

**Temporal expectations in isochronous sequences**

by

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# **Abstract**

Temporal expectation relates to the probability of occurrence of stimuli; it is necessary to evaluate such probabilities in relation to people's perceptual latency, in order to have better understanding of probabilistic distortion in timing perception. Therefore, to highlight the importance of temporal expectation in regular sequences, we carried out two studies to clarify the influence not only from the timing itself, but also the extra non-temporal elements, melody and tones. In all studies participants were presented with auditory isochronous sequences, consisting of different numbers of identical timing intervals. In chapter two, we manipulated attention by altering presentation types, interleaved or blocked. We found perceived isochrony of stimuli affected by temporal expectation and the final stimulus of the sequences were anticipated. In chapter three, we manipulated the predictability by altering the sequence of tones used to demarcate the time intervals. We found increased sensitivity with melodically ordered tones and demonstrated how patterns in non-temporal properties can also create expectations. The outcomes contributed to the advanced understanding of expectation in perceived regularity and patterning of time, with its underlying computational mechanisms.

# Included papers and contribution

## Journal articles

1. **Li, M. S.,** Rhodes, D., & Di Luca, M. (submitted). For the last time: Temporal sensitivity and perceived timing of the final stimulus in a regular sequence.
2. **Li, M. S.,** & Di Luca, M. (in preparation for submission). Non-temporal properties in sensory predictions: Tone sequences and its structures.

## Conference abstracts

1. **Li, M. S.,** Rhodes, D., & Di Luca, M. (2014). Probabilistic distortions of temporal judgments with isochronous sequences. *Procedia Social and Behavioural Studies*, ICTTP 2014. Paper presented at the *International Conference on Timing and Time Perception*, Corfu, Greece.
2. **Li, M. S.,** Rhodes, D., & Di Luca, M. (2015). Perceptual distortions of subjective time in isochronous sequences. Paper presented at the *16<sup>th</sup> International Multisensory Research Forum (IMRF)*, Pisa, Italy.
3. **Li, M. S.,** & Di Luca, M. (2015). Temporal properties in sensory predictions. Paper presented at the *2015 European Conference on Visual Perception (EVP)*, Liverpool, U.K.

## Contribution

The candidate took the major part in literature review, experimental design, stimuli generation and programming, data collection, data analysis and manuscript writing of all the studies in this dissertation.

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# Chapter 1: Literature review

The clock is an objective representation of time, however, it does not necessarily represent how humans perceive time, because psychological time is subject to distortions by a multitude of non-temporal factors (e.g., Allan, 1979). This is reflected in terms such as ‘time flies’ and ‘days wear on like years’ people use to describe their feelings of the passage of time. Quantitative evaluation of objective and subjective time started as long ago as late 19 century (e.g., Woodrow, 1935); more recently, researchers have drawn the attention from clinical aspects (Lemlich, 1975) to social aspects (Joubert, 1983), and even more recently the cognition aspects of time perception have been placed under investigation (e.g., Kanai & Watanabe, 2006; Pariyadath & Eagleman, 2007). Although large numbers of previous investigations provided a broad overview of which and how different factors affect time perception, there are still elements that are tightly related to time but yet not clearly explained.

Temporal expectation is one of the unclear issues that plays an important role in sensory processing of all modalities, not only at the unisensory but also the multisensory level (Mistlin & Perrett, 1990; Todorovic et al., 2011; van Ede et al., 2011). Auditory studies on temporal expectations are particularly interesting given that it can be widely applied in our daily life, for example, music production (Lange, 2009; Zatorre, Chen, & Penhune, 2007), multisensory integration (Buetti & Macaluso, 2010), sensory prediction and working memory (Chennu et al., 2013; Wilsch et al., 2014). One simple way of generating expectation from a temporal sequence is an isochronous stimulation that consists of subintervals with equal durations. This simple pattern can be easily applied in experiments to study the optimal effect of expectation. For instance, Schulze (1989), Drake and Botte (1993), Ivry and Hazeltine (1995), and

ten Hoopen et al., (1993) have all experimented with isochronous sequences and modeled the effect of ‘Multiple-look’ – the phenomenon that temporal expectation increases sensitivity as a result of repeated stimulation. However, isochronous sequences can also be used to examine other elements that may be affecting temporal expectation, such as attention and non-temporal stimulus properties. The latter approach is currently lacking research in the literature.

To further study the influence of expectation on timing and time perception, I will be taking a closer look at the factors influencing temporal sensitivity and perceived timing in isochronous sequences. In chapter one, I will be discussing how attention and expectation affects timing in regular rhythms: I will be manipulating attention by presenting different sequence lengths separated by block or at random in the same block. I will also try to distinguish the effect of different sequence lengths, or, violations of expectation at different points in time. I hope to identify the association between expectation, attention and distortions in perceived timing, and provide supporting evidence for facilitated sensory processing from temporal expectation.

In chapter three, I will be investigating the connections between musical patterns based on melodic tones, expectation, and predictability. Previous evidence has shown that rhythmic patterns modulate perceived duration (e.g., Horr & Di Luca, 2015) but rhythm is only one aspect of music. To add to the research on music and time perception, I will investigate another important aspect of music, which is melody. Since the role of melodic patterns is still unclear in sensory processing, I will disentangle how not only temporal patterns but also melodic patterns help with predicting future stimuli in a sequence.

The current thesis aims to demonstrate more precisely what are the sub-structures in temporal expectation – What causes it? What will be affected and how will it affect? All experiments are conducted with classical psychophysical methods and the results are interpreted in the framework of Bayesian statistical inference.

## **Chapter 2:**

For the last time: Temporal sensitivity and perceived timing of the final stimulus in a regular sequence.

This chapter has been submitted to

**Li, M. S.,** Rhodes, D., & Di Luca, M. (submitted). For the last time: Temporal sensitivity and perceived timing of the final stimulus in a regular sequence.

# Abstract

Temporal regularity of sequences creates the expectation that stimuli will appear after an interval equal to the previous ones. Here we study: (1) how such expectation influences sensitivity in discriminating the timing of the last stimulus in the sequence, (2) whether perceived timing of the last stimulus is modified if it follows a regular pattern, and (3) how such effects depend on the knowledge of the sequence length. Participants reported whether the last stimulus of a regularly-timed sequence (3, 4, 5, or 6 beeps) appeared ‘earlier’ or ‘later’ than expected. Sequences lengths were either randomly interleaved or presented in separate blocks. We find that temporal sensitivity increases with longer sequence in the interleaved condition but not in the blocked condition where discrimination performance is higher overall. Results also indicate that the last stimulus in a sequence is perceived to be isochronous if it is presented later than expected (irrespective of how many stimuli the sequence is composed of) and more delay is required in the interleaved condition. We reason that if participants do not know which stimulus is to be judged they need to rely more on sensory prediction, increasing discriminability with longer sequences. We propose a model based on Bayesian statistics that combines expectations from the sequence with sensory information and a prior that encountering a stimulus becomes less probable over time. The model accounts for the pattern of both temporal sensitivity across conditions and change in the perceived timing of stimuli based on different reliability of sensory information.

*Keywords:* temporal perception, perceived timing, rhythm perception, temporal expectation, attention, isochrony, prior entry, perceived isochrony

## 2.1 Introduction

Psychological time is subject to several types of distortions (e.g., Allan, 1979). For instance, temporal structure (Horr & Di Luca, 2015), musical context (Pecenka & Keller, 2011) and, violations of regularity (Pariyadath & Eagleman, 2007; Rose & Summers, 1995) can all influence the perceived duration of events. Here we investigate the effect of temporal regularity on time perception. The simplest form of regularity in time is created by an isochronous sequence, that is, the repetition of identical stimuli after equal temporal intervals. Isochronous sequences create temporal expectations based on their regular rhythm and repeated pattern (Arnal & Giraud, 2012; Large & Jones, 1999) and can influence perceptual judgments and behaviour (Brochard et al., 2013; Coull, 2009; Cravo et al., 2013; Escoffier et al., 2010; ten Oever et al., 2014). The sensitivity of judgments about the temporal properties of sequences is also improved by temporal regularities (Drake & Botte, 1993; Grondin, 2001; Hirsch et al., 1990; McAuley & Kidd, 1998).

Drake and Botte (1993) showed that participants' ability to judge the difference in tempo of two isochronous sequences increases when the sequences are composed of more stimuli. They proposed the Multiple-Look Model (MLM), according to which each interval provides an independent estimate of the tempo to be compared. As the number of 'looks' at each sequence increases, the precision of the estimate improves. The just-noticeable difference (*JND*) for two sequences each of length  $n$  depends on the number of intervals according to:

$$JND_n = \frac{JND_1}{\sqrt{n}} \quad \text{Eq. (1),}$$

where  $JND_1$  is obtained by comparing the perceived *duration* of two sequences

having one interval each. It should be noted that the MLM predicts increasingly better performance with longer sequences and perfect performance with  $n \rightarrow \infty$ .

The MLM predictions from Eq. 1 assume that the number of intervals in each of the two sequences to be compared should be equal, and thus it is not possible to discern whether the decrease in the *JND* is related to the number of intervals in one or the other sequence. To solve this, Miller and McAuley (2005) suggested a generalized multiple-look model whereby the two sequences (denoted  $n_1$  and  $n_2$ , respectively) make independent contributions to the performance. As with the original MLM (Drake & Botte, 1993), the model of Miller and McAuley predicts that the  $JND_{n_1:n_2}$  should decrease as the number of ‘looks’ increases (here  $JND_{1:1}$  refers to the comparison of two single-interval sequences). However, the contribution of the two sequences varies depending on a weight parameter,  $w$ :

$$JND_{n_1:n_2} = \sqrt{\frac{w(JND_{1:1})^2}{n_1} + \frac{(1-w)(JND_{1:1})^2}{n_2}} \quad \text{Eq. (2)}$$

If  $w = 1$  then the discrimination performance is determined only by the intervals in the first of the two intervals, whereas if  $w = 0$  then the *JND* is determined only by the number of comparison intervals. In practice, the value of  $w$  cannot have these extreme values, but it will have a value that depends on the contribution of the two intervals to the overall performance.

