# Linear vector models of time perception account for saccade and stimulus novelty interactions.

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## Abstract:

Various models (e.g. scalar, state-dependent network, and vector models) have been proposed to explain the global aspects of time perception, but they have not been tested against specific visual phenomena like perisaccadic time compression and novel stimulus time dilation. Here, we tested how the perceived duration of a novel stimulus is influenced by 1) a simultaneous saccade, in combination with 2) a prior series of repeated stimuli in human participants. This yielded a novel behavioral interaction: pre-saccadic stimulus repetition neutralizes perisaccadic time compression. We then tested these results against simulations of the above models. Our data yielded low correlations against scalar model simulations, high but non-specific correlations for our feedforward neural network, and correlations that were both high and specific for a vector model based on identity of objective and subjective time. These results demonstrate the power of global time perception models in explaining disparate empirical phenomena and suggest that subjective time has a similar essence to time's physical vector.

**Keywords:** time perception, perisaccadic time distortion, stimulus repetition, vector timing, neural network, scalar timing

## 1- Introduction

Time perception studies generally assume that subjective or perceived time is distinct from objective time[1–3] and have explained this difference from two opposing perspectives: either from the perspective of global theories of time perception, or post-hoc explanations of specific empirical phenomena. Previous theories of time perception include linear dedicated models[4] such as internal clock models[2,3,5], and non-linear models such as state-dependent networks (SDNs)[6–8]. Conversely, empirical studies have shown that various sensory and behavioral factors influence human time perception[9–13], for example, perisaccadic time compression [12–17], and dilated time for a novel visual stimulus following repeated stimului[18–20]. Perisaccadic time compression (i.e., compressed time just before and during saccades, as opposed to post-saccadic time expansion[21] has been explained in terms of perisaccadic remapping[14,15,17] and transient cortical responses[22], whereas temporal expansion of a novel stimulus (after a series of repeated stimuli) has been attributed to a release from repetition suppression mechanisms[19,20,23]. While this post-hoc approach has the advantage of empirical grounding, it poses the risk of leading to an unlimited set of explanations, unrelated to either to each other or the more global theories[24,25]. Here, we attempted to reconcile these approaches by implementing global models and testing them against the previously unexplored interactions between perisaccadic time compression and time dilation of a novel stimulus after a series of repeated stimuli.

We considered three types of model (Figure 1). In scalar timing models (Fig. 1-a), subjective time is viewed as a scalar parameter that can be generated by an internal pacemaker/accumulator structure[3] or related to levels of energy spent in the brain[13,26]. Such models predict that specific time distortion effects (e.g., stimulus repetition vs. saccades) should add linearly. In contrast, SDN models[6–8,27] (Figure 1–b) are nonlinear[8], being based on network training. These models assume that time distortion effects can be coded by different connectivity patterns in specific neural networks[28]. Such models can account for possible non-linear interactions between stimulus repetition and saccades. Finally, we considered a recently proposed vector model for subjective time (Figure 1-c), based on a physical concept of time[29,30]. In this model, neural time units are defined by a directional arrow and a magnitude (i.e., a vector) as in temporal physics[30–32]. In this framework, simultaneous time distortions can be integrated by a neuro-information approach[29,30]. For example, if the distortion effects of saccade and stimulus repetition are added to a vector of subjective time, they can then expand or compress subjective time within this vector space.

To evaluate these models, we employed a repetitive stimulus / saccade / novel stimulus paradigm in human participants (Figure 2). Participants judged the duration of a novel test stimulus relative to a previously viewed series of reference stimuli with a different orientation (Fig. 2-a). After the reference stimuli, we cued a saccade, which commenced toward the end of the test stimulus (Fig. 2-b. We then analyzed the interactions between perisaccadic time compression and repetition-induced time dilation of the test stimulus and compared these to simulations of the models described above. This yielded the novel results that time dilation after a series of repeated stimuli supersedes saccade-induced time compression, and more importantly, linear vector model simulations provided the best fits to this data (in terms of accuracy and specificity) compared to the other models of time perception. This demonstrates that global time perception models can explain specific empirical phenomena and suggests that subjective time follows the rules of objective time in a physical framework.

## 2- Results

Ten participants performed the experiment, in counterbalanced blocks corresponding to three *tasks* (Figure 2-a). In each task, participants judged the variable duration (140, 170, 230, or 260 ms) of a test stimulus (a horizontal or vertical grid) relative to the fixed-duration (200 ms) of the last stimulus in a previously viewed series of reference stimuli with the opposite (orthogonal) orientation (Fig. 2-a). Participants were initially cued (by a small cross) to fixate their gaze just beyond one of four corners of the centrally located reference stimuli. In the main *Saccade Task*, this fixation cross shifted to the adjacent corner, triggering a vertical saccade with a stereotypical latency (268.4 ± 35.5 ms). The test stimulus appeared just before saccade onset, such that saccades commenced at or near the end of the test stimulus, depending on its duration (Fig. 2 b). Note that in this task, the test stimulus appeared at the same location as the reference stimuli but stimulated a different area of the retina (i.e., same spatial, different retinal location). To control for these spatial factors, we also included a *Fixation Task*, where the test stimulus appeared at the same location, but the fixation cross did not shift to induce a saccade (same spatial, same retinal location), and a *Retina-Fixed Task,* where the test stimulus shifted like the fixation cross to stimulate the retinal location of the pre-saccadic stimuli (different spatial, same retinal).

During analysis, we grouped the data from each of the above tasks into three different *conditions* to test the influence of a saccade (S), stimulus repetition (R; more than one reference stimulus), or the joint influence of both saccade and repetition (SR). To quantify participants' responses in each condition we computed individual timing performance (ITP) indices (Figure 2-c). The ITP is an index to show whether participants overestimated or underestimated the duration of the final, novel test stimulus in presence of time distortion effects. ITPs > 1 signify overestimation of test stimulus duration, whereas ITPs < 1 signify underestimation of test stimulus duration relative to the reference stimulus (see method section).

