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Brian C. Fidali, Ève Poudrier & Bruno H. Repp

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ORIGINAL ARTICLE

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Abstract Jones et al. in Journal of Experimental Psychology Human Perception and Performance 21:293–307, 1995, showed that a temporal perturbation is easier to detect in a 3:2 polyrhythm than in a single-stream isochronous baseline condition if the two isochronous pulse streams forming the polyrhythm are perceptually integrated: integration creates shorter inter-onset interval (IOI) durations that facilitate perturbation detection. The present study examined whether this benefit of integration outweighs the potential costs imposed by the greater IOI heterogeneity and memory demands of more complex polyrhythms. In "Experiment 1", musically trained participants tried to detect perturbations in 3:5, 4:5, 6:5, and 7:5 polyrhythms having one of two different pitch separations between pulse streams, as well as in an isochronous baseline condition. "Experiment 2" included an additional 2:5 polyrhythm, additional pitch separations, and instructions to integrate or segregate the two pulse streams. In both experiments, perturbation detection scores for polyrhythms were below baseline, decreased as polyrhythm complexity increased, and tended to be *lower* at a smaller pitch separation, with little effect of instructions. Clearly, polyrhythm complexity was the main determinant of detection performance, which is attributed to the interval heterogeneity and/or memory demands of the pattern formed by the integrated pulse streams. In this task, perceptual integration was disadvantageous, but apparently could not be avoided.

B. C. Fidali · È. Poudrier
Yale University, New Haven, CT, USA

B. H. Repp (✉)
Haskins Laboratories, 300 George Street,
New Haven, CT 06511-6624, USA
e-mail: repp@haskins.yale.edu

Introduction

Perception and production of polyrhythms have been of considerable interest to researchers in music cognition and motor control because of the challenges they pose, and because of the important role they play in the music of various cultures. The polyrhythms studied usually consist of two isochronous sequences (pulse streams) whose periods are related by a non-integer ratio, such as 2:3 or 3:4. The pulse streams are usually distinguished by an auditory feature such as pitch and/or by the limb that is used to produce them (e.g., left or right hand). They typically start in phase, and successive points of coincidence define the cycles of the polyrhythm. Polyrhythmic ratios generally stay reasonably simple in this research, otherwise the duration of the cycle would become overly long or the tempo would become overly fast. Moreover, even polyrhythms with relatively simple ratios such as 3:4 or 3:5 can be difficult to produce and may pose problems for perception as well.

Studies of polyrhythm production generally focus on the relative difficulty of execution as a function of ratio complexity, cognitive strategies, and practice. Difficulty increases with ratio complexity (Deutsch, 1983), and more complex polyrhythms tend to be simplified in production, especially when the tempo is increased (Peper, Beek, & van Wieringen, 1995). A number of studies have also shown that the isochronous pulse streams of a polyrhythm are easier to execute simultaneously when they are conceptualized as a sequentially integrated rhythmic pattern (Pressing, Summers, & Magill, 1996; Summers, 2002; Summers, Ford, & Todd, 1993a; Summers & Kennedy, 1992; Summers, Rosenbaum, Burns, & Ford, 1993b; Summers, Todd, & Kim, 1993c). Indeed, much of the evidence suggests that integration is the only way to produce polyrhythms accurately.

Independent parallel control of the two hands in polyrhythmic finger tapping is difficult (Klapp, 1979; Klapp, Hill, Tyler, Martin, Jagacinsky, & Jones, 1985; Klapp & Jagacinsky, 2011; Klapp, Nelson, & Jagacinsky, 1998; Kurtz & Lee, 2003), though it has been demonstrated in pianists playing or tapping at fast tempi (Bogacz, 2005; Krampe, Kliegl, Mayr, Engbert, & Vorberg, 2000; Shaffer, 1981). Studies in which the pitch separation of the two pulse streams was varied have found that a smaller separation, which facilitates perceptual integration, also facilitates production of the polyrhythm (Jagacinsky, Marshburn, Klapp, & Jones, 1988; Klapp et al., 1985; Summers et al., 1993).

In this study, we are concerned solely with perception of polyrhythms. Studies on this topic are less numerous than those on polyrhythm production. Some polyrhythm perception studies have focused on factors that influence which pulse listeners hear as the most salient. For example, Oshinsky and Handel (1978) and Handel and Oshinsky (1981) asked participants to tap along with the most salient pulse, while various characteristics of the polyrhythms were manipulated. Handel (1984, 1989) summarized the results of this research, noting that pulse salience was influenced by interval ratio, presentation speed, pitch, and several other factors.

Given that perceptual integration of pulse streams is important in the production of polyrhythms, researchers have also explored the importance of integration versus segregation in the perception of polyrhythms. *Auditory stream segregation* (or streaming) refers to the phenomenon whereby rhythmic tone sequences alternating between two or more pitches are perceived as splitting into two or more independent streams (Bregman, 1990). Although listeners may be able to focus on one or another stream, it is generally assumed that the rhythm formed by the combination of the two streams is no longer perceived when streaming has occurred. Frequency separation, presentation rate, and attentional focus can determine whether or not auditory streaming occurs (Bregman, 1990; Jones 1976). Streams are more likely to be segregated as their frequency separation increases (Bregman & Campbell, 1971; van Noorden, 1975). Similarly, increasing presentation rate encourages segregation, especially with larger pitch separations (Jones, 1976). Van Noorden (1975) identified two perceptual boundaries: Below the "fission boundary" (pitch separations of <3–4 semitones, independent of tempo), streams are always integrated. Above the "temporal coherence boundary" (which corresponds to a rapidly increasing pitch separation as tempo decreases), segregation always occurs. When the pitch separation and tempo of a multi-stream sequence make it fall between these two boundaries, not only pitch separation and tempo, but also deliberate attentional strategies may determine whether the streams are integrated or segregated.

Applying these principles to polyrhythm perception, Beauvillain (1983) found that participants could tap in synchrony with either of the two streams of a simple (2:3 or 3:4) polyrhythm (separated by 10 semitones) when the tempo was fast. However, when the tempo was slow, they could tap only with the faster stream; the slower stream seemed to be obscured by integration of the two streams. Moelants and van Noorden (2005) showed that increasing the pitch separation (favoring segregation) reduced the salience of the coincidence points (beginnings of repeating pattern cycles) in polyrhythms.

Studies of stream integration and segregation often require participants to report their subjective impression on a rating scale. However, it is also possible to use indirect and more objective indicators of stream integration versus segregation. Jones, Jagacinski, Yee, Floyd, and Klapp (1995) applied such a method to polyrhythm perception. They introduced perturbations (shifts of a single tone by ±60 ms) in the slower (2-pulse, i.e., two pulses per cycle) stream of a 2:3 polyrhythm whose faster (3-pulse) stream was 3 or 43 semitones (st) higher in pitch. The two-pulse stream was also presented alone as a baseline condition. Detection of perturbations was better in the 3 st pitch separation condition (which favored integration) than in either the 43 st pitch separation condition (which encouraged segregation) or the single-stream baseline condition. Instructions to either integrate or segregate the streams had little effect: pitch separation, not deliberate strategies of attention, determined detection performance. In another experiment, Jones et al. used intermediate pitch separations of 7 and 19 st. Because the tempo of the polyrhythm was relatively slow, all these stimuli fell short of van Noorden's (1975) temporal coherence boundary, so that segregation was by no means obligatory. Deliberate segregation might have been possible, however, as the stimuli were above the fission boundary and, therefore, not obligatorily integrated. Nevertheless, the detection results suggested that the polyrhythm was perceived as integrated, regardless of instructions.[1]

Jones et al. (1995) argued that integration of the two streams of a 2:3 polyrhythm improves performance in a perturbation detection task because the resulting non-isochronous rhythm includes shorter inter-onset intervals (IOIs) than the simple pulse stream that serves as the baseline. Whereas the two-pulse baseline stream of Jones et al.

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[1] As it is generally believed that attentional strategies affect the subjective perception of multi-stream stimuli between the fission and temporal coherence boundaries (Bregman, 1990; Van Noorden, 1975), it is likely that the participants would have judged the stimuli to be more integrated (segregated) when they had been instructed to integrate (segregate) them. Therefore, the results suggest that detection performance depended more on objective stimulus properties than on subjective impressions of integration/segregation (which were not assessed).