The goal of the Multiple-Look Model is to quantify the discrimination performance with two sequences of regular intervals. With this task, several studies have reported results consistent with the MLM (Grondin, 2001; Ivry & Hazeltine, 1995; McAuley & Jones, 2003; McAuley & Kidd, 1998; ten Hoopen, et al., 2011), although others have not found a close match with its predictions (Grondin, 2001; Hirsch et al., 1990, ten Hoopen et al., 2011). Furthermore, Grondin (2001) demonstrated a Multiple-Look effect with visual stimuli only if tempo was compared

in two separate sequences, whereas the effect was not present if a change in tempo happened within one sequence. Ivry and Hazeltine (1995) also compared one sequence performance with two sequences performance, but with auditory stimuli, finding a Multiple-Look effect in both. Ten Hoopen et al. (2011) investigated the issue of temporal sensitivity within a single sequence of audio stimuli finding that the Multiple-Look effect can be found also in one sequence of stimuli. More importantly, they found a significantly higher increase in performance when the number of intervals was increased *before* the tempo change. They model performance using a reciprocal diminishing returns function:

$$JND = a_x + \frac{b_x}{n_x} \quad \text{Eq. (3)}$$

where  $a$  is the asymptotic performance (which does not necessarily lead to  $JND=0$  as in Eq. 1 and 2) and  $b$  is the amount of performance increase for each added interval to  $n$ . The index  $x$  of the terms  $a$ ,  $b$ , and  $n$  indicates that the parameters differ before and after the tempo change. Their results show that performance increment is higher for changes before the tempo change ( $b_1 > b_2$ ). Eq. 3 should be compared to Eq. 1, as it's important to note the added constant  $a$  and the missing root square on the  $n$  parameter.

In this paper, we also investigate the effect of the number of intervals within a single sequence. We utilize stimuli and conditions taken from Schulze (1978; 1989) whilst also including one of the conditions of ten Hoopen et al. (2011), where observers are presented with a sequence of isochronous tones (identical intervals) except for the last interval. In Schulze's (1989) original experiment, the last interval could be either equal or longer than the preceding intervals, whereas ten Hoopen et al. allowed the final interval to also be shorter. Both Schulze and ten Hoopen et al. found that discrimination performance improved as the number of intervals before the last one increased from two to six. The situation can be captured by both the generalized

MLM (Eq. 2) and by the reciprocal return function (Eq. 3), as the comparison of the number of identical intervals to a single interval.

In contrast to Schulze's studies (1978; 1989), we allowed the last interval to be either longer or shorter than the previous ones. That is, the last stimulus could be presented anisochronously compared to the previous sequence, either too early or too late. The task also differs from Schulze's and is similar to ten Hoopen et al.'s (2011), as participants judged whether the last stimulus was presented 'earlier' or 'later' than isochrony (i.e., they reported whether the last interval was shorter or longer than the previous ones). The analysis of 'earlier' vs. 'later' judgments allows us to determine whether temporal expectations generated by the sequence of stimuli with identical interval can cause a consistent bias in perceived isochrony, an analysis that was possible but has not been performed by ten Hoopen et al. The motivation for this new analysis is a departure from previous accounts of perceptual phenomena with isochronous sequences, as here we try to account for biases in perceived isochrony by appealing to a modification of the perceived timing of the last stimulus in the sequence. This requires a difference in the formulation of the problem: rather than an analysis of perceptual duration, we analyse the perceived timing of stimuli. In particular, we analyse the time at which the last stimulus in the sequence is perceived, which is presented right after the change in tempo.

Titchener (1908) was the first to suggest that attention (among other factors) can modulate perceived timing of individual stimuli as a fully attended stimulus is processed faster than an unattended one. Summerfield and Egner (2009) investigated the contribution of attention in a recognition task supporting the idea of prioritized processing of attended stimuli. Such attentional facilitation speeds up perception, an effect termed *prior entry*, which has been highlighted in studies involving temporal

judgments (Sternberg & Knoll, 1973; Vibell et al., 2007; Zampini et al., 2005; Shore et al., 2001; for a review see Spence & Parise, 2010) and at the neural level (McDonald et al., 2005). According to a time-frequency analysis of electroencephalographic (EEG) recordings by Rohenkohl and Nobre (2011), decreased brain activity in the alpha band for expected stimuli is correlated with faster responses, tentatively suggesting a neural basis for the prior entry hypothesis.

To evidence the relationship between attention and perceptual acceleration we manipulated task demand by presenting stimulus sequences of different length either in an interleaved or blocked presentation. We posit that in the interleaved condition, participants do not know when the sequence will end and, thus, will have to pay closer attention. Such uncertainty will increase the reliance on sensory predictions, which should result in a stronger prior entry effect. The perceived timing of stimuli in the interleaved condition should be accelerated and, consequently, perceived isochrony should be obtained with slightly delayed stimuli (and, thus, slightly longer intervals) rather than stimuli presented at the expected time point.

## **2.2 Methods and materials**

### **2.2.1 Participants**

Twenty-five undergraduate students (age range from 18 to 25 years and mean age of 21.3 years) with self-reported normal hearing were recruited by the research participation system of the University of Birmingham. They gave informed consent before taking part in the experiment and were rewarded with course credits or a payment of six pounds per hour. Ethical guidelines have been followed in all the experiments and were approved by the STEM Ethics Committee of the University of Birmingham.

### **2.2.2 Design**

There were two sessions, one with interleaved presentation and one with blocked presentation of trials with different sequence lengths: 3, 4, 5 or 6 stimuli (2, 3, 4 or 5 intervals). For every sequence length, the timing of the last stimulus was selected among 15 possible anisochronies: 0,  $\pm 20$ , 40, 60, 80, 100, 150, and 200 ms. The trial types resulting from the combination of blocked/interleaved presentation (2), sequence length (4), and anisochrony of the last stimulus (15) were repeated 8 times in order to determine the parameters of eight psychometric functions (see results) for a total of 960 trials per participant.

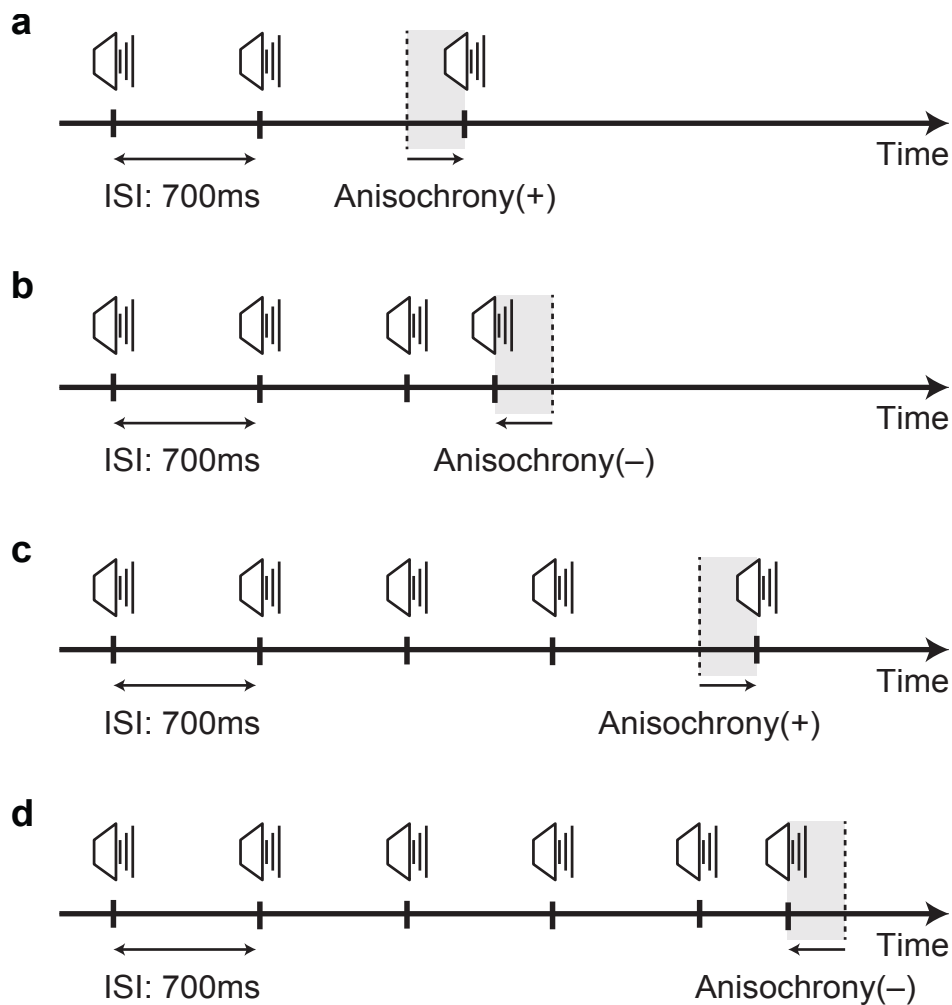
### **2.2.3 Stimuli**

Stimuli were identical tones produced by a speaker located on a desk approximately 50 cm from the participant (20 ms with 5 ms linear ramp, 1 kHz, 75.1

dBa). Trials were composed of a different number of stimuli in sequence where intervals between successive stimuli in the sequence remained the same (IOI = 700 ms) for all but the final stimulus, which could be presented at different anisochronies.

#### 2.2.4 Procedure

Participants sat in a quiet testing cubicle. A sequence of auditory stimuli of different lengths were presented in which the participants had to respond whether the anisochrony of the final stimulus was ‘earlier’ or ‘later’ than the expected timing (**Fig. 1**). Sequence lengths were either presented blocked or interleaved and the order of the two presentations was counterbalanced across participants.



**Figure 1.** Examples of trials with different sequence length. (a) Sequence of three stimuli (two intervals) where the final stimulus is presented later than expected (+ Anisochrony). (b) Sequence of four stimuli (three intervals) where the final stimulus is presented earlier than expected (- Anisochrony). (c) Sequence of five stimuli (four intervals) where the final stimulus is presented later than expected (+ Anisochrony). (d) Sequence of six stimuli (five intervals) where the final stimulus is presented earlier than expected (- Anisochrony).

