Can Musicians Track Two Different Beats Simultaneously?

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The simultaneous presence of different meters is not uncommon in Western art music and the music of various non-Western cultures. However, it is unclear how listeners and performers deal with this situation, and whether it is possible to cognitively establish and maintain different beats simultaneously without integrating them into a single metric framework. The present study is an attempt to address this issue empirically. Two rhythms, distinguished by pitch register and representing different meters (2/4 and 6/8), were presented simultaneously in various phase relationships, and participants (who were classically trained musicians) had to judge whether a probe fell on the beat in one or both rhythms. In a selective attention condition, they had to attend to one rhythm and to ignore the other, whereas in a divided attention condition, they had to attend to both. In Experiment 1, participants performed significantly better in the divided attention condition than predicted if they had been able to attend to only one rhythm at a time. In Experiments 2 and 3, however, which used more complex combinations of rhythms, performance did not differ significantly from chance. These results suggest that in Experiment 1 participants relied on the composite beat pattern (i.e., a nonisochronous sequence corresponding to the serial ordering of the two underlying beats) rather than tracking the two beats independently, while in Experiments 2 and 3, the level of complexity of the composite beat pattern may have prevented participants from tracking both beats simultaneously.

POLYRHYTHM AND POLYMETER ARE IMPORTANT compositional techniques in a wide range of musical practices, from West African drumming ensembles (Arom, 1991; Locke, 1982) to jazz (Folio, 1995; Pressing, 2002), rock-derived genres (e.g., the Swedish death metal group Meshuggah; see Pieslak, 2007), and 20th century Western art music. In the latter, composers whose stylistic orientations range from experimentalism (notably in the works of the American composers Charles Ives, Henry Cowell, and Conlon Nancarrow) and modernism (Elliott Carter and György Ligeti, the latter having been influenced by the music of the Aka Pygmies; see Taylor, 2003) to minimalism and "New Complexity" (as represented by Steve Reich, John Adams, and Michael Gordon on the one hand, and Brian Ferneyhough and Michael Finnissy on the other) have combined the use of polyrhythms with other types of rhythmic devices, such as syncopation, metric modulation, irrational subdivisions of the beat, and tempo fluctuations. As represented by these repertoires, the simultaneous presence of distinct metric frameworks can function as an expressive tool that aims to generate a wide range of musical experiences for composers, performers, and listeners. For example, by superposing three different rhythms in *Yo Shakespeare*, Michael Gordon seeks to create the effect of "three different dance rooms with three different dance bands playing at the same time" (Baker, 2002). Contrastingly, in the works of Elliott Carter, "giant polyrhythms" (i.e., slow polyrhythms that span the entire duration of a work) provide a background for different types of polymetric structures (Poudrier, 2009) and for the interplay of contrasting musical characters whose dramatic interaction is made perceptible to the initiated listener by the use of associated pitch materials, rhythmic gestures, and tempi (Ravenscroft, 1993; Roeder, 2006; Schiff, 1998). Little is known, however, about the psychological basis of such polymetric structures.

Theoretical Framework

At the outset, it is crucial to make a distinction between *polyrhythm* and *polymeter*. A *rhythm* can be defined as any auditory sequence of event onsets. Musical rhythms, however, often have underlying temporal regularities that can lead to their being perceived as metrical. *Meter* is commonly described as a nested hierarchy; that is, an underlying network of at least two periodic pulses (i.e., series of evenly spaced time-points) where non-adjacent time-points at a faster pulse level become adjacent time-points at a slower pulse level (e.g., Lerdahl & Jackendoff, 1983; Yeston, 1976). *Metric*

entrainment is the dynamic process by which internal or external periodic processes (such as oscillatory brain activity, attention, expectations, or motor activity) are aligned with one or several of these periodic pulses (Jones, 1976, 2009; Large & Jones, 1999; London, 2004; Nozaradan, Peretz, Missal, & Mouraux, 2011). A polyrhythm results from the superposition of two or more rhythms that are distinguishable from each other along some dimension (e.g., pitch, timbre, tempo). In practice, the term is most often used to refer to the superposition of two or more pulse trains (i.e., isochronous series of event onsets) whose periods are related by a frequency ratio other than N:1, where N is an integer (such as 3:2). We will refer to this type of structure as a *simple polyrhythm*. The superposed pulse trains that make up a simple polyrhythm may be in-phase, which means that they are characterized by the cyclical return of coinciding onsets, or out-of-phase (no coinciding onsets). Most experimental studies on polyrhythm perception and production have used simple in-phase polyrhythms (e.g., Handel, 1984; Pressing, Summers, & Magill, 1996). By contrast, we define *complex polyrhythm* as a structure that results from the superposition of two or more nonisochronous rhythms, some of whose underlying periodicities (or pulse levels) are related by a ratio other than N:1. Complex polyrhythms, too, can be in-phase or out-of-phase. Polymeter, then, refers to the simultaneous presence, at either a descriptive or psychological level, of two distinct metric frameworks. Although all polyrhythms are potentially polymetric, we contend that simple polyrhythms are rarely so perceived because simple pulse trains are generally insufficient to give rise to independent metric hierarchies. Rather, the common way to perceive such polyrhythms is as a sequentially integrated rhythmic pattern (a "composite rhythm") within a single (perhaps ambiguous) metric framework, or else as two unrelated pulse streams, neither (or perhaps only one) of which is associated with a metric hierarchy. By contrast, because the rhythms that form a complex polyrhythm frequently imply more than one recurring period (and thus, pulse level), complex polyrhythms have the potential of supporting distinct metric frameworks simultaneously.[1]