(1995) had two IOIs of 800 ms per cycle and the three-pulse stream had three IOIs of 533 ms per cycle, the integrated rhythmic pattern had IOIs of 533, 267, 267, and 533 ms per cycle. The perturbed tone was always the second tone of the two-pulse stream, which resulted in a ±60/800 = ± 7.5% change in adjacent IOIs in the baseline sequence, but in a ±60/267 = ± 22.5% change in the integrated rhythm. Even though exact proportionality (Weber's law) does not hold for duration discrimination (Grondin, 2001), the same temporal perturbation is more noticeable in a short than in a long interval (Hirsh, Monahan, Grant, & Singh, 1990; Monahan & Hirsh, 1990). The just noticeable difference (jnd) for a change in duration decreases with duration down to 200–300 ms (e.g., Friberg & Sundberg, 1995) and thus is certainly lower in an interval of 267 ms than in one of 800 ms. Therefore, when the same perturbation is more easily detected in a polyrhythm than in a single-stream baseline condition (which could be either the slower or the faster stream), this suggests that the two streams of the polyrhythm have been integrated. Otherwise, segregation of the pulse streams can be inferred.

We conducted two experiments to investigate whether this argument can be extended to polyrhythms with more complex interval ratios than 2:3. We suspected that this extension might not be as straightforward as it seemed at first. Certainly, integration of the isochronous pulse streams of more complex polyrhythms will again result in shorter IOIs, which should make it easier to detect perturbations than in a single-stream baseline condition. For example, consider a 3:4 polyrhythm with a cycle duration of 1,800 ms. Then the three-pulse stream has three IOIs of 600 ms per cycle, the four-pulse stream has four IOIs of 450 ms per cycle, and the integrated rhythmic pattern has IOIs of 450, 150, 300, 300, 150, and 450 ms per cycle. So, detection of any perturbation should be better in the integrated rhythm than in a three-pulse or four-pulse single-stream baseline condition.[2] This principle applies to any polyrhythm, regardless of complexity. However, two other factors come into play that may counteract this benefit of integration. First, in order to reap the benefit, participants must remember the non-isochronous rhythmic pattern that is repeated from cycle to cycle. More complex polyrhythms place higher demands on participants' short-term memory, and these demands may make it more difficult to detect perturbations. Second, the greater variety of IOI durations, which inflicts the greater memory demands, may in itself inhibit the detection of perturbations, even if the integrated rhythmic pattern is remembered well. This is so because contextual temporal variability may increase the variability of internal timekeeping processes that are needed to determine whether every tone occurs at its expected time (see, e.g., Repp, 2002; Yee, Holleran & Jones, 1994).

The question we wished to address, then, is whether the perturbation detection advantage (relative to a single-pulse baseline) offered by the shorter IOIs in a complex integrated polyrhythm outweighs the disadvantages of having to process and remember the integrated rhythmic pattern. These disadvantages increase with polyrhythmic complexity, whereas the advantage due to increasingly shorter IOIs does not increase much beyond a certain level of complexity because the IOIs get rather short, and the jnd is fairly constant once intervals get shorter than 200–300 ms (Friberg & Sundberg, 1995). Therefore, one plausible prediction is that, as polyrhythmic complexity increases, an initial advantage for perturbation detection will turn into a disadvantage, and detection performance will eventually fall below rather than above the baseline level. This disadvantage might be avoided to the extent that intentional perceptual segregation of the polyrhythmic pulse streams is possible. We conducted two experiments to test these predictions, with "Experiment 2" being an elaboration of "Experiment 1".

Experiment 1

We defined complexity simply as the number of pulses per polyrhythmic cycle. For "Experiment 1", we chose polyrhythms with ratios of 3:5, 4:5, 6:5, and 7:5, consisting of 7, 8, 10, or 11 pulses per integrated rhythm cycle, respectively (given that the initial pulses of the two streams coincide). Perturbations were introduced exclusively in the five-pulse stream, which had a fixed tempo and also served as the single-stream baseline. The pitch separation of the two pulse streams was 1 or 7 st.

Integration was expected to be obligatory in the 1 st pitch separation condition, as it was below the fission boundary (van Noorden, 1975). The 7 st pitch separation, which is still relatively small but clearly above the fission boundary, was intended to make segregation possible, if that was participants' intention. (No specific instructions to integrate or segregate the pulse streams were given in "Experiment 1".) Moreover, because we held the tempo of the five-pulse stream constant, the tempo of the other stream increased along with polyrhythm complexity. This resulted in an increase of the overall event rate, which might facilitate stream segregation in the more complex polyrhythms. Thus our prediction was that, with the 1 st

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[2] It might seem that this statement should be qualified by adding "unless the first tone in the polyrhythm cycle is perturbed" because that tone is surrounded by 450-ms IOIs, like the tones in the four-pulse stream. In fact, however, perturbation of the first tone in either stream should be easy to detect because it changes the synchrony of the two cycle-initial tones into an asynchrony. Thus, this perturbation would not be detected on the basis of a change in the adjacent IOIs, but on the basis of asynchrony.

pitch separation, an initial perturbation detection advantage (relative to baseline) would turn into a disadvantage as polyrhythm complexity increases, whereas with the 7 st pitch separation this trend would be less pronounced, to the extent that this moderate pitch separation permits intentional stream segregation.

Method

Participants

Nine paid volunteers (6 women, 3 men, ages 21–27) and author BHR participated. The paid participants were highly trained musicians, graduate students at the Yale School of Music, who had studied their primary instrument for 10–24 years. BHR is an amateur pianist and was 66 years old at the time. All were regular participants in rhythm and synchronization experiments in BHR's laboratory.

Materials and equipment

An isochronous baseline sequence (the 5-pulse stream) was created by repeating digital piano tones with an IOI of 504 ms. (The implied cycle duration thus was 2,520 ms.) The tones had the pitch C4 (262 Hz), a nominal (MIDI offset minus MIDI onset) duration of 60 ms, and a fixed intensity (MIDI velocity). Polyrhythms with ratios of 3:5, 4:5, 6:5, and 7:5 were created by adding isochronous tone sequences with IOIs of 840, 630, 420, and 360 ms, respectively, at a pitch that was either 1 or 7 st higher (C#4, 277 Hz, or G4, 392 Hz). All polyrhythms had the same cycle duration of 2,520 ms, and the two streams were in phase (i.e., their pulses coincided at the beginning of each cycle). A schematic drawing of one cycle of each rhythm is presented in Fig. 1. (The 2:5 rhythm was included only in "Experiment 2".) The IOI durations of each integrated rhythmic pattern are shown as small numbers.

Perturbations were introduced into the five-pulse stream exclusively and consisted of delaying a single tone by either 30 or 50 ms, which lengthened the preceding IOI and shortened the following IOI by the same amount. These delays occurred in one of four possible cycle positions (2–5); position 1 was not perturbed in order to maintain synchrony of the coinciding tones that marked the polyrhythmic cycles. Two delays and four possible positions resulted in eight combinations, and these eight perturbations occurred in a random order within each trial. A trial consisted of 19 continuous cycles of a polyrhythm or of the five-pulse baseline sequence. A single perturbation occurred in each of the even-numbered cycles, starting with the fourth cycle.

A program written in MAX 4.6.3 controlled the experiment. The tones (piano timbre) were produced on a Roland RD-250s digital piano that was connected to the computer via a MOTU Fastlane MIDI interface. Participants listened over Sennheiser HD280 Pro headphones at a comfortable intensity.