### 2.2.5 Data Analysis

We analyzed the proportion of ‘later’ responses for each anisochrony of the last stimulus, to obtain a distribution for each sequence length with interleaved and with blocked presentation. In order to determine if a change in the perceived isochrony of stimuli changes due to temporal expectations and attention, we calculate the *Point of Subjective Equality (PSE)* as the anisochrony at which participants are most unsure about whether the final stimulus was presented earlier or later. Thus, the *PSE* is the time point at which the last stimulus needs to be presented in order for it to be perceived as being isochronous. The *PSE* is obtained by calculating the first order moment of the difference between successive proportions of responses using the Spearman-Kärber method (see Ulrich & Miller, 2004, for further details of this method). The second order moment is proportional to the inverse slope of the psychometric function, which here is termed *JND*.

To obtain *PSE* and *JND* we employ the Spearman-Kärber method, which is a non-parametric estimate that avoids assumptions about the shape of the psychometric functions underlying the participants’ responses. The formulae below are used to estimate the first and second moment of the psychometric function underlying the

data. First we define the 15 anisochronies of the final stimulus, where  $ANI_i$  with  $i=\{1, \dots 15\}$  and  $p_i$  with  $i=\{1, \dots 15\}$  as the associated proportion of ‘later’ responses. We further define  $ANI_0=-250$  ms,  $ANI_{16}=+250$  ms and we assume  $p_0=0$  and  $p_{16}=1$ , to be able to compute the intermediate  $ANI$  between two successive ones

$$s^i = \frac{ANI_{i+1} + ANI_i}{2}, \text{ with } i=\{0, \dots 15\} \quad \text{Eq. (4)}$$

and the associated values of the difference in proportion of responses

$$dp_i = p_{i+1} - p_i, \text{ with } i=\{0, \dots 15\} \quad \text{Eq. (5)}$$

With these indexes we can express  $PSE$  and  $JND$  analytically as such:

$$PSE = \sum_{i=0}^{15} s_i dp_i \quad \text{Eq. (6)}$$

and

$$JND = \sqrt{\sum_{i=0}^{15} dp_i (s_i - PSE)^2} \quad \text{Eq. (7)}$$

## 2.3 Results

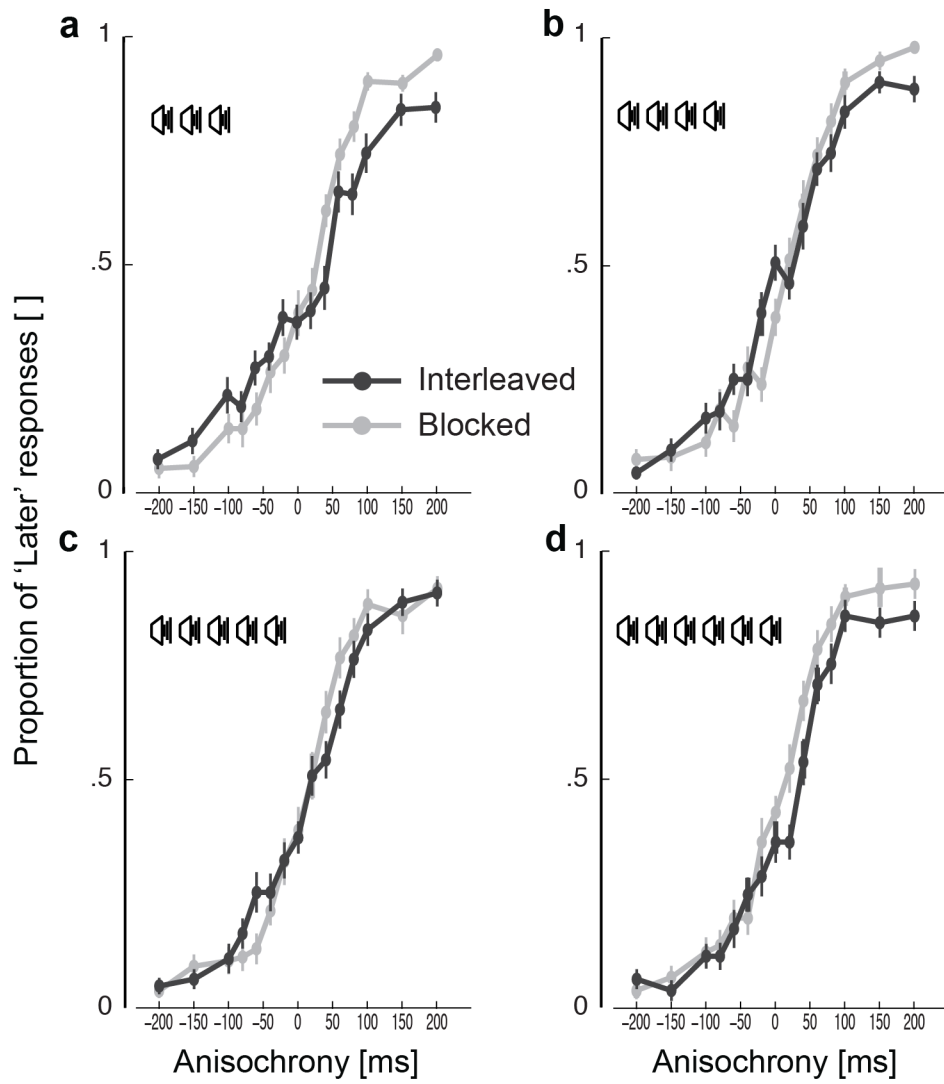
The average proportion of responses across participants for sequences of different lengths and type of presentation (interleaved and blocked) are shown in Fig. 2a-d. A consistent difference of the response distributions with blocked and interleaved presentation is evident across the various sequence lengths.

Discrimination performance was characterised by *JND* values (Fig. 3a,b), which are calculated according to the Spearman-Kärber method (see method section). To determine whether temporal sensitivity improves with sequence length, and whether differences in sensitivity existed between blocked and interleaved presentations, *JND* values were submitted to a two-way repeated measure ANOVA with factors condition (blocked or interleaved) and number of intervals in the sequence (2, 3, 4 or 5). Results indicate better discrimination with blocked presentation of sequence length ( $F(1,24)=14.8, p=0.001, \eta_p^2=0.38$ , Fig. 3c), an improvement in performance due to sequence length ( $F(3,72)=5.1, p=0.001, \eta_p^2=0.17$ ), and a significant interaction between the two factors ( $F(3,24)=14.8, p=0.001, \eta_p^2=0.38$ ). Such an interaction suggests that the improvement in temporal discrimination due to sequence length is present with the interleaved presentation of different sequence length (one-way repeated measure ANOVA with factor sequence length:  $F(3,24)=6.4, p<0.001, \eta_p^2=0.21$ ) but performance is not affected with blocked presentation of one length ( $F(3,24)=1.5, p=0.21, \eta_p^2=0.06$ ).

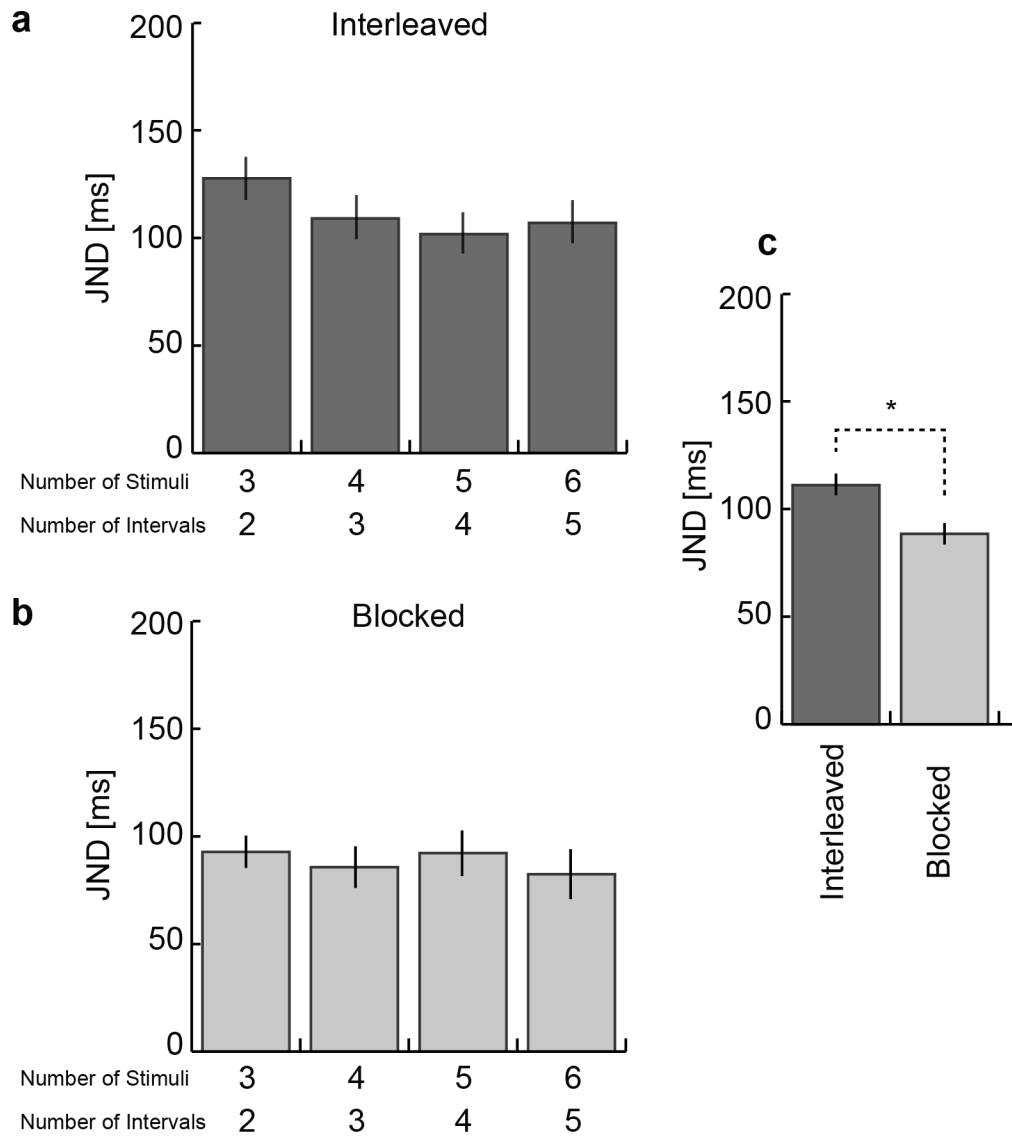
Biases in perceived isochrony are captured by *PSE* values (Fig. 4) which are also calculated according to the Spearman-Kärber method (see method section). In both conditions we find that stimuli presented physically isochronous are actually