## 2-1 Behavioral results

General effects and interactions were tested statistically using a repeated measure analysis of variance (ANOVA), where the conditions (fixations vs. saccade, 1 to 3 repetitions of the reference stimulus) were selected as within-subject factors. We found significant differences of the ITP between different conditions and repetitions after Bonferroni correction. Since Mauchly's test indicated that repetition and interaction of conditions within participants were not significant, sphericity was assumed. The ANOVA revealed significant main effects of both repetition ($F(2)=24.225$, $p<0.001$, $\eta^2=0.729$) and *Saccade/Fixation Tasks* ($F(2)=9.048$, $p=0.002$, $\eta^2=0.501$). The interaction between these effects was also significant ($F(4)=8.030$, $p<0.001$, $\eta^2=0.472$). Overall, these data suggest that subjective time is disrupted by repetition, saccades, and interactions between these factors.

Pairwise interactive comparisons showed that repetition of the reference stimulus altered time judgment in all three tasks (See Supplementary Analysis) but did not differentiate between these tasks. To differentiate the influence of repetition on time judgement in saccades vs. two fixation control tasks, we looked at the pairwise interactive comparisons of repetitions as a factor of task (Figure 3). No significant differences were observed between our two control tasks (*Fixation* and *Retina-Fixed*) for various repetitions of the reference stimulus presentation(s). However, for 1 presentation of the reference, Bonferroni correction showed a significant difference between the *Saccade* and *Fixation Tasks* (mean difference=0.331, SD= 0.089, p=0.009) and saccade and *Retina-Fixed Task* (mean difference=0.568, SD= 0.1, p=0.001). For 2 or 3 trials reference stimulus presentations, no significant differences between conditions were observed (Figure 3).

These results show that a relative time dilation was always present after repetition (2-3 presentations) of the reference stimulus, and that this effect superseded the time compression effect in the presence of a saccade. To investigate the individual results of each participant, we first examined individual ITPs. The ITP for individual participants was always under 1 when saccades were performed after a single reference stimulus (Supplementary Figure 1), i.e. perceived time of the test stimulus was compressed after a saccade. However, when the reference stimulus was repeated once (two presentations), all participants exhibited ITPs higher than 1. When two repetitions were presented, nine of 10 participants showed an ITP greater than 1. This trend suggests that repetition of a pre-saccadic reference stimulus eliminates perisaccadic time compression.

To further explore the results, we computed the psychometric functions based on the percentage of test stimuli perceived to be longer than reference stimuli (Figure 4). The point of subjective equivalence (PSE) for the test stimulus shows subjective time dilation in trials with repetition of reference stimulus before test (Figure 4-a). This result was observed for all tasks (i.e. *Saccade, Fixation*, and *Retina-Fixed Tasks*). To simplify our dataset for visualization, interpretation, and simulations (see modeling section below), we further divided this dataset into pools where the test stimuli were either shorter (140, 170 ms) or longer (230, 260 ms) than reference stimuli. On average, shorter trials were judged correctly (shorter) in all the tasks / repetitions, whereas longer trials were perceived incorrectly (shorter) when a single reference stimulus was followed by a saccade (Figure 4-b). This underestimation shows a loss of sensitivity (less difference between the two long and two short tests) in the saccade case compared to no saccade. Again, the perisaccadic time compression was negated (and even reversed to time dilation) when the reference stimulus was presented repeatedly (two or three times) before the test.

## 2-2 Modeling results

In the second part of this study, we used the empirical data described above to test between the models shown in Figure 1. The mathematical implementation of these models is described in the Supplementary Figure 4. To test the ability of each model to explain our observed S-R interactions, the S and R conditions were used as inputs of models and outputs were responses in SR condition. Two criteria were selected to testify the models. 1) Sensitivity (outputs of the model should correlate with the actual behavioral data). 2) Specificity (i.e., for specific model predictions these correlations should disappear when the data are randomly shuffled, whereas correlations due to overfitting the data should persist). These were determined through linear correlation analysis between output of models and original/shuffled data (see methods).

Figure 5 shows original data (upper row) and shuffled data (lower row) as a function of simulated model outputs. As noted above, the *linear scalar model* represents temporal variables as scalar numbers that should interact additively. The outputs of this model showed relatively low and nonsignificant (after Bonferroni correction) correlations with both the original (R=0.37, p=0.32) and random shuffled data (R=0.38, p=0.36). In contrast, the *neural network model* can be trained to fit various non-linear input-output relationships. The outputs of this model showed relatively high and significant (after Bonferroni correction) correlations for both the original data (R=0.81, p=0.0001), and the randomly shuffled data (R=0.65, p=0.0048). Finally, the *vector model* works by representing time units as vectors and predicting the angles between these vectors. The outputs of the linear vector model exhibited high and significant correlation with the original data (R=0.79, p<0.0001), but not for the shuffled data (R = 0.38, p = 0.061). These findings suggest that the linear vector model could not explain our dataset, the neural network model performed better but was not specific to the actual dataset, whereas the linear vector model fit both of our criteria: it performed well, and was specific to the original unshuffled datasets.

## 3- Discussion

In this study, we asked how two separate time distortion effects (repetition time dilation and perisaccadic time compression) interact, and which time perception model can best explain the derived results. Overall, the behavioral results confirm previous findings on perisaccadic time compression[14,33]and relative effect of time dilation after a series of repetitive stimuli[19,20,23] but expand on this by showing how they interact. Results showed the relative time dilation induced by repetition of a reference stimulus before test stimulus neutralized the presence of an intervening saccade (i.e. the interactive effect of perisaccadic time compression and repetition time dilation is similar to single effect of repetition time dilation alone). To model this interaction, the resulting data were used as inputs/outputs for models of time perception (scalar clock, non-linear neural network, linear vector). The linear vector model performed best, both in terms of specificity and ability to fit the data. Here, we will consider the experimental results in more detail, and discuss their implications for broader time perception theories.

In agreement with previous investigations[12,14,15,33], our results showed that saccades compress the subjective perception of the duration of a briefly presented visual stimulus. Whereas previous investigations used empty temporal intervals (i.e. the interval between presentation of two stimuli[14] has been judged instead of duration of one presented stimulus), we presented the test stimulus during perisaccadic interval and participants judged the duration of the stimuli themselves. This demonstrates that, notwithstanding the presence of different mechanisms for time perception of brief empty or filled intervals[34], saccadic time compression occurs in both cases. On the other hand, our results support previous studies[13,19,20,23] that found the relative duration of a novel stimulus after a series of repeated stimuli is perceived to be longer than the last repeated stimulus (in the repetitive series) with the same objective duration.