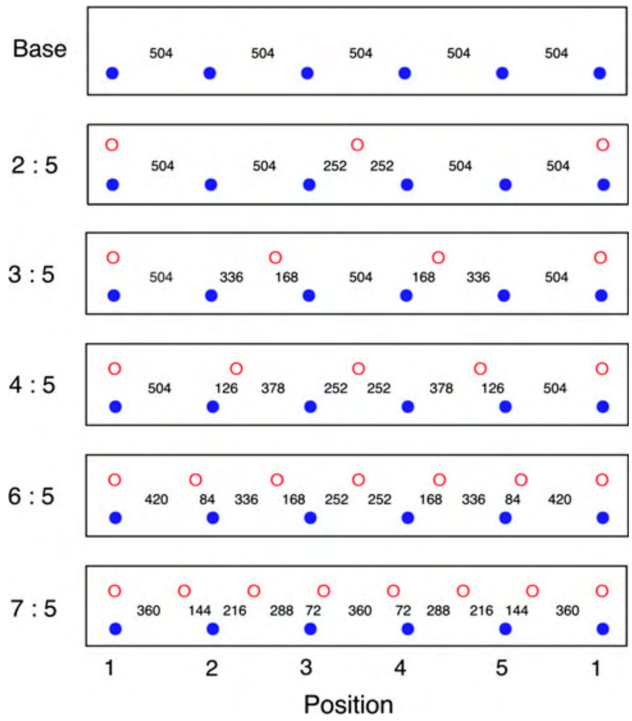

Fig. 1 Schematic illustration of one cycle of each polyrhythm used in Experiments 1 (except for 2:5) and 2. *Filled circles* represent tones in the five-pulse stream; *unfilled circles* represent tones in the other stream of each polyrhythm. *Small numbers* indicate interval durations in the integrated rhythmic pattern. *Base* baseline sequence

Procedure

Trials were presented in blocks of nine: the five-pulse stream baseline, the four polyrhythms with 1 st pitch separation, and the four polyrhythms with 7 st pitch separation, in random order. Participants started a trial by depressing the space bar on the computer keyboard. They were instructed to rest their right index finger on the "down arrow" key throughout each trial and to press the key quickly whenever they detected a deviation from the rhythm that was established at the beginning of the trial (during the first three cycles). They were told that there would be multiple deviations in a trial, and that these deviations would always occur in the lower pulse stream, which occurred by itself in one trial. They were also told that they could attend either to the integrated rhythmic pattern or to the lower stream only, whichever strategy they found more helpful in accomplishing the task. Their response latencies were measured from the onset of the shifted tone, which corresponded to the end of the first changed IOI duration. Participants saved their data in a file after each block of trials. Each participant completed five blocks.

Analysis

Responses with latencies between 150 and 1,200 ms were considered correct responses (hits); all other responses were considered false alarms.[3] Due to an undiagnosed programming error, the same type of perturbation (defined by the combinations of delay and position) sometimes occurred repeatedly in a trial, while some other types were missing. In such cases, we randomly chose one of the repetitions and left missing data points blank. These occurrences were infrequent enough not to seriously bias the data. However, because of the somewhat uneven representation of perturbation positions, we refrained from analyzing position effects in this experiment (see "Experiment 2" instead). The results were analyzed with repeated-measures ANOVAs, and the Greenhouse–Geisser correction was applied automatically to p values of effects of variables with more than two levels.

Results

We first examined the false alarm rates, to make sure they were not excessively high, which might have biased the hit rates. On average, 1.02 false alarms occurred per trial. A 2 (pitch separation) × 4 (polyrhythm ratio) ANOVA on the individual false alarm rates (excluding the baseline condition) revealed a significant effect of polyrhythm ratio, $F(3, 27) = 4.67$, $p = 0.043$. False alarm rates were highest with the 6:5 ratio (1.71/trial), followed by 7:5 (1.22), 4:5 (0.63), and 3:5 (0.61). The false alarm rate in the baseline condition was 0.84/trial. If a single response were made at random in a trial, the chance of it being scored as a hit would be about 20%.[4] However, as there were eight perturbations per trial, the chance level of a hit for any particular perturbation was only 2.5% per random response. Therefore, false alarms cannot have had much influence on the hit rates. Given the relatively low false alarm rates and the fact that they cannot easily be expressed as proportions (they are not truly random responses, and our paradigm is not a standard signal detection task), we did not attempt to calculate d' indices, but focused on hit percentages instead.

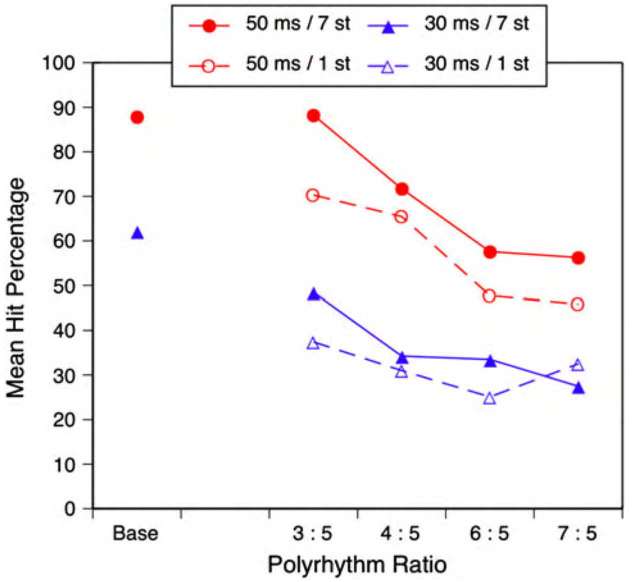

Fig. 2 Mean hit percentages in "Experiment 1" as a function of polyrhythm ratio (*Base* baseline), perturbation size (30 or 50 ms), and pitch separation (1 or 7 st)

Figure 2 shows the mean hit percentages for the baseline condition and the four polyrhythms, with separate data points for the 1 and 7 st pitch separation conditions, and for 30- and 50-ms perturbations. A 2 (perturbation size) × 2 (pitch separation) × 4 (polyrhythm ratio) ANOVA was conducted on these data, excluding the baseline condition. Clearly, 50-ms perturbations were easier to detect than 30-ms perturbations, $F(1, 9) = 48.86$, $p < 0.001$. Performance decreased as polyrhythm complexity increased, $F(3, 27) = 23.23$, $p < 0.001$, and was better in the 7 st than in the 1 st pitch separation condition, $F(1, 9) = 7.13$, $p = 0.026$. The main effect of polyrhythm ratio was nonlinear, having a significant quadratic component, $F(1, 9) = 11.00$, $p = 0.009$, in addition to the obvious linear trend: the effect decreased as ratio complexity increased, with little difference between 6:5 and 7:5. No interactions were significant, although the one between perturbation size and polyrhythm ratio approached significance, $F(3, 27) = 3.29$, $p = 0.062$, reflecting larger effects of ratio when the perturbation size was 50 ms.

We had expected the hit rate for the simplest polyrhythm (3:5) to be above baseline. However, that was not the case. On the contrary, a separate 2 (perturbation size) × 2 (baseline vs. 3:5 polyrhythm) ANOVA showed that performance for the 3:5 polyrhythm was significantly below baseline, $F(1, 9) = 16.18$, $p < 0.01$. The main effect of perturbation size was significant, $F(1, 9) = 30.73$, $p < 0.001$, but the interaction did not reach significance, $F(1, 9) = 3.48$, $p = 0.095$.

We also analyzed the reaction times (RTs) of the hits. One participant who had several missing data points due to

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[3] Occasionally, a true false alarm may have been scored as a hit, or a very slow response to a perturbation may have been considered a false alarm. The wide window was justified by the fact that participants were likely to respond to the change in the shorter of the two consecutive IOIs that were affected by a shifted tone. If the shorter IOI was the second one, the response was actually triggered by the next tone, resulting in a longer RT.

[4] The response window for hits was 1200 − 150 = 1,050-ms long. The response windows of the eight perturbations thus occupied 8 × 1,050 = 8,400 ms in 17 cycles of 2504 ms duration each, or 19.7% of the total time of 17 × 2,504 = 42,568 ms. (Participants did not know that perturbations occurred only in even-numbered cycles, only that they could not occur in the first three cycles.)

