TEMPORAL PERCEPTION OF ACOUSTICALLY PRESENTED TIME SERIES

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Abstract

Data from three experiments on serial perception of temporal intervals are reported. Sequences of short acoustic signals ('pips') separated by periods of silence were presented to the observers (N = 24, 16, 12). The inter-pip intervals were generated to form geometric or alternating series, while the modulus $1{+}\delta$ *of the stimulus series and the base duration* T_0 *(in the range from 1.1 to 6 seconds) were varied as independent parameters. The observers had to judge whether the pips sequences were accelerating, decelerating, or uniform, or to distinguish regular from irregular sequences. 'Intervals of subjective uniformity' (*ISU*) were obtained by fitting Gaussian psychometric functions to individual subjects' responses. Progression towards longer base durations (*$T_0 = 4.4$ *or 6 seconds) shifts the* ISU*s towards negative* δ*s, i. e., accelerating series. This finding is compatible with the phenomenon of 'subjective shortening' of past temporal intervals, accounted for by the lossy integration model of internal time representation.*

In a standard duration discrimination task, pairs of intervals marked by e. g. acoustic or visual stimuli are presented to the observer who indicates which member of the pair was perceived as longer or shorter (2AFC paradigm), or reports their subjective indifference (3AFC paradigm). In the serial variant of the task, sequences of intervals generated by a recursive rule are presented to the observer who has to categorize the series as a whole, according to a given instruction. The idea behind this procedural modification is that the 'subjective evidence' underlying the global judgment of the stimulus builds up sequentially from 'local' comparisons between subsequent intervals. Therefore, the sequential procedure should allow to study discrimination processes more efficiently than by collecting responses from pairwise comparisons. In the study reported here we investigated discrimination of acoustically presented intervals in the supra-second domain, resulting in judgments of 'acceleration' vs. 'deceleration', or 'regularity' vs. 'irregularity' as the global property of the stimulus.

Methods

Apparatus and stimuli

Stimuli were generated by a dedicated program running under BSD Unix on a portable iBook G4 (Apple Inc.) computer, with a pointing device ('mouse') and an external LCD monitor attached. The sound output of the computer was fed via an amplifier (Sony TA-FE310R) to a pair of headphones (Sennheiser HD 201) worn by the observers during the experimental session. The acoustic markers ('pips') of time intervals were sound signals with a frequency of 2000 Hz and a duration of 20 ms. The control program generated two types of stimuli: monotonically modulated time series (mode mono), or alternating time series (mode mach[1]), using the formulae

$$T_n = (1+\delta)\,T_{n-1} \qquad (\mathsf{mono})$$
$$T_n = (1+(-1)^n\,\delta/2)\,T_0 \qquad (\mathsf{mach})$$

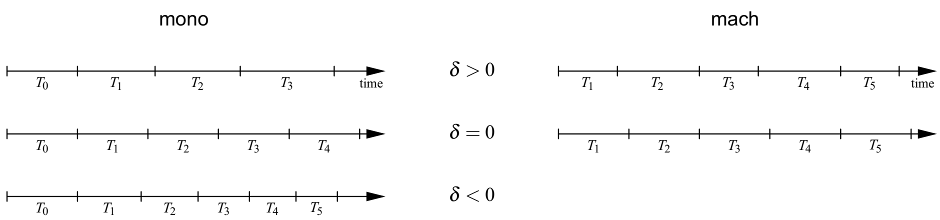

Figure 1. Monotonic (left) and alternating (right) pips sequences for different values of δ.

T_0 (base duration) and δ are two control parameters determining the temporal structure of the stimulus (Fig. 1), which were varied according to the experimental design (see below).

