall in the long-term memory has a higher variance, the interactions between these distorted representations of the reference durations would lead the working memory to make inaccurate comparisons, which could in turn result in increased 'long' responses.

Computational Model

The dataset obtained from the above experiment was modeled using a simple decision model that fits the data, although biologically infeasible. This computational model is a two-step Gaussian model which has only two free parameters and is capable of reproducing the characteristics of the empirical data. The memories of the short and long reference durations in the temporal bisection task are modeled using scalar Gaussian distribution. The Gaussian helps depict the inherent noise in human memory (Kopec & Brody, 2010).

Description of the Model

The model proposed by us comprises of two steps. In step I, the model determines if the given stimulus is one of the reference durations, in which case, it responds accordingly, or is an intermediate duration, in which case it moves to the second step in order to make a decision. In step II, the model computes the difference between the stimulus and its memories of both the reference durations, and responds according to the one which is lesser in magnitude (Kopec & Brody, 2010). Each of the two steps is explained in detail below.

Model Step I

The memory of each of the two reference durations is modeled as a Gaussian distribution over durations, with a mean equal to the reference duration, and a standard deviation proportional to the reference duration. This proportion, referred to as the coefficient of variation, is randomly chosen from a suitable range of values (discussed in "Results and Analysis: Computational Model" section). The height of the Gaussian distribution of a particular reference duration at a given stimulus duration is taken as the probability of the stimulus being labelled as that reference duration(pL and pS). As a participant can potentially classify the reference duration correctly

with 100% accuracy, discounting human error, the Gaussian distributions range from 0 to 1 (Kopec & Brody, 2010). We take the probability of a stimulus duration being labeled as 'intermediate' (pI), to be the sum of the probabilities of the two reference memory distributions at that stimulus duration subtracted from 1, i.e. $pI = 1 - (pL + pS)$.

If the probabilities of the 2 reference memory density distributions at the stimulus duration are approximately equal, then the model responds either 'short' or 'long' with an equal probability. Otherwise, a choice is made if a given stimulus is long, short or intermediate depending upon the values of their respective probability distributions, *pL*, *pS* and *pI*. If the stimulus is determined to be either the short or the long reference duration, then the model responds 'short' or 'long', respectively. If the stimulus is deemed to be 'intermediate', the model proceeds to step 2.

Model Step II

The model computes if the stimulus duration 's' is closer to either reference duration stored in memory and responds accordingly. The scalar Gaussian distributions for the short(TS) and long(TL) standards are used to model the reference duration values pulled from memory. One value ts is drawn from the TS distribution, and one value tl is drawn from the TL distribution. In order to model the shift in PSE brought about due to caffeine administration, the model is explicitly biased in this step towards responding 'short' or 'long', depending upon whether it's simulating the control group or the experimental group. The bias factor, B, is randomly picked from a certain optimal range (discussed below) depending upon the group. If $abs(ts - s) * B < abs(tl - s)$, then the subject responds 'short', and otherwise, the subject responds 'long'.

Results and Analysis: Computational Model

The model contains only two free parameters, the coefficient of variation (CV) of the two probability distributions used to model the reference memories, and B, an intrinsic bias factor influencing the decision process. The values for these parameters were chosen by testing the parameter space over a range of values ($CV\,range : 0.18 - 0.27$, $resolution : 0.01$; $Brange : 0.6 - 1.4$, $resolution : 0.1$). The data generated by a certain value of CV and B was evaluated on the basis of an independent samples t-test between the data generated by the model and the empirical dataset collected from the control group. It can be observed from the Figure 4 that the following range of values are optimal for the 2 parameters:-

- For experimental group, $CV : 0.23 - 0.26$ and $B : 1.0 - 1.4$
- For control group, $CV : 0.17 - 0.22$ and $B : 0.6 - 1.0$

The lesser the p-value, the more significant the difference between the simulated data and the data collected from the control group. Thus, Figure 4 shows that for low values of CV and B, the data generated by the model is significantly similar to the empirical data for the control group.

