# Interval timing in a hierarchical violation-of-expectation task: Dissociable effects of local and global predictions

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## Abstract

Predictability associated with an event influences its perceived time. The two forms of predictions that are often discussed and have a dissociable influence on perceived time are repetition and expectation. However, predictions based on expectation can be seen at multiple levels, potentially leading to an inconsistency in the pattern in which expectation influences perceived time. Therefore, the present study aimed to investigate how different levels of predictions impact perceived time. In two separate experiments utilizing visual and auditory stimuli, we used a hierarchical violation-of-expectation paradigm that can dissociate two types of predictions based on local and global rules. Results from analysis of variance computed with local and global predictions revealed a pattern of local and global predictions having a distinct influence on perceived time. More specifically, while the local predictions that consider the immediate stimulus exposure reduced the perceived time, the global predictions that consider the overall regularities of a given context increased the perceived time. These results integrate well with the recent theoretical models rooted in a predictive coding framework that emphasizes the opposing effects of the first order and second order predictions on perceived time.

**Keywords** Levels of prediction · Perceived time · Predictive coding · Prediction violations

## Introduction

The ability to time intervals in the subsecond range is critical to nearly all aspects of behavior. Converging evidence indicates that the human perception of time is prone to various distortions arising from factors such as an event's predictability (Pariyadath & Eagleman, 2007; Schindel et al., 2011), learned regularities (Cai et al., 2015; Rhodes & Di Luca, 2016), and contextual relevance (Schweitzer et al., 2017). One specific temporal phenomenon that has garnered huge attention in the past two decades and has a heavy reliance on the predictions associated with an events' occurrence is the *temporal oddball effect* (Pariyadath & Eagleman, 2007; Schindel et al., 2011; Tse et al., 2004). In the temporal oddball effect, a novel stimulus followed by a series of repeated stimuli is perceived as lasting longer than its veridical duration. This specific effect is replicable across multiple modalities (Fromboluti & McAuley, 2020;

McAuley & Fromboluti, 2014; van Wassenhove et al., 2008) and is often considered as arising from the violation of local level predictions, which are formed based on immediate stimulus exposure (Pariyadath & Eagleman, 2007; Schindel et al., 2011). This effect can also be observed in tasks involving probabilistic manipulations, with rare stimuli exhibiting an enhanced perceived duration (Matthews, 2011; Ulrich et al., 2006). Such probabilistic manipulations entail global-level predictions that consider the overall regularities of a given context.

One dominant theoretical model that is prevalent in explaining the mechanisms behind the temporal oddball effect is the *coding efficiency* account (Birngruber et al., 2015; Eagleman & Pariyadath, 2009; Matthews, 2011). As per neural coding efficiency, our subjective time is a byproduct of neuronal energy used when a stimulus is encoded. An odd stimulus among a repeated trail of stimuli is perceived longer because it evokes a larger neural response for an efficient representation. On the other hand, the repeated stimuli are perceived shorter as it evokes lesser neuronal activity (Pariyadath & Eagleman, 2012), an effect known as *repetition suppression* (RS) (Henson, 2003). Repitition suppression is thought to be a manifestation of *predictive coding* (Grotheer & Kovács, 2016; Rao & Ballard, 1999; Todorovic & de Lange, 2012), a model that views perception as arising from

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hierarchical predictive processing (Friston, 2005). Under this framework, the brain constantly generates predictions about the upcoming sensory information based on prior experience. These predictions are matched with the incoming sensory information, and prediction errors are generated if there is any discrepancy observed. These prediction errors then aid in updating the mental model. Consistent with this idea, the temporal oddball effect is shaped by the predictive code that reflects the discrepancies between the expected and actual stimulus (Pariyadath & Eagleman, 2012; Schindel et al., 2011). Depending on how deviant the odd stimulus is, the perceived time also follows a linear pattern.

While the preliminary studies viewed the temporal oddball effect as a consequence of repetition suppression (Matthews, 2011; Pariyadath & Eagleman, 2012), there were potential complications to it. Predictions evoked by repetition were often conflated by predictions evoked by expectations (Larsson & Smith, 2012; Matthews & Gheorghiu, 2016; Summerfield et al., 2008), which demanded a need to further dissociate the influence of these two forms of predictions independently and orthogonally. One such attempt to dissociate the two forms of predictions provided evidence for a unified framework of repetition effect rooted in predictive coding, which argued that the first-order repetition and second-order repetition – based on expectation – have a distinct influence on perceived timing (Matthews, 2015). While first-order predictions based on repetition reduce the perceived time, second-order predictions based on expectation increase the perceived time.

Although few studies have provided evidence for this unified framework, there are inconsistencies among those studies, especially with regard to how expectation is defined and conceptualized. While few studies have argued expectation effects to be outweighing or attenuating the effect of repetition on timing (Matthews, 2015; Skylark & Gheorghiu, 2017), few other studies showed repetition effects unaffected with any expectation manipulations (Cai et al., 2015). Studies manipulating expectation by altering the frequencies associated with the target involve probabilistic inference. Such probabilistic manipulations can lead to a reduction in perceived duration (Kim & McAuley, 2013; Ulrich et al., 2006). However, there is evidence to show that the usual underestimation of repeated stimuli can reduce or diminish when the series are embedded in a high repeated block of trials, which is thus expected (Matthews, 2015; Skylark & Gheorghiu, 2017). In these studies, higher-order expectations based on probabilistic inference were outweighing the usual repetition effect. In contrast, evidence also shows that the repetition effect of an oddball is unaffected with regard to any higher-order expectations induced through different means (Cai et al., 2015). Similarly, manipulations based on self-generated (Birngruber et al., 2018), contextually associated (Schweitzer et al., 2017), as well as positional

expectations (Wehrman et al., 2020), yielded contradictory findings from what was understood from the earliest studies on expectation effects of timing (Ulrich et al., 2006).

While there is a reasonable acceptance that the first-order repetition influences perceived time through the mechanism of repetition suppression (Matthews, 2011; Pariyadath & Eagleman, 2012), the mechanism by which the second-order expectation influences perceived time remains unclear. One possible reason for this lack of clarity and the inconsistency observed is the levels at which expectation has been manipulated. Hierarchically, the prediction induced by expectation is processed on a higher level compared to the prediction induced by repetition (Todorovic & de Lange, 2012). Studies that show higher-order expectations as outweighing the effect of repetition entails a more globally oriented predictive processing of information (see Matthews, 2015; Skylark & Gheorghiu, 2017). That is, the mode of stimulus time processing in those studies considers the overall regularities of the stimulus sequence. Similarly, studies also pinpoint the possibility that the purported effect of reduced perceived duration can result from a local level predictive processing, irrespective of any higher-order expectations (Cai et al., 2015). In these studies, the effect of local repetitions was outweighing the global level expectation manipulations. Under what conditions the expectation or repetition outweighs the other can be understood only if one knows at what levels do they operate. To address this, the present study specifically focussed on the levels at which information is predicted and its impact on perceived timing.

