The detection of anisochrony in monaural and interaural sound sequences

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Nakao and Axelrod (1976) and van Noorden (1975) showed that the threshold for discriminating an anisochronous duple rhythm (a series of clicks with a temporal offset on every other one) from an isochronous rhythm (no offset) is poorer when the clicks are presented alternately to the two ears than when they are presented to the same ears. Van Noorden reported that the difference between the thresholds in the alternating and nonalternating conditions varied with the tempo of the sequence. Nakao and Axelrod found invariance of this threshold difference with sequence speed. According to our quantification of temporal processing of interaural sequences, the latter result should be expected. We carried out five psychophysical experiments to establish interaural and monaural discrimination between isochronous and anisochronous rhythms. Across experiments, base time intervals of 60–720 msec were spanned. The main result was that we replicated the poorer discrimination for interaural sequences. This deterioration in discrimination was the same for all sequence speeds. It was also the case that the thresholds were almost constant up to a sound repetition rate of about 3 per second, but increased linearly with slower rates. This result supports evidence in the literature that temporal processing of sequences faster than about 3–4 sounds per second differs from temporal processing of slower sequences.

Temporal discrimination has been studied by means of the two-duration-discrimination paradigm, the main purpose being to investigate whether Weber's law holds (see, e.g., Getty, 1975; see also Allan, 1979; Fraisse, 1982; and Nakajima, 1987, for surveys). There have also been inquiries into the ways in which nontemporal factors, such as the spectra and intensities of the sounds marking empty time intervals, affect the discrimination process (see, e.g., Divenyi & Danner, 1977), and the effect of multimodal markers has been studied as well (see, e.g., Rousseau & Kristofferson, 1973). The aim of these studies has been to unravel the processes responsible for the variation in duration discrimination. Although the cause of duration discrimination variability is still under investigation (see, e.g., Grondin & Rousseau, 1991), in the last decade attention has turned increasingly toward the discrimination

process in serial temporal patterns. Instead of presenting only two empty time intervals to be discriminated, or of utilizing the single stimulus method (as Kristofferson, 1977, did), longer sound sequences have been presented in which one time interval (or more) can deviate from the base time interval.

In a seminal study, Halpern and Darwin (1982) used sequences of four clicks to mark three base time intervals. Listeners judged the last click, which could be offset from its isochronous position either away from or toward the third click, as being "too early" or "too late." The results showed that the difference limen (DL) increased linearly with the base time interval between 400 and 1,450 msec.

Other studies (Hibi, 1983; Hirsh, Monahan, Grant, & Singh, 1990), using longer isochronous sequences, measured thresholds for anisochrony as a function of tempo and the position of the temporal deviation in the sequence. Sorkin, Boggs, and Brady (1982) investigated the effect of the serial pattern of tone frequencies on temporal discrimination between isochronous sequences and sequences with jittered time intervals. Pollack (1968) first reported that anisochrony thresholds were higher for a train of pulses delivered randomly between the ears than for pulses delivered diotically. In the present study, we were concerned with regular anisochrony rather than jitter, and we included sequence rates slower than Pollack's slowest rate of 30 pulses per second.

More precisely, we investigated discrimination between isochronous rhythms (/ / / / / / /) and anisochronous, duple rhythms (// // // //) as a function of spatial conditions. Sequences can be presented to one ear (monaural

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presentation) or alternated sound by sound between the ears (interaural presentation). To our knowledge, in only two studies have thresholds between isochrony and duplexity been established for these spatial conditions: those done by Nakao and Axelrod (1976) and van Noorden (1975). In both studies, it was found that anisochrony thresholds were higher for interaural sequences than for their nonalternating counterparts (monaural in Nakao & Axelrod's study, and diotic in van Noorden's).

The result that discrimination performance was worse with interaural sequences than with nonalternating sequences is but one example of the finding that switching auditory material between ears can produce deterioration in processing (see, e.g., Cherry & Taylor, 1954; Deutsch, 1979; Guzy & Axelrod, 1972; Massaro, 1976; ten Hoopen & Vos, 1981; Treisman, 1971).

Although Nakao and Axelrod's (1976) and van Noorden's (1975) studies qualitatively confirmed the deterioration of processing interaural stimuli, the patterns of their results differed. Nakao and Axelrod found an average difference between the interaural and monaural thresholds of 21 msec, whereas van Noorden found an average difference of 14 msec. Nakao & Axelrod found no dependence of the difference on the speed of the sequence (20 msec at 8 sounds per second, and 22 msec at 4 sounds per second), whereas van Noorden reported that the threshold difference varied with the sequence's speed. In view of our previous work on the quantification of interaural temporal processing (e.g., Akerboom, ten Hoopen, Olierook, & van der Schaaf, 1983; ten Hoopen, 1985; ten Hoopen, Vos, & Dispa, 1982), the former result should be expected.

In our earlier work, we posited that the *perceived* time between consecutive interaural sounds is longer than that between monaural sounds, although the objective time elapsing between the sounds is the same (see Figure 1). In other words, ear-alternating sound sequences have a slower subjective speed than their nonalternating counterparts have—a phenomenon first reported by Axelrod and co-workers (Axelrod & Guzy, 1968; Axelrod, Guzy, & Diamond, 1968; Guzy & Axelrod, 1972). This illusory phenomenon is probably related to what has been called "the sluggishness of the binaural system" (Moore, 1989, p. 222). We quantified the subjective temporal expansion of interaural sequences by studying subject's performance in three converging operations: estimating, counting, and stop reaction tasks (ten Hoopen, 1982).