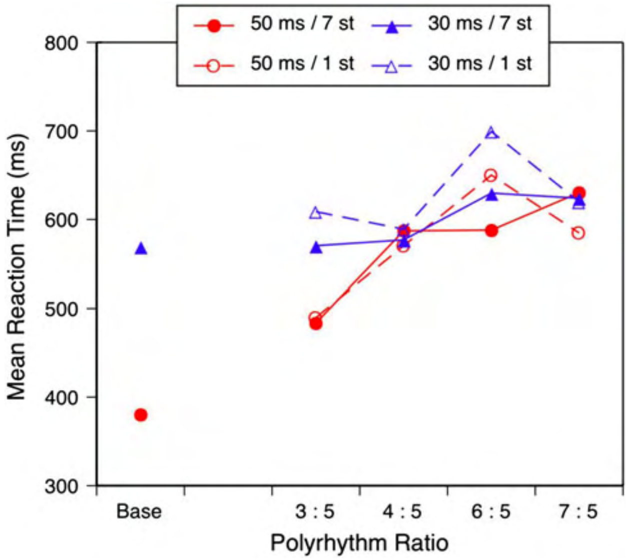

Fig. 3 Mean reaction times in "Experiment 1" as a function of polyrhythm ratio, perturbation size, and pitch separation

zero hits in some cells of the design was omitted in this analysis.[5] The mean RTs of the remaining participants are shown in Fig. 3. In the baseline condition, RTs were clearly faster with the larger perturbations, $t(8) = 9.00$, $p < 0.001$. Surprisingly, however, this difference was much less evident in the polyrhythmic conditions. A 2 × 2 × 4 ANOVA on the polyrhythm data indicated that RTs increased as the polyrhythm ratio became more complex, $F(3, 24) = 4.83$, $p = 0.017$. The effect of ratio complexity again tended to level off between 6:5 and 7:5, with the quadratic trend being almost significant, $F(1, 8) = 5.09$, $p = 0.054$. The main effect of perturbation size, $F(1, 8) = 5.08$, $p = 0.054$, and its interaction with polyrhythm ratio, $F(3, 24) = 3.14$, $p = 0.058$, also approached significance: RTs tended to be faster with larger perturbations, but this difference was primarily due to the 3:5 polyrhythm.

Discussion

As predicted, increasing polyrhythmic complexity impaired participants' ability to detect perturbations. Unexpectedly, however, participants performed below baseline level even with the simplest polyrhythm (3:5), which imposed only relatively modest memory demands. Performance was generally lower with the 1 st than with the 7 st pitch separation, which indicated that perturbation detection did not benefit from integration of the two pulse streams, even though the perturbed IOIs in the integrated rhythm were shorter than those in the baseline condition. Whatever degree of intentional stream segregation the 7 st pitch separation afforded seems to have made perturbations easier to detect, but performance generally remained well below baseline, suggesting that selective attention to the lower-pitched pulse stream was difficult and/or was not attempted by many participants. Another possibility is that the higher stream continued to interfere as a distractor, even when it was not attended (see "General discussion").

The results of "Experiment 1" thus suggest that polyrhythmic complexity is a far more important determinant of detection performance than is the relative duration of the perturbed IOIs. To detect perturbations in the integrated rhythmic pattern, participants had to remember that pattern, and this became increasingly difficult as the complexity of the polyrhythm increased. Even if memory demands had not been a problem, the increasingly heterogeneous interval structure of the polyrhythms may have increased the variability of internal timekeeping processes. The number of different IOI durations in each cycle (which occur in a palindromic sequence) ranged from three (3:5) to five (7:5) (see Fig. 1). Therefore, both memory demands and interval heterogeneity as such probably played a role in the negative impact of polyrhythmic complexity on detection performance.

Experiment 2

"Experiment 2" extended, modified, and improved the design of "Experiment 1" in several ways. First, we included a 2:5 polyrhythm to see whether at least this simple stimulus would show a benefit of integration, as found by Jones et al. (1995) for a 2:3 polyrhythm. (Like 2:3, the integrated 2:5 polyrhythm has only two different IOI durations; see Fig. 1.) Second, rather than leaving it to participants to decide whether to integrate or segregate the two pulse streams when the pitch separation was large enough, we instructed participants to employ one or the other attentional strategy, as Jones et al. also had done. Third, we extended the range of pitch separations, which had been somewhat narrow in "Experiment 1", to give participants a better opportunity for intentional stream segregation. Fourth, to compensate for the increased number of stimuli and conditions, we used only one perturbation size, intermediate between the sizes used in "Experiment 1". Finally, we corrected the programming error that had led to a somewhat uneven representation of perturbation positions in "Experiment 1", which enabled us to conduct a proper analysis of position effects.

In this experiment, we used two pitch separations (5 and 10 st) in each of two instruction conditions (integration vs. segregation). In addition, the integration condition contained polyrhythms at a single pitch (i.e., the integrated

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[5] Individual differences were very large, with average hit percentages ranging from 14.2% (the omitted participant) to 87.9%. BHR achieved 55.3%.

rhythmic pattern as such), whereas the segregation condition included polyrhythms with a pitch separation of 20 st, as well as single-stream baseline trials. We expected that the different contexts provided by these additional trials might facilitate the requested attentional strategies for the 5 and 10 st pitch separations that were shared by the two instruction conditions.

With regard to the effect of instructions, we thought that if IOI duration is the primary determinant of perturbation detection performance, as might be the case with the newly added 2:5 polyrhythm, an integrative strategy should lead to better performance. If memory demands and IOI heterogeneity are the dominant factors, which we expected to be the case with the more complex polyrhythms, a segregative strategy should be beneficial. Thus, the effects of instructions might interact with polyrhythm complexity and/or with pitch separation.

Method

Participants

The participants were the same as in "Experiment 1" except for one who was no longer available. Instead, author BCF (amateur percussionist, age 22 years) participated. Several months elapsed between the experiments.

Materials and equipment

In addition to the 3:5, 4:5, 6:5, and 7:5 polyrhythms, "Experiment 2" included a 2:5 polyrhythm with a two-pulse IOI of 1260 ms (see Fig. 1). The five-pulse stream was again played at pitch C4 and served as the baseline. The pitch of the second pulse stream was either the same (0 st separation) or 5, 10, or 20 st higher, with the 0, 5, and 10 st separations occurring in the integration condition, and the 5, 10, and 20 st separations in the segregation condition. The nominal (MIDI) tone duration was reduced to 20 ms to avoid acoustic overlap in the 0 st separation condition, as some rather short IOIs occurred in the most complex polyrhythms (see Fig. 1). Perturbations were again introduced in positions 2–5 of the five-pulse stream. They consisted of a tone delay of 40 ms. Each trial consisted of 11 cycles of a polyrhythm or of the five-pulse baseline sequence and contained four perturbations in different cycle positions, randomly ordered. A single perturbation occurred in each of the even-numbered cycles, starting with the fourth cycle. The equipment was the same as in "Experiment 1".

Procedure

The basic procedure was the same as in "Experiment 1", except materials for "Experiment 2" were divided into two sets with instructions to either integrate or segregate the two pulse streams of the polyrhythms. These two instruction conditions were administered in separate 1-h sessions, typically 1 week apart. Their order was counterbalanced across participants.

Each block of the integration condition contained 15 randomly ordered trials, representing the five polyrhythms with pitch separations of 0, 5, and 10 st. Each participant completed five blocks of trials. Participants were instructed to attend to the integrated rhythmic pattern and to listen for deviations from the pattern that was established during the first three polyrhythmic cycles. They were told that it was important to maintain this attentional strategy, as the research was concerned with its effect on performance.

Each block of the segregation condition contained 18 randomly ordered trials, representing three baseline trials and the five polyrhythms with pitch separations of 5, 10, and 20 st. Each participant completed five blocks of trials. Participants were instructed to attend to the lower pulse stream and to ignore the higher pulse stream while listening for deviations from perfect regularity in the lower stream. They were informed that all perturbations occurred in the lower stream and that the higher stream was always perfectly regular.

Analysis

The analysis proceeded as in "Experiment 1". In addition, we analyzed the effects of perturbation position within the polyrhythmic cycles.