In two separate experiments using visual and auditory stimuli, the present study investigated the dissociable influence of local and global level predictions in perceived time. The study used a hierarchical violation-of-expectation paradigm having two levels of predictions – local and global – applied to both visual and auditory modalities. Global predictions were manipulated block-wise, employing probabilistic manipulations, and local predictions were manipulated trial-wise, using a three-stimulus stream, with the third stimulus being either a repeat or novel. This design thus led to four conditions: global standard-local standard (GSLS), global standard-local deviant (GSLD), global deviant-local standard (GDLS), and global deviant-local deviant (GDLD). It was expected that the perceived duration of local elements would vary as a function of global rules. More specifically, we expected the duration to be least distorted in GSLS, where there is no violation of any levels of prediction involved, and a maximum distortion (towards overestimation) in GDLD, where both the predictions are violated. If global-level predictions elicit a stronger effect than local predictions, then the perceived time was expected to reduce and increase in GSLD and GDLS, respectively.

## Experiment 1

### Methods

#### Participants

A sample of 38 healthy individuals (27 males, 20–34 years, $M_{age}$ = 27.31, $SD_{age}$ = 3.41) from various Institutes of India provided digital consent to participate in the study. Except one, all participants were right-handed, had a normal or corrected-to-normal vision, and were naive to the purpose of the study. All participants had completed secondary school, with an average of $5.37 \pm 1.4$ years of higher education. Data from five participants who had a below chance level performance in the two extreme intervals in one or more conditions were excluded from the analysis. Their psychometric functions were almost flat, discrimination measures were unreliably large and PSE estimates fell outside the interval range used. The final sample size of 33 (24 males; $M_{age}$ = 27.45, $SD_{age}$ = 3.6) was determined to be adequate through an a priori sample size ($\alpha$ = 0.05; power = 0.8) calculated using G*Power (Faul et al., 2007), based on the effect sizes reported in previous studies (Matthews, 2015; Skylark & Gheorghiu, 2017). Ethical clearance was granted by the Institute Ethics Committee of Indian Institute of Technology Bombay, India.

#### Stimuli/apparatus

Participants completed the study on their personal laptop or desktop. The experiment was created and hosted using an online platform, Gorilla Experiment Builder (Anwyl-Irvine et al., 2020). The use of such online platforms for behavioral studies has become increasingly common and has been accepted by the scientific community. With careful design and implementation, online experiments have been proven to yield reliable data indistinguishable from the lab-based cognitive/perceptual studies (Germine et al., 2012) including time perception (Wehrman & Sowman, 2021).

Stimuli consisted of a black circle or triangle presented against a white background. All stimuli were presented right at the center of the screen subtending a visual angle of not more than 4°. To match for visual angle, participants were instructed to do the screen calibration using a standard size credit card seated at a distance of approximately 60 cm from the center of the screen. The feedback sound during the practice consisted of 350-Hz sinewave tones played for 100 ms following every correct response given by the participant. During the practice session, participants were asked to wear headphones with the volume set to their comfort level.

#### Research design

The study made use of a hierarchical violation-of-expectation paradigm that can dissociate two types of predictions, based on local rules and global probabilities (Bekinschtein et al., 2009; Wacongne et al., 2011). This design manipulated the predicted occurrence of an event at both local and global levels independently. The experiment had two series of visual stimuli: local standards (a series of three identical shapes, denoted xxx) and local deviants (two identical shapes followed by a different shape, denoted xxy). These series were presented in two blocks in which one series was presented with a high probability (initially 100% (for adaptation), then 75%) and the other series rare (25%) (Fig. 1). This design thus enabled the local deviancy of the target stimulus to be separated from the global deviancy of the entire sequence.

### Procedure

Participants were recruited by direct mail and word-of-mouth referrals from different Institutes of India. A Google form was floated first to identify the prospective participants and an online briefing session was scheduled with those who met the inclusion criteria. Following the instruction and briefing, the experiment link was shared with the participants through which they gave consent and performed the task.

The experiment consisted of two major blocks of trials, which indicates the global rule followed in each block (Fig. 1). Each trial started with a fixation cross (500 ms) right at the center of the screen. Following a 250-ms interval, a series of three images were presented with an inter-stimulus interval of 250 ms between each of the stimuli. The duration of the first two (standard) stimuli was uniform (500 ms) whereas the duration of the third stimulus varied from 320 to 680 ms at a step of seven duration levels. As soon as the third image disappeared, the response screen was presented. The participants were asked to judge the duration of the third image relative to the first two standard images. They were required to provide their response using two keys on the keyboard ("S" for shorter; "L" for longer). A 300-ms gap followed the participant response, after which the next trial started.

At the beginning of each block, a practice session that also served to indicate the global rule was given to the participants. During the practice session, a brief beep sound (100 ms) was presented for every correct response made. Following that, the participants performed the main task which was interleaved with global deviant trials. There were 280 trials per block, 210 trials corresponding to global rules, and 70 trials violating the global rules. This resulted in a total of 420 trials for global standard condition, 140 trials for global deviant condition, and 280 trials for local standard and local deviant condition each. Practice trials comprised of 30 trials that satisfy the global rules defined for each block. The order of the two blocks was counterbalanced across participants.