The latter paradigm provides the basis for answering the following question: Why is there a difference between the detection of anisochrony in interaural and monaural sound sequences? In the stop reaction time (stop RT) paradigm, subjects were required to respond as quickly as possible to the unpredictable end of interaural and monaural sequences. The hypothesis was that it is not the objective interval (which we called *stimulus onset asynchrony*, or SOA), but rather its mental template (which we called *perceptual onset asynchrony*, or POA), that is instrumental in the detection of the end of the sequence.

Figure 1. Although the monaural and interaural sequences have the same stimulus onset asynchrony (SOA) between the sound markers (real time axis), the perceived onset asynchrony (POA) between the interaural sounds is larger than the POA between the monaural sounds (mental time axis).

Each next sound percept in the sequence is expected to arrive at the end of another POA, but if the anticipated sound is not perceived then, the stop response can be initiated. Under the assumption that the response initiation (RI) process is invariant with presentation mode, the difference between interaural and monaural stop RTs reflects the difference between the respective POAs. Averaged over many studies (see Table 5 in the General Discussion), the average stop RT difference was about 20 msec. We also found that this difference was invariant with respect to sequence speed, at least between base SOAs of 40–2,130 msec (Akerboom et al., 1983).

To conceive that the stop RT comprises only two components, POA and RI, is actually too simple (although this conception was sufficient for our previous purposes). At least one additional component should be part of the stop RT: the just noticeable (time) difference (JND) expiring after the POA. Only when the listener has gained sufficient evidence about the absence of the anticipated sound percept can the stop response be initiated.

Consider now the task of detecting anisochrony. Our task analysis is inspired by the work of Jones (cf. Jones, 1990; Jones & Boltz, 1989; Jones & Yee, 1993). We may take as an example a case in which the last sound of an isochronous sequence is offset (see Figure 2). When one is listening to an isochronous sound sequence, temporal anticipation highlights or favors isochronous positions in future time for the appearance of next events. The expected moment of arrival of the next sound is the endpoint of the unfolding of the POA, which starts at present

Figure 2. The upper diagram depicts the time course of anisochrony detection in monaural mental time. The lower diagram represents such a time course in interaural mental time. See text for explanation.

time (N in Figure 2). Because the perceived past (the remembered time course of Events $N-1$, $N-2$, etc.), governs unfolding, it takes the interaural POA 20 msec more to unfold into future time than it does the monaural POA.

The detection of anisochrony is accomplished by comparing the expected and actual arrival times of the sounds ($E[n+1]$ and $A[n+1]$ in Figure 2). Because the difference between the interaural and the monaural POA corresponds to 20 msec in physical time, and because thresholds are of course measured in physical time, the interaural threshold for anisochrony should also be 20 msec larger than the monaural one. This was our first prediction. Because we showed that the POA difference was invariant with SOA, our second prediction was that the threshold difference should also be invariant with SOA. We will describe a series of five experiments, in which anisochrony thresholds were established with the use of several psychophysical methods, and consider the results in terms of these two predictions.

EXPERIMENT 1

We carried out an improved replication of the anisochrony detection task by using more subjects than van Noorden (1975) did and by including more sequence speeds than Nakao and Axelrod (1976) used. We decided to use equal offset increments of the even-numbered tones at all tempi. Nakao and Axelrod, as well as van Noorden, utilized larger offsets with slower tempi, but this implicit Weberian notion may not be warranted in view of departures of Weber's law for time perception (cf. Allan, 1979; Michon, 1964; Nakajima, 1987). We used the method of limits to establish the thresholds between isochronous and anisochronous, duple rhythms.

Method

Subjects. Five subjects, 1 female and 4 males, who were affiliated with Leiden University, participated. With one exception, they were authors and coauthors of previous studies from our laboratory. They passed an audiometric screening for left and right ears; the criterion was a loss of no more than 10 dB and a left-right ear difference of no more than 5 dB.

Stimuli and Design. Monaural (MON) and interaural (INT) sequences composed of silent intervals marked by white noise bursts of 10 msec, with an envelope shaped by 2-msec linear rise and fall times, were generated by Coulbourn Instruments modules under the control of a computer. The number of noise bursts in the sequence was 16. The level of the white noise was 87 dBA when played continuously, as measured by a precision sound level meter (Brüel & Kjaer, Type 2203), mounted with an artificial ear (Brüel & Kjaer, Type 4152) and a condensor microphone (Brüel & Kjaer, Type 4144).

The base SOA between noise bursts (onset to onset) was 100, 150, 200, 250, or 300 msec. In each of the 10 conditions (MON/INT $\times$ 5 SOAs), the sequence could start either isochronously (ascending [A] series) or anisochronously (descending [D] series). Each time the sequence was repeated, the even-numbered bursts were offset by a 3-msec increment or decrement. For example, at a base SOA of 100 msec, the A series contained the following SOA patterns: (1) 100, 100, 100, 100, . . . ; (2) 97, 103, 97, 103, . . . ; (3) 94, 106, 94, 106, . . . , and so on. In the D series, the consecutive patterns were: (1) 46, 154, 46, 154, . . . ; (2) 49, 151, 49, 151, . . . ; (3) 52, 148, 52, 148, . . . , and so on. At the other base SOAs, the offset increments and decrements were also 3 msec and the initial SOA patterns in the D series always sounded clearly duple.