Results

False alarms were even less frequent than in "Experiment 1". The mean number per trial was 0.33. A 5 (polyrhythm ratio) × 3 (pitch separation) ANOVA on the individual false alarm rates in the integration condition yielded significant main effects of both variables, $F(4, 36) = 15.41$, $p < 0.001$ and $F(2, 18) = 7.86$, $p = 0.011$, respectively. As in "Experiment 1", false alarm rates were highest for the 6:5 polyrhythm (0.61), followed by 7:5 (0.54), 4:5 (0.24), 3:5 (0.23), and 2:5 (0.19). False alarm rates decreased as pitch separation increased. A similar ANOVA on the data of the segregation condition (excluding the baseline trials) yielded only a main effect of polyrhythm ratio, $F(4, 36) = 8.90$, $p < 0.001$, again with the highest rates for 6:5 (0.55) and 7:5 (0.42), followed by 3:5 (0.33), 2:5 (0.19), and 4:5 (0.14). Here, there was no tendency for the false alarm rate to decrease as pitch separation increased. The baseline false alarm rate was 0.22. A 2 (instruction condition) × 5 (polyrhythm ratio) × 2 (pitch separation) ANOVA on the two pitch separations shared by the two instruction conditions (5 and 10 st) yielded only a significant main effect of polyrhythm ratio, $F(4, 36) = 14.31$, $p < 0.001$.

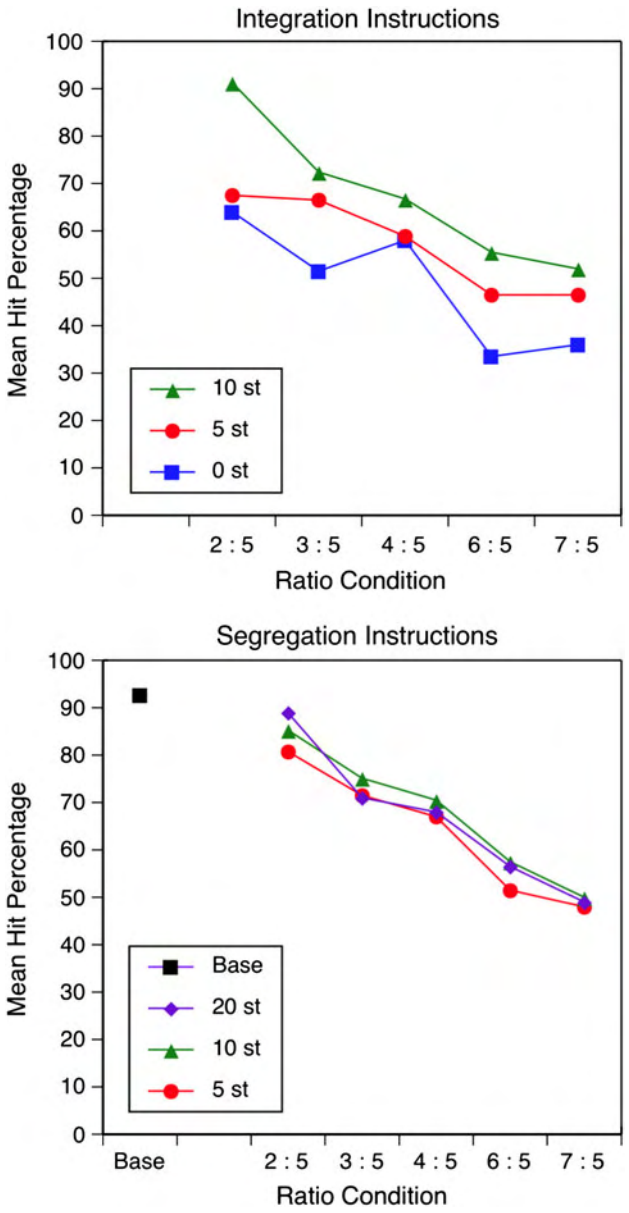

Fig. 4 Mean hit percentages in "Experiment 2" in two instruction conditions (integration vs. segregation) as a function of polyrhythm ratio and pitch separation

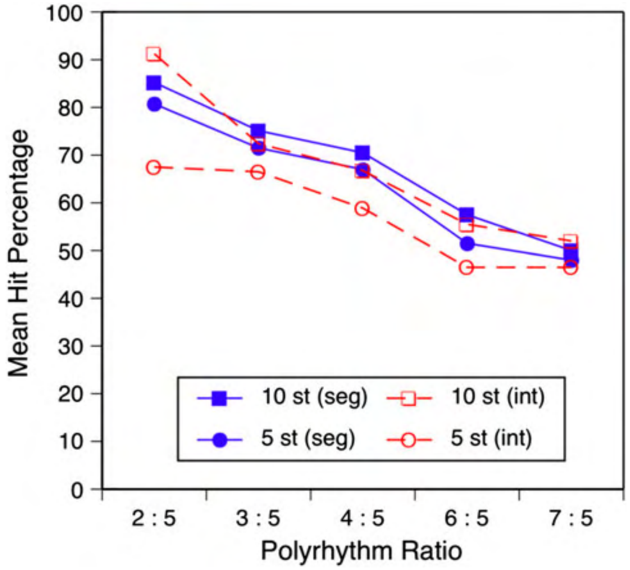

Fig. 5 Mean hit percentages for 5 and 10 st pitch separations in the segregation (seg) and integration (int) instruction conditions

Figure 4 shows the mean hit percentage as a function of polyrhythm ratio for the integration and segregation instruction conditions. Separate 3 (pitch separation) × 5 (polyrhythm ratio) ANOVAs were conducted on the two instruction conditions, excluding the baseline in the segregation condition. (The two instruction conditions are compared directly in the next figure.) Performance decreased in both instruction conditions as polyrhythm complexity increased, $F(4, 36) = 13.90$, $p < 0.001$, and $F(4, 36) = 34.73$, $p < 0.001$, respectively. Unlike in "Experiment 1", these effects had no significant nonlinear trends here, although there was again little difference between 6:5 and 7:5. Pitch separation had an effect only in the integration condition $F(2, 18) = 6.62$, $p = 0.027$, where performance was lower at smaller pitch separations (Fig. 4a). Performance in the baseline condition (Fig. 4b) was higher than with all polyrhythms in the segregation condition, including the simplest (2:5) polyrhythm, $t(9) = 2.68$, $p = 0.025$.

To compare the integration and segregation conditions directly, Fig. 5 plots the data for the 5 and 10 st pitch separation stimuli shared by the two conditions. Although the effect of pitch separation seems larger in the integration condition, a 2 (instruction condition) × 2 (pitch separation) × 5 (polyrhythm ratio) ANOVA did not reveal any significant interactions. Rather, only the main effect of pitch separation (lower performance at the smaller separation) was significant, $F(1, 9) = 13.60$, $p = 0.005$, as well as the main effect of polyrhythm ratio, $F(4, 36) = 24.84$, $p < 0.001$, again without any nonlinear trend. Instructions to integrate or segregate the two pulse streams had no reliable effect on performance with the shared stimuli, $F(1, 9) = 0.70$, $p = 0.426$.

The mean RTs for the two instruction conditions are shown in Fig. 6. In the integration condition, there was only a main effect of polyrhythm ratio, $F(4, 36) = 6.12$, $p = 0.005$. The effect was nonlinear, due to an increase in RT up to the 6:5 ratio, but a subsequent decrease for the 7:5 ratio. Polynomial decomposition showed this quadratic trend to be significant, $F(1, 9) = 28.72$, $p < 0.001$. In the segregation condition, there was a more straightforward increase in RT as the complexity of the polyrhythm increased, $F(4, 36) = 12.92$, $p < 0.001$, with only the linear trend being significant. RTs for the 2:5 polyrhythm were similar to those in the baseline condition.