Throughout the experiment, the participants were instructed to maintain their focus right at the center of the screen and keep the index fingers of both hands on the
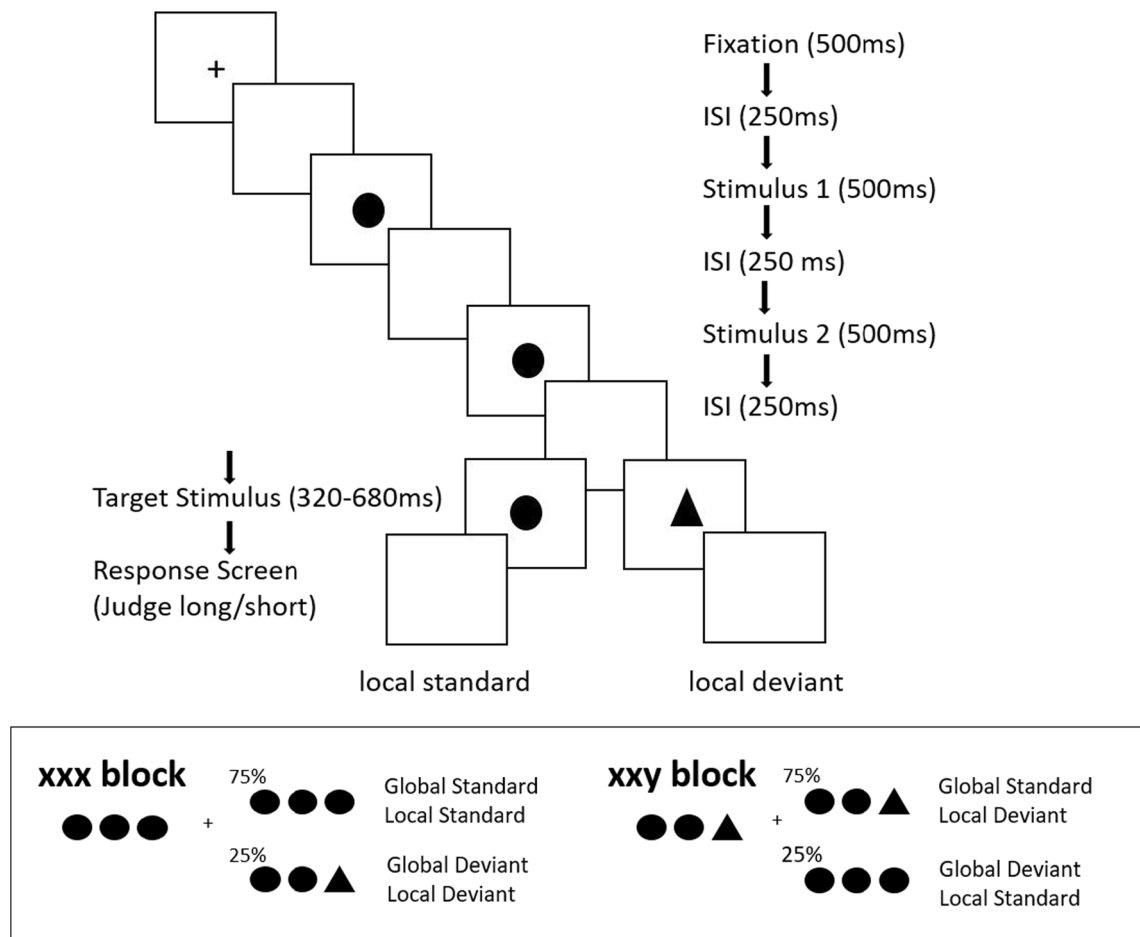
**Fig. 1** The trial structure that was followed. The predicted target of the sequence was manipulated both at the global and local levels. In a given block, one particular series was presented with a higher probability and the other relatively rare. This forms the global rule of that particular block.

The transitivity of the target within each series irrespective of the frequency with which they were presented denotes the local rule. In the above figure, xxx represents the global rule of the first block, and xxy represents the global rule of the second block

corresponding keys on the keyboard. Each block was interleaved with a 1.5 min break after every 70 trials. Participants were required to press the space bar to continue after every break. Participants were thanked and debriefed at the end of the experimental session.

### Analysis

All analyses were performed using MATLAB® (2018b, Math Works, Natick, MA, USA). The individual data were first sorted into four conditions as defined by the standard and deviant series within global and local rules each. The main analysis concerns the proportion of longer responses across different target intervals independently fitted for each participant under each condition. Each data was modeled with a psychometric function derived through probit analysis using a maximum likelihood procedure (Bausenhart et al., 2018; Finney, 1952). The descriptive values such as the point of subjective equivalence (PSE) and difference limen (DL) ($[(x_{75} - x_{25}) / 2]$ were extracted from the psychometric

function. The PSE corresponds to the subjective duration that is perceived as equivalent to the standard duration. Having a smaller PSE value indicates a relative underestimation of duration. The DL indexes participants' discrimination sensitivity, with smaller values indicating a higher level of sensitivity.

Confidence intervals for each of the parameters of the four functions were estimated via bootstrapping (Efron, 1987). For each condition, the percentage of relative overestimation and underestimation are reported. A $2 \times 2$ repeated-measures ANOVA with factors local and global, each having two levels, standard and deviant were performed on the parameters PSE and DL. Effect size measures of $\eta_p^2$ were computed to determine the strength of the obtained effect. Post hoc analysis was performed using *Holm's* correction (Holm, 1979). Effect sizes (Hedges's g) and corresponding bootstrap 95% confidence intervals (3,000 samples) are reported for the pairwise comparisons (Hentschke & Stüttgen, 2011).

To verify that the participants' estimates of global probability were stable across the trials within each block, the data that exhibited a global effect was reexamined by a split trial

analysis. For each block that satisfies a particular global rule, the data was divided into two halves and ANOVAs were computed. Participants whose PSE estimates fell outside the range of two extreme intervals were discarded from the analysis in both halves. Further, a paired t-test was performed for each condition comparing first and second half trials.