Procedure. The subjects had to judge when the series changed from isochronous to duple or vice versa, and to press a button at the changing point. The computer then registered that SOA pattern as the threshold, stopped the series, and presented the next one. Each subject received 160 experimental series (2[MON/INT] $\times$ 5[SOAs] $\times$ 2[A/D] $\times$ 8[replications]), divided equally over four experimental sessions. Within each session, the subject heard either all MON series or all INT series first, with the order reversed in the following session. Within the listening condition (MON/INT),

the order of SOAs was balanced across subjects according to a 5×5 Latin square. There was ample training, and in each session there were warm-ups. The series were presented via headphones (AKG-Cardan K140S) in a sound-attenuated booth. All other equipment was located outside the booth.

Results and Discussion

The data of 1 subject (the nonauthor) were excluded from analysis because they were very noisy (large threshold differences between A and D, and between replications, in comparison with data from the other subjects). The thresholds between isochronous and duple rhythms, averaged over the remaining 4 subjects, are given in Table 1 as a function of presentation mode and SOA.

A 2 (MON/INT) $\times 5$ (SOAs) $\times 2$ (A/D) $\times 8$ (replications) $\times 4$ (subjects) analysis of variance (ANOVA), with all repeated measures and factors fixed except subjects, showed that thresholds were higher for the INT mode than for the MON mode [$F(1,3) = 17.80, p < .05$]. The main effect of SOA was not significant, as the pattern of thresholds in Table 1 already suggested. The main effect of A/D was not significant either. The main effect of replications, however, was significant [$F(7,21) = 3.60, p < .01$]; thresholds decreased over replications. The interaction between MON/INT and SOA, relevant with regard to our predictions, was not significant [$F(4,12) = 1.97, p > .16$].

We inspected whether the average pattern reflected the behavior of individual subjects. For each subject, we performed a 2 (MON/INT) $\times 5$ (SOAs) $\times 2$ (A/D) $\times 8$ (replications) ANOVA, with repeated measures and factors fixed except replications. For all subjects, the pattern of effects corresponded closely to that for the overall analysis.

The overall difference between the INT and MON thresholds in the 100- to 300-msec SOA range was about 8 msec. Our results differ from those of van Noorden (1975), who found a smaller difference between spatial thresholds at the larger SOAs; we found this difference to be constant with increases in SOA. However, van Noor-

den also established invariance of the *nonalternating* threshold within his 120–240 msec range. The invariance of the threshold difference we found is in line with the results from Nakao and Axelrod (1976), although the magnitude of their difference was larger than ours. In addition, we could not replicate the increase of the thresholds with increases in SOA. They found an increase of 18 msec when going from 125- to 250-msec SOAs, whereas we found no increase at all.

EXPERIMENT 2

The subjects in Experiment 1 reported difficulties in determining the turnover point between isochrony and dupleness (the consecutive patterns in the series changed minimally). Because we wanted to hire less experienced subjects for the subsequent experiments in this series, we replicated Experiment 1 with a constant method: in a trial, we presented an isochronous standard and a comparison sequence that was more or less duple.

Method

Eight paid students from Leiden University, 6 females and 2 males, participated in the study. They met the hearing criteria mentioned under Experiment 1.

In each trial, two sequences of white noise bursts were presented successively, separated by a short silent interval. The sequences could be MON or INT and had base SOAs of 100, 150, 200, 250, or 300 msec. The number of bursts in these sequences was 24, 16, 12, 10, and 8, respectively. In half of the trials, the first sequence was isochronous and the second one anisochronous (order I/A). In the other half, the order was reversed (order A/I). Anisochrony was induced by offsetting all even-numbered sounds from their isochronous positions toward the odd predecessors. The amount of offset was 3, 6, 9, . . . 36 msec in the MON condition, whereas it was 12, 15, 18, . . . 45 msec in the INT condition.¹ In total there were 2 (MON/INT) $\times 2$ (I/A, A/I) $\times 5$ (base SOAs) $\times 12$ (offsets) = 240 different trials.

The presentation of these trials was blocked with respect to all factors except for amount of offset, which was randomized within blocks. Thus, there were 20 different blocks of 12 trials each. The

Table 1
Thresholds (T , in Milliseconds) for Anisochrony and Their Standard Deviations (SD), as a Function of Base Stimulus Onset Asynchrony (SOA) and Spatial Condition (Interaural, INT, and Monaural, MON, as Established in Experiment 1 by the Method of Limits and in Experiment 2 by a Constant Method)

Condition	Base SOA									
	100		150		200		250		300	
	T	SD	T	SD	T	SD	T	SD	T	SD
Experiment 1										
INT	26.5	7.51	27.0	6.89	27.0	6.91	27.5	5.72	28.0	6.86
MON	19.0	5.20	19.0	4.08	19.0	4.83	18.5	4.94	18.5	4.73
INT – MON	7.5		8.0		8.0		9.0		9.5	
Experiment 2										
INT			23.5	12.0	23.0	11.5	25.0	12.0	24.5	11.5
MON	9.5	4.5	10.0	3.5	11.5	4.0	13.5	6.0	13.5	6.5
INT – MON			13.5		11.5		11.5		11.0	

Note—INT – MON, difference between interaural and monaural thresholds. In Experiment 2, T s and SD s were graphically determined. Therefore the SD s are only precise to one decimal place. In the case of INT at 100 msec, graphic determination could not reliably be made.

subjects attended one training session containing the 20 blocks, after which they heard the 20 blocks twice, divided over four experimental sessions. The orders of base SOAs, of I/A and A/I, and of spatial condition (MON/INT) were balanced as far as possible.

The subjects were required to determine whether the two sequences in each trial had the same or different rhythms and to press the corresponding button, which was registered by the computer and which elicited the next trial. All other procedures were the same as in Experiment 1.