In *the Retina-Fixed Task*, the test stimulus was presented in a different spatial location (but same retinal location) relative to the repeated reference stimulus. Thus, in this task, the test stimulus shows two types of novelty compared to the reference stimuli: different location and different orientation. However, in this condition time dilation was not significantly different from that in our *Fixation Task* (where the test stimulus was presented in the same objective and retinal location as the reference stimulus). This suggests that objective spatial location did not have a strong effect on perceived time. This might be because the new location of our test stimulus was always predictable, and one could predict that the test stimulus would be presented in another possible location that was different from the location of reference stimulus. Whereas the randomized number of repetitions was not predictable in all tasks.

Various, often disconnected explanations have been provided for these phenomena. Saccadic remapping[14,35], transient responses in visual cortex[22], saccadic suppression[16,26,35,36] and attention[16] have been assumed to be associated with perisaccadic time compression, whereas time dilation of a novel stimulus (after a series of repeated stimuli) has been explained by attention[23] and repetition suppression mechanisms[13,26]. The latter two explanations (neural suppression and attention) are common to both phenomena (saccadic time compression and time dilation after a series of repeated stimuli) but the other proposed mechanisms for saccadic suppression can not explain time dilation for the novel stimulus following a repeated stimulus. Therefore, when considering how these phenomena might interact, we will focus on attention and neural suppression.

We will first consider the joint effects of attention on time distortions induced by saccade and repetiiton[16,23], because this can be directly related to the internal time clock model simulated above. In the internal clock model, attention is considered as a switch between pacemaker and accumulator[3,5,37]. Higher level of attention allocation can turn on the switch and connect pacemaker to accumulator (Figure 1-a). It causes to collect more timing pulses and may bring overestimation of time. Based on this assumption, the overestimation of time for a novel stimulus after a series of repeated stimuli can be explained by increased allocation of attentional resources to the novel stimulus (that is presented following the repeated stimuli) in comparison to repeated stimuli[23,38]. On the other hand, in saccade trials, attention is allocated to the saccade target, decreasing attentional allocation to the test stimulus, leading to perisaccadic time compression[16]. Based on this model, subjective time is a scalar parameter[3] that has accumulative property. This model thus predicts that a scalar combination of saccade and repetition trials should correlate with saccade-repetition trials (Fig. 1-a and Fig. 6). However, this did not occur in our results: instead, repetition obliterated the saccades effect. Thus, when these data were used to simulate the internal clock model, poor correlations resulted. By corollary, this also tends to refute current models based on scalar attention parameters.

The idea that suppression of brain activity can compress time perception was originally presented by Eagleman and Pariyadath as an *energy model* in time perception[12,18–20,26]. The basic idea is that just before and during saccade execution (the perisaccadic interval) certain brain areas show reduced activity[35,39–41], and thus energy expenditure[12,13,26]. Since stimulus novelty (especially after a repeated stimulus) can increase neural activity / energy expenditure, it can (according to this theory) also dilate perceived time[13,26]. A limitation of this model is that the causal link from energy metabolism *to* information processing is indirect, at best. However, taking this theory at face value, when both effects (repetition and saccade) occur simultaneously, the level of energy spent in the brain will be decreased by one factor (the saccade) and increased by other (novelty after repetition). Again, this can be represented mathematically as a combination of two energies (scalar parameters) that are spent in different brain regions. Based on this assumption, behaviorally, we expect that one effect would cancel or weaken another effect (Supplementary figure 2). However, the correlation between outputs of the scalar model and empirical data was not significant. Thus, in this case scalar models of time perception (e.g. internal clock, and energy models) were not able to describe the joint time distortion effect of repetition and saccades.

Since the scalar timing models failed to justify the joint time distortion effects of saccade and repetition, SDNs model was employed as an alternative method. This model explains state-dependent computations in neural network level presents subjective time[7,8,42–44]. Previous SDNs modeling studies have showed that artificial neural networks can simulate the behavioural responses in different timing conditions such as rhythm perception[8] and can encode time-varying sensory and motor patterns[45]. This approach is similar to other artificial neural network studies that try to model a connectivity structure between incoming visual/auditory stimuli and behavioural responses. By this way, non-temporal perceptual classification approaches (e.g. feedforward neural networks) that are usually working based on Hebbian law, can be used to classify and predict subjective time[28]. Consistent with the above studies, our, artificial neural network was able to fit the data in our study. However, such a network can fit almost anything, including a random shuffle of our data, i.e., it may have succeeded through overfitting. Thus, while this model was able to retroactively predict our data, the prediction was not specific.

A common element between scalar timing and SDN models is that they do not explicitly consider the concept of time in modern physics (time in Minkowski space). Objective time in these models is supposed to be the sequence of events, leading to subjective time perception. There is an interesting similarity between internal clock model and Newtonian absolute time, because both frameworks assumed an absolute generator that can create passage of time (Table 1). On the other hand, the SDN models assume moments can be coded via a nontemporal classification network and a Hebbian law is involved in learning and recognition of temporal patterns. However, based on modern physics theories each observer measures time as an intrinsic property from the environment, and this property can be changed based on information (entropy) and speed of both the environment and observer[31,46]. If we consider the brain as a physical observer, the same timing parameters should be hold in the brain and in the physical universe (Table 1). As time is characterized as a vector in Minkowski space, we used this concept in our last modeling approach. This vector model was originally suggested for time perception in long durations[29] but it can be proposed as a general time perception model for all intervals[30].

Our modeling results show that the vector model[29,30] exhibited both sensitive and specific simulations of joint saccadic and repetition time distortion effects, i.e. in this model separate saccade and repetition result inputs predicted the combination of both effects. By representing perceptual effects as vectors and predicting the angles between these (Supplementary Figure 4), this model was able to predict their interactions accurately and specifically. Conversely, in this model different time distortion effects can be considered as vectors in different directions that are added/subtracted to/from the original time vector (A detailed mathematical description of the specific vector interactions in our model can be found in *Supplementary Discussion*).

Overall, the results of vector timing model confirmed our hypothesis that subjective time has deep similarities to physical time and satisfied the first postulate of the special relativity theory[46]. In this model, more information than magnitude (that is considered in scalar models) is thought to be required to model dilation and compression of subjective time. Then, subjective time is characterized by vector units of time with two properties: magnitude and direction. When two time distortion effects are simultaneously interfered subjective time, two vectors with different magnitudes and directions are added to subjective time. Presumably, this information theory model is instantiated at the level of neural networks and cellular signals, but at this time the biological mechanism is unknown.