## Results

Figure 2 summarises the plot depicting the fitted psychometric function (Fig. 2a), relative duration distortion (Fig. 2b), point of subjective equivalence (Fig. 2c), and duration limen (Fig. 2d) corresponding to each of the four conditions - global standard-local standard, global standard-local deviant, global deviant-local standard, and global deviant-local deviant. In the global deviant condition, the targets were judged to be 8.86% ± 1.68% longer when they were local deviants and 9.06% ± 2.14% shorter when they were local standards. On the other hand, in the global standard condition, the targets were judged to be 7.37% ± 1.45% longer in the local deviant trials, and the judgment remained almost unaffected in the local standard trials (0.37% ± 1.42%). Each of these except the global
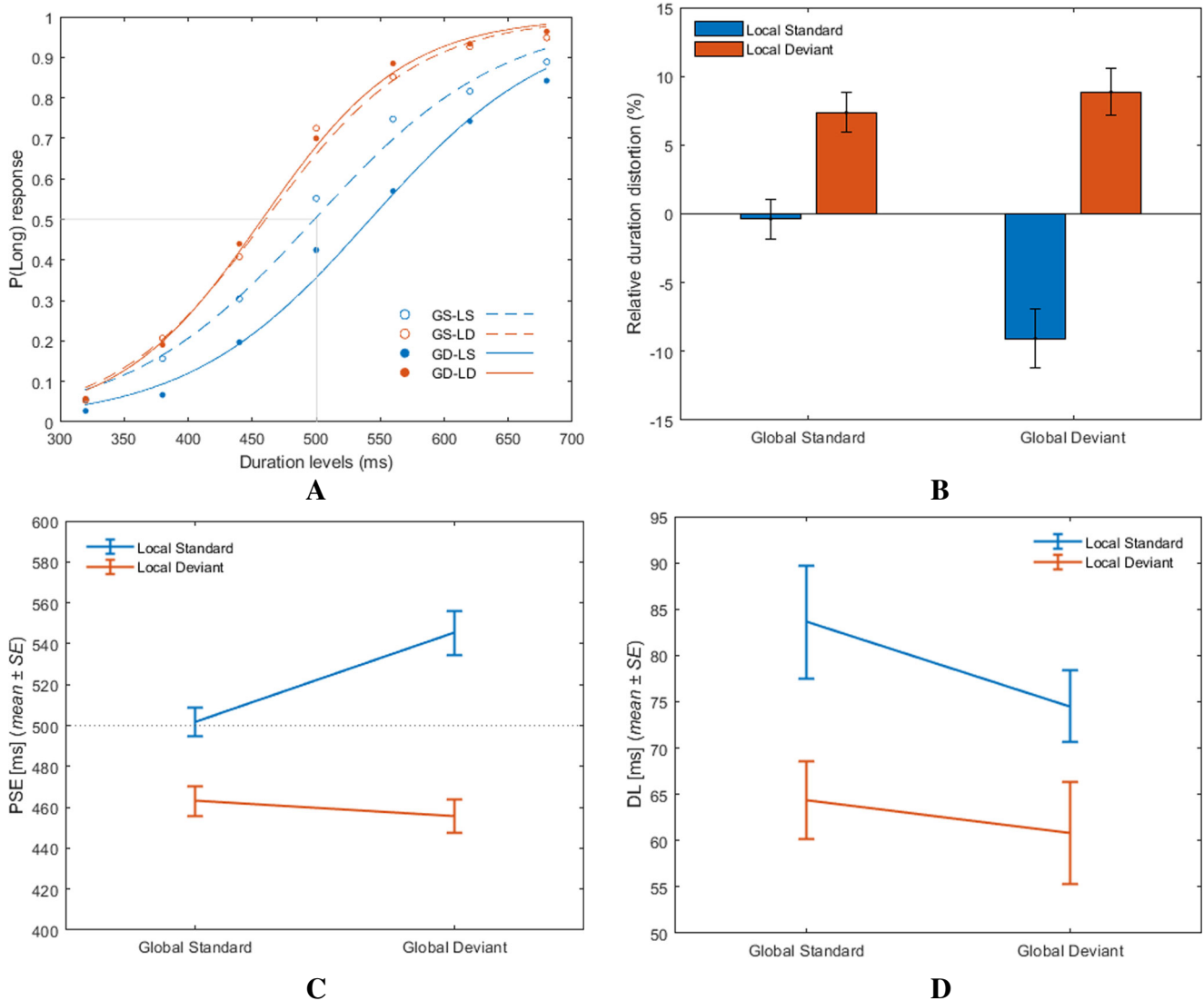


**A**

**B**

**C**

**D**

**Fig. 2** **a** Plot depicting the fitted psychometric function for the data corresponding to each of the four conditions: global standard-local standard (GS-LS), global standard-local deviant (GS-LD), global deviant-local standard (GD-LS), and global deviant-local deviant (GD-LD). The proportion of "long" responses are plotted against each of the seven duration levels. The plot represents the data averaged across all participants. Note that this plot is only for illustration; analysis was based on individual fits (see Online Supplemenary Material). **b** Percentage of relative duration distortion for each condition. Values above 0 indicate an increase in perceived duration. Error bars correspond to the standard error of mean. **c** Point of Subjective Equivalence (PSE) as a function of global and local conditions. Higher (lower) PSE value indicates longer (shorter) perceived duration. Error bars correspond to the standard error of mean. **d** Difference Limen (DL) as a function of global and local conditions. Higher (lower) values of DL indicate a lower (higher) level of sensitivity. Error bars correspond to the standard error of mean

standard-local standard, significantly differed from zero (two-tailed t-test, p < .0001), confirming the presence of the basic temporal oddball effect (Table 1).

The ANOVA computed with PSEs revealed a significant main effect of factor Local $F(1,32) = 54.6$, $p < 0.001$, $\eta_p^2 = 0.63$, 95% CI [0.51, 0.77], with local deviant trials having a lower PSE value as compared to the local standards. The main effect of factor Global, ($F(1,32) = 15.2$, $p < 0.001$, $\eta_p^2 = 0.32$, 95% CI [0.13, 0.53]), as well as interaction between Global and Local, ($F(1,32) = 17.8$, $p < 0.001$, $\eta_p^2 = 0.36$, 95% CI [0.16, 0.56]) was significant. The PSE value in the global standard condition was significantly lower in comparison to the global deviant condition.

Post hoc comparisons revealed a significant difference between local standards and local deviants in both global standard ($t(32) = 4.43$, $p < 0.001$, $g = 0.92$, 95% CI [0.58, 1.32]) and global deviant conditions ($t(32) = 7.38$, $p < 0.001$, $g = 1.59$, 95% CI [1.26, 2.05]). However, the difference comparing local deviant trials embedded among global standard and global deviant conditions was not significant ($t(32) = 1.24$, $p < 0.22$, $g = 0.16$, 95% CI [-0.09, 0.46]). That is, a significant difference between global standard and global deviant trials was present only when they were local standards ($t(32) = -4.88$, $p < 0.001$, $g = -0.81$, 95% CI [-1.15, -0.54]). Finally, as observed from relative duration distortion (Fig. 1b), the magnitude of temporal oddball effect was larger when the trials were embedded in global deviant conditions as compared to global standard conditions ($Mean_{diff} = 50.94$, $t(32) = 4.22$, $p < 0.001$, $g = -0.82$, 95% CI [0.44, 1.34]).

The results in split data sets for PSE replicate the pattern similar to that observed with the full data set. For both the split halves, there was a significant main as well as interaction effect of factors global and local (see Online Supplementary Materials (OSM) for inferential statistics and figures). The data did not significantly differ for each of the four conditions

comparing two halves (global standard-local standard, $t(30) = -1.95$, $p < 0.06$, $g = 0.33$, 95% CI [-0.00, 0.75]; global standard-local deviant, $t(30) = -1.85$, $p < 0.07$, $g = 0.27$, 95% CI [0.00, 0.53]; global deviant-local standard, $t(30) = -2.03$, $p < 0.06$, $g = 0.31$, 95% CI [-0.00, 0.66]; global deviant-local deviant, $t(30) = -1.55$, $p < 0.13$, $g = 0.19$, 95% CI [-0.05, 0.48]). For split trial analysis, the reported P values were not corrected for multiple comparisons

The ANOVA conducted with DL revealed a significant main effect of Local, ($F(1, 32) = 60.3$, $p < 0.001$, $\eta_p^2 = 0.65$, 95% CI [0.51, 0.79]), with lower DL value observed on local deviant trials. By contrast to the results from PSE, the main effect of Global, ($F(1, 32) = 3.10$, $p < 0.08$, $\eta_p^2 = 0.08$, 95% CI [0.00, 0.27]), as well as the interaction between Global and Local, ($F(1, 32) = 0.432$, $p = 0.51$, $\eta_p^2 = 0.01$, 95% CI [0.0, 0.15]), was not significant.