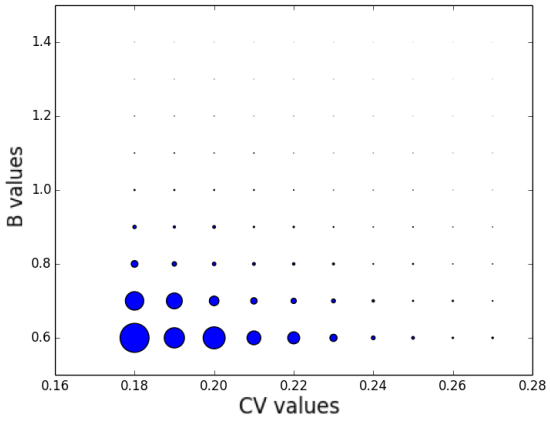

Figure 4: Bubble chart of p-values of independent samples t-test between the empirical data of the control group and the simulated data at varying CV and B values.

The final model generates a dataset over 12 runs consisting of 350 trials each, simulating 12 subjects each for both the control and experimental groups. At the beginning of each run, the values for CV and B are randomly chosen from the optimal range for the concerned group.

To analyse the data generated by the model, the proportion of 'long' responses was calculated for each probe duration for every run. The point of subjective equality (PSE) was calculated for each run by fitting a Weibull curve to the plot of proportion of 'long' responses vs probe durations. The PSEs for the 200mg caffeine group ($M = 0.907, SD = 0.022$), similar to the empirical data, was found to be lower than the PSEs for the control group ($M = 1.014, SD = 0.047$). An independent samples t-test between the data showed a statistically significant difference between the two groups, $t(22) = 6.736, p < 0.001$.

Discussion: Computational Model

From the statistics regarding the PSEs for the 2 groups, we can see that for corresponding groups, the simulated dataset as well as the human dataset gives similar mean PSE values. The standard deviation of the PSEs generated by the model is considerably lesser than the same in the human dataset. The higher variance in the human dataset might be due to human error, fatigue and slight inconsistencies in perception of time by different participants. The model tries to incorporate this variance between the PSEs for different subjects, by randomly picking a CV and B value, for each run, from the optimal range for the concerned group. Yet, this does not give rise to sufficient variation in the generated data as compared to the human dataset. However, the mean PSE is accurately simulated for both groups.

The independent samples t-test and the Weibull fit between the generated datasets for the experimental and control groups show that the model closely mimics human temporal judg-

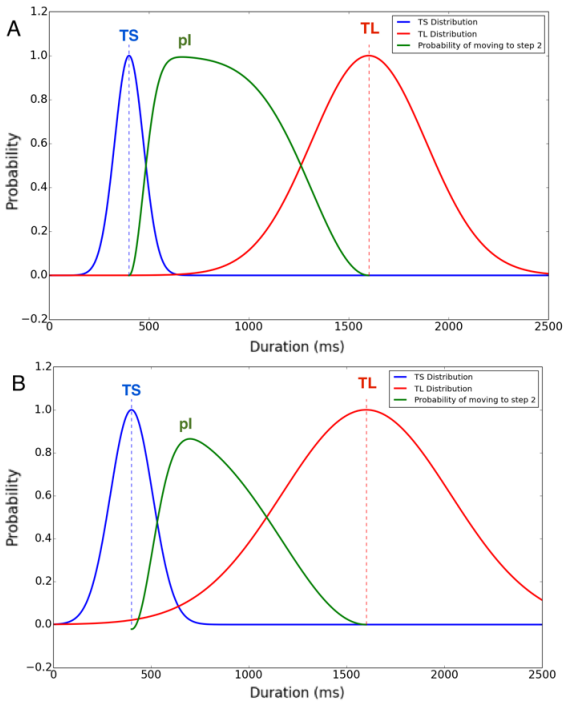

Figure 5: Effect of setting the parameter CV on the size of decision regions **A**. When CV is set to optimal values found for the 0mg group, the central region expands **B**. When CV is set to optimal values found for the 200mg group, the central region shrinks and there is more overlap of the Gaussians corresponding to the reference durations.

ment.