Figure 1 presents diagrams that illustrate this distinction between simple and complex polyrhythms, and their likely underlying metric frameworks. In this schematic representation, each vertical line represents an event onset in a musical surface and each dot corresponds to a time-point within an underlying pulse level. In Figure 1a, which presents a simple in-phase 3:2 polyrhythm, the frequent recurrence of coinciding event onsets is likely to give rise to the emergence of a unifying tactus ("1") for the composite rhythm (CR) formed by the two component pulse trains, especially if the tempo is relatively fast. In a musical work, depending on the prescribed tempo, this tactus level might correspond to the notated beat, a subdivision of the notated beat, or even a measure. Whether the meter of the composite rhythm is perceived as duple (2:1) or triple (3:1) will depend on the tempo as well as on associated parameters (melodic patterns, dynamic accents, harmonic rhythm, etc.) that make one of the two pulse trains more salient than the other; otherwise, the meter will remain ambiguous. Given that the competing layers are nested within the tactus and thus effectively function as subdivisions of the tactus, there is no firm basis for duple and triple meters to be construed simultaneously. In the complex (albeit still relatively simple) polyrhythm presented as Figure 1b, the two rhythms (corresponding to 2:1:1 and 3:1:1:1 duration series) can be described in terms of two well-formed metric frameworks, each of which exhibits a nested hierarchy of three pulse levels, 4:2:1 and 6:2:1 respectively. The slowest pulse level ("1") corresponds to the onset of the repeating duration series. (In a complex polyrhythm, the even slower pulse corresponding to the points of coincidence of the "1" pulses is generally too slow to function as a unifying tactus.) As defined above, a polymetric framework implies two or more metric frameworks with at least one pair of competing pulses (i.e., pulses with periods that are not related by a N:1 ratio). In the complex polyrhythm shown here, while the fastest pulse is common to the two metric frameworks, the middle and slower pulse levels are nonisochronous across metric frameworks, each pair expressing a 3:2 ratio. Each of these pairs is thus representative of two different pulses that could theoretically serve simultaneously as unambiguous beats of the complex polyrhythm.

As shown at the bottom of Figure 1b, in a complex polyrhythm, the competing pulses could be combined into a *composite beat pattern* (i.e., a nonisochronous sequence corresponding to the serial ordering of the two underlying beats) akin to the composite rhythm of a simple polyrhythm (though typically slower). In other words, complex polyrhythms can be conceived as elaborations of simple polyrhythms in which the competing pulses are not literally given but are inferred from

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[1] The term "complex" is used here to refer to the type of polyrhythmic structures that may be more likely to support polymetric percepts. In actuality, there may be various degrees of complexity, depending on factors such as rate of presentation, period and frequency ratios, phase relationship, and pattern structure.
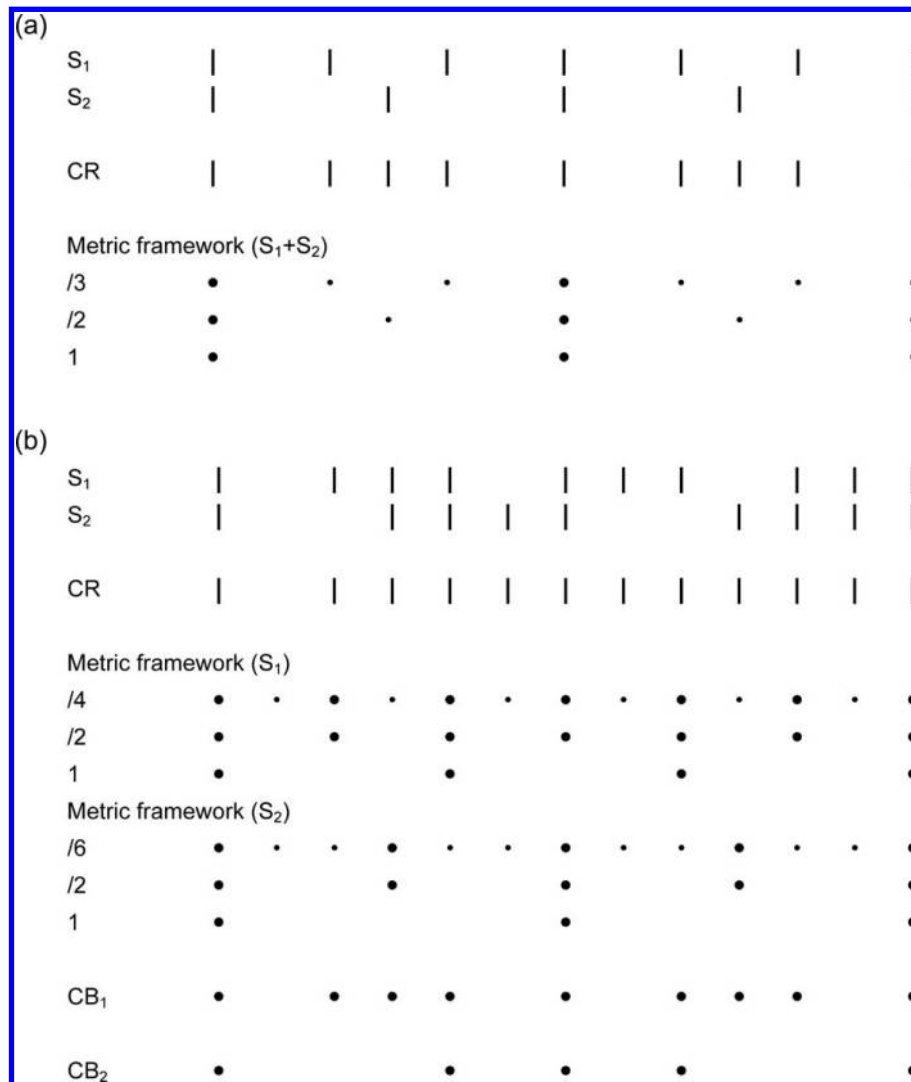
FIGURE 1. Simple vs. complex polyrhythms (S = rhythmic sequence; CR = composite rhythm; CB = composite beat pattern). Diagram (a) shows a simple polyrhythm of 3 against 2, the resulting composite rhythm, and the underlying metric framework. The two pulse trains coincide every three or two pulses, giving rise to a single tactus ("1"). By contrast, (b) shows a complex polyrhythm in which two nonisochronous rhythms give rise to a polymetric framework. Here, there are at least two possible composite beat patterns, CB_1, representing integration of the middle pulse levels, and CB_2, representing integration of the slowest pulse levels of the metric frameworks S_1 and S_2.