Post hoc tests conducted for DL revealed a significant difference between local standards and deviants when they satisfied the global rules ($t(32) = 4.93$, $p < 0.001$, $g = 0.62$, 95% CI [0.42, 0.94]). There is a marginal difference between local standards and local deviants when they violated the global rules ($t(32) = 2.51$, $p < 0.051$, $g = 0.49$, 95% CI [0.11, 1.06]). Difference limen did not significantly differ between global standards and global deviants when they were local standards ($t(32) = 1.51$, $p < 0.27$, $g = 0.30$, 95% CI [-0.094, 0.64]) or local deviants ($t(32) = 0.69$, $p < 0.48$, $g = 0.12$, 95% CI [-0.18, 0.51]). All reported P values of post hoc tests were corrected for multiple comparisons.

## Discussion

Experiment 1 revealed that the perceived duration, as well as the sensitivity to the stimulus, is higher in the local deviant trials, consistent with the phenomena of temporal oddball effect. On manipulating the global rule for each block, the perceived duration was observed to be longer in the global standard condition as compared to global deviants. As hypothesised, the perceived duration of local standards was modulated as a function of global rule. However, the duration was underestimated in the local standard-global deviant condition as compared to the local standard-global standard condition.

When events are predicted, the perceived duration is expected to contract (Pariyadath & Eagleman, 2007; Schindel et al., 2011; Ulrich et al., 2006). However, when local standards themselves form the global rule, there is a second-level prediction that would impact the purported effect. Having a predicted global and local event should further escalate the contraction of perceived duration in comparison to having a predicted local and unpredicted global event. In the present study, the predictive value associated with the local standard-global standard condition and the local standard-global deviant condition is different, with the latter being more unpredictable, and therefore is expected to invoke a duration expansion.

**Table 1** Mean PSE (point of subjective equivalence) and DL (difference limen) values corresponding to each condition in the visual and auditory task. Confidence intervals for each parameter were estimated using bootstrapping

| Global | Local | PSE (ms) [95% CI] | DL (ms) [95% CI] |
|---|---|---|---|
| Visual Task | | | |
| Standard | Standard | 501.87 [486.36;515.45] | 86.60 [73.67;97.49] |
| Standard | Deviant | 463.15 [445.25;474.48] | 64.39 [57.44;74.87] |
| Deviant | Standard | 545.33 [525.83;566.12] | 74.51 [67.55;82.54] |
| Deviant | Deviant | 455.67 [437.47;470.75] | 60.86 [52.01;74.36] |
| Auditory Task | | | |
| Standard | Standard | 342.46 [335.99;347.89] | 30.88 [27.81;34.62] |
| Standard | Deviant | 327.65 [320.27;334.88] | 31.28 [28.05;35.57] |
| Deviant | Standard | 362.59 [351.16;377.40] | 36.95 [31.09;53.49] |
| Deviant | Deviant | 333.99 [323.83;342.74] | 29.90 [26.64;33.39] |

However, the results revealed are contrary to this hypothesis, with a longer duration perceived in the global standard trials in comparison to the global deviant trials. Consistent with the previous evidence (Matthews, 2015; Skylark & Gheorghiu, 2017), this potentially suggests that the prediction manipulations at the local and global levels, as defined by repetition and expectation in prior studies, do have an opposing influence on perceived time. Although there is a difference in the perception of local standards with respect to whether they followed a global rule or not, the global regularities do not influence the local prediction violation effects. This implies that, in processing time, the local level prediction violations have a stronger behavioral consequence than global predictions. This explanation is corroborated by the observation in local deviant trials, which shows a relatively equal magnitude of temporal oddball effect irrespective of whether they followed any global rule or not.

One question that emerges from these findings is that whether the observed pattern of interaction is specific to visual domain or can also be replicated in the auditory domain. Although the temporal oddball effect observed on the visual and auditory domain shares similar patterns pointing to a central timing mechanism (Tse et al., 2004), the former studies that looked at the dissociable effect of the first order and second order predictions have largely used visual stimuli. Furthermore, the neural signatures corresponding to the violation of various levels of predictions in the auditory domain have also been shown to vary as a function of perceived duration (Ernst et al., 2017; Van Wassenhove & Lecoutre, 2015). In the following experiment, we aimed to address how differentially the local and global predictions contribute to the perceived duration in the auditory domain.

## Experiment 2

The findings from Experiment 1 suggest that the local and global predictions have a distinct influence on the perceived duration of visual events. While predictions at the local level reduced the perceived time, predictions at the global level increased the perceived time. The findings also revealed a robust interaction between local and global predictions, such that the participants' perceived duration of predicted local visual elements depended on the global rules defined for each block. In the following experiment, we aimed to test whether the same pattern of results can be replicated in the auditory time perception.

### Methods

#### Participants

Thirty-six healthy individuals (15 males, 20–36 years, $M_{age} =$ 26.5, $SD_{age} = 4.11$) from various educational institutes of India

provided digital consent to participate in the study in accordance with the Ethics Committee of Indian Institute of Technology Bombay. All participants reported normal or corrected-to-normal vision and hearing, and had completed secondary school, with an average of $4.83 \pm 1.81$ years of higher education. Except for one, all participants were right-handed. Data from two participants who had a below chance level performance in the two extreme intervals and whose PSE estimates fell outside the range of duration levels used were excluded from the analysis. The final sample size of 34 (14 males; $M_{age} = 26.64$, $SD_{age} = 4.12$) was determined to be adequate through the a priori sample size calculation done for the visual task.

#### Stimuli/apparatus

The experiment protocols were similar to those used in the previous experiment except for the following differences. The standard stimulus was a 350-ms 400-Hz sine wave tone and the target stimuli were either a 400 or 550Hz sine tone that varied in duration. All stimuli were generated using MATLAB software (The Mathworks, Inc). The feedback during the practice session consists of a centrally presented happy emoticon (100 ms) following every correct response given by the participant. Throughout the experimental session, participants were asked to wear headphones with the volume set to their comfort level.