As mentioned in the previous section, high values of the parameters, CV and B, were found to be suitable to model the experimental group, while low values of CV and B were suitable to simulate the control group. These parameter ranges might lend us some insight into the mechanism of caffeine action, as discussed below.

In the model, the value for B increases or decreases the distance of the stimulus from the short standard, depending upon whether it is high or low. If the distance of the stimulus from the short standard is higher than the distance from the long standard, the model would respond 'long'. This explains why a high value of B is suitable for modeling the experimental group and vice versa. We can, therefore, infer that this range of values for 'B' can be indicative of the frequency of the pacemaker. A rise in the rate at which pulses are generated would lead to more pulses being accumulated for a given duration and could lead to a perceived expansion of time.

In addition to the range of B-values, we also find that high values of CV are suited to modeling the experimental group. This can be explained as follows (see Figure 5). In step 1 of the model, the probability distribution for the 'long' reference duration has a larger standard deviation, as it has the same coefficient of variation as the 'short' reference duration, despite having a larger mean. This implies that for a given stimulus, if the decision is made in step 1 itself, there is a higher probability that the response be 'long'.

The decision to proceed to step 2, is dependent on the value of pI, i.e., the probability that the stimulus is judged as 'intermediate' in step 1. In the experimental group, as the model uses higher CV values, for a given stimulus, the values of pS and pL would be higher than the values for the same in the control group, where the model uses lower CV values. This would cause a decrease in pI for a given stimulus in the experimental group's simulation. Therefore, the probability of the decision being made in step 1 increases, implying that there is a higher probability of the response being 'long' as compared to the control group, as explained in the previous paragraph.

A higher value of CV, while mean remains fixed, implies a larger standard deviation (SD). As the experimental group is being modeled accurately with a higher range of CV values as compared to the control group, the width of the Gaussian distributions used to model the reference durations is higher in the experimental group. This change in the width implies that caffeine might have the potential to cause distortion in the memory of durations. This leads us to infer that caffeine mechanism possibly works via the memory pathway rather than an attentional pathway, as the latter would require a leaner spread of the probability distribution. Despite investigative experiments, there is no general consensus on the nature of acute effects of caffeine on memory (McLellan et al., 2016). However, our model indicates an increase in uncertainty in the reference memory caused by caffeine.

Limitations and Future Work

One major shortcoming of the model suggested by us is that it is purely a decision model and does not take into account the neural circuitry mediating time perception in humans. The model is pitched at an abstract level and in order to obtain biologically rooted insights, there is a need for a more realistic model.

Substantial evidence has been found that indicates that the basal ganglia and its dopaminergic pathways control time perception to an extent. For instance, it has been observed that PD patients, when administered medication that brings the dopamine concentration back to normal, are capable of performing time estimation accurately, unlike when off-medication (Jones, Malone, Dirnberger, Edwards, & Jahanshahi, 2008). Furthermore, time perception studies can help in the early detection of such diseases that affect dopamine production and will also increase our understanding of the pathways and the brain areas that may be involved in such diseases.

The fundamental circuitry behind caffeine's action has been established to be the antagonism of adenosine receptors in the central nervous system which leads to interaction with dopamine receptors (Davis et al., 2003; Ferré, 2016). Caffeine blocks A2A receptors in the striatum and promotes a direct excitatory potentiation of D2 receptors. This leads

to an increase in the stimulation of psychomotor activity by dopamine (Ferré, 2016). Hence, we think that a model can be conceptualised which shows caffeine indirectly affecting time processing in the basal ganglia by modulating dopamine.

Alternatively, it has been observed that a cortical neuronal network, without the use of any kind of pacemaker, may have the potential to track duration by storing recent information (Mauk & Buonomano, 2004). This can be used as inspiration for another biologically feasible model. Furthermore, there is indication in literature that a reinforcement learning based model of interval timing might be able to explain several behavioural as well as neural phenomena (Gershman, Moustafa, & Ludvig, 2014). These are few methods that can be explored to further investigate the effect of caffeine on time perception.

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