Results and Discussion

For each of the 10 experimental conditions (2 [MON/INT] $\times$ 5 [base SOAs]), there were 32 judgments at each of the 12 offsets. We defined the threshold as the amount of offset that produced 50% *different* judgments. Because linear fits through the z transformations of the percentages yielded several coefficients of determination below .90, we established the thresholds for anisochrony by graphical means. The offsets corresponding to the 25% and 75% *different* judgment points were averaged to obtain the thresholds (D'Amato, 1970). These 50% discrimination points between isochrony and anisochrony are given in Table 1.

The present thresholds are smaller than those in Experiment 1. However, again the INT thresholds were higher than MON thresholds for the whole SOA range by 12 msec (8 msec in Experiment 1). Moreover, the thresholds as well as the threshold differences were almost invariant with respect to the base SOA. The fact that the same pattern of thresholds could be observed with a different psychophysical procedure supports our conclusions from Experiment 1.

EXPERIMENT 3

In Experiments 1 and 2, the range of SOAs was restricted from 100 to 300 msec. This was sufficient to answer our questions concerning Nakao and Axelrod's (1976) and van Noorden's (1975) studies. But the question remains whether the threshold difference between INT and MON conditions can also be found for slower sequences. Also unknown is what happens with the thresholds per se when the SOA increases. In Experiments 1 and 2, we found that they were almost invariant with respect to SOA, but Halpern and Darwin (1982), although invoking anisochrony in a different way and using only a nonalternating presentation condition, found that the anisochrony threshold increased linearly as SOAs increased from 400 through 1,450 msec. Experiment 3 was undertaken to address these issues.

Method

Six students of psychology, 1 female and 5 males between 21 and 25 years of age, participated to fulfill course requirements. The psychophysical procedure was the same as that in Experiment 2. The base SOAs were 60, 80, 120, 240, 360, 480, 600, and 720 msec. In the MON condition, the offset varied between 0 and 30 msec (in steps of 3 msec) for base SOAs of 60–240 msec. For the base SOAs of 360–720 msec, the offset varied between 0 and

51 msec (also in steps of 3 msec). The latter offset range was also used in the INT condition for base SOAs of 60–240 msec. For the SOAs of 360–720 msec, the offset range for the INT condition was 0–66 msec (see note 1).

We added larger offsets to those used in Experiment 2 because Halpern and Darwin's (1982) data strongly suggest a threshold increase beyond 400 msec. We added shorter offsets to the INT condition because in Experiment 2 the smallest offset was 12 msec, and because with that value less *same* judgments had been given than we had expected. And because the total percentage of different judgments in Experiment 2 was 65, we included three extra offsets of 0 msec at each SOA in order to attain a better balance between *same* and *different* judgments.

The number of sounds in a sequence was 24 at SOAs of 60, 80, and 120 msec. At the SOAs of 240 and 360 msec, it was 16, and at the longer SOAs, the sequence contained 8 noise bursts. Each subject completed eight experimental sessions of 1.5 h.

Results and Discussion

At each base SOA and at each offset, we had 48 judgments—except for the zero offset, for which we had $3 \times 48 = 144$ judgments. As intended, the addition of more trials with zero offset resulted in a better balance between *same* and *different* judgments (47%–53% in the MON condition, and 53%–47% in the INT condition). The anisochrony percentages were plotted against the amount of offset for each of the base SOAs at both spatial conditions. We applied z transformations and fitted linear equations. One of the 16 r^2 s was .87; the other 15 ranged between .90 and .98. The 50% thresholds are given in Table 2.

At each of the eight SOAs, the INT thresholds were higher than those for their MON counterparts. We performed eight Wilcoxon tests, one at each SOA, to test the hypothesis that the percentages of anisochrony judgments were higher for the MON condition than for the INT condition. The matched pairs were the percentages at corresponding offset values. All eight tests yielded a $p < .005$ (one-tailed).²

Although the presentation order of the isochronous standard and the anisochronous comparison was balanced only as a control measure, we divided the judgments according to these orders (I/A and A/I) and calculated the corresponding thresholds. This analysis showed that the thresholds were consistently lower when the isochronous sequence was presented first. Thus the detection of a duplicate rhythm was better when a trace of an isochronous rhythm was already available. This is another example of the time order error in psychophysics.

Table 2 also gives the differences between the INT and MON thresholds. These differences do not vary much between SOAs from 60 through 240 msec, but at 600 and 720 msec, the difference is smaller. A possible explanation is that the anisochrony-judgments (at the two longest SOAs) did not exceed 90% at the largest offsets—in other words, the psychometric functions may have been less reliable than those at the other SOAs. To test this, we conducted a follow-up study with larger offsets to attain more complete psychometric functions. In this follow-up, we included not only base SOAs of 600 and 720 msec, but

Table 2
Thresholds (T , in Milliseconds) for Anisochrony and Their Standard Deviations (SD), as a Function of Base Stimulus Onset Asynchrony (SOA) and Spatial Condition (Interaural, INT, and Monaural, MON) as Established by a Constant Method in Experiment 3 and in a Follow-Up

Condition	Base SOA															
	60		80		120		240		360		480		600		720	
	<i>T</i>	<i>SD</i>	<i>T</i>	<i>SD</i>	<i>T</i>	<i>SD</i>	<i>T</i>	<i>SD</i>	<i>T</i>	<i>SD</i>	<i>T</i>	<i>SD</i>	<i>T</i>	<i>SD</i>	<i>T</i>	<i>SD</i>
Experiment 3																
INT	24.0	13.92	22.5	13.19	27.0	15.71	24.5	12.59	27.5	14.22	35.0	16.87	37.0	19.53	41.0	24.45
MON	7.5	3.67	8.5	4.50	10.0	5.43	10.5	5.68	16.5	9.05	23.5	12.88	28.0	15.85	32.0	18.97
INT – MON	16.5		14.0		17.0		14.0		11.0		11.5		9.0		9.0	
Follow-Up																
INT					20.5	12.57	21.0	11.85					33.5	17.64	37.5	21.11
MON					6.5	3.88	8.0	4.23					23.0	13.67	29.0	17.12
INT – MON					14.0		13.0						10.5		8.5	

Note—INT - MON, difference between interaural and monaural thresholds.

also SOAs of 120 and 240 msec. This we did to balance the range of SOAs and to replicate the non-Weberian finding that, across spatial conditions, the thresholds remained constant when the base SOA was increased from 120 to 240 msec.