#### Research design

In each trial, a series of three tones were presented (Fig. 3). The duration of the third target tone (550 Hz) varied from 230 to 470 ms, symmetrically arranged around 350 ms (standard tone), in steps of 40 ms and seven duration levels. Inter-stimulus-interval between two successive stimuli was always 250 ms. Throughout the trial, a fixation cross was presented right at the center of the screen. Immediately following the third tone, the response screen was presented. The participants were asked to judge the duration of the third tone relative to the first two tones using two keys on the keyboard ('S' for shorter; 'L' for longer).

#### Procedure

The procedures followed were identical to the previous experiment. Prior to the practice session, a sound-check phase was provided to the participants where they were presented with a tone (5,000 ms) similar to those used during the experimental session. They were instructed to play the sound and adjust the volume as per their comfort level. Throughout the experiment, they were instructed to maintain their focus right at the center of the screen and keep the index fingers of both hands on the corresponding keys on the keyboard.
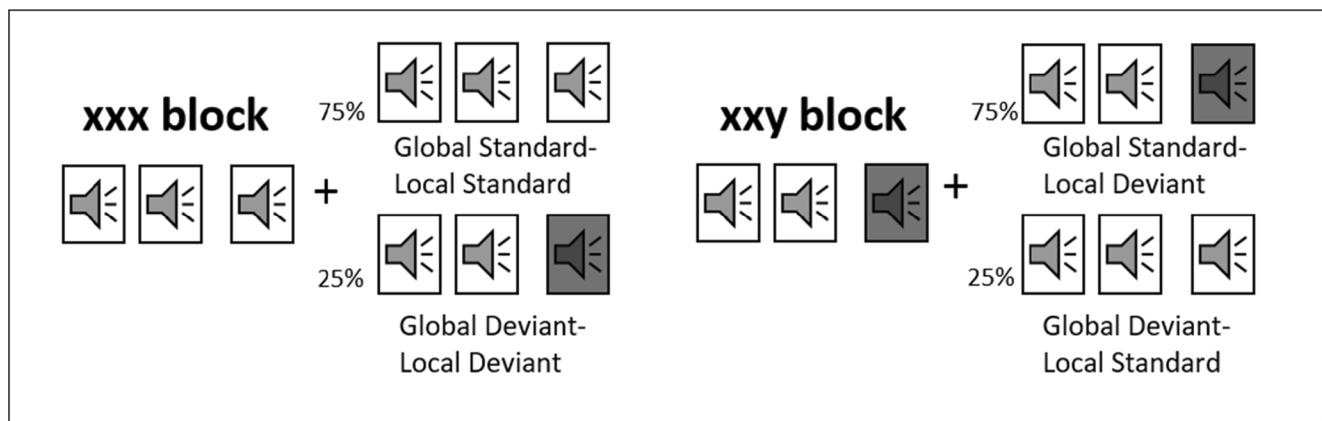
**Fig. 3** Predicted target of the tone sequence manipulated at the global and local levels. In a given block, one particular series of tones was presented with a higher probability and the other series relatively rare. This forms the global rule of that particular block. The transitivity of tones within each series irrespective of the probability with which they were presented denotes the local rule. In the above figure, xxx represents the global rule of the 1st block, which includes three identical tones and xxy represents the global rule of the 2nd block, which includes two identical tones followed by a different tone

## Analysis

The analysis steps followed were identical to those in the visual task.

## Results

Figure 4 summarises the fitted psychometric function (Fig. 4a), relative duration distortion (Fig. 4b), point of subjective equivalence (Fig. 4c), and duration limen (Fig. 4d) corresponding to each of the four conditions: global standard-local standard, global standard-local deviant, global deviant-local standard, and global deviant-local deviant. In the global deviant condition, the targets were judged to be 4.57% ± 1.38% longer when they were local deviants and 3.59% ± 1.94% shorter when they were local standards. On the other hand, in the global standard condition, the targets were judged to be 6.38% ± 1.06% longer in the local deviant trials and 2.15% ± 0.85% longer when they were local standards. Each of these except the global deviant-local standard significantly differed from zero (two-tailed t-test, $p < .0001$) (Table 1).

The ANOVA computed with PSEs revealed a significant main effect of factor Local, $F(1, 33) = 32.5$, $p < 0.01$, $\eta_p^2 = 0.49$, 95% CI [0.35, 0.64], with local standards having larger PSE values as compared to local deviants. The main effect of factor Global was significant, $F(1, 33) = 11.8$, $p < 0.01$, $\eta_p^2 = 0.26$, 95% CI [0.12, 0.42], with larger PSE values observed on global deviant condition. The interaction between global and local was not significant, $F(1, 33) = 3.12$, $p < 0.08$, $\eta_p^2 = 0.08$, 95% CI [0.00, 0.27]. However, the post hoc comparisons revealed a similar trend of results as observed in the visual task. There was a significant difference between local standards and local deviants in both global standard ($t(33) = 3.94$, $p < 0.01$, $g = 0.74$, 95% CI [0.38, 1.17]) and global deviant conditions ($t(33) = 4.24$, $p < 0.01$, $g = 0.82$, 95% CI [0.55, 1.16]). A significant difference between global standards and global deviants was observed only when the trials were local standards ($t(33) = -3.09$, $p < 0.01$, $g = -0.64$, 95% CI [-0.98, -0.33]) (For local deviants, $t(33) = -1.51$, $p < 0.14$, $g = -0.24$, 95% CI [-0.61, 0.06]).

From the split trial analysis, the results of the first half reliably replicated the main analysis. There was a significant main effect of factors local and global while its interaction was not significant (see OSM for inferential statistics and figures). In contrast, for the second split-half trials, the significant main effect of factor global did not emerge. Nevertheless, the pattern observed is similar to that observed in the grand average analysis. The paired t-tests comparing first and second half trials revealed a significant difference in global deviant-local standard ($t(31) = -3.49$, $p < 0.01$, $g = 0.58$, 95% CI [0.27, 1.01]) and global deviant-local deviant ($t(31) = -2.98$, $p < 0.05$, $g = 0.45$, 95% CI [0.15, 0.81]) condition of two halves. However, for conditions that fulfilled the global rule, the pattern of data remains the same as the grand average. The two halves did not significantly differ for conditions global standard-local standard, $t(31) = -1.59$, $p < 0.12$, $g = 0.21$, 95% CI [-0.05, 0.47], and global standard-local deviant, $t(31) = -1.14$, $p < 0.25$, $g = 0.17$, 95% CI [-0.12, 0.46].