more or less complex surface rhythms and thus constitute underlying beats. The complex polyrhythm shown as Figure 1b could give rise to at least two different composite beat patterns, depending on which pulse levels are taken as representing the beats (CB_1 corresponds to the integration of the middle pulse levels and CB_2 to that of the slowest pulse levels).

For the purpose of this study, we define polymetric perception as the simultaneous perception and tracking of two independent beats. Perception of the composite beat pattern within a single metric framework would

arguably not qualify as polymetric perception.[2] Even less polymetric would be the integration of the two component rhythms into a composite rhythm (see Figure 1b), which could easily be construed as being in a single meter or be metrically ambiguous. Thus, there

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[2] To be assembled into a composite beat pattern, the beats would either have to be inferred separately before they are combined (in which case polymetric perception might precede and be replaced by integration of the beats) or they might already exist as a composite pattern in memory, based on previous experience inside or outside the laboratory.

would appear to be four conditions in order for poly-metric percepts to arise: (1) within each component rhythm there are at least two constituent pulses related by a N:1 ratio, each rhythm resulting in a distinct metric framework; (2) between the two component rhythms, at least two of the constituent pulses are not related by a N:1 ratio; (3) the component rhythms are perceived as separate streams rather than being sequentially inte-grated; and (4) the competing beats are tracked inde-pendently (presumably using divided rather than integrative attention).[3] The third and fourth conditions rest on the hypothesis that polymetric perception involves some form of parallel processing (i.e., each rhythm is perceived as a separate stream with an iso-chronous beat of its own) and would thus be hampered by sequential integration. Therefore, to allow for the investigation of the possibility of polymetric perception, surface integration must be discouraged; for example, by presenting the different rhythms in widely separated registers or with different instrumental timbres.

Previous Research

Given the widespread use of simple and complex poly-rhythms in music, it is surprising that there are very few previous experimental studies that focus on the percep-tion of polymetric structures. One reason may be a possibly widespread belief that polymetric perception is psychologically impossible. For example, London (2004), after pointing out that "meter serves as a tempo-ral ground for the perception of rhythmic figures" (p. 48), argues that "the need to maintain a single coher-ent ground seems to be universal" (p. 50). Another reason may be that nearly all pertinent research was carried out with simple polyrhythms, which are not well suited to address questions of polymetric perception. One rare exception is a study by Vuust, Roepstorff, Wallentin, Mouridsen, and Østergaard (2006), in which musicians were asked to tap to the main meter of a musi-cal excerpt that presented three measures in a simple 4/4 meter followed by three measures emphasizing a superimposed counter meter with faster beats in a 4:3 ratio. Imaging results supported the interpretation of an auditory bistable percept that activates brain areas

associated with language processing (i.e., Brodmann area 47). Another notable example is a study by Keller and Burnham (2005), which involved the concurrent tasks of reproducing and memorizing rhythms that could differ in their metric structure. They found that participants' performance in this dual task was better when the two metric structures matched than when they did not, which could reflect the difficulty or impos-sibility of polymetric perception.

More generally, studies on the perception and pro-duction of polyrhythms have often focused on the influ-ence of various factors on the perceptual parsing of these stimuli (e.g., Beauvillain, 1983; Handel & Lawson, 1983; Handel & Oshinsky, 1981; Moelants & van Noor-den, 2005; Pitt & Monahan, 1987). In a seminal series of sensorimotor synchronization studies, Handel and his associates found that participants' tapping patterns were influenced by timing between elements, pulse train frequency, polyrhythm configuration, element accentu-ation, and individual preferences (Handel, 1984). Given that participants were asked to "tap along with the perceived beat" using a single telegraph key, the experi-ments could only distinguish between tapping patterns that showed a preference for a single meter and integra-tive strategies that combined elements from two or more pulse trains ("cross-rhythms"), some of which were classified as "a-metric."

Other studies have examined the bimanual perfor-mance of simple polyrhythms (e.g., Bogacz, 2005; Grieshaber & Carlsen, 1996; Klapp, Nelson, & Jagacinski, 1998; Krampe, Kliegl, Mayr, Engbert, & Vorberg, 2000; Shaffer, 1981) as well as the interaction between their perception and production (Beauvillain & Fraisse, 1984; Deutsch, 1983; Klapp et al., 1985; Peper & Beek, 2000; Pressing et al., 1996; Summers, Todd, & Kim, 1993), and more specifically, the role of atten-tion (Jagacinski, Marshburn, Klapp, & Jones, 1988; Jones, Jagacinski, Yee, Floyd, & Klapp, 1995; Klein & Jones, 1996). The findings from most of these studies suggest that simple polyrhythms are typically integrated into a composite rhythm, implying a single metric framework. For example, in a study on the bimanual performance of a 3:2 polyrhythm, Jagacinski et al. (1988) not only found that the pattern of covariances among produced interval durations suggested inte-grated rather than parallel processing of the two pulse trains, but also that when participants were primed toward an integrated percept, their performance was less variable than when they were primed toward per-ceiving the two strands of the polyrhythm as separate auditory streams. Similarly, Jones et al.'s (1995) inves-tigation of "integrative" versus "selective" attending