reported more often to appear earlier than expected. Perceived isochrony is obtained when the last stimulus was presented later than it should – i.e., with a longer last interval (single sample t-test of *PSE* calculated on the data against 0: interleaved,  $t(24)=5.9, p<0.001$ , blocked:  $t(24)=2.5, p=0.019$ ). In order to test whether there is a consistent difference of this effect with blocked or interleaved presentation of sequence lengths, we submitted *PSE* values a two-way repeated-measures ANOVA with factors presentation condition (interleaved or blocked) and number of interval in the sequence (2, 3, 4 or 5). Results indicate a change in *PSE* depending on the presentation condition ( $F(1,24)=11.9, p=0.002, \eta_p^2=0.33$ ), as the final stimulus in the interleaved condition has to be presented 22.9 ms (3.8 ms SEM) after isochrony in order to be perceived isochronous, whereas the last stimulus in the blocked condition has to be presented 11.1 ms (4.4 ms SEM) after isochrony. The difference between both interleaved and blocked condition was 11.7 ms (3.4 ms SEM). We find no main effect of sequence length or an interaction (both  $p > 0.12$ ).

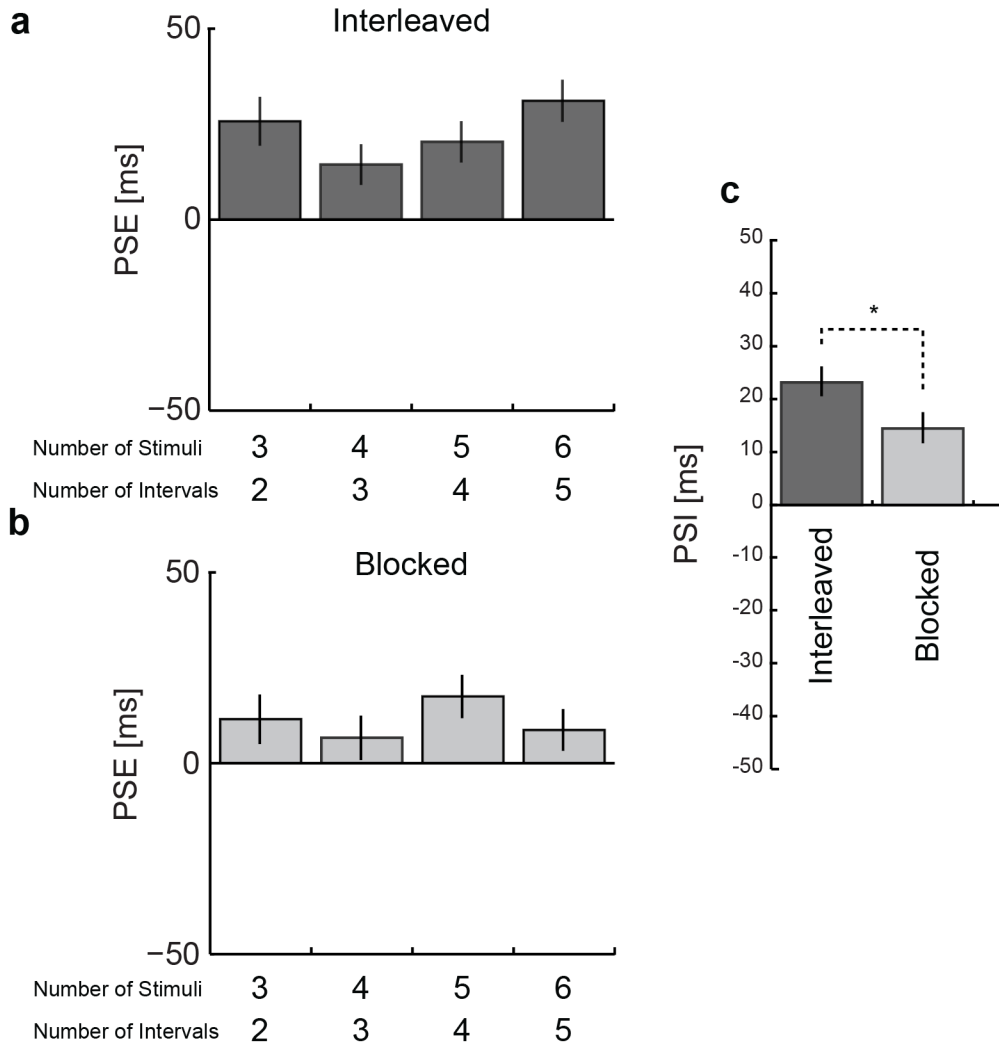
In sum, the sensitivity of detecting anisochrony increases with longer sequences if different lengths are interleaved but is overall higher if only one sequence length is presented in a block. Perceived isochrony is consistently biased and the observed bias does not change due to sequence length, but it is affected by the presentation condition (interleaved and blocked). Not knowing the serial position of the interval to be judged leads to a higher bias, so that the sequence is perceived as being isochronous if the last stimulus is presented slightly later, i.e., after a longer interval compared to the previous ones.



**Figure 2.** Proportion of 'later' responses as a function of the anisochrony of the final interval in the sequence for (a) 2, (b) 3, (c) 4, and (d) 5 intervals for interleaved and blocked presentation. Error bars represent the standard error of the mean.



**Figure 3.** *JND* values as a function of sequence length for (a) interleaved and (b) blocked presentation. The predictions of the MLM model are obtained using the *JND* for a sequence of 3 stimuli (2 intervals) and fitting the parameter  $w$  to the data of each participant. (c) *JND* values calculated on the proportion of ‘later’ responses across sequence lengths for blocked and interleaved conditions. The asterisk indicates significant differences between the two conditions. Error bars represent the standard error of the mean.



**Figure 4.** *PSE* values as a function of sequence length for (a) interleaved and (b) blocked presentation. (c) *PSE* values calculated on the proportion of ‘later’ responses across sequence length for interleaved and blocked presentation. The asterisk indicates significant differences . Error bars represent the standard error of the mean.

### 2.3.1 Multiple Look Model Predictions

The ML model predicts that sensitivity to changes in tempo increases with longer sequences in a statistically optimal fashion (Drake & Botte, 1993; Miller & McAuley, 2005). In the generalized ML model (Eq. 2), the weight parameter  $w$  ranges between 0 and 1 and describes how much reliance a subject has on the first of two

sequences to be compared. Here, we consider a modification of this model, to capture discrimination performance with a single sequence having a single final deviant interval. The model is based on the presence of a memory store to which future intervals are compared (Treisman, 1963). After comparison, the memory store is updated integrating every presentation of intervals, i.e., to form an internal reference (see Dyjas et al., 2012). Discrimination performance in this case can be captured by:

$$JND'_N = \sqrt{JND_2^2 \left( \frac{w}{N} + (1 - w) \right)}, \text{ with } N=\{3,4,5\} \quad \text{Eq. (8).}$$

This formula expresses the predicted  $JND$  with sequences having  $N=3, 4$ , and  $5$  intervals ( $JND'_N$ ) from the empirical  $JND$  obtained with sequences of 3 stimuli ( $N=2$  intervals;  $JND_2$ ). Note that  $N$  in Equations 1 and 7 refers to the duration of the whole experimental sequence, whereas  $n$  in Equations 2 and 3 indicates the intervals to be compared before and after the tempo change, so here  $n_1=N-1$  and  $n_2=1$ . In the formula, the weight  $w$  captures which proportion (across trials) the participant stores a combined memory trace of all previously presented intervals. With  $w = 1$ , the store is used in a statistically optimal fashion, combining information from all the preceding intervals. In this case, the  $JND'_N$  is determined by the limited precision of the comparison of the last interval with such a memory trace. With  $w = 0$ , instead, the store does not integrate information across intervals, thus it only contains a representation of the latest interval presented. Performance reflected by  $JND'_N$  with  $w = 0$  is thus determined by the precision in comparing the last interval in a sequence with the previous one, regardless of how many preceding intervals there are. In order to find the best fit for the weight parameter  $w$ , for each participant we found the minimum sum of squares difference between the predicted  $JND'_N$ , and the empirical  $JND_N$ . Here we allowed individual participants' weights to span a range between -0.5 and 1.5 as noise between successive estimates can be correlated (see Schulze, 1989

and Oruç et al., 2003, for more detail). Predicted values of  $JND'_N$  are overlaid to the empirical values in Fig. 5. Average weights are  $0.39 \pm 0.09$  and  $0.24 \pm 0.11$  for the interleaved and blocked condition respectively and do not differ significantly ( $t(24)=1.1, p=0.26$ ). The model captures the increasing sensitivity to detecting if a stimulus is early or later than expected in the interleaved condition (Fig. 5a left panel) as well the lack of improvement in sensitivity for the blocked condition (Fig. 5a right panel). The model, however, does not capture biases in perceived isochrony registered as consistent deviations of PSE from 0 in Fig. 5.

### 2.3.2 Diminishing Returns Model Predictions

We also fitted the results using the diminishing returns (DR) model proposed by ten Hoopen et al. (2011). Akin to the MLM model, the DR model predicts that temporal sensitivity to irregularities increases with the amount of intervals presented. However, with each additional interval, the increase in sensitivity is less. We applied Eq. 3 to our data and found the best fit for the parameters  $a$  and  $b$ , by finding the minimum sum of squares difference between the predicted  $JND'_N$ , and the empirical  $JND_N$  for each participant. Predicted average values of  $JND_N$  with such individually tuned parameters are presented in Fig. 5a (left panel). We find that the values that best fit the empirical data for the interleaved condition are  $a = 79.8$  ms and  $b = 59.5$  ms; and for the blocked condition:  $a = 60.5$  ms and  $b = 52.7$  ms. The model accurately captures the increasing sensitivity to temporal irregularities – but only for the interleaved condition. The model cannot account for the flat course of the empirical  $JND_N$  in the blocked condition.