The ANOVA conducted with DL revealed no significant main effect of Local, ($F(1, 33) = 3.15$, $p < 0.08$, $\eta_p^2 = 0.08$, 95% CI [0.00, 0.26]), Global, $F(1, 33) = 1.29$, $p < 0.26$, $\eta_p^2 = 0.03$, 95% CI [0.00, 0.16], or their interaction, $F(1, 33) = 2.52$, $p < 0.12$, $\eta_p^2 = 0.07$, 95% CI [0.00, 0.21].

## Discussion

The pattern of results obtained in the auditory task is fairly consistent with that observed in the visual task. The perceived duration was longer in the local deviant condition, thus exhibiting the basic temporal oddball effect. With

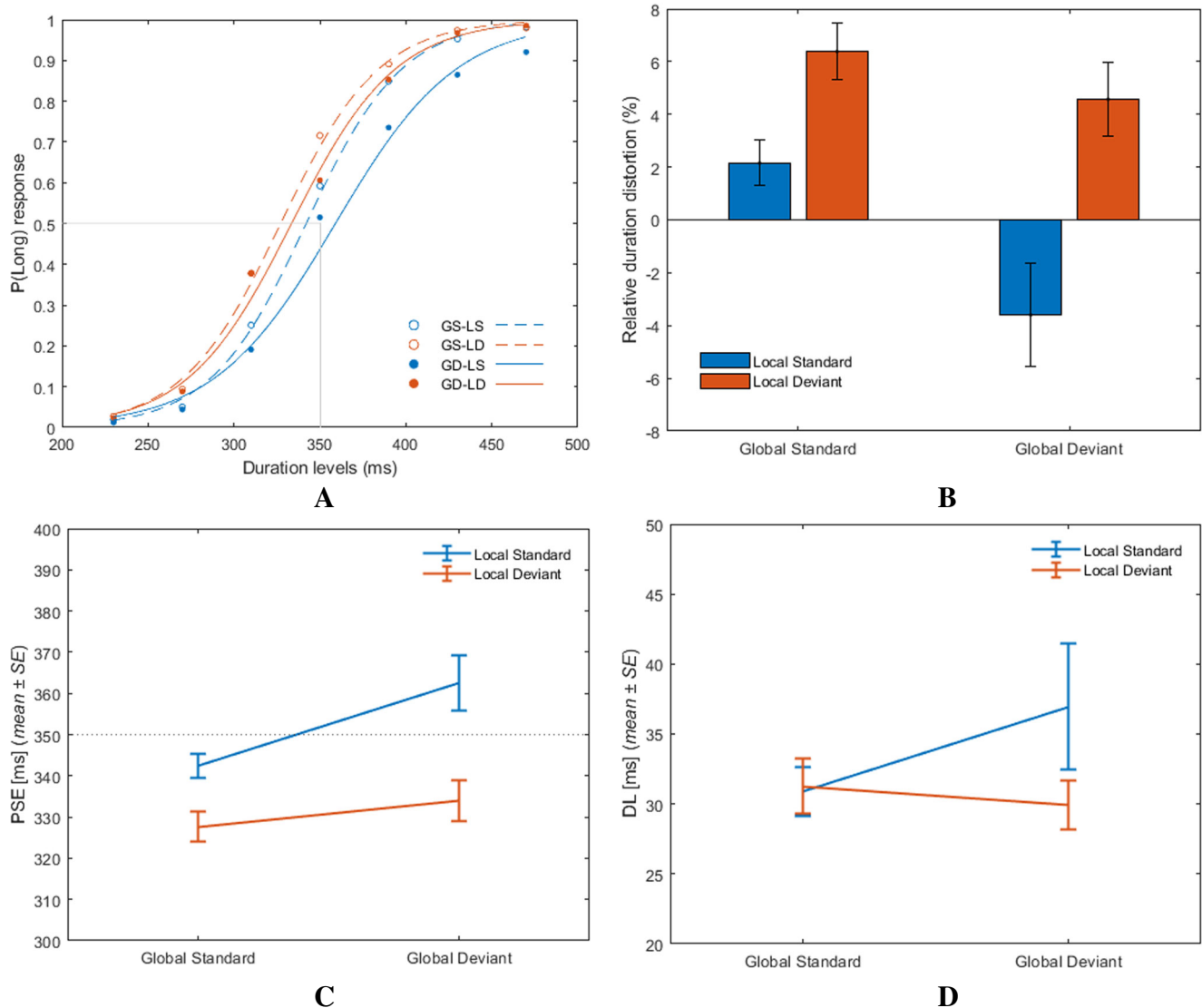**A**



**B**



**C**



**D**

Fig. 4 **a** Plot depicting the fitted psychometric function for the data corresponding to each of the four conditions: global standard-local standard (GS-LS), global standard-local deviant (GS-LD), global deviant-local standard (GD-LS), and global deviant-local deviant (GD-LD). The proportion of "long" responses are plotted against each of the seven duration levels. The plot represents the data averaged across all participants. Note that this plot is only for illustration; analysis was based on individual fits (see Online Supplementary Material). **b** Percentage of relative duration distortion for each condition. Values above 0 indicate an increase in perceived duration. Error bars correspond to the standard error of mean. **c** Point of Subjective Equivalence (PSE) as a function of global and local conditions. A higher (lower) PSE value indicates a longer (shorter) perceived duration. Error bars correspond to the standard error of mean. **d** Difference Limen (DL) as a function of global and local conditions. Higher (lower) values of DL indicate a lower (higher) level of sensitivity. Error bars correspond to the standard error of mean

global manipulations, the perceived duration was longer whenever the global rules were satisfied. Although the interaction between local and global rules was not reliably replicated, the perceived duration of local standards was modulated as a function of global rule manipulations. The duration was underestimated in the local standard-global deviant condition as compared to the local standard-global standard condition. However, contrary to the results obtained in the visual task, perceived duration in the local standard-global standard condition was significantly longer than the standard duration.

Prior research indicates a top-down mediation of repetition suppression by probabilistic manipulation in the early auditory cortex (Todorovic et al., 2011). For instance, the more frequent the repeated tone was, the more its evoked response was suppressed. In contrary to repetition suppression account of perceived time, as put forth by Pariyadath and Eagleman (2012), the present results did not elicit a further reduction in perceived time when the global predictions as defined by the probabilistic manipulations were fulfilled. These results along with the pattern observed in the visual task potentially shed some doubt on the neuronal magnitude-based account of

subjective time as previously suggested (Eagleman et al., 2009; Eagleman & Pariyadath, 2009; Pariyadath & Eagleman, 2012). It could be that subjective time does not directly reflect the efficiency with which a stimulus has been encoded. Rather, the coding efficiency determined by various levels of predictions may have distinct behavioral consequences in the perception of time.