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[3] The presence of two concurrent beats could also be understood as resulting in two different rhythmic rates (i.e., polytempo), and thus, a polymetric percept might also manifest itself as the simultaneous perception of different speeds. However, perceived tempo is not only related to the tactus but may also emerge from the perceived rate of events at the musical surface (London, 2011). In this study, we felt that it was necessary to limit our theorizing to polymeter based on beat percepts, which is also more closely related to our experimental design.

with a task that required detection of timing deviations showed that participants' performance was poorer in conditions with wide (streamed percept) as opposed to narrow (integrated percept) frequency separations. Jones and her associates also found that although participants with music training were more sensitive to timing deviations, they did not exhibit greater flexibility in perceptual organization. In fact, most of the studies on polyrhythm perception and production have found no essential difference in the timing mechanisms used by participants with no prior experience and those with more extensive experience, although experienced performers, and especially percussion players, were more accurate and flexible in the production of more complex patterns, e.g., 3:4 as compared with 2:3 (Pressing et al., 1996).

Two studies have provided some evidence for parallel timing control in the performance of simple polyrhythmic sequences by expert pianists. Shaffer (1981) found that a pianist's performance of Chopin's Etude in F minor, from *Trois Nouvelles Études*, exhibited timing patterns supporting a model in which each hand is associated with a separate clock. Similarly, Krampe et al. (2000) found that while a model with a single central clock provided the best match for the timing patterns of a 3:4 polyrhythm and a syncopated rhythm at slow speeds, those for the same rhythms at fast tempi suggested multiple timekeepers operating in parallel. However, these results are contradicted by Bogacz (2005), whose investigation of 5:3 polyrhythms performed at slow, moderate, and fast speeds (from 1 to 16 notes per second) by highly trained pianists yielded no evidence of parallel processing and provided further support for an integrated hierarchical model for timing control.

Nevertheless, it is not clear if and how the findings of studies on the perception and production of simple polyrhythms would apply to the perception of polymeter, considering that most of these experiments use some form of motor task, and that sequential integration of polyrhythmic pulse trains into a composite rhythm is a common strategy in the teaching and practicing of polyrhythmic patterns (Clayton, 1972; Grieshaber & Carlsen, 1996; Magadini, 2001; Weisberg, 1993). Furthermore, the reproduction of two "meters" simultaneously would necessarily result in the performance of competing pulses, and some composite beat patterns might be too complex to reproduce, especially in cases where the two meters are out-of-phase or do not share a readily performable common pulse unit. It is also possible that the kind of attention necessary to track different meters simultaneously requires specialized training. Musicians are especially skilled at using

various forms of selective and divided attention, for example, when tracking changes in an ensemble while performing their own part (Keller, 2008). Findings from both behavioral and neuroimaging studies also suggest that musicians have enhanced abilities in the hierarchical processing of temporal patterns (Brochard, Abecasis, Potter, Ragot, & Drake, 2003; Drake, Jones, & Baruch, 2000; Drake, Penel, & Bigand, 2000; Geiser, Sandmann, Jäncke, & Meyer, 2010).

In a recent historically informed analytical study of the chamber music of Haydn and Mozart, Mirka (2009) adopts the "parallel multiple-analysis model" (developed by Jackendoff, 1991) to explain an imagined 18th-century listener's experience of metric manipulations. In Jackendoff's computational model, multiple metric interpretations may coexist at the subconscious level, but only a single preferred interpretation will reach consciousness through the "selection function." While acknowledging that two meters may not be perceived simultaneously (mostly on the basis of the findings from studies on polyrhythm perception and production), Mirka (2009) proposes that a listener's hearing of "antimetrical regularity" provides evidence of the selection and surfacing to consciousness of two analyses that "exceed some threshold of perceivability [. . .], even if one is preferred over the other" (p. 169). This scenario comes fairly close to polymetric perception, but it remains a theoretical idea in need of empirical support. The current study is a first attempt to gather data relevant to the perceptual challenge of simultaneous multiple metric interpretations.

The Present Research

We conducted three experiments to explore highly trained musicians' ability to track the beats of two different rhythms presented concurrently, whose beat periods were in a ratio of 3:2. To avoid a conflation of perception and production, we used a perceptual probing paradigm (Palmer & Krumhansl, 1990). Thus, after a period of beat induction corresponding to one polymetric cycle at the measure level, participants heard a probe during a second cycle and had to report whether or not it coincided with a beat position in one or both rhythms.

The experimental design was based on the assumption that tracking two different beats simultaneously would require: (1) the induction of two unambiguous beats of different periods not related by a N:1 ratio; and (2) the perception of the two rhythms and their implied beats as independent streams rather than their integration into a single stream (composite rhythm and
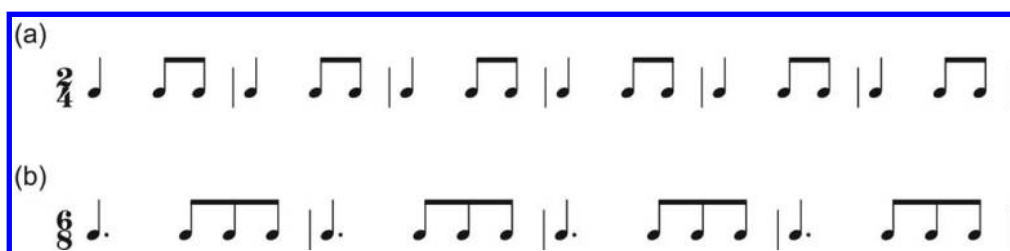
FIGURE 2. The rhythms used in Experiments 1 and 2; (a) shows the A-rhythm and (b) shows the B-rhythm.