In conclusion, we show here that global theories of time perception can be used to predict interactions between seemingly disparate experimental phenomena and conversely, those such interactions can help test between global theories. In particular, this study is the first to show the interaction between saccadic time suppression and repetition time dilation, and that this interaction follows the specific predictions of the vector model of time perception. In terms of broader implication, this is the first empirical-theoretical investigation that directly shows subjective time can be represented by the same time parameter as that used in physics.

## 4- Method

**4-1 Participants.** Ten volunteers (age: mean=31.5, range between 23 and 39, 5 female) participated in this study (included one of the authors; A. G.). All the participants had normal/corrected to normal vision and they did not report any visual or movement disorder. All the participants signed a written informed constant and study was approved by the office of research ethics (ORE) at York University. The sample size was selected based on previous studies. In three studies that considered saccadic time compression for brief durations (100 to 200 ms), sample size was less than ten (in two of them sample size was just three subjects)[14,15,22] and we did not find any saccadic-timing study that has used more than seven participants for clarifying the timing distortion effect in this range of durations. Previous studies about expansion of time across repetitive stimulus to a novel one, has used around ten subjects [19,20]. Since the number of participants in previous studies is not enough to provide a power analysis. In this situation, the best thing that we could do was to select the maximum number of participants in previous studies (i. e. 10) and evaluate the individual results. Also, the effect size ($\eta^2$) was calculated for each comparison. The results of this study showed acceptable effect sizes for saccade and repetition main effects as well as interaction between them (see result section).

**4-2 Setup.** Stimuli were back projected on a black display screen (1.9 × 1.4 m) with luminance level of 0.015 cd/m$^2$ and temporal resolution of presentation was 60 Hz. Participants sat in a dark room while their distance from the screen was 40 cm. After setting of this distance, participants asked to push their teeth on dental impression bar. Eye movement tracking was performed (in the *Saccade* and *Fixation Tasks*) using an Eyelink-2 system via a camera that was focused on right pupil. The task was programed by C++ and build by Borland C++ version 5.02.

**4-3 Stimuli.** Tree white parallel horizontal lines (thickness of line: 1°, distance between them: 4°, total size 11° ×11°) were presented as reference stimulus, while the test stimulus had same configuration with different orientation (vertical lines). Stimuli were presented at the right visual field (10° from the center) and a fixation point was horizontally shown at center (x=0). In the *Fixation Task*, fixation point was randomly presented at 12.5° above or below of center (x=0°, y=±12.5°), while the location of stimuli was x=10° and y=0°. In the *Retina-Fixed Task*, fixation point was always presented at center (x=0°, y=0°) but stimuli (both of reference and test) was randomly shown 12.5° above or below of center line (x=10°, y=±12.5°). In the *Saccade Task*, the location of stimuli was same as the *Fixation Task* (x=10°, y=0°) but the location of fixation point was randomly changed from x=0 and y=±12.5 to a symmetric location below or above of center horizontal line of screen. All the stimuli were shown on a black background.

**4-4 Trials details and experiment design.** In each task, 240 trials were presented. There were three conditions for repetition (0, 1, 2 repetitions) and four conditions for duration of test stimulus (140 ms, 170 ms, 230 ms, 260 ms). Then, 20 trials (240/(3*4)) are allocated to each condition. In all the conditions, a reference stimulus preceded a test stimulus. Duration of test stimulus was always 200 ms and interstimulus interval was 300 ms. In the *Saccade Task*, the fixation point was moved 100 ms before presentation of test stimulus (200 ms after reference stimulus presentation). After presentation of test stimulus participants were asked to judge which stimulus was longer, target or last reference stimulus? The procedure is presented in Figure 2. Trials are divided into two equal numbers for position of fixation point or stimuli (120 trials for up of the center line and 120 trials for below).

**Saccade latencies.** Saccades were detected by Eyelink-2 system and recorded by a subroutine generated by visual C++ in two separate computers. The eye position signals were sent via serial port from eye tracking computer (first device) to eye movement recording computer (second device). The task was presented on a different computer (third device) and a trigger was sent via parallel port to eye movement recording computer (second device) when the location of fixation point was changed (saccade command). The time difference between saccade command and eye movement was considered as saccade latency. The acceptable saccade latency was between 150 ms and 400 ms. Trials that are not involved in this criterion were removed. Since the test stimulus was always presented during saccade preparation / execution (perisaccadic interval) and vanished before fixation of the eyes at their new position (Fig. 2-b), the related time distortion effect is thought to be perisaccadic time compression[14] rather than time expansion or chronostasis which may occur immediately following a saccade[21].

**4-5 Data analysis.** The exclusion criteria for rejected trials were including: 1) Performing saccades during standard/test stimuli presentations during fixation intervals. 2) Late (later than 400 ms after fixation-point movement) or early (earlier than 150 ms after fixation-point movement) saccade execution in saccade trials. 3) Trials with no responses. 4) When eyes were fixated over a point out of fixation point location (e. g. stimulus) during stimuli presentation. 5) When participants were affected by any unintended external stimulus (e. g. extra noises, talking, movement and so on) during the trial presentation. Based on these criteria, the percentage of data exclusion was less than 30 % of all trials for each participant (mean=16.8%, SD=8.79%). Trial rejection was performed by self-developed subroutines in MATLAB R2018a.

A repeated measure analysis of variance (ANOVA) with post hoc Bonferroni test was performed to evaluate within subject significant differences in general effects (two factors of repetitions and tasks) and interactions between them. Before the parametric analysis, normality and equal variance assumptions were satisfied, and sphericity was assumed according to Mauchly's test. The statistical analysis was performed using IBM SPSS Statistics 19.

For the objective of data presentation and statistical analysis the individual timing performance (ITP) was defined. The ITP measured the longer trials that were correctly judged longer in saccade and repetition conditions. To calculate ITP the $t_{S,}\ t_R, t_{SR}$ (the percentage of longer trials that were correctly judged longer in saccade, repetition and both saccade/repetition trials, respectively) were divided by the $t_{pure}$ (the percentage of longer trials that were correctly judged longer in trials without saccade and repetition) as:

$$ITP_{S,R,SR} = \frac{t_{S,R,SR}}{t_{Pure}} \qquad \text{(eq. 1).}$$

Based on this formulization, when ITP>1, overestimation of time has been occurred while ITP<1 shows underestimation of time. ITPs were calculated for each participant using MATLAB R2018a.