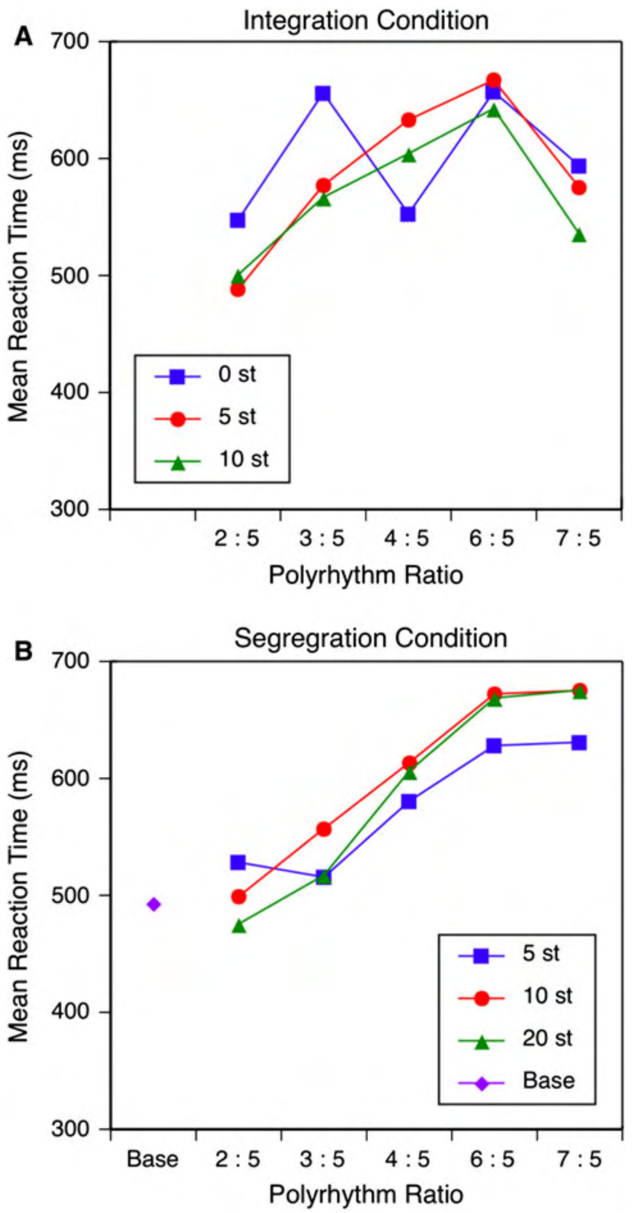

Fig. 6 Mean reaction times in "Experiment 2" in two instruction conditions (integration vs. segregation) as a function of polyrhythm ratio and pitch separation

Figure 7 shows the RT results for the pitch separations shared by the two instruction conditions. An ANOVA on these data yielded, in addition to a main effect of polyrhythm ratio, $F(4, 36) = 7.96$, $p = 0.001$, a significant interaction of ratio with instruction condition, $F(4, 36) = 3.85$, $p = 0.031$. This interaction can be attributed to faster RTs for the 7:5 ratio in the integration condition than in the segregation condition.

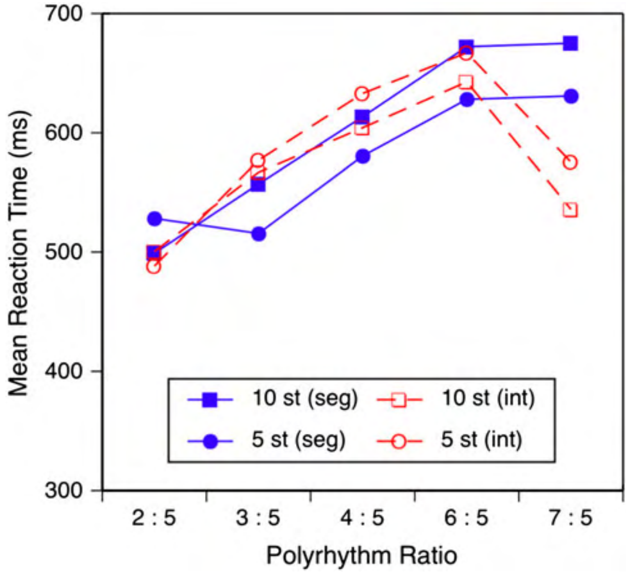

Fig. 7 Mean reaction times for 5 and 10 st pitch frequency separations in the segregation (seg) and integration (int) instruction conditions

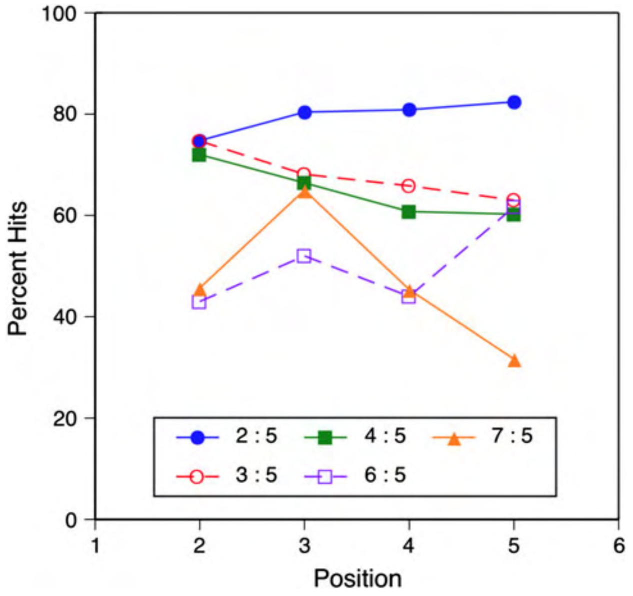

Fig. 8 Mean hit percentages in "Experiment 2" as a function of within-cycle position within each polyrhythm

Finally, we examined how the hit percentage varied with perturbation position within the polyrhythmic cycles. If IOI duration played any role at all, then hit percentages should have been higher when shorter IOIs were perturbed. Although two successive IOIs were perturbed by a delayed tone, detection would generally be based on the change in the shorter of the two because it would be easier to perceive. Figure 8 shows grand average hit percentages (averaged across instruction conditions and pitch separations) as a function of position in the five polyrhythms. Because position effects are polyrhythm specific, we conducted separate 3 (pitch separation) × 4 (position) ANOVAs on each polyrhythm, and separately for each instruction condition because of their different pitch separations (0, 5, 10 st vs. 5, 10, 20 st). In the integration condition, there was a significant main effect of position for polyrhythms 6:5, $F(3, 27) = 10.80$, $p < .001$, and 7:5, $F(3, 27) = 4.27$, $p = .029$. In the segregation condition, the position effect was significant only for the 7:5 polyhythm, $F(3, 27) = 6.30$, $p = .010$. It can be seen in Fig. 8 (where the data are averaged across instruction conditions) that performance was best in position 5 in the 6:5 polyrhythm, and better in positions 2 and 3 than in positions 4 and 5 in the 7:5 polyrhythm. We will explain soon what may have caused these effects. No interactions with pitch separation were significant.

Discussion

As in "Experiment 1", perturbations were increasingly difficult to detect as polyrhythm complexity increased. Even with the simple 2:5 polyrhythm, performance was below baseline, although its integrated rhythmic pattern was certainly easy to remember. The fact that it contained two different IOI durations does not seem a sufficient explanation for the below baseline performance because the integrated 2:3 polyrhythm of Jones et al. (1995) also contained two different IOI durations and nevertheless yielded better detection performance than their baseline condition. One important difference between the studies, however, is that in Jones et al. there was no uncertainty about the position of the perturbation: participants knew that it occurred always in position 2 of the two-pulse stream and in either the second or fourth of five polyrhythm cycles. In our study, by contrast, there were four possible perturbation positions within a cycle, and participants were not informed that every other cycle contained a perturbation (though some may have discovered this on their own). This positional uncertainty within a non-isochronous rhythm may well have been responsible for the difference in results relative to baseline.

It should also be noted that the results of Jones et al. (1995) rested on the detection advantage for changes in two short IOIs (in the 2:3 polyrhythm) versus changes in two long IOIs (in the baseline 2-pulse sequence). In our 2:5 polyrhythm, the perturbation could change either a short and a long IOI if it occurred in positions 3 or 4, or two long IOIs if it occurred in positions 2 or 5 (cf. Fig. 1). If IOI duration had played a role, perturbations in positions 3 and 4 should have been easier to detect than perturbations in positions 2 and 5. There was a tendency for hit rates to be lowest in position 2 (see Fig. 8), but it was not significant. Temporal uncertainty may have eliminated any effect of IOI duration within the 2:5 polyrhythm. Similarly, the 3:5 and 4:5 polyrhythms did not show any significant position effects, although on the basis of IOI duration (considering only the shorter of the two that were changed by a perturbation) one might have expected higher hit rates for perturbations in positions 3 and 4 of the 3:5 polyrhythm, and in positions 2 and 5 of the 4:5 polyrhythm (cf. Fig. 1). The relevant IOIs of these rhythms were within a range (126–336 ms) where the absolute detection threshold does not change very much (Friberg & Sundberg, 1995), which may account for the absence of significant position effects.