## General discussion

Using a hierarchical violation-of-expectation task, we sought to dissociate the influence of local and global predictions on perceived time in both visual and auditory domains. Our results revealed a pattern of enhanced perceived duration when local predictions were violated. This pattern is consistent with the result expected in the phenomena of temporal oddball effect (Pariyadath & Eagleman, 2007; Schindel et al., 2011), and this effect was present irrespective of whether the trials were globally predicted or not. In contrast, the perceived duration was longer when the global predictions were fulfilled. While there was a robust interaction between local and global prediction conditions in the visual task, the corresponding interaction was not reliably observed in the auditory task. However, the pattern of results obtained in the auditory task is consistent with that observed in the visual task. Broadly, in both the tasks, participants' perceived duration of predicted local series depended on the global rules defined for each block. More specifically, the perceived duration of only local standards was modulated as a function of global rule.

The magnitude of the temporal oddball effect was found to be larger in the global deviant condition. This is particularly driven by the local standards that were presented less frequently in the global deviant condition. Although the local standards were expected to have a reduced perceived duration irrespective of whether it followed the global rule or not, the present results showed that local standards do not elicit a reduction in perceived time when they satisfy the global rule. These specific results are consistent with the prior studies that showed a distinct influence of repetition effect on timing when the probability of repetition rate was manipulated (Matthews, 2015; Mcfeaters & Voyer, 2019; Skylark & Gheorghiu, 2017). The local standard-global standard condition in the present study is analogous to the high repetition block in the study by Matthews (2015), and our results showed no reduction in perceived duration. In contrast, the duration remained unaffected in the visual task and even increased in the auditory task, thus reducing the magnitude of temporal oddball effect in the global standard condition.

Recent studies grounded in predictive coding models postulated that repetition suppression (RS) and expectation suppression (ES) operate at distinct levels and has a distinct behavioral consequence (Grotheer & Kovács, 2016; Larsson &

Smith, 2012; Todorovic & de Lange, 2012). While the first-order repetition effect, which involves RS, leads to a contraction of duration, the second-order repetition, based on ES, which considers the overall regularities of the environment, leads to an expansion of perceived duration (Matthews, 2015; Matthews & Gheorghiu, 2016). Predictions that occur at the global level are often conceived as involving top-down mediation (Todorovic et al., 2011), with expectation suppression as its underlying mechanism (Todorovic & de Lange, 2012). On the other hand, predictions at the local level involve repetition suppression as its underlying mechanism (Eagleman et al., 2009). Global rules in the present study entailed second-order prediction, which considers the overall regularities of each block, and consequently leads to an expansion of duration when they were fulfilled. Contrary to the prior findings that observed a larger response suppression with the frequently repeated events (Matthews, 2015; Skylark & Gheorghiu, 2017), the perceived duration in the local standard-global standard was almost equivalent to the objective duration, implying that the duration contraction of the local standard was attenuated. In this condition, the global predictions outweighed the effect of local predictions. Whereas in the local standard and global deviant condition, the perceived duration was further reduced, implying that the duration contraction increased.

Although several studies have indicated an effect of probabilistic-based expectation on the perceived duration of local elements (Matthews, 2015;Mcfeaters & Voyer, 2019 ; Skylark & Gheorghiu, 2017), the present results suggest that there is no effect of such higher-order regularities specifically when local predictions are violated. For instance, in the present study, the perceived duration of local deviants did not vary as a function of global rules followed. Along a similar line, in one prior study where the probability of stimulus sequence type was manipulated, Cai et al. (2015) found that the perceived duration is not influenced by any such probabilistic manipulations. The target condition in Cai et al.'s (2015) Experiment 1 always had a deviant stimulus that is similar to the local deviant condition in the present study. This broadly suggests that the global predictions, which are often probability-based, are not capable of outweighing the effect of local level prediction violations, but rather the perceived duration of only locally repeated elements.

Our results further demonstrate that the participants' discrimination sensitivity could vary as a function of local prediction manipulations in the visual task. Although the locally predicted elements had a reduced sensitivity, no such difference emerged for the global predictions, further pointing to a distinct influence of the two levels of predictions on perceived time. The lack of a robust interaction for sensitivity observed in the present study is consistent with some prior studies where similar probabilistic manipulations were employed in evoking an expectation effect (Mcfeaters & Voyer, 2019;

Skylark & Gheorghiu, 2017). One possible mechanism that may have contributed to the enhanced sensitivity of locally deviant elements is attention. Prior studies indicate that deviant events grab exogenous attention due to their transient property (Tse et al., 2004). The potential mediatory role of attention in response to the deviant event in a series has been confirmed with the presence of an associated neural marker (Bekinschtein et al., 2009; Ernst et al., 2017; Wacongne et al., 2011). Further experimental studies with the concurrent tracking of attention are required to rigorously evaluate whether the purported effect of larger discrimination sensitivity of local deviants emerged as a consequence of elevated attention.

As an extension to the recent theories rooted in a predictive coding framework that emphasizes the opposing influence of first order and second order predictions on perceived time, the present findings show that the information about the global regularities influences the perceived duration of local elements in both visual and auditory domains. If the global level manipulations entail probabilistic information, then the highly probable events are perceived to be longer, and can potentially cancel out the effect of any local level predictions. On the other hand, violation of global predictions does not outweigh the effect of local predictions. This suggests that there is no clear and cut link between neuronal coding efficiency and subjective time. If at all a correlation exists as suggested in some prior studies (Eagleman & Pariyadath, 2009; Sadeghi et al., 2011), it is applicable only with the manipulation involving low-level stimulus properties, which demand a locally oriented processing of information.

Apart from the main objective of the study, the present study gives a clear hint on the efficacy of the phenomena of temporal oddball effect to be replicated outside a lab-based environment. This comes as an extension to the recent studies that indicate the potential of time perception research to be taken online (Wehrman & Sowman, 2021). Furthermore, the pattern of data observed in the visual task mimics some prior lab-based studies where similar probabilistic manipulations were incorporated to the repetition effects of perceived time (Matthews, 2015; Skylark & Gheorghiu, 2017).

## Conclusion

In sum, these results suggest a potential hierarchy in the predictive processes involved in time perception. Predictions at the local and global level have a distinct influence on our perceived time, which unifies well with the recent theoretical framework rooted in predictive coding that provided a two-step model of prediction effect on time perception.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.3758/s13414-022-02533-z.

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