composite beat pattern). To discourage integration into a single metric framework, the rhythmic sequences should project two clearly distinct and unambiguous meters that are relatively balanced in terms of metric strength (i.e., the likelihood that their surface pattern will give rise to metric entrainment). The two chosen rhythms (later referred to as "A" and "B", respectively) are shown in Figure 2. We thought that two different repeated patterns of long (L) and short (S) interonset intervals (IOIs), LSS (Figure 2a) and LSSS (Figure 2b), would provide a good basis for beat induction, as the tones initiating the long IOIs would be likely to be perceived as accented and associated with beat positions (e.g., Lerdahl & Jackendoff, 1983, p. 84; Povel & Essens, 1985). Each of these patterns also clarifies the underlying metric hierarchy as it defines at least three pulse levels, two of which exhibit a 3:2 ratio across rhythms (i.e., the measure-to-measure and beat-to-beat time-span units; see also Figure 1b). The measure level (2/4 or 6/8) encompasses the whole rhythmic pattern, the beat level (quarter or dotted-quarter note) corresponds to the onset of the long IOI and that of the first of the group of two or three consecutive short IOIs, and the sub-beat level (eighth note) serves as common time-span unit.[4] Therefore, even though meter is never totally unambiguous, we felt justified in assuming that metric perception of each of these rhythms would strongly favor the meters indicated by the time signatures in Figure 2. Moreover, participants were told during instructions what the meters were supposed to be.

To discourage integration of the simultaneous rhythms into a single composite rhythm, we presented them in widely separated registers (e.g., Bregman, 1990; Jones, 1976; van Noorden, 1975). Participants performed the probe tone task under two conditions: a selective attention (SA) condition, during which participants attended to either the high or low rhythm while the other rhythm was to be ignored, and a divided attention (DA) condition, during which participants were required to attend to both rhythms. The crucial question was whether participants would perform better in the DA condition than predicted under the null hypothesis that they would be able to attend only to one rhythm (and hence only one periodic beat) at a time. If participants performed better than predicted in the DA condition, we would have some evidence that two beats can be tracked simultaneously, supporting the possibility of polymetric perception. Secondary questions that we explored relate to structural factors that might favor one rhythm over the other when trying to allocate attention, and to the strategies participants might use in tracking the beats of the two rhythms.

Even though the wide pitch separation of the two rhythms discouraged their integration into a single auditory stream, we considered the possibility that participants might integrate the two induced beats into a composite beat pattern at a more abstract perceptual/motor level, thereby evading the task of tracking two independent beats. Because the composite beat pattern was relatively simple in Experiment 1, we increased its complexity by aligning the rhythms differently in Experiment 2 and additionally varied the rhythms from trial to trial in Experiment 3, in order to discourage a strategy of beat level integration.

Experiment 1

METHOD

Participants. The participants in this experiment were 9 graduate students and one postgraduate of the Yale School of Music (5 men, 4 women, ages 22-26), who were paid for their efforts. All were regular participants in synchronization and rhythm perception experiments

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[4] The metric interpretation for each of these two rhythms also obeys several of the Metric Preference Rules (MPRs) presented in Lerdahl and Jackendoff's *A Generative Theory of Tonal Music* (1983): MPR 1 (Parallelism), the repeated measures exhibit the same duration series; MPR 2 (Strong beat early), each measure begins with the longer IOI; MPR 3 (Event), all onsets are aligned with time-points within the proposed metric hierarchy; and MPR 5a (Length), stronger beats correspond to longer IOIs.

in the second author's lab. Their primary musical instruments were piano (2), violin (3), viola, cello, oboe, and bassoon, which they had studied for 13-21 years; the two pianists were primarily composers.

Stimuli and design. The stimuli consisted of two super-imposed rhythms ("A-rhythm" and "B-rhythm" as represented in Figure 2). Each rhythm was monotone and exhibited contrasting patterns of long and short IOI durations in simple ratios (2:1 and 3:1, respectively). Each rhythm was expected to induce beats that were isochronous within the rhythm but nonisochronous across rhythms. All IOIs were divided equally into sound and silence, with the common unit (equivalent to an eighth note) corresponding to a basic IOI of 400 ms.[5] We felt that tones of equal duration would have made the meters more ambiguous, and the common unit established a temporal coordination of the two rhythms, which is common in music where polymetric structures are found. (The fact that tone duration varied will be taken into account in the analysis.) Each trial consisted of two full polymetric cycles of 3:2 measures and 6:4 beats each (as shown in Figure 2), with a basic cycle duration of 4,800 ms (12×400 ms) and a basic total duration of 9,600 ms. The first cycle served as an induction period, and the second cycle as the test period during which the probe tone occurred. To avoid habituation to tempo, the IOIs and tone durations were randomly changed on each trial by a scaling factor of -10, -5, 0, 5, or 10%.

There were 78 different trials, resulting from the combination of two register conditions, three phase conditions, and 13 probe positions. The two register conditions presented each rhythm in a different register, either "A-high + B-low" or "B-high + A-low" (high = G5; low = C3). In the three phase conditions, the two rhythms either began at the same time ("in-phase") or there was a delay of one eighth note between them ("A-first" or "B-first"). The purpose of this variable was to discourage the learning of a single sequentially integrated rhythmic pattern or composite rhythm. Finally, there were 13 different probe positions corresponding to the eighth-note positions in the test period of a trial. The final probe position corresponded to a beat in one or both rhythms (depending on the phase condition) that was not marked by a tone in that rhythm. All other beats were marked by tones. The probe tone had the

pitch of E7 and was 20 ms in duration. Each probe coincided with either a beat in both rhythms, a beat in the A-rhythm, a beat in the B-rhythm, or a non-beat position in both rhythms.[6] It is important to keep in mind that the two rhythms have *congruent* beat and non-beat positions as well as *non-congruent* positions where a beat in one rhythm coincides with a non-beat position in the other rhythm. Diagrams of the test periods of the three phase conditions are shown in Figure 3; they include all event onsets and probe positions, with beat designations.