Procedures and designs

In each trial, the observer was listening to the pips series played through the headphones; thereafter a list of possible responses was displayed on the monitor, from which the observer had to choose. Duration of the pips series was limited to max. 1 minute, but the observer could interrupt the stimulus presentation by pressing a button, after which the response menu was displayed immediately. An exception from this was Exp. 3 where the number of presented intervals n_P was fixed by design. The 3AFC paradigm with response categories 'accelerating', 'uniform', and 'decelerating' was used for the monotonic series (mono). The 2AFC paradigm with response categories 'regular' and 'irregular' was used for the alternating series (mach).

Experiment 1: Twenty-four observers (12 women and 12 men, age range 21–33 years, mean age 25.8 years) participated in the experiment. Three blocks, each consisting of twelve trials, were run with different base durations in a fully permuted order, using $T_0 = 1.5, 3, 6$ s for a sub-group of twelve subjects, and $T_0 = 1.1, 2.2, 4.4$ s for the other twelve subjects. Each block consisted of two parts. In part 1, δ varied from -0.05 to $+0.05$ in steps of 0.02, following an interlaced up-and-down staircase scheme, with two repetitions for each δ value. A point of subjective uniformity (PSU) was roughly estimated from the data, and a new range of δs distributed symmetrically around the PSU with halved steps of 0.01 was used in part 2, following the same scheme. This two-phase procedure was designed to adapt the δ-sampling scheme to the subject's individual performance.

Experiment 2: Sixteen observers (8 women and 8 men, age range 21–29 years, mean age 24.4 years) participated in the experiment. Each session consisted of two blocks, one block with monotonic series (mode mono) and the other block with alternating series (mode mach). Two base durations were used in each block, $T_0 = 2.2$ or 4.4 s with nine subjects, and $T_0 = 3$ or 6 s with seven subjects, in a permuted order.[2] A mono block consisted of 26 trials, with δ varied from -0.06 to $+0.06$ in steps of 0.01, with two repetitions for each δ value. A mach block consisted of 22 trials, with δ varied from 0 to 0.25 in steps of 0.025 for base durations 2.2 s and 3 s, or a doubled range up to 0.5, and doubled steps of 0.05 for base durations 4.4 s and 6 s. These settings were based on a series of pilot experiments showing that the discrimination in the mach mode was definitely inferior to that in the mono mode. An up-and-down staircase δ-sampling scheme similar to Exp. 1 was used.

Experiment 3: Twelve observers (6 women and 6 men, age range 21–28 years, mean age 24.7 years) participated in the experiment. Unlike Exps. 1 and 2, the number of presented intervals was limited to $n_P = 2$, 5, or 10. The observer had to listen to the entire sequence before

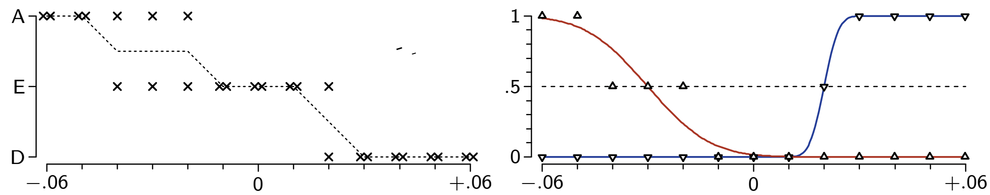

Figure 2. Transformation of a 3AFC dataset to two PMFs. Left: Individual responses (×) for δ varying from -0.06 to $+0.06$: A = accelerating, E = uniform, D = decelerating, dashed broken curve = central response tendency. Right: Relative frequencies of responses 'accelerating' (△) and 'decelerating' (▽), to which psychometric functions $\psi_A(\delta)$ (red) and $\psi_D(\delta)$ (blue) are fitted; the two curves cross the dashed line $P = 0.5$ at points $\delta = \theta_A$ and $\delta = \theta_D$, respectively. (Illustrative data from Experiment 2, mode mono, $T_0 = 3$ s.)

giving a response.[3] The three n_P values were combined factorially with two base durations, $T_0 = 3$ and 6 s, thus resulting in six blocks, each block consisting of 18 trials. For $n_P = 5$ and 10, δ varied from -0.1 to $+0.1$ in steps of 0.025; for $n_P = 2$, the δ range was adjusted to $[-0.4, +0.4]$, and the steps increased accordingly to 0.1. Again, these settings were based on exploratory pilot experiments. An up-and-down staircase δ-sampling scheme similar to Exp. 2 and Exp. 3 was used.