Significant position effects were found only in the two most complex polyrhythms, 6:5 and 7:5, even though their range of relevant IOIs was even narrower (72–168 ms). The peaks in hit rates within these rhythms suggest that further shortening of a very short IOI was relatively easy to detect: in position 5 of the 6:5 polyrhythm, a delayed tone reduced an 85-ms IOI to 45 ms, and in position 3 of the 7:5 polyrhythm, it reduced a 72-ms IOI to 32 ms, which gets close to synchrony of two pulses. Monahan and Hirsh (1990) found a similar asymmetry in monotone rhythmic sequences (similar to our stimuli with 0 st pitch separation), suggesting that a shortening of a very short interval is easier to detect than a lengthening. Hit rates were unusually low in position 5 of the 7:5 polyrhythm; the reason for this is not clear.

Instructions to integrate or segregate the polyrhythmic pulse streams had little effect. In the integration condition, there was an effect of pitch separation. Performance was poorest in the 0 st pitch separation condition where integration was a *fait accompli*. Most likely, the difficulty of these stimuli was caused by the fact that cycle boundaries were not clearly marked, which made the patterns more difficult to remember and anticipate. In all other polyrhythmic stimuli, cycle boundaries were marked by the coincidence of tones of different pitch. There is no clear evidence that integration instructions were responsible for the performance difference between the 5 and 10 st pitch separation stimuli, a difference favoring the stimuli with the wider pitch separation, because a similar (smaller, but not significantly different) difference was observed in the segregation condition. If anything, integration hindered rather than helped detection of perturbations, as also observed in "Experiment 1". The reason is probably an increased memory load.

It was surprising that segregation instructions had no effect at all. This finding cannot be attributed to a pre-instructional bias to segregate the pulse streams. If participants had been able to segregate the pulse streams and selectively attend to the lower stream that contained the perturbations while ignoring the isochronous higher stream, their performance should have approached baseline, especially when the pitch separation was large (20 st). The fact that increasing pitch separation did not facilitate perturbation detection, together with the steadily declining performance as polyrhythm complexity increased, indicated either that participants were unable to segregate the pulse streams in any of the pitch separation conditions or that the higher pulse stream continued to interfere with performance even when it was subjectively segregated from the lower pulse stream. Because, like Jones et al. (1995), we did not assess participants' subjective impressions of integration/segregation (see Footnote 1), we do not know which of these scenarios is closer to the truth, but we should note that no participant complained that he or she was unable to follow instructions, and authors BHR and BCF as participants felt that it was not difficult to attend to the lower pulse stream. Therefore, we suspect the correct conclusion is that selective attention did not eliminate interference from the ignored pulse stream (or, rather, created it by turning the unattended stream into a distracter): the polyrhythm remained effectively integrated, as far as detection of perturbations was concerned.

General discussion

Extending the paradigm of Jones et al. (1995) to more complex polyrhythms, we conducted two perturbation detection experiments to determine whether the benefits of hearing changes in shorter IOI durations as a result of the integration of polyrhythmic pulse streams outweigh the costs of increased memory demands and interval heterogeneity. The results clearly indicate that the costs of integration are much greater than the benefits. Even in the simple 2:5 polyrhythm, detection performance was below baseline. We attribute this result to the presence of different interval durations (i.e., increasing temporal irregularity) combined with uncertainty about the position of the perturbation. As polyrhythm complexity increased, the number of different IOIs in the integrated rhythmic pattern and the difficulty of keeping the pattern in memory increased, and therefore perturbations became increasingly difficult to detect. This was true regardless of the pitch separation of the two pulse streams (up to 20 st) and regardless of instructions to perceptually integrate or segregate the two pulse streams.

The perturbation detection results suggest that all polyrhythms in our study were effectively perceived as integrated, despite pitch separations of up to 20 st and despite spontaneous or instructed selective attention to the lower pulse stream. The literature on auditory streaming indicates that such attention should have been possible. Van Noorden (1975) defined the temporal coherence boundary as the combination of IOI duration and pitch separation beyond which intentional stream segregation is no longer possible, implying that such segregation is possible below the boundary, as long as the stimuli are above the fission boundary. More to the point, Bregman (1990) writes: "The task of trying to hear two streams (you can actually pay attention to only one at a time) is much easier [than integration]. It is always possible to do this successfully unless the tones are less than a few semitones apart" (p. 60). Because it is likely that all our stimuli fell below the temporal coherence boundary, given their moderate tempo, why do our data suggest that they could only be perceived as integrated?

When the sequence tempo is not very fast (IOIs greater than about 300 ms in isochronous sequences), the temporal coherence boundary is at large pitch separations or vanishes altogether. Jones et al. (1995), whose 2:3 polyrhythm was similar in tempo to our 2:5 polyrhythm, found evidence of stream segregation with a 43 st separation, but not with a 19 st separation. They did find a (fairly small) effect of integration instructions in the 43 st condition, indicating that participants could still integrate these stimuli intentionally to some extent. However, they did not find any effect of segregation instructions with smaller pitch separations. Their measure of integration/segregation, like ours, was an objective one—perturbation detection. In a recent study using simple rhythms, fast tempi, and pitch separations ranging from 0 to 15 st, Micheyl and Oxenham (2010) found that subjective ratings of stream segregation increased little under segregation instructions (compared to neutral instructions), but decreased greatly under integration instructions. This finding suggests a strong tendency to segregate streams when the tempo is fast, as long as the pitch separation is such that the stimuli are above the fission boundary, while at the same time there is a possibility of integrating the streams intentionally. Conversely, when the tempo is slow, there may be a strong tendency to integrate streams, even when the stimuli are well below the temporal coherence boundary. However, the ability to segregate those streams intentionally may be lost. The perceptual flexibility implied by Bregman's statement, quoted above, may exist only at the rather fast tempi that are typically employed in studies of auditory stream segregation. If we had employed faster tempi and/or larger pitch separations, we might have found evidence of intentional stream segregation. It is also possible that our use of complex rather than pure tones (used in most other studies of auditory streaming) contributed to greater integration of streams.

Van Noorden (1975) already used an objective method to measure stream segregation: he phase-shifted one of two interleaved isochronous tone sequences until the resulting rhythm sounded uneven. The threshold for detecting these relative phase shifts depended strongly on pitch separation when the IOIs between tones were short, with higher thresholds for large separations (indicating segregation), a finding that has been replicated in a number of more recent studies (e.g., Micheyl & Oxenham, 2010; Vliegen, Moore, & Oxenham, 1999). However, the effect of pitch separation in van Noorden's study disappeared (and the detection threshold dropped) when the IOI duration was as long as 400 ms, which suggests that the temporal coherence boundary had vanished and all rhythms were perceived as integrated. Our fastest polyrhythm, 7:5, had IOIs of 360 ms within the seven-pulse stream, but the mean IOI duration of the integrated pattern (see Fig. 1) was 229 ms, which is a duration at which pitch separation (beyond the fission boundary) should still make a difference according to van Noorden's data. But perhaps the limiting factor in our experiments was the relatively slow rates of the individual pulse streams. This warrants further investigation.

It is also possible that stream integration is stronger in polyrhythms than in simpler rhythms. However, the apparent inability of our participants to segregate two pulse streams seems consistent with recent findings of Repp (2009a, b) who used much simpler rhythms. He asked participants to synchronize finger taps with one (isochronous) stream of a two-stream rhythm, while perturbations were introduced in one or the other stream. (The other stream, a sequence of two tones followed by a rest, was not isochronous, but the integrated rhythm was.) The synchronization task encouraged segregation (focusing attention on one stream and ignoring the other), but even a very large pitch separation (46 or 48 st) did not enable participants to evade being affected by the other stream (regardless of whether it had the higher or lower pitch), except at the faster of the two tempi (IOI = 150 ms) in one of two perturbation paradigms (Repp, 2009b). So, judging by the effect perturbations had on finger tapping, these stimuli appear to have been mostly in an obligatory integration zone below the temporal coherence boundary.