**4-6 Models.** We tested three different models (linear scalar model, linear vector model and state dependent network model) based on previous hypotheses about time perception (Figure 1, 6). In all the models, two inputs $ITP_R$, $ITP_S$, and one output $ITP_{SR}$ were considered.

For all the models, totally 40 patterns were made by four conditions (1 repetition in control-1×saccade, 2 repetitions in control-1×saccade, 1 repetition in control-2×saccade, 2 repetitions in control-2×saccade) of ten participants. Regression analysis between output of models and real data was used to validate sensitivity of models (is model working for real data?). A set of random permuted data was also used to test the specificity of models (is model not working for random data?).

The linear scalar model was implemented based on a wide range of studies that considered the internal clock and scalar expectancy theory[3,47]. In this model, saccade and repetition have been considered as distortion effects that can accelerate or decelerate the accumulation rate of pacemakers (clocks). This acceleration/deceleration were linearly applied on perceive time in absence of distortions ($t_{Pure}$) by applying positive weights to adjust the rate of pacemakers. All the possible weighs were applied to find the best performance of the model. Schematic/mathematic framework of this model has been presented in Supplementary Figure 4.

The second model was implemented based on state depended network model[6–8]. To this end, an artificial neural network (ANN) with multi layer perceptron structure (two inputs perceptron, two hidden layers with 10 perceptrons in each layer and one output perceptron) was employed. A back-propagation algorithm was used for ANN training. We used 30 data as train data and 10 data as test data. To evaluate the effect of different datasets on efficacy of ANN and to avoid overfitting problem, we used 100 different patterns as training and testing datasets (Supplementary figure 3). Since other models contain 40 data in regression analysis, we consider the results of 4 training and testing (that has highest correlation coefficients (R values) among all datasets during test) in regression analysis. The mathematical processes of this modeling method are presented in Figure 6. We used artificial neural network toolbox in MATLAB 2019b to create the ANN model.

The third model was accomplished based on our previous hypothesis that state time in the brain has same properties with physical time and generate/observe via vector units[29,30]. In this model, time distortions are considered as different vector units to strengthen (dilation) or destroy (compression) the vector of perceived time in absence of distortion effects ($t_{Pure}$). This linear vector model was implemented by applying the $\cos(\phi, \psi)$ (instead of the acceleration/deceleration weights of perceived time in scalar models). Where $\phi, and\ \psi$ were the assumed angles between the vectors of time distortion effects (i.e. saccade and repetition, respectively) and the vector of time in absence of time distortion effects. This model fellows a linear formula where two distortion effects are linearly added to $t_{Pure}$. All the possible angles were tested, and model efficiency was obtained for these various angles (Supplementary figure 3). Supplementary Figure 4 exhibits this model mathematically and schematically. All the models have been generated by MATALB 2019b.

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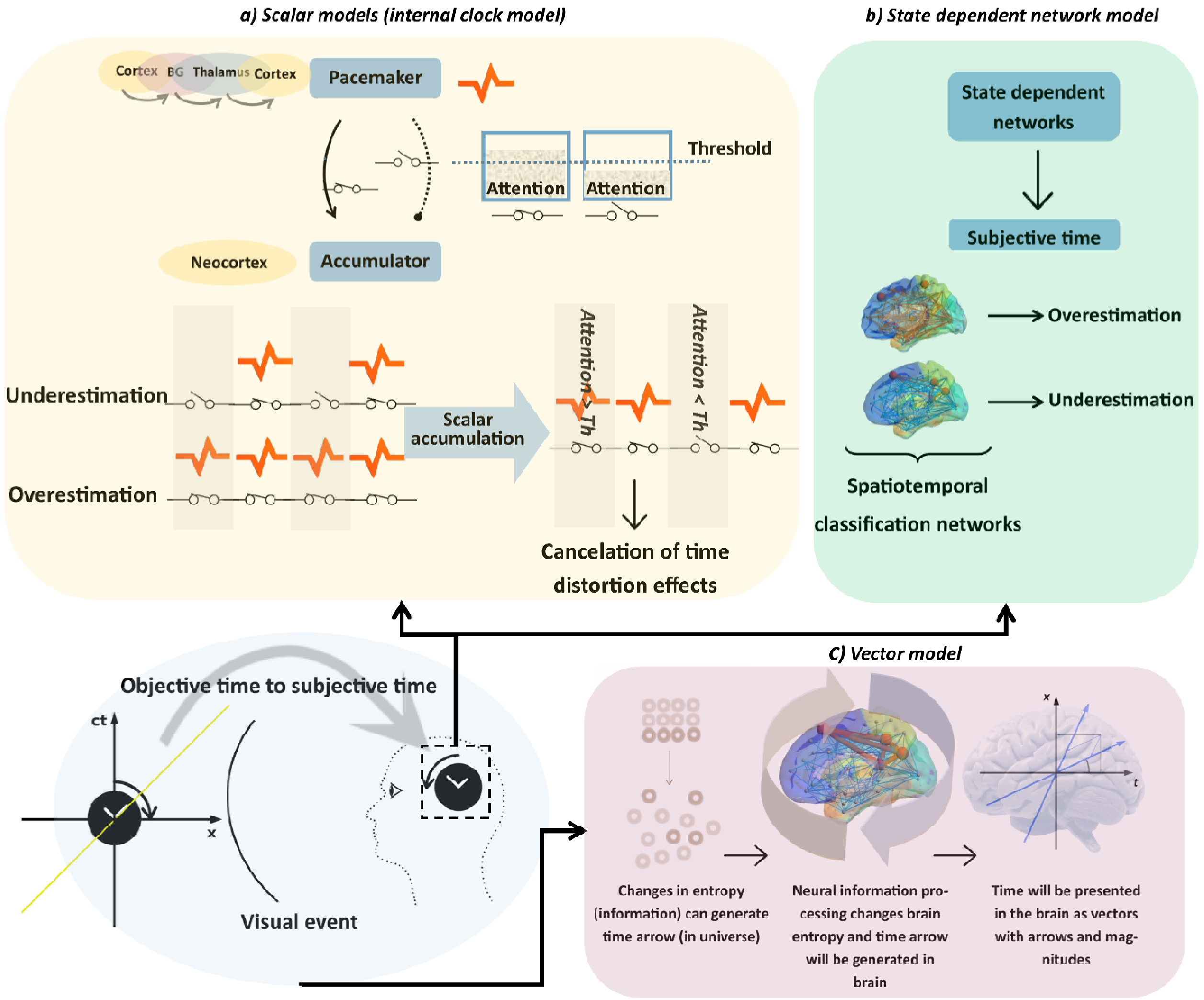


Figure 1:

- How brain can process time. The objective time that is embedded in a visual event and subjective time that is measured in the brain are characterized in two separate frameworks (universe and brain).