### 2.3.3 Bayesian Model Predictions

We propose an alternative model for the results by hypothesizing that instead of representing discrete intervals, the brain represents the timing of single events. We adopt a *Bayesian Decision Theory* (BDT) approach which has been successfully employed in several perceptual domains (Kersten & Yuille, 2003; Knill & Richards, 1996; Mamassian et al., 2002; Petzschner & Glasauer, 2011; Wolpert & Ghahramani, 2000) including interval timing (Jazayeri & Shadlen, 2010; Petzschner et al. 2015; Shi et al, 2013). Here, however, we propose that the brain uses a Bayesian inference process at each point in time where perception is obtained through the dynamic updating of temporal expectations. Perception is obtained from the posterior probability, which is the product of the probabilities of the likelihood  $p^l(t)$ , of the expectation  $p^e(t)$ , and of the prior  $p^p(t)$ .

$$p^q(t) = p^l(t) \cdot p^e(t) \cdot p^p(t) \quad \text{Eq. (9)}$$

The likelihood  $p^l(t)$  is characterized as the probability of sensing a stimulus at time  $t$ . A Gaussian distribution having mean  $\mu$  equal to the timing at which the stimulus is presented and variance  $\sigma^2$  is used as the likelihood function. The variance ( $\sigma^2$ ) is the only parameter used to fit the model to the data.

Expectations  $p^e(t)$  are obtained by iteratively updating the probability of encountering a stimulus at each time. The expectation probability  $p^e(t)$  is obtained by using the posterior probability  $p^q(t)$  for the previous stimulus:

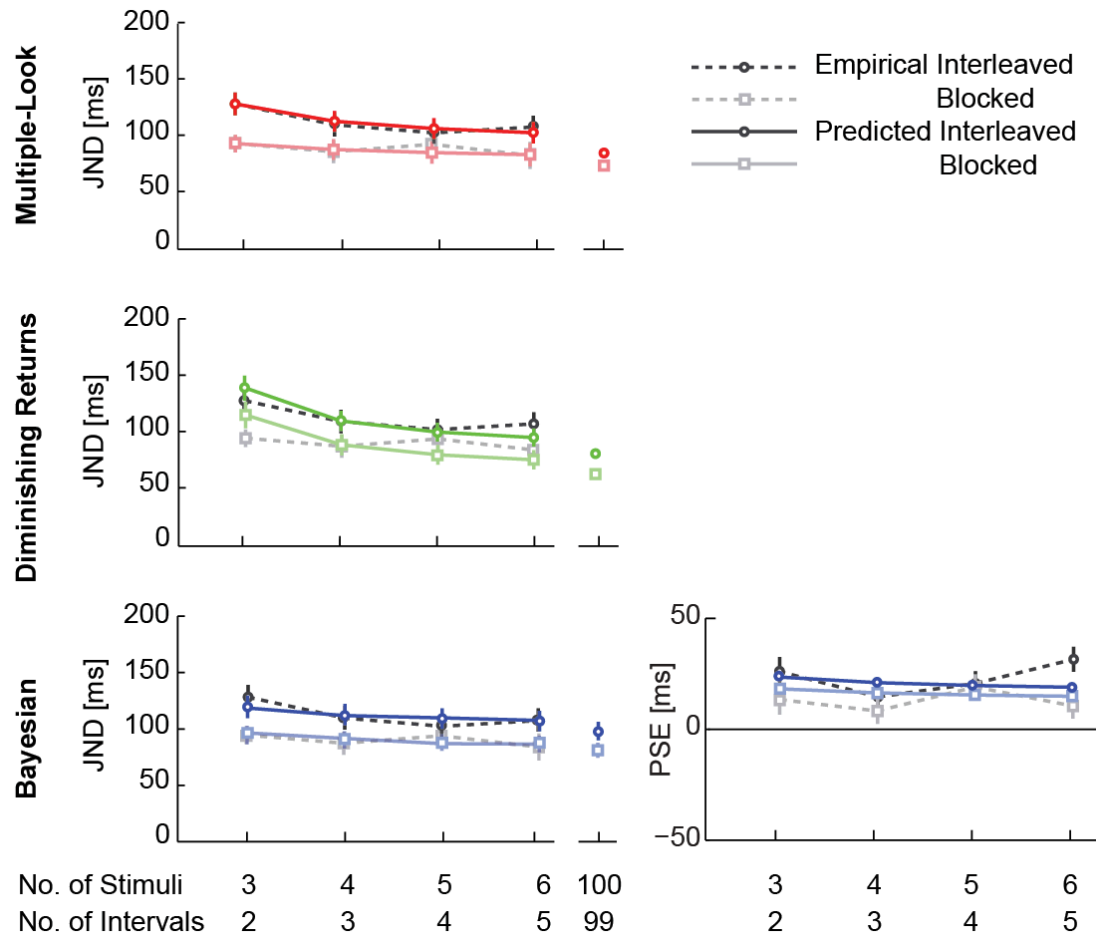
$$p^e(t) \propto p^q(t - ISI) \quad \text{Eq. (10)}$$

The last component of the posterior, the prior probability  $p^p(t)$ , is modelled as a decreasing exponential function. In practice, the parameters of the exponential do not have a large influence as any monotonically decreasing function that makes the

probability of encountering a stimulus to decrease after the previous one is sensed would work as well.

To obtain the predictions for  $PSE$  and  $JND$ , we calculated the values of the posterior probability distributions for the last stimulus in the sequence (3, 4, 5 or 6) by applying Equations 9 and 10 iteratively. We obtained a  $PSE'_N$  by taking the mean of the posterior distribution.  $JND'_N$  is calculated by taking the root sum of square of the standard deviation of the posterior and of the likelihood of the final stimulus.

We fit the model by minimizing the sum of squares difference between the empirical  $JND_N$  of each participant and the predictions of the model  $JND'_N$  by using the parameter  $\sigma^2$ . Note that we don't fit the  $PSE$  values, but we obtain them from the same  $JND$  fitting. We obtain best fit for  $\sigma=97.1$  ms (8.1 ms SEM) for the interleaved model, and  $\sigma=76.8$  ms (8.2 ms SEM) for the blocked condition. Predicted values are displayed in Fig. 5. The predicted  $PSE'$  difference between interleaved and blocked conditions is 6.6 ms (10.8 ms SEM), which is consistent with the empirical value of 11.7 ms (3.4 ms SEM).



**Figure 5.** Predictions of Multiple-Look, Diminishing Returns, and Bayesian models (see Results). The ML Model accurately captures the increase in temporal sensitivity as the sequence length increases across the two conditions. The Diminishing Returns Model instead captures the negatively accelerating course of the JND only for the interleaved condition but cannot account for flat course of JND in the blocked condition. The Bayesian model integrates sensory likelihood, expectations, and an exponentially decreasing prior into an estimate of stimulus timing. The model captures the pattern of empirical JNDs in both conditions. Crucially, this is the only model that makes predictions about PSE values highlighting a non-zero value and a small difference between interleaved and blocked conditions.

## 2.4 Discussion

We investigated the detection of a temporal deviation in a regular stimulus sequence. Similar to Schulze (1989), we manipulated sequence length across trials (2, 3, 4 or 5 intervals in a sequence). The final interval in the sequence could be presented too early or too late, and participants needed to identify which of the two cases it was. We also tested whether presenting the sequences either interleaved (difficult task as participants do not know the sequence length to be judged) or blocked (simpler task because participants know which interval could be deviant) has an impact on perception. Temporal discriminability (quantified by *JND* on the proportion of ‘later’ than expected responses) is found to be higher in the blocked condition than in the interleaved condition. Furthermore, we find that temporal sensitivity increases as a function of sequence length in the interleaved condition, but not in the blocked condition (Fig. 3b), which is qualitatively consistent with the findings of Schulze (1989) and ten Hoopen et al. (2011). However, Schulze found a larger increase in performance with longer sequences than we report here and thus it is possible that such a difference could be due to the use of final intervals that could only be longer than the previous ones. By presenting the final stimulus either earlier or later as ten Hoopen et al. (2011) did, we could eliminate response biases that affected the measure of sensitivity.

We reason that sensitivity to temporal deviations is lower in the interleaved condition due to the uncertainty about which interval should be judged. In contrast to the blocked condition, participants know exactly when the sequence will end. We can speculate that sensitivity to temporal deviations increases with longer sequences in the interleaved condition because later intervals have higher conditional probability to be

the ones that need to be judged (see Table 1). The hazard conditional probability for each successive stimulus is related to temporal expectations (Nobre et al., 2007) and has been shown to lead to better discrimination and faster reactions (Coull, 2009).

By using stimuli that deviate in two directions and asking whether the last stimulus was presented early or late we could determine the duration of the last interval that made the sequence appear to be isochronous. Our results evidence a consistent bias in responses – isochrony is perceived when the final interval in the sequence is, on average, 17 ms longer than the previous ones. Such an effect is consistent with a positive time-order error (TOE; see Woodrow, 1935 and Allan, 1979 for a review) and a perceptual acceleration of the final stimulus, an effect compatible with prior entry (Spence & Parise, 2010). The fact that the duration of the last interval was underestimated is particularly interesting if we consider that the intervals used in our experiment are lower than the commonly used indifference point of 700 ms (Woodrow, 1935). The effect size does not change across the sequence durations tested, but we find that the delay required for perceived isochrony is 12 ms larger in the interleaved condition than in the blocked presentation.