Five of the 6 students again served as subjects, with one unavailable student replaced by the author A.G. (female, 20 years of age, normal hearing). Even though the anisochrony percentages now reached 100, as a result of which we had more reliable psychometric functions, the difference between INT and MON was still slightly smaller at the long base SOAs. Table 2 further shows that the pattern of thresholds per se was almost the same: there was only a negligible increase of thresholds from 120 to 240 msec, and a not so negligible increase from 600 to 720 msec.

EXPERIMENT 4

In Experiments 2 and 3, the anisochronous sequence and its isochronous counterpart were presented in each trial. Therefore, the judgment regarding anisochrony could have been based on the availability of an *overt* isochronous template or on that of a *covert*, internal isochronous template. To determine whether the same results could be obtained when no overt template of isochrony was given for comparison, in Experiment 4 we used the method of single stimuli. In a typical trial, only one sequence was presented; it was either isochronous, or more or less anisochronous. The listener had to tell whether the sequence sounded either isochronous or duple.

A second purpose of the present experiment was to investigate the possibility of a confounding that might have occurred in Experiments 2 and 3. In those experiments, the number of sounds in a sequence, and thus the number of SOAs, was smaller when the SOA value became larger. If the discriminating listener profits from the number of SOAs available (the "repeated- or multiple-look" notion), the dependency of the thresholds on SOA cannot be interpreted unambiguously. To investigate this matter, we covaried two values of SOA and two numbers of SOAs in the sequence.

Method

Four subjects, 1 female and 3 males (the authors I.A., K.D., N.M., and G.t.H.) participated. The spatial conditions were INT and MON, the base SOAs were 80 and 360 msec, and the number of sounds (square waves of 880 Hz, lasting 10 msec) in the sequence was either 8 or 16. Thus there were 2 (MON/INT) $\times$ 2 (80/360 msec SOA) $\times$ 2 (8/16 sounds) = 8 conditions. The conditions were recorded on tape as blocks. The sequences within blocks were either isochronous or anisochronous to various extents, and their order was random. The grid of offsets by which the even-numbered sounds were displaced from their isochronous positions was 5 msec. The offset ranges for the MON/80 and the MON/360 conditions were 0–25 msec and 0–45 msec, respectively. For the interaural counterparts they were 0–55 msec and 0–75 msec (see note 1). In each block, each offset value was presented five times, but the zero offset was presented 15 times to achieve a balance between isochronous and anisochronous judgments. As a result, there were 40 trials in the MON/80 block, 60 trials in the MON/360 block, 70 trials in the INT/80 block, and 90 trials in the INT/360 block. After ample training, the subjects were presented the eight blocks twice. After each trial, the subjects had 2 sec to mark one of two categories, "regular" or "irregular," on a response sheet.

Results and Discussion

The thresholds were computed as those offset values which corresponded to zero z scores in the normal ogive fits. The r^2 s were sufficiently high. Table 3 gives the thresholds and their standard deviations as a function of spatial condition, base SOA, and number of sounds in the sequence.

Table 3
Thresholds (T , in Milliseconds) for Anisochrony and Their Standard Deviations (SD), as a Function of Base Stimulus Onset Asynchrony (SOA), Number of Sounds in the Sequence and Spatial Condition (Interaural, INT, and Monaural, MON) as Established in Experiment 4 by the Method of Single Stimuli

Condition	Base SOA							
	80				360			
	8 Sounds		16 Sounds		8 Sounds		16 Sounds	
	T	SD	T	SD	T	SD	T	SD
INT	16.0	16.67	18.2	10.00	23.9	14.28	26.2	16.66
MON	10.5	7.14	9.1	5.56	12.2	9.08	13.6	9.18
INT - MON	6.5		9.1		11.7		12.6	

Note—INT - MON, difference between interaural and monaural thresholds.

As in the previous experiments, INT thresholds were higher than MON thresholds and the difference was of the same magnitude. We could not observe a lower threshold with an increasing number of sounds (i.e., an increasing number of SOAs). In three out of four cases, the thresholds even increased slightly with increasing number of SOAs, exactly opposite the direction predicted by a "multiple-look" notion. There was only a negligible threshold decrease in the MON condition when 16 sounds were presented instead of 8 (thresholds of 9.1 and 10.5 msec, respectively). We concluded that in the previous experiments in this study, temporal discrimination did not profit from increasing the sample of time templates.³

EXPERIMENT 5

Experiment 4 showed that the threshold difference between INT and MON could also be established by the method of single stimuli. However, only two SOA values (80 and 360 msec) were used. We were interested in whether the spatial threshold difference could also be established at other SOA values with the method of single stimuli. In addition, we wanted to replicate the finding in Experiment 3 (constant method) that thresholds per se did not differ between SOAs of 120 msec and 240 msec, and that they increased linearly as SOAs were increased beyond 240 msec.