**a) Scalar models)** *Internal clock model:* In this model, an anatomical pacemaker-accumulator structure is suggested to generate and collect scalar timing pulses. A cortico-basal ganglion-thalamocortical pathway is suggested as pacemaker[5,48,49] and different cortical regions are suggested as accumulator[5,24,48,50]. In this model, attention is assumed to connect the pacemaker to accumulator as a switch[3]. Usually an attention threshold is considered, and the switch will be closed when the attention is higher than this level. Otherwise, the switch is open, and accumulator can not collect timing pulses. Then higher level of attention cause to overestimation of time and lower attentional allocation will lead to underestimation of time.

When separate time distortion effects alter the level of attention in different directions (one increases attention and other decreases that) the underestimation and overestimation effects cancel each other. **b) State dependent network model:** In this model different states of neural networks can demonstrate various time perception states. Then, the brain can recognize long and short durations via Hebbian learning law and by spatiotemporal classification network instead of specialized temporal structures.

**c) Vector model:** A vector model explains the subjective and objective times are processed in the brain and universe via same formulization. This model describes physical parameters (e.g. entropy and speed that are involved in measurement of objective time) are also corresponded in subjective time. For example, as the entropy of universe is increased and objective time is passed, information processing in the brain increases the level of entropy in the brain and subjective time will be passed. In this framework, brain and universe are considered as observer and environment, respectively. Objective time can be measured in the brain as subjective time. Both timing contexts can be formulated in Minkowski space as vectors (with arrows and magnitudes).

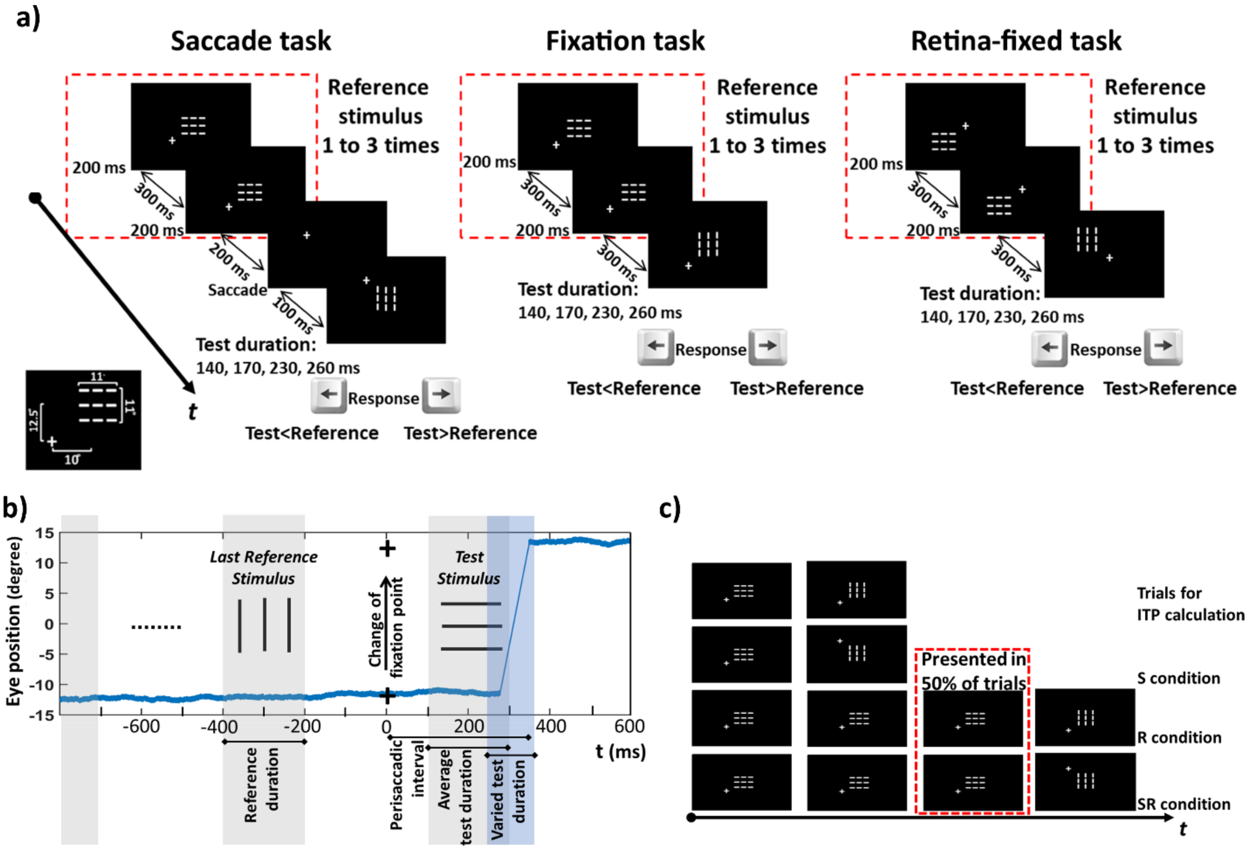


Figure 2: a) Experimental design. We asked participants to judge the duration of a novel test stimulus (a horizontal or vertical grid) in comparison with the most recently presented reference stimulus (a grid with the opposite orientation. Participants fixed at one of the four corners relative to these stimuli. Three stimulus tasks (saccade, and two fixation controls) were presented in separate blocks, counterbalanced across. In each block, a series of 1-3 (randomized) 200ms reference stimuli were presented at centre, followed by the test stimulus (140, 170, 230 or 260ms, randomized) at the same or 90 deg rotated orientation. After each trail, participants responded the test stimulus duration was shorter or longer than the reference stimulus. Participants always began fixating 8.3 degrees diagonally from one of the four corners of the reference stimulus location. In the *Saccade Task*, the fixation point shifted up or down to the opposite corner on the same horizontal side, 100 ms before test presentation, eliciting a 25 degree vertical saccade during display of the test stimulus (and causing the retinal location of the stimuli to shift). The *Fixation Task* was performed with fixed gaze and stimuli locations whereas gaze was fixed in the *Retina-Fixed Task*, but the location of the test stimulus was shifted to match the retinal locations of the *Saccade Task*. b) Temporal evaluation and eye position in the *Saccade Task*. After presentation of the last reference stimulus (200 ms), the location of fixation point was changed. Then, the test stimulus was