If this result is interpreted as an acceleration of the last stimulus, it should be considered that the difference in hazard probability would suggest greater expectation and thus more anticipation with longer sequences. Hazard probability alone, therefore, does not explain why there should be a perceptual acceleration of the last stimulus in the blocked condition, where no uncertainty about which stimulus to judge is present. Our data, in fact, show more anticipation for the interleaved condition, where intervals are actually more uncertain than in the blocked condition. Higher predictability in the blocked condition, instead, should have led to a stronger prior entry phenomenon.

**Table 1.** Probabilities associated with each of the interval in the sequences in the interleaved condition (see also Coull, 2009).

	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
Probability of interval	1	3/4	2/4	1/4
Conditional probability of judgment	1/4	1/3	1/2	1

Interval-based models provide an explanation for the increase in sensitivity to temporal properties with longer sequences. The Internal clock model (Gibbon et al., 1984; Treisman, 1963), for example, proposes that sequence duration is judged as the accumulation of ‘ticks’ from an internal pacemaker. With exposure to multiple intervals, the representation of the duration increases in precision thus leading to better performance (Dyjas et al., 2012; Schulze, 1979). The last interval presented is then compared with a memory trace that integrates information across previous intervals. Our data suggest that such integration is not complete. Our fit of the MLM model to the data fails to find a difference in the weight assigned to the intervals with blocked and interleaved presentation. This result is logical, as memory integration should not be affected by whether the sequence is presented interleaved with other sequence lengths. On the other hand, performance is overall better for the blocked condition and consequently an improvement in performance is only found in the interleaved condition. The predictions of the model proposed by ten Hoopen et al. (2011) as we implemented cannot account for such a difference. The parameters that best fit participant’s performance leads to similar performance increase in the two conditions and does not capture the relatively flat trend in the blocked condition.

A way the Diminishing Return model and the generalised MLM model should differ is the asymptotic maximal performance with long sequences. The MLM expressed by Eq. 1 should lead to a progressive increase in performance as the

sequence increases in length. On the other hand, the generalised MLM of Eq. 2 and 8 has an additional parameter that limits the integration of memory traces (see Dyjas et al., 2012; Schulze 1978, 1989). To assess whether this parameter prevents indiscriminate performance increase, we generated predictions of the two models, as well as the novel Bayesian model, for a sequence of 100 stimuli. We find that the three models differ only minimally in their predicted performance (the difference in predictions is 12% of the performance). Such similarity suggests that the parameter capturing suboptimal integration in the generalised MLM in practice limits the possibility that maximum performance asymptotes at infinity.

Because the goal of the MLM and of the Diminishing Returns models was to account for performance in a task that was conceptualised in terms of represented duration, not of the timing of individual stimuli, both models predict no consistent bias in the duration that is perceived to be isochronous, an effect that we find instead in our results. An alternative explanation for this aspect of the data could be provided by models that explicitly represent aspects of stimuli related to relative timing of stimuli, rather than the duration that two stimuli subtend. Our model, uses the Bayesian framework to capture the probability of stimuli. As the ‘a-priori’ probability of encountering a stimulus decreases with time, the time at which stimuli are perceived is always slightly accelerated (more with unreliable sensory estimates). Thus predicted *PSE* values are slightly positive overall. Predicted performance captured by *JND* values shows an improvement with longer sequences because of the successive refinement of estimates. The model also predicts an asymptotic performance that differs depending on the noise of the likelihood without an explicit parameter to describe ceiling performance with long sequences. The difference in performance and in bias between blocked and interleaved conditions is captured

jointly by the difference in reliability to temporal judgments – the inverse variance of the likelihood function. In contrast, the accounts based on interval representation do not predict such consistent bias in perceived isochrony and neither its change depending on interleaved presentation of sequence length.

Entrainment models, propose that an adaptive oscillator couples its phase and frequency to the timing of stimuli presented in sequences: The longer the sequence, the better the coupling and thus the better discrimination of early and late stimuli (Large & Jones, 1999; Schulze, 1978). One could speculate that with blocked presentation of one sequence length the entrainment should be better tuned to the number of stimuli presented, thus leading to increased prior entry for expected stimuli and thus a larger bias in perceived isochrony. Our data, instead, shows a larger bias for the less-precisely expected interleaved condition. Here we propose instead that expectations can be related to the entrainment of neural activity leading to tuned attentional deployment (Henry & Herrmann, 2014; Lakatos et al., 2008; Rohenkohl and Nobre, 2011) and thus more precise sensory representation. More precise representation of stimulus timing outweighs the effect of the prior in the blocked condition, thus leading to a larger perceptual bias in the perception of isochrony for stimuli presented in the interleaved condition.

## 2.5 Conclusions

The present study demonstrates how sequence duration and interleaved presentation influence temporal judgments in isochronous sequences. Our results show that discrimination sensitivity increases for longer sequences in interleaved presentation and is overall better for blocked presentation. The results also evidence that perceived isochrony is obtained if the last interval is longer than the previous one – i.e., with the last stimulus presented with a delay between 10-20 ms – a finding that is consistent with a perceptual acceleration of the last stimulus in a sequence. Interval-based models such as the MLM and DR do not make explicit predictions for such a bias, and they do not capture the better performance and the lack of improvement with longer sequences in blocked presentation. Explanations based on stimulus probability can account for the difference in performance between the two conditions, but they do not explain why there should be an anticipation effect with blocked presentation of a sequence length and why perceptual anticipation is larger with interleaved conditions. We have devised a Bayesian model that accurately captures both the increase in temporal sensitivity for the interleaved condition as well as the changes in PSE. An explanation based on neural entrainment, can qualitatively account for better discrimination performance with longer sequences and for a sensory anticipation due to prior entry. We speculate that a higher task demand in the interleaved condition increases attentional deployment leading to stronger anticipation of the last stimulus.

## **Chapter 3:**

### **Non-temporal properties in sensory predictions: Tone sequences and its structures**

This chapter has been prepared for submission as a journal article:

**Li, M. S., & Di Luca, M.** (in preparation). Non-temporal properties in sensory predictions: tone sequences and its structures

# Abstract

Predicting the time of stimulus onset is a key component of temporal judgements in daily life; however, human's sense of time is not as objective as a clock. Previous investigations of perceived timing have focused on the effect of stimulus properties such as rhythm and temporal irregularity, but the influence of non-temporal properties has not been well considered. The present study aimed to understand how predictability of stimulus properties, tones, specifically can improve temporal sensitivity and perceived timing. We presented isochronous sequences of 3, 4, 5 and 6 auditory tones interspersed at random within each block. The timing of the last stimulus could slightly deviate from isochrony and participants reported whether it was either 'earlier' or 'later' relative to the expected regular timing. In two conditions, the tones of the stimuli were either composed into musical scales or in randomized order. Experiment 1 did not indicate significant perceptual distortions but discrimination performance was generally better in the scale condition. However, the frequency of tones to be judged were varied at all trials, thus in Experiment 2 the last tone of all sequences was fixed to 440 Hz. Results confirmed the higher sensitivity in scale condition than in random condition and also showed better discrimination performance in the longest sequence than shortest sequence. The effects may be explained by the melodic pattern acting as a predictive cue and thereby providing better discriminability also on stimulus onset timing.

*Keywords:* tone frequencies, expectation, perceived timing, temporal sensitivity, melodic pattern, isochrony

### 3.1 Introduction

The ‘Canon’ is a piece of music written for different instruments to repeat the same melody at different time point. Many things in our daily life are like the music ‘Canon’: it repeats the musical notes, the speed, and the identical intervals, which all come together as a pattern. However in the psychophysical aspect, what has been performed may not be what is perceived, for example, the repetition of an object may influence the subjective perception (e.g., Humphreys, Besner, & Quinlan, 1988; Maljkovic & Nakayama, 1994). The effect of repetition is a process of perceived information build up, that is, once we receive information from the external world, we store the information in a memory trace for future reference. It is like digging the foundation – the more of consistency from similar information perceived, the more solid is the foundation.

Duration, for instance, can be repeated as several intervals in a sequence, to present with audio, visual or tactile stimuli. This is, for example, the case in isochronous sequences, the simplest example of temporal patterns consisting of identical timing intervals that repeat to form one single sequence. Some modelling works has been done to demonstrate the temporal sensitivity change in the isochronous sequences, for example the Multiple-Look model by Drake and Botte (1993) and Miller and McAuley (2005), discussed and modelled on the improvement of temporal judgement discriminability with increased interval numbers in one sequence. While it has been shown empirically that objects in a regular order are easier perceived and more intervals in a sequence generate greater sensitivity, but it does not seem realistic to assume that an increase of interval numbers to infinity will lead to infinite sensitivity. Ten Hoopen et al. (2011) instead tried to add an effect

boundary to the idea of ‘the more intervals, the better performance’ and proposed a model that the ‘best looks’ (the greatest improvement effect of having multiple intervals) were limited to the first two or three intervals, and then the increase of sensitivity was rather small.

Moreover, the previous literature has also drawn attention to test the variation of different temporal structures, such as isochronous with auditory presentation (Ivry & Hazeltine, 1995; Schulze, 1978), irregularity (Horr & Di Luca, 2015) and with visual presentation (Grondin, 2001). Up to date the effects of regularity are well discussed, however, the works on applying non-temporal properties to isochronous sequences are yet novel. The present study is interested in the non-temporal properties other than timing itself that can possibly influence (1) temporal sensitivity and (2) perceived timing. Because the auditory modality has the highest temporal sensitivity, musical stimuli came into our consideration. Several studies have proposed a close relationship between rhythm and melody (Janata & Paroo, 2006). For instance, Boltz (1989) found that participants judged a sequence ended of a melody as the most completed sequence and relatively, the sequences which ended out of the structure of a tune were judged toward incomplete trials. Interestingly, the ratings of melodies were even higher if the final stimulus was ended ‘on time’ according to the timing of previous notes presented. More recently, Repp and Doggett (2007) carried out a tapping study aimed to investigate the performance differences with various inter-onset intervals (IOIs) and motor coordination of on-beat and off-beat stimuli. They have also included a condition of tapping with tone sequences (with one fixed tone for all stimuli) and scale sequences, and were expecting to see the differences in musicians’ tapping performance on synchronization and accuracy. Such auditory studies gave good insights of addressing tones and melodic properties into the time

domain and we thought it would be interesting to demonstrate the influence of melodic tones on temporal sensitivity and perceived timing in a regular sequence.