Method

Sixteen subjects participated: the four authors who participated in Experiment 4, and 12 students with normal hearing from Leiden University.

The sequences were INT and MON, which comprised eight sounds, and the SOAs were 60, 80, 100, 120, 180, 240, 300, 360, 480, and 600 msec. Thus there were 2 (MON/INT) $\times$ 10 (SOAs) = 20 conditions, and these conditions were tape recorded as blocks. Within a block the sequences were isochronous or anisochronous to several extents, and randomized. The maximum offsets from the isochronous position of the even-numbered tones were 20, 25, 30, 30, 30, 40, 45, 60, and 65 msec for the respective base SOAs of 60–600 msec in the MON presentation. In the INT presentation, these values were 50, 55, 60, 60, 60, 60, 70, 75, 90, and 95 msec, respectively (see note 1). The offset grid was 5 msec, and at each offset value there were 5 replications, except at the zero offset, for which there were 15 replications.

Each of the 16 subjects heard the 20 blocks in a different order (the 16 orders were chosen from a 20 $\times$ 20 Latin square). Stimuli

were presented with an open-reel Revox tape recorder (B77), and the times taken by reeling back and forth between the blocks were the breaks. After each sequence, the listener marked one of the response categories—"regular" or "irregular." The 12 new subjects participated in a training session. There were two experimental sessions for each subject, in each of which, 10 blocks were presented.

Results and Discussion

Percentages of anisochrony judgments were calculated for each of the 20 conditions at each offset value. At the zero offset value, the percentages were based on 16 subjects $\times$ 15 replications = 240 judgments; at the other offsets, on 16 $\times$ 5 = 80 judgments. Applying z transformations and linear fits resulted in satisfying r^2 s for 17 curves (the average r^2 was .94). However, for the INT presentation at base SOAs of 60, 80, and 100 msec, the fits were poor (r^2 s were .64, .80, and .68, respectively). A close inspection of the response sheets and interviews with the subjects revealed what had happened in these conditions: For very large offsets in these (interaural) patterns, the even-numbered tones in one ear came so close to their odd predecessors in the other ear that about half of the subjects apparently heard binaural patterns instead of interaural ones. As a result, they marked the category "regular" on the response sheets for these cases, which were intended to be the most irregular ones.

Such unexpected behavior was not observed in Experiment 3, in which the required judgment was whether the isochronous standard and the comparison had the same or a different rhythm. Fast interaural sequences in which the even-numbered sounds were offset to a comparable degree could be easily discriminated from their overt isochronous standard, thus yielding *different* judgments. The constant method used in Experiment 3 therefore seems preferable.⁴

Given the above, Table 4 only presents the thresholds at SOAs of 120–600 msec. Thresholds in the INT condition were on the average 9.14 msec higher than those in the MON condition. Wilcoxon tests showed that these differences were significant at all SOAs ($p < .005$, one-tailed). So the first question of Experiment 5 was answered clearly: Whether an overt isochronous template is available or not, anisochrony thresholds are higher for interaural sequences. Also the second question was answered: Thresholds increased beyond an SOA of 240 msec.

Table 4
Thresholds (T , in Milliseconds) for Anisochrony and Their Standard Deviations (SD), as a Function of Base Stimulus Onset Asynchrony (SOA) and Spatial Condition (Interaural, INT, and Monaural, MON) as Established in Experiment 5 by the Method of Single Stimuli

Condition	Base SOA													
	120		180		240		300		360		480		600	
	T	SD	T	SD	T	SD	T	SD	T	SD	T	SD	T	SD
INT	18.8	27.03	12.8	27.77	15.8	20.00	18.2	20.41	18.9	23.26	23.3	26.32	29.5	28.57
MON	8.0	9.00	8.7	9.26	6.4	7.52	8.2	14.49	11.9	13.34	15.8	19.61	14.3	22.72
INT - MON	10.8		4.1		9.4		10.0		7.0		7.5		15.2	

Note—INT - MON, difference between interaural and monaural thresholds.

GENERAL DISCUSSION

Our first prediction was that the value of the difference between anisochrony thresholds for the INT and MON conditions was attributable to the difference between the corresponding POAs. In the introduction, we stated that this POA difference equaled the stop RT difference between INT and MON. Leon van Noorden (personal communication, June 1990) and Yoshitaka Nakajima (personal communication, October 1989) remarked, independently of each other, that this would be the case only numerically if the slopes of the linear equations relating stop RT to SOA equaled one, and, furthermore, is logically not correct. They argued that it is not the vertical distance D_v between the INT and MON regression lines through the stop RTs, but the horizontal distance D_h instead, that reflects the POA difference (see Figure 3).

On the basis of their arguments, we calculated the value of D_h by dividing D_v by the slope of the regression lines for all of our previous studies (summarized in Table 5). The corrected POA differences can be read in the last column of Table 5. The POA differences for SOA ranges, comparable to the ranges that were used in the present study, vary between 12 and 22 msec. Thus, according to

Figure 3. A diagram showing the regression of interaural (INT, dashed line) and monaural (MON, drawn line) stop reaction time (RT) on stimulus onset asynchrony (SOA). The slopes of both lines are equal and larger than one. The vertical distance D_v , the difference between INT and MON stop RTs, reflects the subjective difference or perceived onset asynchrony (POA). The horizontal distance D_h is the corresponding objective value (SOA). An "iso-POA line" is inserted to illustrate a cohort of INT and MON sequences that have the same subjective tempo (POA), although the SOA between members differs by D_h .