presented (after 100 ms) and eye poison was changed (after saccade latency). Presentation of the test stimulus (with variable durations) was occurred during perisaccadic interval. c) Different trials have been affected by different types of time distortion effects: i.e. saccade (S), repetition (R) and both saccade and repetition (SR). Trials that were not affected by time distortion effects have been used to calculate ITPs. Statistical analysis and modeling processes have been performed using this arrangement of trials.

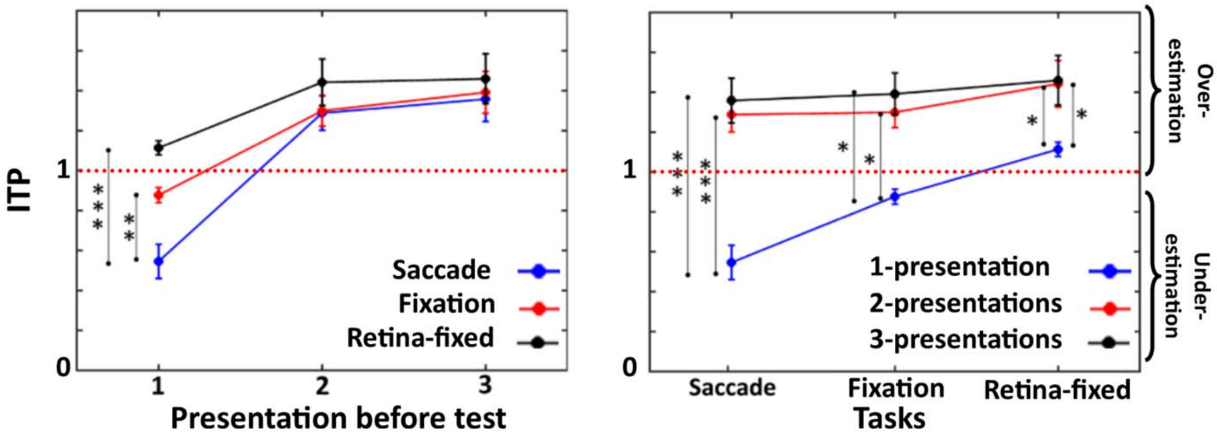


Figure 3: Statistical results to show significant results between different tasks and presentations of test stimulus. One-star (*) indicates (p<0.05), two-stars (**) indicates (p<0.01), and three-stars (***) shows (p<0.001). Error bars are standard error of means.