To access the changes in sensitivity and perceived timing we calculated the Just Noticeable Difference (JND, also known as difference limen) and the Point of Subjective Equality (PSE, referring to when the participants subjectively perceive ‘on-time’). Thus, we have designed the tasks as a simple two-alternative forced choice task, asking the participants to answer whether the final stimulus in a sequence was either ‘earlier’ or ‘later’ as compared to the expected time point. Similar to Repp and Doggett (2007)’s design, the two main conditions of our experiments are ordered tones (scales) and non-ordered tones (randomized tones): in the scales condition, we have chosen the classical diatonic scales with melodic scale-step and correct frequency that was converted from exact pitch level. In the randomized tones condition, there was no order or pattern of the scale-step, the sound frequencies of tones had a completely random order and therefore, tones of stimuli cannot be expected and predicted. Moreover, we have avoided carrying out current experiments on musically well-trained listeners and musicians, because previous literature showed significant difference on precision of task performances between the musicians and non-musicians (Repp & Doggett, 2007). The professional training may raise the precision of perceived stimulus onsets and the speed of detection so, as a result of this issue, professionals are likely to perform differently; therefore we recruited only the non-musicians for the present case, who had no trainings beforehand and can represent the general population.

With the supportive evidence from previous literatures of patterns benefiting the detectability of off-time stimuli, what we are expecting to see from our results is a significant decrease on JND values in the scale condition. On that note, it would also

be reasonable to observe a stronger multiple-look notion on the JND performances due to sensory facilitation from both temporal regularity and melodic pattern. Furthermore, by only manipulating the predictability levels of two experiments, we are not sure what results to expect from the PSE values. The adjustment of given attention to different tasks may lead to different levels of anticipation, but there were no supportive literature and the current manipulation is novel. In all, it is important for the field of auditory perception to identify the role patterns play in perceived stimulus timing increasing its use beyond basic time perception to music perception.

## **3.2 General Methods**

### **3.2.1 Participants**

A total of thirty-seven undergraduate students, non-musicians, with self-reported normal hearing were recruited by research participation system (SONA) of the University of Birmingham. They participated in only one of the experiments, gave informed consent before taking part and were rewarded with either course credits or a payment of six pounds per hour. Ethical guidelines have been followed in all the experiments and were approved by the STEM Ethics Committee of the University of Birmingham.

### **3.2.2 Design**

In every trial participants were presented with sets of isochronous sequences consisting of 60 ms tone stimuli either with scale condition or randomized-tone condition. All sessions had trials with different number of stimuli (either 3, 4, 5 or 6 stimuli in a sequence) and different sequence lengths were presented randomly intermixed within each session. For every single sequence, the intervals between successive stimuli (ISI) were fixed at 700 ms apart from the final stimulus, which was slightly deviant from 15 levels of possible anisochronies: 0,  $\pm 20$ , 40, 60, 80, 100, 150, and 200 ms. Participants had to report whether the final stimulus was ‘earlier’ or ‘later’ than the expected timing. All trial types resulting from the combination of scale and random tone presentations (2), sequence lengths (4), and anisochronies of the last stimulus (15) were repeated 8 times in order to determine the parameters of 8 psychometric distributions (see Results). This resulted in a total of 960 trials per participant. All sounds were presented via headphones.

### **3.2.3 Data Analysis**

We analysed the proportion of ‘later’ responses for each anisochrony of the last stimulus, to obtain a distribution for each sequence length with scale and randomized-tone presentation. The PSE is obtained by calculating the first order moment of the difference between successive proportions of responses using the Spearman-Kärber method (Ulrich & Miller, 2004). The second order moment is proportional to the inverse slope of the psychometric function, which here is termed JND.

## 3.3 Experiment 1

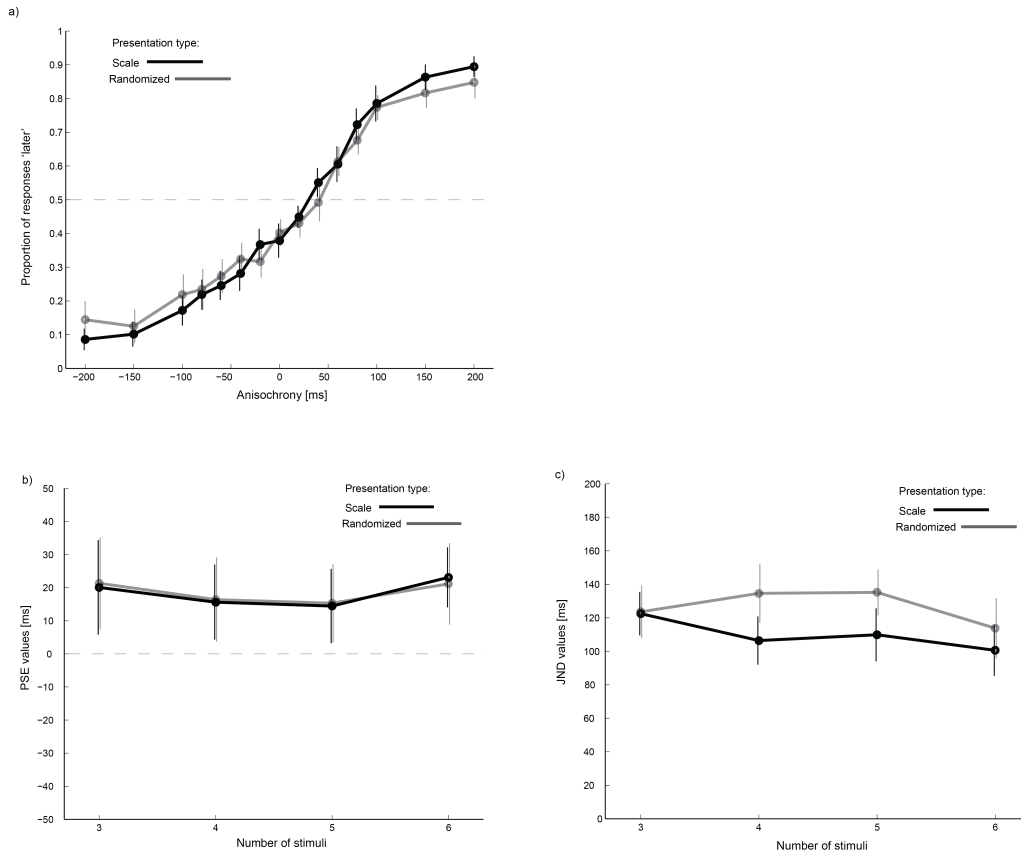
The first experiment was conducted to investigate whether and how the temporal structure of frequencies influences the perceived timing and discrimination performance.

### 3.3.1 Material and methods

Sixteen students participated in the experiment. All trials of four different lengths were presented interleaved and the order of testing conditions was counterbalanced. For the scale condition, stimuli were constructed into four sets of ascending scales in F, C, D, and E major with sound frequencies ranged from 261.6Hz to 587.3Hz. For the randomized-tone condition, each stimulus within a sequence was randomly selected from a frequency range of 250Hz and 600Hz.

### 3.3.2 Results and discussion

The average proportion of responses across participants for data pooled from sequences of different lengths and the two sound sequence distribution conditions are shown in Figure 2a. We obtained the PSE and JND values for each level of anisochrony, which are shown in Figure 2b for participants' performance on perceived isochrony and temporal sensitivity.



**Figure 2.** Results of experiment 1. (a) Averaged proportion of ‘later’ responses across all sequence lengths, where the light grey curve corresponds to randomized-tone condition and black curve represents the scale condition. Both psychometric curves were shifted toward right and scale condition showed more precise discrimination at most anisochrony levels. (b) The PSE values were positive of both conditions but did not significantly show a perceptual acceleration effect. (c) It is visible that scale condition led to higher temporal sensitivity as the JND values were lower and notably, longest sequence had lower JNDs than shortest sequence in scale.

A two-way repeated measure ANOVA was conducted with two levels of factor condition (scale or randomized-tone) and four levels of sequence lengths (3, 4, 5 or 6). The JND results indicate higher temporal sensitivity with scaled presentation ( $F(1,15)=5.94$ ,  $p=0.028$ ,  $\eta p^2=.28$ ) and a significant difference between the four

sequence lengths ( $F(3,45)=4.00, p=0.013, \eta p^2=.21$ ). However the interaction effect was not significant ( $p=.0.22$ ) and we found no significant main effect of PSE values in perceived timing: scaled and non-scaled presentation ( $p=0.41$ ), sequence lengths ( $p=0.55$ ), and interaction ( $p=0.99$ ).