Table 5

Summary of Our Previous Stop Reaction Time (RT) Studies and the Corrected Estimates of the Differences Between Interaural and Monaural Perceptual Onset Asynchronies

Study	SOA Range	Stop RT Difference	POA Difference
ten Hoopen, Vos, & Dispa (1982)	125-250	26	21
	125-250	23	22
ten Hoopen & Akerboom (1983)	50-600	19	17
Akerboom & ten Hoopen (1983)	150-450	20	18
Akerboom, ten Hoopen, Olierook, & van der Schaaf (1983)	40-160	29	19
	75-600	18	15
	200-1,100	27	23
	480-1,680	35	32
	630-2,130	25	23
	100-400	13	12
Akerboom, ten Hoopen, & van der Knoop (1985)	200-300	14	13

Note—SOA, stimulus onset asynchrony; POA, perceptual onset asynchrony. All values are in milliseconds.

our quantitative prediction, the anisochrony threshold differences between INT and MON should occupy this range. The average differences we established in the present experiments were 8.5 (Table 1), 12 (Table 1), 13 (Table 2), 11.5 (Table 2), 10 (Table 3), and 8 msec (Table 4). Hence, our quantitative prediction is only marginally supported. It was surprising that the average anisochrony threshold differences found by Nakao and Axelrod (1976; 21 msec) and by van Noorden (1975; 14 msec) fit far better into the range we predicted than our own data did.

Our second prediction was that the spatial threshold difference is invariant with changes in SOA. To test this, we performed the following analysis: we defined two SOA ranges on a posteriori grounds. First, the present experiments showed that up to an SOA of about 300 msec, the thresholds were almost invariant with increases in SOA, whereas a steady threshold increase could be observed as SOAs increased beyond that. Second, there is accumulating evidence in the literature that temporal processing of fast sequences differs fundamentally from that of slow sequences, with the border somewhere between three and four sounds per second (see Handel, 1992; Handel, 1993; Hibi, 1983; ten Hoopen, 1992).

We plotted the thresholds for SOA ranges of 60-300 msec, and 360-720 msec and calculated the linear regression lines at MON and INT (see Figure 4). Our second prediction was supported more convincingly: the threshold difference between INT and MON was invariant with SOA, in the short as well as in the long SOA range.

For both spatial conditions, there was a very small threshold increase as SOAs increased up to 300 msec, but a much larger increase (about 4 msec per 100 msec) for increase in SOA from 360 to 720 msec. This latter pattern agrees well with Halpern and Darwin's 1982 results. These authors found a linear increase with a slope of 3.3 msec per 100 msec of the DL for anisochrony in an SOA range from 400 to 1,450 msec. The fact that there is a breakpoint of threshold behavior at about 300 msec

Figure 4. A plot of all pairs of interaural (filled symbols) and monaural (open symbols) anisochrony thresholds (T) as a function of the base stimulus onset asynchrony (SOA) that could reliably be established in the present study. For both spatial conditions, two linear regression lines were fitted: one in a short SOA range from 60 to 300 msec, and the other in a long SOA range from 360 to 720 msec. The monaural (MON) equations were: $T_{\text{mon}} = 9 + .014 \times \text{SOA msec}$, and $T_{\text{mon}} = -2 + .043 \times \text{SOA msec}$ for the short and long ranges, respectively (drawn lines). The interaural (INT) equations were: $T_{\text{int}} = 21 + .009 \times \text{SOA msec}$, and $T_{\text{int}} = 9 + .041 \times \text{SOA msec}$, respectively (dashed lines).

is a consistent finding in many anisochrony studies (ten Hoopen, 1992).

Note that we called our dependent variable *threshold for anisochrony* and not DL. The kind of anisochrony that we imposed (offsetting all even-numbered sounds from their isochronous positions toward the odd predecessors) did not permit us to establish a point of subjective equality (PSE), and consequently, no DL could be established. With the present kind of anisochrony, it is not easy to develop a procedure to obtain PSEs. Offsetting the even-numbered sounds toward their odd successors yields temporally isolated sounds at the start as well as at the end of the sequence (// // // //). In that case, one has a confounding of two kinds of anisochrony: the "duple" kind in the middle, and anisochrony caused by singular temporal deviations at the "edges" of the sequence. With such stimuli it is quite conceivable that the listener does not base the anisochrony judgments solely on the duple kind. This may have happened in Nakao and Axelrod's (1976) study, in which both directions of offset were used, but not in Van Noorden's (1975) experiment, because he applied only forward offset.

Our previous stop RT research showed that the difference between INT and MON processing should be attributed to perceptual factors. However, the analysis we have presented in this paper does not permit one to distinguish sensory from response factors. To address this, we applied a TSD analysis to the data, which we obtained

by the constant method and the method of single stimuli. These classic tasks can also be conceived of in terms of discriminating a signal (= anisochrony) from a nonsignal or noise (= isochrony) (see Gescheider, 1985; Massaro, 1975; McNicol, 1972). If a stimulus is anisochronous and the subject says so, we have a *hit*, but if he/she says it is isochronous, we have a *miss*. If a stimulus is isochronous but is labeled as anisochronous, we have a *false alarm*. Finally, if the isochronous sequence is called isochronous, we have a *correct rejection*.

For Experiment 3, its follow-up, and Experiment 5, our TSD analysis proceeded as follows. At each SOA value and for both spatial conditions, the number of anisochrony judgments at the zero offset value (the "noise") was counted and divided by the number of zero offset trials to obtain the false alarm rate. At the nonzero offset values (the "signal"), we counted the number of anisochrony judgments and divided it by the number of nonzero offset trials to obtain the hit rate. There was one minor problem: Because the offset ranges in the INT conditions were larger than those in the MON conditions, we had to extrapolate the MON offset range to equalize the "signal strength" and had to estimate the numbers of anisochrony judgments for those offsets.