Data reduction

Separately for each subject and base duration T_0, data were sorted by δ, relative frequencies of response categories were calculated, and psychometric functions (PMF) were fitted to the frequencies using the maximum-likelihood method. For the 3AFC data (mode mono), probabilities of responses 'accelerated' or 'decelerated' as functions of δ (cf. Fig. 2) are given by

$$\psi_A(\delta) = \Phi\left(\frac{\delta - \theta_A}{\sigma_A}\right), \qquad \psi_D(\delta) = \Phi\left(\frac{\delta - \theta_D}{\sigma_D}\right).$$

For 2AFC data acquired in the mode mach, the probability of response 'regular' is

$$\psi_R(\delta) = \Phi\left(\frac{\delta - \theta_R}{\sigma_R}\right)$$

Where Φ denotes the normal Gaussian CDF, parameters θ_A and θ_D delimit an 'interval of subjective uniformity' (ISU),[4] and θ_R determines a threshold for detection of irregularity.

Results

Of interest are primarily dependences of the ISUs on experimental conditions, i. e., base durations T_0, presentation modes (mono, mach) and number of presented intervals n_P.

Experiment 1

The ISU width $\theta_D - \theta_A$ varied from $\sim$0.023 at shortest base durations, 1.1 and 1.5 s, to 0.052 for the longest, $T_0 = 6$ s, whereas the ISU midpoints $\tilde{\theta} = (\theta_A + \theta_D)/2$ shifted from $+0.005$ to -0.004 (Fig. 3a). A closer look at the data reveals that these effects are due to a significant and systematic shift of the acceleration threshold towards negative values with increasing T_0 (Fig. 3b), verified by intraindividual pairwise t tests (all with $df = 11$): 1.1 vs. 2.2 s: $t = 1.94$

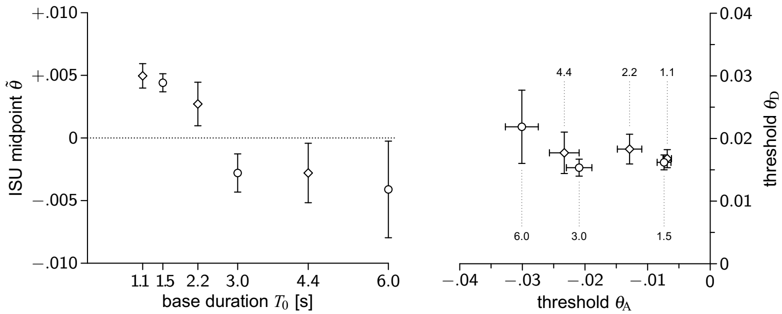

Figure 3. Dependence of ISU on base duration T_0 in Experiment 1. Left: Mean ISU midpoint $\bar{\tilde{\theta}}$ plotted as a function of base duration T_0. Right: Interrelation between mean thresholds $\bar{\theta}_A$ and $\bar{\theta}_D$ across different base duration T_0 (indicated by tiny numbers and dotted lines). Group means ±1 SEM are shown ($N = 12$ for each data point). Two subsets of different T_0 are distinguished by graphic symbols ⋄ and ∘.

($P \approx 0.082$), 1.5 vs. 3 s: $t = 5.00$ ($P < .005$), 2.2 vs. 4.4 s,: $t = 3.57$ ($P < .02$), 3 vs. 6 s: $t = 2.62$ ($P < .05$). On the other hand, the 'deceleration threshold' θ_D did not change significantly with T_0, only varied around ∼0.018. This 'dissociation' between acceleration and deceleration threshold is also supported by insignificant pairwise correlations between θ_A and θ_D.