Apparatus and procedure. The experiment was controlled by custom programs written in Max/MSP 4.0.9 and running on an Intel iMac computer. The tones were produced by a Roland RD-250s digital piano, and participants listened over Sennheiser HD280 pro headphones. A musical notation of the rhythms (Figure 2) was shown to participants during instructions to clarify which pulse level corresponded to the beat.[7] This notation was not in view during the experiment. The experimental session consisted of four blocks, each containing the same 78 trials in different random orders and lasting about 16 min. The first and fourth blocks presented the divided attention (DA) condition; the two middle blocks presented the selective attention (SA) condition, with the order of attended register (high or low, one block each) counterbalanced between participants. In the SA condition, participants were instructed to attend to either the high or low rhythm and ignore the other rhythm, while in the DA condition participants were instructed to divide their attention between both rhythms. The arrangement of conditions was motivated by a desire to obtain measures of performance in the DA condition both without and with previous exposure to the rhythms and tasks.

Participants were instructed that during the second half of each trial, a brief high-pitched probe tone (clearly higher than the higher-pitched rhythm) would sound, and that their task was to tell whether or not that tone fell on a beat of the attended rhythm(s). The question "Is the high-pitched tone on the beat?" was shown on the computer screen and participants replied by clicking on a "Yes" or "No" button at the end of a trial. A post-experiment questionnaire asked participants about strategies they used in the SA and DA conditions.

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[5] As digital piano tones were used, the equal division into sound and silence is nominal because each tone offset was followed by a damped decay of the sound. However, recent research has shown that the offsets of piano tones are perceived to occur very soon (about 10 ms) after their nominal offsets (Repp & Marcus, 2010).

[6] To avoid potential acoustic artifacts, there was a 2 ms programmed asynchrony between the rhythm and probe tones.

[7] Nevertheless, one participant misunderstood and was found to have tracked the measure level instead of the beat level. The participant repeated the session later, and the data from this repeat were used.
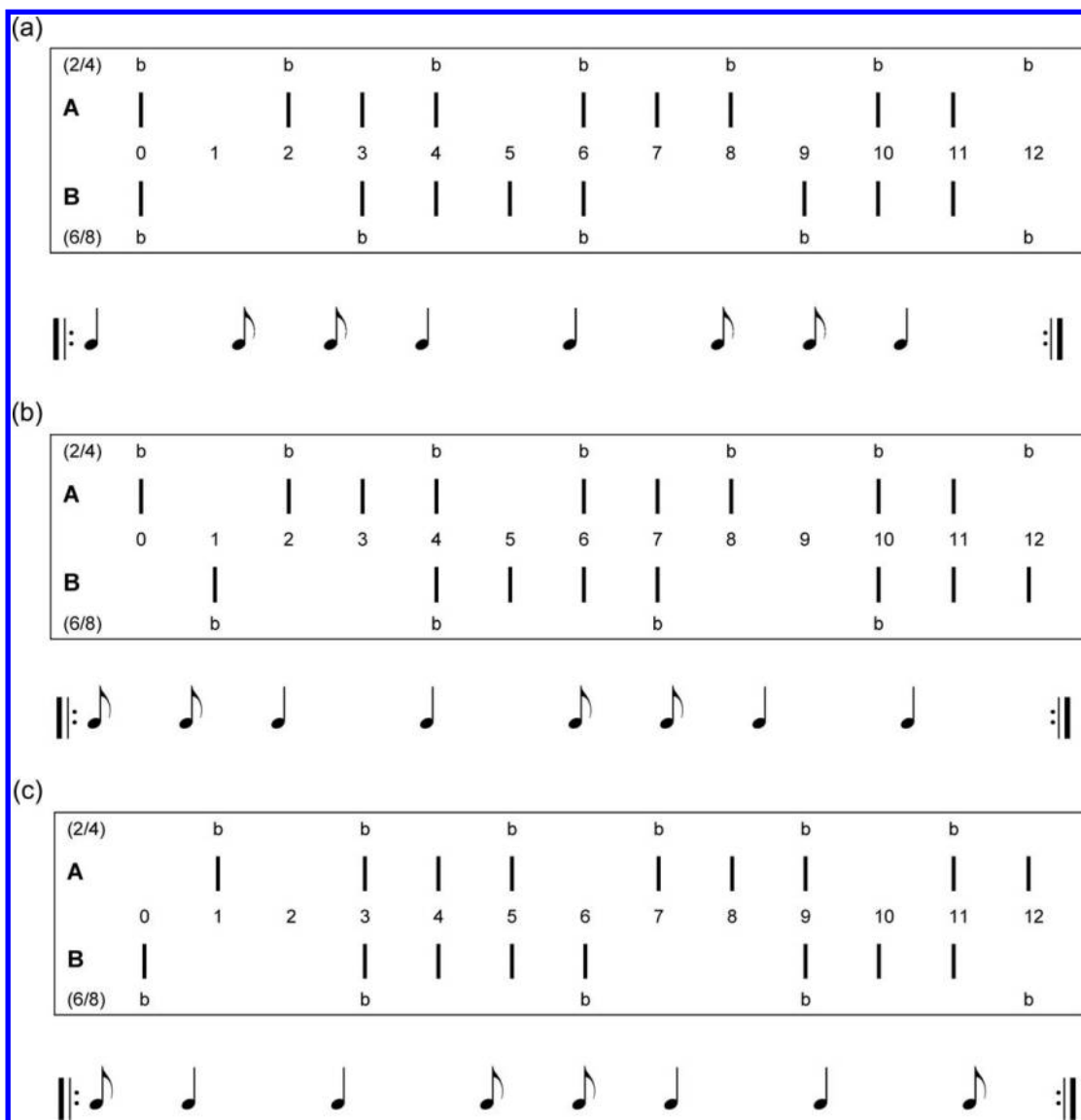
FIGURE 3. Diagrams of the test periods for each of the three phase conditions of Experiment 1, including all event onsets (vertical lines) and probe positions (numbered from 0 to 12), with beat designations ("b"). Diagram (a) shows the in-phase condition, (b) shows the A-first condition, and (c) shows the B-first condition. The corresponding composite beat pattern is shown in musical notation below each diagram.