## 3.4 Experiment 2

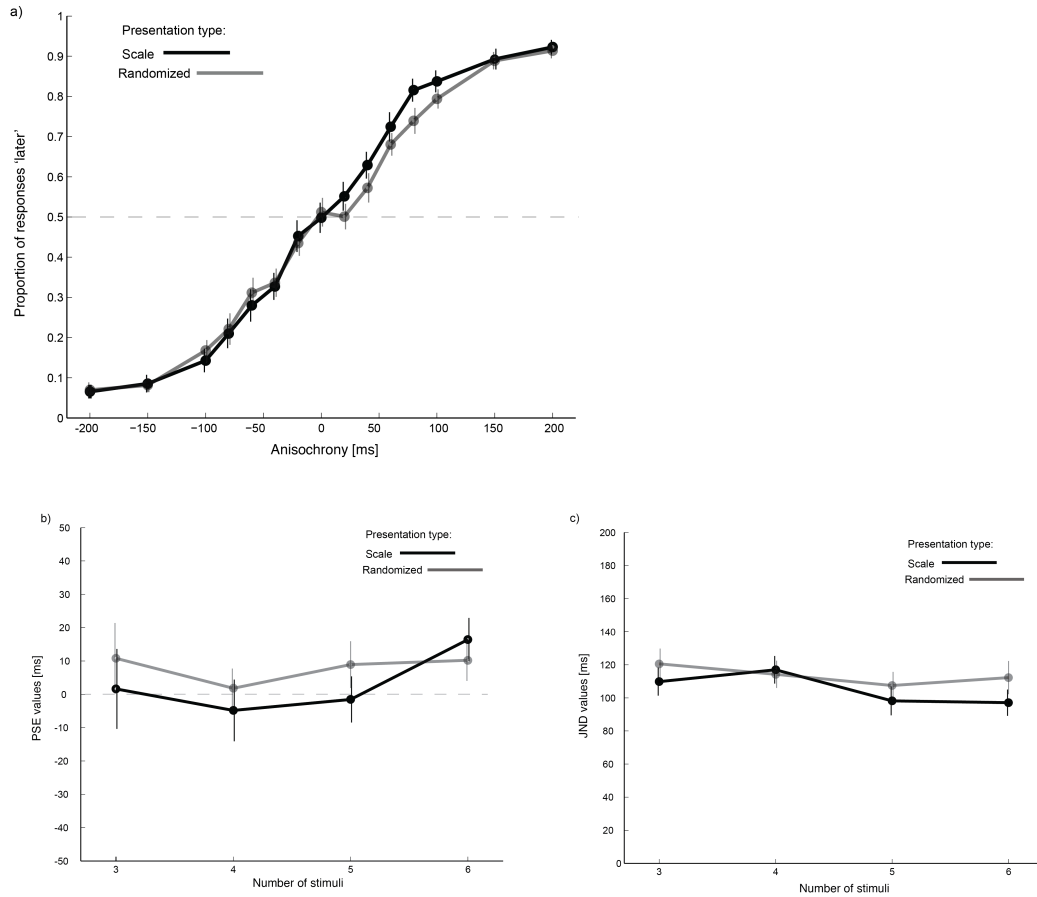
In Experiment one, the frequency of last tone of sequences varied across trials, thus the temporal judgments may have been based on differences in the individual sequences. We carried out Experiment 2 in order to rule out perceptual distortions due to the sound frequency of the stimulus to be judged.

### 3.4.1 Material and methods

Twenty-one students participated in the experiment. All different sequence lengths were presented interleaved and the order of testing conditions was counterbalanced. For the scale condition, stimuli were constructed into four sets scales: ascending C major scale, ascending C minor scale, descending F major scale and descending F minor scale. The order of the scales was random and counterbalanced. For the randomized-tone condition, every stimulus was randomly assigned with one frequency used in the scale condition, apart from the last stimuli of sequences. The last stimulus of all sequences was fixed at 440Hz.

### 3.4.2 Results and Discussion

The results are shown in Figure 3 and replicated the findings from Experiment 1. The two-way repeated measure ANOVA showed the significant effect on JND values of tone factors ( $F(1, 20)=4.36, p=.049, \eta p^2=.17$ ) and sequence lengths ( $F(3, 20)=3.21, p=.030, \eta p^2=.13$ ) but not the interaction ( $p>.17$ ). Again, there is no significant effect present in PSE values.



**Figure 3.** Results of Experiment 2. (a) Averaged proportion of ‘later’ responses across all sequence lengths at each level of anisochrony. Both psychometric curves followed the same pattern. (b) The PSE values did not show significant perceptual distortion. (c) Although the sequences of 4 stimuli showed very similar effect on JND values, in general the two conditions were significantly different on discrimination of anisochrony detection.

## General Discussion

The present study aimed to examine the role of non-temporal patterns and predictability in auditory time perception. As previous literature suggested, in view of expectation, temporal patterns acted as an accelerative facilitation in sensory processing. However, most of the studies focused on the effect of tempo and rhythm, whereas in the present study we wished to identify the influence of non-temporal property: frequencies (tones) pattern in time. The results did not indicate perceptual distortion of time due to the pattern of tones, however the sequences with stimuli composed into musical scales lead to better discrimination performance. By simply changing the composition of the frequencies' order in a sequence, we showed a strong impact of expectation and prediction on participants' discriminability performance. In short, when the stimuli were arranged into patterns, the sensitivity improved.

The result of significant change in temporal sensitivity can be explained considering a few different aspects. First of all, it is straight-forward that repeated patterns are effective for reducing the task demands, due to familiarity and quantity of sensory information given from stimulus timing. The performance of scale condition benefited from a series of repeated scales consisting equal temperaments (scale-step) and as we predicted, less errors were made on the temporal judgment tasks. Furthermore, repeated patterns create expectations. In the current study, there were two resources of pattern building up the expectation of future stimuli: temporal regularity and equal temperament tones. Expectation is usually generated from the previous stimuli presented and it allows better prediction of up-coming events and enhances the sensitivity of judgments. The present study gives evidence that patterns

in general, not only limited to temporal rhythm but also non-temporal properties, can have influences on the reliability of temporal judgments.

Notably, our data also demonstrated an effect of sequence lengths, that is, we found the best discrimination of temporal judgments with longer sequences. Our finding is in accordance with the multiple-look model (e.g., Drake & Botte, 1993; Miller & McAuley, 2005; ten Hoopen et al., 2011): The increase of temporal sensitivity due to longer sequence length could be based on the phenomenon that a larger number of stimuli or intervals in one successive sequence provide relatively more isochronic information and, thus, result in greater temporal sensitivity and better precision of temporal judgments.

Although the JND values gave clear insight of changes on temporal sensitivity, we were not able to observe the perceptual distortion by the given PSE values. Even if the melodic pattern has enhanced the expectation of future stimuli, the final stimulus was not predictable in Experiment 1. However this was not the case in Experiment two, where all sequences ended with the same frequency tone stimuli. Experiment two was designed to be completely predictable – the lower or higher frequency the sequence started with, the longer length the sequence will have. Although this was not disclosed in particular to the participants beforehand, Experiment two has lower task demands. Therefore in view of selective attention and prior entry – attended stimuli were prioritized and processed faster; but this does not seem to make an obvious difference in the PSE values we found.

The PSE values from both conditions followed a very similar pattern, especially in Experiment one, and were not significantly accelerated or delayed. It may be a problem of focused attention on temporal regularity rather than the melodic pattern: participants relied their temporal judgments heavily on the timing onsets of

each stimulus. We suspect that when the sequences were presented isochronously, melody patterns were limited to support as the secondary resources. Although the current study was not able to differentiate the usage of two different resources, time and pitch, and their underlying mechanism together in one task, further experiments can be carried out not only asking for temporal order judgments, but also the pitch or melody discriminations, so that the two resources will be equally weighted in the task.

In the current study, we only examined the simplest form of rhythm and tones patterns: we have chosen to start the test with just isochronous sequences and ascending or descending scales. The simplest form of temporal and melodic regularities only provided the basic understanding of improvement on temporal sensitivity. Future experiments in the field should consider applying more complex and richer melodic pattern, to demonstrate the variation of patterns and its effect on time perception.

## 3.6 Conclusion

The present study aimed to determine the influence of melodic tones. Inspired by the effect of temporal patterns on perceived timing, we applied the music scales onto isochronous sequences to investigate differences as compared to isochronous sequences without a set scale of tones. We found greater temporal sensitivity with scale-composed sequences as well as with longer sequences. We demonstrated how tone sequences enhanced the prediction of upcoming stimuli and the importance of predictability in temporal judgment tasks. The most exciting and novel conclusion from our findings is the identification of active role of non-temporal properties in time perception. With this evidence, we hope to draw the attention in current research field from temporal properties further, to non-temporal properties, for instance, to investigate the effect of coloured presentation of stimuli in isochronous visual sequences.

## Chapter 4: Summary

Time perception is very often subjective, especially with the influences of expectation, thus studying the active role of expectation has been a long-term tradition in psychophysics field. The current thesis carried out two main chapters of experiments, investigating the further understanding of two objective measurements in time: temporal sensitivity and perceived timing of stimulus.

In chapter two we examined more than just temporal sensitivity of the isochronous sequences; we also measured the perceived isochrony of final stimulus to clarify the timing distortion at particular time-point. We tested these two measurements by manipulating two objects in design: the sequence lengths and presentation types. Varying the lengths of sequence allowed us to identify the temporal discrimination performance at different time-points and, to have another close look at the multiple-look notion on regularities. Other than that we manipulated the required amount of attention on the tasks by presenting different sequence lengths either in blocked or interleaved conditions. We replicated the multiple look effect that the temporal detectability increased with longer sequences, and we also found higher sensitivity with blocked condition judgments. Moreover, our data indicated an acceleration effect of final stimulus in a sequence. It is a new discovery and that multiple-look models was not able to account for the change in perceived timing, therefore, we fitted our data and proposed a model, based on the Bayesian framework to explain the distortion. Our results also pointed out the influences from attention, directly showed a facilitation effect to sensory processing. However, the effect is only present above a certain level of task demands – when the conditional probability of

future stimulus remained the same for all trials, for example in the blocked condition, participants lost attention in tasks and, therefore, no prior entry effect was then found.

In chapter three we further discussed the effect of regularity and patterns, but in the musical time domain. We questioned whether it is only the temporal pattern, that had an influential effect on time perception, or it is the patterned effect in general that generated such expectational influences. We applied tones in frequencies onto the stimuli and arranged them either in order, a scale, or not in order. We have also adjusted the predictability in two experiments but both demonstrated better discriminability with scaled tones and showed no perceptual timing distortions. The results also benefited from both temporal and melodic patterns and showed that temporal judgments of longer sequences were easier detected with greater sensitivity.

Based on the notion of multiple-look, both experiments successfully demonstrated the effect of sensory information build up, that more of the identical information perceived increases the sensitivity of judgments. However from the predictability point of view, better predicted stimuli required less attention, generated less expectation and thus the less predictable stimuli were more likely to have led to the anticipated perception of time. The results also brought us to the realization that adding tone frequencies onto auditory stimuli did not help with temporal discrimination, but if the tones were sorted into patterns, the effect of increased sensitivity was then obvious. The conclusions brought us to the next level of understanding expectations in general regularities in life and we hope to highlight that not only conditional probabilities should be taken into account for temporal expectations, but also the attention, melody, and other characteristics. Future studies can consider applying complex patterns onto the stimuli, to observe how these characteristics process together in time.

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