Interestingly, three subjects failed to detect an acceleration within the entire range of δ (one subject at $T_0 = 4.4$ s, two subjects at $T_0 = 6.0$ s). These cases can be interpreted as extreme manifestations of the 'θ_A traveling' effect.[5]

Experiment 2

The results for the mono mode only partially confirm those from Exp. 1. Comparisons between $T_0 = 2.2$ and 4.4 s show a negative shift of *both* θ_A ($t = 2.15$, $df = 8$, $P \approx .067$) and θ_D ($t = 2.60$, $df = 8$, $P < .05$), resulting in a significant shift of the midpoint $\tilde{\theta}$ of the *entire* ISU ($t = 3.34$, $df = 8$, $P \approx .01$). Comparisons between $T_0 = 3$ and 6 s show also negative but non-significant shifts of the ISU.

As for the mach mode, mean regularity thresholds $\bar{\theta}_R$ were 0.221 for $T_0 = 2.2$ s, and slightly lower for longer base durations: 0.141 ($T_0 = 3$ s), 0.188 ($T_0 = 4.4$ s), and 0.163 ($T_0 = 6$ s). These values, which are by almost one order of magnitude higher than mean θ_A or θ_D, indicate that recognition of deviation from regularity is considerably more difficult for non-directed than directed (monotonic) interval series. Intraindividual pairwise comparisons between shorter and longer base durations (2.2 vs. 4.4 s, or 3 vs. 6 s) do not reveal any significant differences. No significant correlations were found between θ_A and θ_R, or θ_D and θ_R. There seems to be no strong relation between duration discrimination in the two modes, mono and mach.[6]

Experiment 3

The mean ISU width $\theta_D - \theta_A$ decreased from 0.388 for $n_P = 2$ via 0.118 for $n_P = 5$ to 0.084 for $n_P = 10$ (average across both base durations, 3 and 6 s).[7] This effect obviously reflects a reduction of the observer's uncertainty with increasing number of perceived intervals. For all three n_P conditions, the ISU midpoints $\tilde{\theta}$ shifted from positive values at $T_0 = 3$ s to negative values at $T_0 = 6$ s, reflecting simultaneous shifts of *both* θ_A and θ_D. In spite of this common pattern, ISU shifts are statistically significant only for $n_P = 5$: for θ_A, $t = 2.80$ ($P < .02$), for θ_D, $t = 3.16$ ($P < .01$), for $\tilde{\theta}$, $t = 3.48$ ($P < .01$) (all t tests have 11 *df*). The ISU width did not change significantly with base duration.

Discussion

In three experiments we studied serial perception of 'empty' temporal intervals marked by acoustic signals ('pips'). There is a large volume of literature on perception of empty vs. filled intervals on the one hand, and on perception of rhythm on the other hand, which cannot be discussed here for space limitations. We only point out that the major focus of our study is on the transition from the circa-second to the supra-second domain, where serial perception changes qualitatively, from rhythmic patterns to series of discrete events.

We assume that detection of a global property of a time series results from accumulating a series of comparisons between subsequent intervals. Two types of stimuli, geometric series (mono), or alternating series (mach) were used, for which the following relations hold:

$$\frac{T_{n+1}-T_n}{T_n} = \delta \quad \text{(mono)}, \qquad \frac{T_{n+1}-T_n}{T_n} \approx \pm\delta \quad \text{(mach)},$$

This constancy of Weberian ratios between durations of subsequent intervals[8] suggests a more-or-less uniform accumulation of cognitive evidence resulting in the observer's response. Elaboration of a more specific mathematical model of the process is a task for the future.

Our use of a three alternatives response scheme (3AFC) in trials with monotonic time series was based mainly on observations from early pilot experiments: in some subjects the region of subjective uncertainty between 'accelerating' and 'decelerating' may be quite wide, so it is favourable to provide a neutral alternative ('uniform', 'neither–nor'). We prefered not to force the participants to give responses that do not match their subjective perceptual experience. The 3AFC paradigm turned out to be a fortunate choice, as it allowed us to analyze temporal discrimination in terms of two parameters, θ_A and θ_D, delimiting the interval of subjective uniformity (ISU).