Analysis. To measure performance, we used percent correct as well as separate percentages of hits and false alarms. (As we will explain, it was not necessary for our purposes to calculate the signal-detection-theory statistic d'.) A hit was defined as a "yes" response to a probe falling on a beat location in the attended rhythm in the SA condition and in either rhythm in the DA condition. A false alarm was defined as a "yes" response to a probe falling on a non-beat location in the attended rhythm in the SA condition and in both rhythms in the DA condition. The complement of the false alarm percentage is

the percentage of correct rejections (i.e., "no" responses to non-beat positions). Percent correct was defined as the average of hit and correct rejection percentages. All percentages were calculated separately for A- and B-rhythms before averaging, so as to take into account the unequal numbers of beats of these rhythms. To investigate the effects of various variables (attention condition, rhythm, phase, congruent versus non-congruent positions, beat tone length), we used repeated-measures ANOVA on hit percentages. The main question, however, was whether performance in

the DA condition would be better than predicted by the null hypothesis that participants would be able to attend to only one rhythm at a time. Our method for addressing this question is described later in the Results section.

RESULTS

Selective attention (SA) condition. With one exception (omitted from analysis), participants were quite successful in the SA condition.[8] The mean percent correct score in the SA condition was 98.1 (range = 93.6-100), the mean hit percentage was 96.5, and the mean false alarm percentage was 0.4. Given such near-ceiling performance, any further comparisons between stimulus conditions or probe positions within the SA condition could be expected to yield only small differences, and therefore we dispensed with detailed analyses of this condition. Because of the restricted variance of the SA scores, it was also not advisable to include these data in a joint ANOVA with the DA scores.

Divided attention (DA) condition. As expected, participants did not perform as well in the DA condition as in the SA condition. The mean percent correct score was 87.9 (range = 73.3-98.4), significantly lower than the score in the SA condition, $t(7) = 3.75$, $p = .007$. The mean hit percentage in the DA condition was 86.2, and the mean false alarm percentage was 8.9. The hit percentage was clearly higher for beats in congruent (96.9) than in non-congruent (75.7) positions, $t(7) = 4.47$, $p = .003$. This is not surprising because congruent beats afford correct judgments regardless of which rhythm is attended. For this reason, we considered only hit percentages for beats in non-congruent positions in the subsequent analyses.

We submitted those data to a $2 \times 2 \times 2 \times 3$ ANOVA with the variables of DA block (first, second), rhythm (A, B), register (high, low), and phase (in-phase, A-first, B-first). There were only two significant effects. One was the main effect of DA block, $F(1, 7) = 12.16$, $p = .01$: Participants performed better in the second block (80.8% hits) than in the first block (70.7% hits), evidently due to practice. (There was a simultaneous decline in false alarms.) The other effect was a triple interaction between DA block, rhythm, and register,

$F(1, 7) = 6.49$, $p = .04$. To unpack this interaction, we performed separate three-way ANOVAs on the data for each block. There were no significant effects in Block 1. In Block 2, however, the Rhythm × Register interaction was significant, $F(1, 7) = 7.38$, $p = .03$: The hit percentage was higher in the A-high + B-low condition (85.4) than in the A-low + B-high condition (76.3). This was true for both rhythms: The A-rhythm had more hits in the high than in the low register (87.5% vs. 79.6%), whereas the B-rhythm had more hits in the low than in the high register (83.3% vs. 72.9%). (Because observed false alarms derived solely from congruent non-beat positions in the DA condition, they could not be attributed to either of the two rhythms or registers and thus were irrelevant to this interaction.)

We now wish to address the crucial question: Did participants perform better in the DA condition than would be expected if they had been able to track only the beats of one rhythm at a time and had no clue about the beats in the other rhythm? Under this null hypothesis, we derived predictions for the DA condition as follows. Probes could fall either on non-congruent (beat/non-beat) positions or on congruent non-beat positions. (We excluded congruent beat positions, for reasons mentioned earlier.) If the probe fell on a non-congruent position, we assumed under the null hypothesis that there was a 50% chance that participants attended at that moment to the rhythm that had a beat in that position. In that case, they would respond "yes" about as often as they did in the SA condition (i.e., almost always, except for occasional misses due to inattention or interference by the unattended rhythm). On the other 50% of these trials, they would be attending to the rhythm that does not have a beat in the probe position. In that case, too, they might respond "yes" as often as in the SA condition (i.e., very rarely; these unobserved false alarms would have been scored as hits in the DA condition). However, participants knew in addition that a probe in a non-beat position of the attended rhythm could coincide with a beat in the unattended rhythm. Therefore, they might guess sometimes and say "yes" even though the other beat was not tracked, and this would also result in a hit. They would guess equally often if the probe fell on a congruent non-beat position, for they would not know that the unattended rhythm contains a non-beat in that position. In that case, however, the guess would result in a false alarm. Therefore, the observed false alarm rate in the DA condition can be used to infer the guessing rate.