However, Repp also asked participants to detect the perturbations, a task that encouraged integration of the two streams because IOIs were shorter in the integrated rhythm. Performance was above baseline at a small pitch separation (2 st) and returned to baseline at a moderate pitch separation (10 st), suggesting that integration was supplanted by segregation (quite contrary to the synchronization results). At a large pitch separation (46 st) and a fast tempo—the only condition in which synchronization performance indicated successful segregation—detection of perturbations actually was well *below* the single-stream baseline, indicating *interference* from the apparently segregated and ignored stream (regardless of whether that stream had the higher or the lower pitch). This finding suggests that even when two streams appear to be integrated by one objective measure, they may appear to be segregated by another objective measure; and when they appear to be segregated by the first measure, interference may arise in the other measure, indicating that the segregated stream cannot be ignored. Thus, whether two streams appear to be integrated or segregated may depend on the measure that is used, and of course that includes subjective judgment as well. It is possible that different measures tap into different levels of processing, and that streams that are segregated at one level are integrated at another level (Pressnitzer, Sayles, Micheyl, & Winter, 2008; Winkler, Takegata, & Sussman, 2005).

Our results, in conjunction with these earlier findings, point to a need for more thorough investigations of stream integration and segregation in the broad region between the fission and temporal coherence boundaries, using both subjective ratings and multiple objective methods. It may well turn out that multi-stream rhythm perception in that region is highly stimulus and task dependent, and not as flexible as one might think.

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References

Beauvillain, C. (1983). Auditory perception of dissonant polyrhythms. *Attention, Perception and Psychophysics, 34*(6), 585–592.

Bogacz, S. (2005). Understanding how speed affects performance of polyrhythms: transferring control as speed increases. *Journal of Motor Behavior, 37*, 21–34.

Bregman, A. S. (1990). *Auditory scene analysis: the perceptual organization of sound*. Cambridge: MIT Press.

Bregman, A. S., & Campbell, J. (1971). Primary auditory stream segregation and perception of order in rapid sequence of tones. *Journal of Experimental Psychology, 89*, 24–244.

Deutsch, D. (1983). The generation of two isochronous sequences in parallel. *Perception & Psychophysics, 34*, 331–337.

Friberg, A., & Sundberg, J. (1995). Time discrimination in a monotonic, isochronous sequence. *Journal of the Acoustical Society of America, 98*, 2524–2531.

Grondin, S. (2001). From physical time to the first and second moments of psychological time. *Psychological Bulletin, 127*, 22–44.

Handel, S. (1984). Using polyrhythms to study rhythm. *Music Perception, 1*, 465–484.

Handel, S. (1989). *Listening: an introduction to the perception of auditory events*. Cambridge: MIT Press.

Handel, S., & Oshinsky, J. (1981). The meter of syncopated auditory polyrhythms. *Perception & Psychophysics, 30*, 1–9.

Hirsh, I. J., Monahan, C. B., Grant, K. W., & Singh, P. G. (1990). Studies in auditory timing: 1. Simple patterns. *Perception & Psychophysics, 47*, 215–226.

Jagacinsky, R. J., Marshburn, E., Klapp, S. T., & Jones, M. R. (1988). Tests of parallel versus integrated structure in polyrhythmic tapping. *Journal of Motor Behavior, 20*, 416–442.

Jones, M. R. (1976). Time, our lost dimension: toward a new theory of perception, attention, and memory. *Psychological Review, 83*, 323–355.

Jones, M. R., Jagacinski, R. J., Yee, W., Floyd, R. L., & Klapp, S. T. (1995). Tests of attentional flexibility in listening to polyrhythmic patterns. *Journal of Experimental Psychology Human Perception and Performance, 21*, 293–307.

Klapp, S. T. (1979). Doing two things at once: the role of temporal compatibility. *Memory & Cognition, 7*, 375–381.

Klapp, S. T., & Jagacinsky, R. J. (2011). Gestalt principles in the control of motor action. *Psychological Bulletin, 137*, 443–462.

Klapp, S. T., Hill, M. D., Tyler, J. G., Martin, Z. E., Jagacinsky, R. J., & Jones, M. R. (1985). On marching to two different drummers: perceptual aspects of the difficulties. *Journal of Experimental Psychology Human Perception and Performance, 11*, 814–827.

Klapp, S. T., Nelson, J. M., & Jagacinsky, R. J. (1998). Can people tap concurrent bimanual rhythms independently? *Journal of Motor Behavior, 30*, 301–322.

Krampe, R. T., Kliegl, R., Mayr, U., Engbert, R., & Vorberg, D. (2000). The fast and slow of skilled bimanual rhythm production: parallel versus integrated timing. *Journal of Experimental Psychology Human Perception and Performance, 26*, 206–233.

Kurtz, S., & Lee, T. D. (2003). Part and whole perceptual-motor practice of a polyrhythm. *Neuroscience Letters, 338*, 205–208.

Micheyl, C., & Oxenham, A. J. (2010). Objective and subjective psychophysical measures of auditory stream integration and segregation. *Journal of the Association for Research in Otolaryngology, 11*, 709–724.

Moelants, D., & Van Noorden, L. (2005). The influence of pitch interval on the perception of polyrhythms. *Music Perception, 22*, 425–440.

Monahan, C. B., & Hirsh, I. J. (1990). Studies in auditory timing: 2. Rhythmic patterns. *Perception & Psychophysics, 47*, 227–242.

Oshinsky, J., & Handel, S. (1978). Syncopated auditory polyrhythms: discontinuous reversals in meter interpretation. *The Journal of the Acoustical Society of America, 63*, 936–939.

Peper, C. E., Beek, P. J., & van Wieringen, P. C. W. (1995). Frequency-induced phase transitions in bimanual tapping. *Biological Cybernetics, 73*, 301–309.

Pressing, J., Summers, J., & Magill, J. (1996). Cognitive multiplicity in polyrhythmic pattern performance. *Journal of Experimental Psychology Human Perception and Performance, 22*, 1127–1148.

Pressnitzer, D., Sayles, M., Micheyl, C., & Winter, I. M. (2008). Perceptual organization of sound begins in the auditory periphery. *Current Biology, 18*, 1124–1128.

Repp, B. H. (2002). Perception of timing is more context sensitive than sensorimotor synchronization. *Perception & Psychophysics, 64*, 703–716.

Repp, B. H. (2009a). Segregated in perception, integrated for action: immunity of rhythmic sensorimotor coordination to auditory stream segregation. *Quarterly Journal of Experimental Psychology, 62*, 426–434.

Repp, B. H. (2009b). Rhythmic sensorimotor coordination is resistant but not immune to auditory stream segregation. *Quarterly Journal of Experimental Psychology, 62*, 2306–2312.

Shaffer, L. H. (1981). Performances of Chopin, Bach, and Bartók: studies in motor programming. *Cognitive Psychology, 13*, 326–376.

Summers, J. J. (2002). Practice and training in bimanual coordination tasks: strategies and constraints. *Brain and Cognition, 48*, 166–178.

Summers, J. J., & Kennedy, T. M. (1992). Strategies in the production of a 5:3 polyrhythm. *Human Movement Science, 11*, 101–112.

Summers, J. J., Ford, S. K., & Todd, J. A. (1993a). Practice effects on the coordination of the two hands in a bimanual tapping task. *Human Movement Science, 12*, 111–133.

Summers, J. J., Rosenbaum, D. A., Burns, B. D., & Ford, S. K. (1993b). Production of polyrhythms. *Journal of Experimental Psychology Human Perception and Performance, 19*, 416–428.

Summers, J. J., Todd, J. A., & Kim, Y. H. (1993c). The influence of perceptual and motor factors on bimanual coordination in a polyrhythmic tapping task. *Psychological Research, 55*, 107–115.

van Noorden, L.P.A.S. (1975). Temporal coherence in the perception of tone sequences. Unpublished doctoral dissertation, Eindhoven University of Technology, Eindhoven, The Netherlands.

Vliegen, J., Moore, B. C. J., & Oxenham, A. J. (1999). The role of spectral and periodicity cues in auditory stream segregation, measured using a temporal discrimination task. *Journal of the Acoustical Society of America, 106*, 938–945.

Winkler, I., Takegata, R., & Sussman, E. (2005). Event-related brain potentials reveal multiple stages in the perceptual organization of sound. *Cognitive Brain Research, 25*, 291–299.

Yee, W., Holleran, S., & Jones, M. R. (1994). Sensitivity to event timing in regular and irregular sequences: Influences of musical skill. *Perception and Psychophysics, 56*, 461–471.