The main result of this study, suggested by Exp. 1 and at least partly confirmed by results of Exps. 2 and 3, is the systematic shift of the ISU with increasing base duration T_0 in monotonic time series. Whether the dissociation between θ_A and θ_D, seen in Exp. 1, is a rule or an exception from the ISU shift as a whole (Exp. 2, 3) is still an open question. Provisionally, the term 'ISU traveling effect' used in this paper covers both cases. Importantly, results from Exp. 1 suggest that the ISU shift is not a linear or linear-like function of T_0, but rather a steep transition occurring between $T_0 = 2.2$ s and 3 s (cf. Fig. 3a). This observation is in line with evidence showing that intervals up to 2 to 3 s are processed differently than longer intervals. Temporal integration of events up to 2 to 3 s has been reported in many qualitatively different experiments in perception and action (Pöppel, 1997; Wackermann, 2007; Wittmann, 2011). Temporal intervals exceeding this window of the 'psychological present' require additional short-term memory processes since a temporal interval covering multiple seconds has to be re-constructed from memory. The ISU shift starting at intervals > 2 s as found in our data adds to the idea of different processing mechanisms for intervals within and beyond the 'psychological present'.

The ISU 'traveling effect' observed for longer durations in the supra-second domain implies an increasing overlap between the ISU and the negative part of the δ continuum; in other words, a region of 'illusory perception' where objectively accelerated series are perceived as uniform. This phenomenon can be explained, at least qualitatively, by the lossy integration model of internal time representation (Sysoeva et al., 2011; Wackermann, 2011), also known as 'dual klepsydra model' (DKM) (Wackermann & Ehm, 2006). The model accounts for the progressive shortening of reproduction responses as well as for the asymmetry in duration discrimination between pairs of intervals (Wackermann & Späti, 2006). Applying the model to series of $n > 2$

intervals, it can be shown (Wackermann, 2008) that the series *must* accelerate to be perceived as a sequence of equal periods.[9] The effect reported here thus supports the evidence for the lossy integration model.

Notes

[1] Mach (1865) was the first to use alternating acoustic series in a study of temporal discrimination.

[2] Due to an operator's error, this distribution deviates from the intended balanced design, 2×8 subjects for each pair of base durations. However, the error does not affect the subsequent statistics.

[3] For $n_P = 2$, the observer's task is reduced to a comparison between two empty intervals marked by three pips. Response alternatives 'the second interval was shorter' or 'the second interval was longer' were used and coded in data as 'accelerating' or 'decelerating', respectively.

[4] Note that an ISU $\equiv [\theta_A, \theta_D]$ is truly an interval in the domain of real numbers; this in contrast to the usual parlance of time research, referring to durations, i. e. single values, as 'intervals'.

[5] For the statistics, the missing θ_A values were replaced by the group mean across all remaining subjects for the same base duration. This is a super-conservative estimate, in fact somewhat counter-acting the observed effect which, however, still remains significant.

[6] Note, however, that the numbers of observations in each of the analyzed data subsets are too small to allow reliable inferences.

[7] Two subjects yielded extremely flat PMFs with $T_0 = 6$ s and $n_P = 2$ or 5, respectively, so that the ISU could not be estimated reliably. Similarly as in Exp. 1, the missing θ_A and θ_D values were replaced by the group means across all remaining subjects for the same conditions.

[8] This, of course, does not imply that we assume duration discrimination to be strictly Weberian.

[9] The recursion rule for 'klepsydraically uniform' time series differs from the linear recursion used in our experiments, so our data do not allow a straightforward estimation of the DKM parameter. We reserve this problem for a later treatment.

[*] Thanks are due to Oksana Gutina for conducting part of the experiments and for general assistance.

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