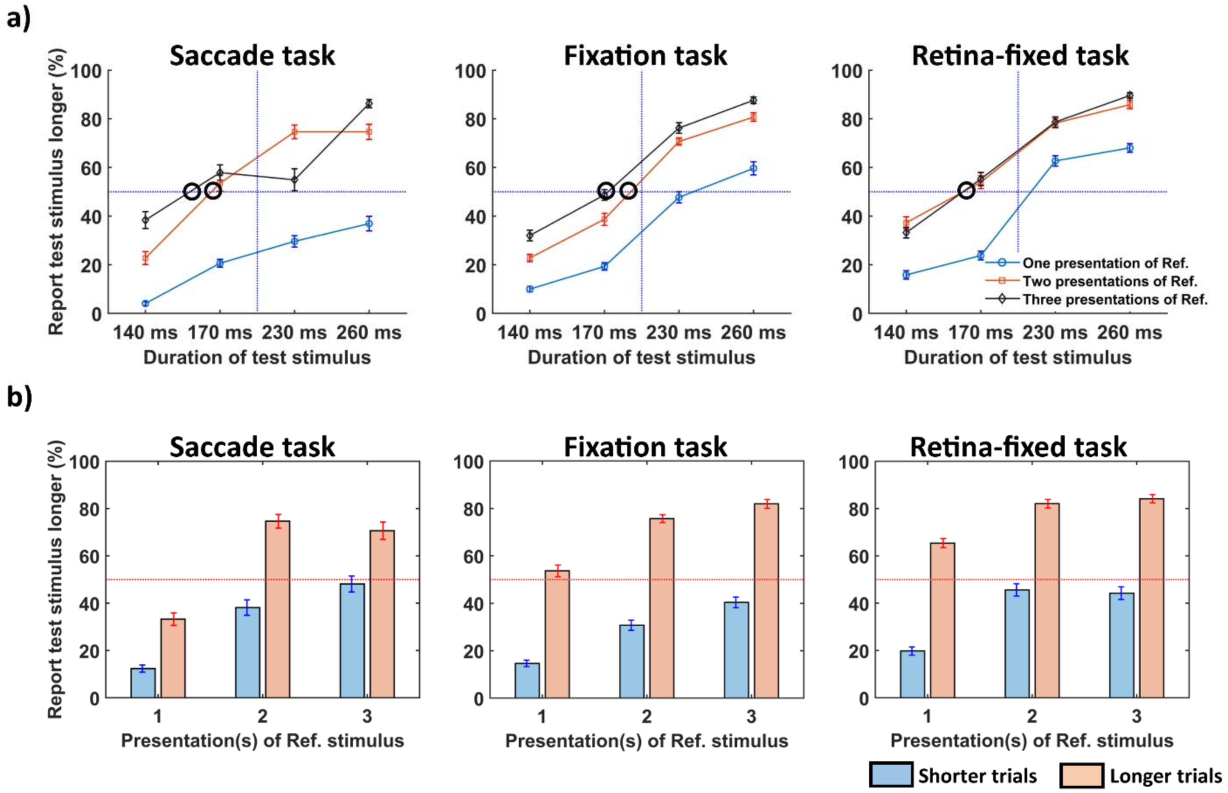
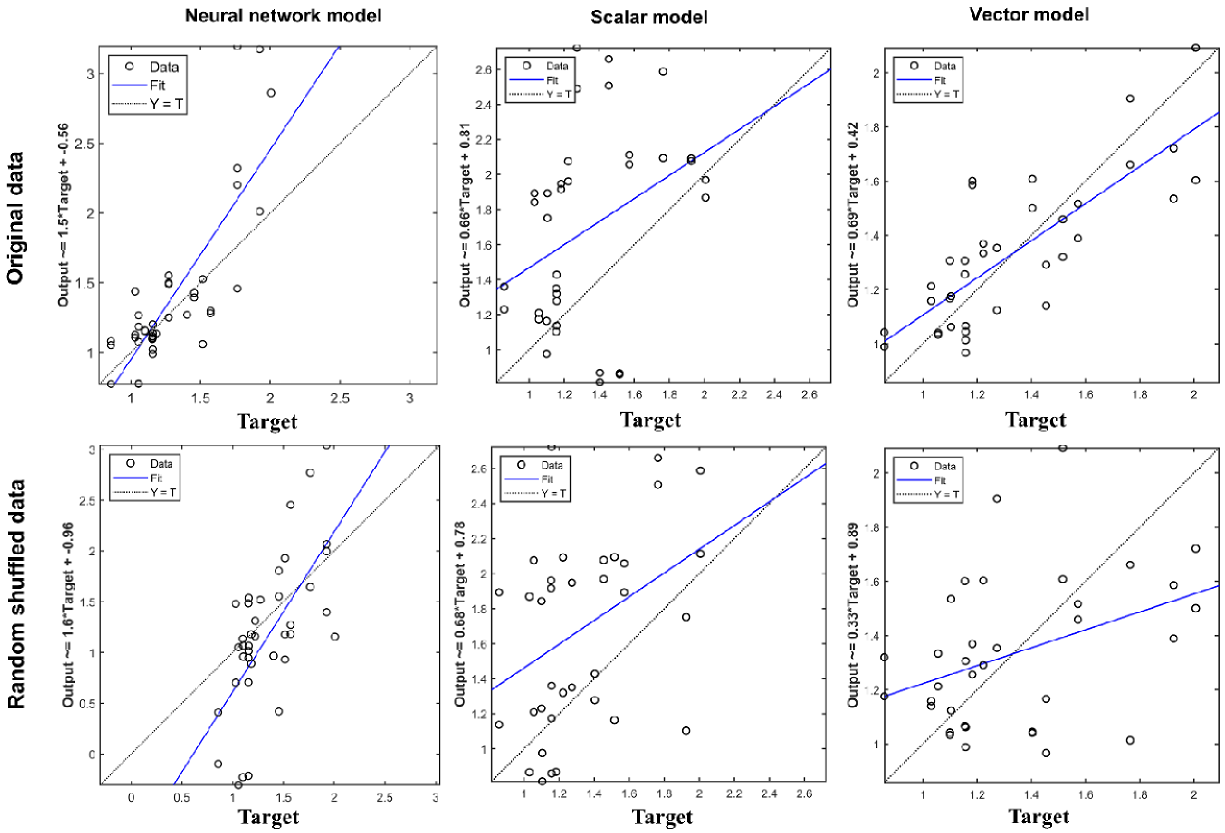


Figure 4: a) Point of subjective equality (PSE) for test stimulus in different conditions (tasks and presentations of reference stimulus). Middle vertical blue line shows the duration of reference stimulus (200 ms). In all tasks (*Saccade, Fixation*, and *Retina-fixed*) charts that are related to two (red) and three (black) reference presentations crossed the 50% line (blue horizontal line) at the left side of middle vertical line (black circles) and this means overestimation of time. The blue chart in the saccade task (that is related to one presentation of reference) has not crossed the 50% line and duration of test stimuli (either longer or shorter) has been perceived shorter than duration of reference in more than 50% of trials. b) Psychometric functions showed the percentage of longer responses for *shorter* and *longer* trials. The charts have been shown for different tasks and different numbers of test stimulus presentation. Longer trial (pink bar) that is located bellow the center red line shows underestimation of time (one presentation in the *Saccade Task*). Otherwise, in the other tasks (*Fixation* and *Retina-fixed tasks*), longer trials have been correctly judged longer. Error bars are standard error of means.



**R values**

| | Scalar model | Neural network model | Vector model |
|---|---|---|---|
| **Original data** | R = 0.37, p-value = 0.32 | **R = 0.81, p-value < 0.01** | **R = 0.79, p-value < 0.01** |
| **Random shuffled data** | R = 0.38, p-value = 0.36 | **R = 0.65, p-value < 0.01** | R = 0.38, p-value = 0.06 |

Figure 5: **Above:** Regression scatter plots, correlation coefficients (R) and p-values of correlation analysis between responses in behavioural tasks and output of models. Datapoints present ITPs for different participants in different conditions. The output of both neural network and vector models exhibited significant correlations with experimental datapoints. But the correlation between output of scalar model and experimental datapoints was not significant. **Bottom**: Models were tested by random shuffled dataset generated from original data (outputs were assigned to irrelevant inputs). Several random datasets were tested, and the best accuracy of models was presented. The output of neural network model is still showed a significant correlation with random shuffled experimental datapoints. However, outputs of vector and scalar models were not significantly correlated with random shuffled experimental results.

Table 1: Objective and subjective time and relation between them in different time perception models.

| Model | Objective time | Subjective time | Timing rule |
|---|---|---|---|
| **Internal clock model** | Successive events | Number of neural pulses | Counting of pulses in specific brain regions can generate time. Same mechanism is suggested in Newtonian framework for physical time. |
| **Energy model** | - | Energy spent in the brain | The value of energy in the brain (a scalar parameter) can generate time. There is no identity in the physics. |
| **State dependent network model** | Successive events | Spatiotemporal classification networks | Different states of brain networks can present time. Hebbian law supports this idea. |
| **Vector model** | Physical time in Minkowski space | Physical time in Minkowski space | Physical properties of brain (i.e. entropy and speed) can measure subjective time.<br>Same mechanism is suggested in modern physics for physical time. |

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