Table 6 gives the hit rates, false alarm rates, and d' values for the INT and MON conditions at the SOAs for which our analysis was applicable. In Experiment 3 (constant method), the d' values were considerably larger

Table 6
Hit Rates (P_{hit}), False Alarm Rates (P_{fa}), and d' Values as a Function of Monaural (MON) and Interaural (INT) Presentation and Stimulus Onset Asynchrony (SOA), as Calculated From the Anisochrony Judgments in Experiment 3, Its Follow-Up, and Experiment 5

SOA	MON			INT		
	P_{hit}	P_{fa}	d'	P_{hit}	P_{fa}	d'
Experiment 3						
60	.89	.04	2.97	.56	.15	1.19
80	.87	.02	3.18	.57	.16	1.17
120	.84	.04	2.75	.50	.14	1.08
240	.83	.04	2.70	.53	.07	1.55
360	.77	.07	2.21	.59	.06	1.78
480	.66	.09	1.75	.50	.06	1.55
Follow-Up						
120	.91	.14	2.42	.67	.17	1.39
240	.89	.09	2.57	.69	.07	1.97
600	.71	.16	1.55	.60	.10	1.53
720	.65	.15	1.42	.54	.12	1.57
Experiment 5						
120	.88	.25	1.85	.66	.29	0.97
180	.87	.23	1.87	.72	.30	1.11
240	.92	.30	1.93	.73	.25	1.29
300	.88	.25	1.85	.74	.20	1.48
360	.84	.29	1.55	.74	.19	1.52
480	.82	.26	1.56	.73	.20	1.45
600	.82	.34	1.33	.68	.20	1.31

Note—Calculation of a nonparametric measure of sensitivity (A') yielded the same pattern as did d' . SOAs are in milliseconds.

for the MON than for the INT condition. In the follow-up, however, this was only so for the shorter SOAs of 120 and 240 msec. In Experiment 5 (method of single stimuli), the d' values for the MON condition were larger than those for the INT condition at SOAs of 120–300 msec.

Thus, the anisochrony threshold difference between spatial conditions seems to be caused by genuine sensory-perceptual factors for SOAs up to about 300 msec. For SOAs of 360 msec and larger, the TSD analysis suggests that the threshold difference is caused by response factors. Whether there is indeed an exchange of perceptual capability and response proclivity between SOAs of 300 and 360 msec, and if so, whether it is related to the tradeoff between non-Weberian and Weberian threshold behavior, remains to be investigated.

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- detection of anisochrony is accomplished at the perceptual, and not the objective, time dimension. As a result of the interaural time dilation, a larger offset is necessary to elicit anisochrony judgments at all in the INT condition. Of course we could have enlarged the MON offset range to make it equal to the INT range, but that would certainly have resulted in the excessive amount of 100% anisochrony judgments and possibly tremendous response bias. In fact, we took careful measures to balance the amount of isochrony and anisochrony judgments without sacrificing reliable psychometric functions for both conditions.

2. The *SD* values of the thresholds found by the method of limits (Experiment 1, Table 1, top panel) cannot be compared directly with the *SD* values reported in the other experiments. In the first case, the *SD*s are based on 16 threshold replications ($A/D \times 8$ replications) per condition, per subject, and they are pooled over the 4 subjects. In the other experiments (constant method and method of single stimuli), the *SD* is an index of the shallowness of the psychometric function. As a result, an ANOVA could be done in Experiment 1 but not in the other ones, where we had only one threshold estimate per condition, stemming from the psychometric functions. In those cases, we tested the difference between INT and MON thresholds by subjecting the percentages of anisochrony judgments at corresponding offset values to Wilcoxon tests—one test at each SOA level. (With this procedure, a possible interaction between INT/MON and SOA could of course not be established statistically.) Although the *SD*s were relatively large (shallow functions), the anisochrony percentages were significantly higher for the MON condition.

3. We should emphasize that we do not wish to refute the notion of "repeated or multiple looks," because it may hold for ranges with fewer numbers of templates. Recently, Drake and Botte (1993) and Drake, Botte, and Baruch (1992) reported evidence for the improvement of temporal discrimination when more time templates were available in the sequence. They found that the just noticeable difference (JND) for tempi decreased with increasing number of intervals in the sequence. The JNDs were 4%, 3.2%, and 3% when the sequences consisted of two, four, and six intervals, respectively. Although the task was to discriminate two isochronous sequences of different speeds, and not to detect deviations from isochrony, it is conceivable that their result can be generalized to anisochrony detection.

4. There was another unexpected effect of the method of single stimuli. Even at perfect isochrony, listeners judged the sequence to have a duple rhythm in about 25% of the cases, for both the INT and the MON conditions. What probably occurred in this absolute judgment task was that a subjective rhythm was imposed on the isochronous sequences (cf. Bolton, 1894). Although this behavior is very interesting as such and has been a topic of many studies (see, e.g., Povel & Okkerman, 1981; Vos, 1973; and see Handel, 1989, for a fine tutorial), it is rather a nuisance in the present kind of study. The psychometric functions have to be based on less complete ranges of percentages, and this is still another reason to prefer the constant method that we used in Experiments 2 and 3.

NOTES

1. One might criticize the fact that we used larger offset ranges for the INT condition than for the MON condition, thereby biasing the results toward a larger difference between the anisochrony thresholds in both conditions. We do not deny the existence of range effects, but the

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