Accordingly, the observed false alarm percentage in the DA condition, FA(DA), which derives entirely from trials in which the probe falls on congruent non-beat

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[8] One participant scored only 74.1% correct, and on closer inspection her false alarm percentage for non-congruent positions (48.6) was found to be almost as high as her hit percentage for non-congruent positions (49.8). This suggested either a complete inability to selectively attend to the rhythm in a given pitch register or, more likely, a misunderstanding of the SA instructions. Therefore, we omitted this participant's data from all analyses, which reduced the N to eight.

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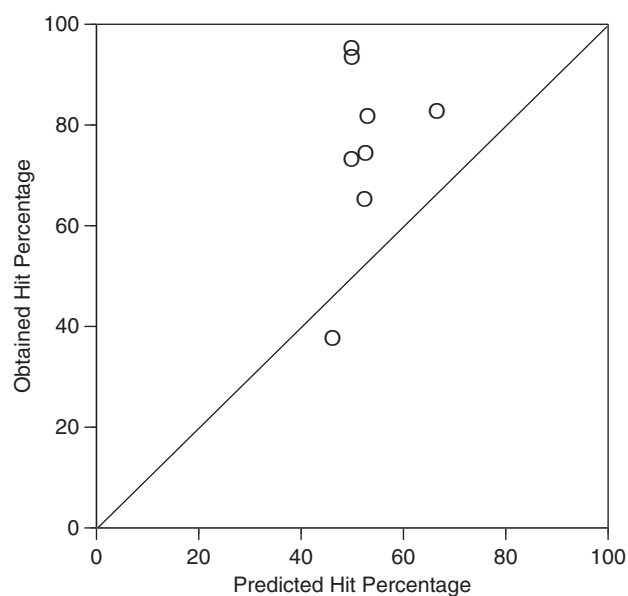All use subject to JSTOR Terms and Conditions

FIGURE 4. Predicted versus obtained hit percentages for non-congruent positions in the DA condition of Experiment 1. Each data point is an individual participant.

positions, can be assumed to be equal to the false alarm percentage in the SA condition, FA(SA), plus an unknown percentage of "yes" responses due to guessing in the DA condition, G(DA):

$$FA(DA) = FA(SA) + G(DA). \qquad (1)$$

FA(DA) also predicts the percentage of fortuitous hits when the probe falls on a non-congruent position and the participant is not attending to the beat in that position (assumed to happen half of the time). If the beat is attended, the hit percentage is assumed to be equal to H(SA), the hit percentage in the SA condition. Therefore, the predicted hit percentage in the DA condition is

$$H'(DA) = [H(SA) + FA(DA)]/2. \qquad (2)$$

Figure 4 plots H'(DA) against the obtained hit percentage, H(DA), for both DA blocks combined, for the 8 individual participants.[9] The diagonal line is the identity line. Seven of the eight participants performed better than predicted, and the obtained hit percentage was significantly larger than the predicted one, $t(7) = 3.37$, $p = .012$ (two-tailed).

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[9] Because there is only a single false alarm percentage, namely the obtained one, which would have to be used to calculate both predicted and obtained d', a comparison of predicted and obtained d' would yield a very similar result to a comparison of predicted and obtained hit percentages. The false alarm percentage cannot be predicted because the guessing rate G(DA) is not known a priori.

We conducted one more analysis to address the possibility that participants identified beat locations on the basis of note (i.e., physical tone) length. All long notes (quarter notes in the A-rhythm, dotted quarters in the B-rhythm) were in beat positions, and they were not only associated with longer IOIs (see Figures 2 and 3) but also with longer physical durations, with their sound occupying half of the interval. This helped induce a strong feeling of a beat in each rhythm but also introduced a stimulus confound. If participants responded on the basis of note length rather than (or in addition to) their sense of a periodic beat, they would have achieved more hits on long-note than on short-note beats in non-congruent positions. To see whether that was the case, we computed long-note and short-note hit percentages separately for A- and B-rhythms in each block of the DA condition, pooling over register and phase conditions, and submitted them to a 2 (blocks) × 2 (rhythms) × 2 (beat note length) ANOVA.[10] The only significant effect was the main effect of block, $F(1, 7) = 6.39$, $p = .039$, which replicates the practice effect reported earlier. Thus there was no reliable difference in hit percentages between long- and short-note beats.

DISCUSSION

The results of Experiment 1 suggest that musicians can, in fact, track the beats of two different rhythms simultaneously, albeit not perfectly. They may have achieved this by dividing their attention between the two rhythms and tracking their beats independently. However, this conclusion may be premature. Given that the rhythms were very simple and constant from trial to trial, strategies other than divided attention could have led to the observed result. In particular, the beats of the two rhythms formed a relatively simple composite pattern, that of an integrated 3:2 polyrhythm, i.e., the durational series 2:1:1:2, a composite pattern that is well known to highly trained musicians. Moreover, this pattern was the same for the three phase relationships of the rhythms, varying only in starting point (see Figure 3). If participants became aware of this fact (although based on their reported strategies, there is no evidence that they did), they may have tracked the composite beat pattern, which can be done within a single metric framework (cf. Phillips-Silver & Trainor, 2007). In other words, they may have tracked the two beats serially as a nonisochronous sequence rather than

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[10] In the non-congruent positions of the three phase conditions shown in Figure 3, there are six long A-beats, six short A-beats, four long B-beats, and two short B-beats.

as two isochronous sequences in parallel. This consideration motivated our subsequent experiments, in which we made the composite beat pattern more complex and hence more difficult to discover and track.

Another potential shortcut in accomplishing the DA task was to respond on the basis of note length (one participant did report "keying into the longer values especially"). Even if note length was not used consciously, the long notes corresponded to a metric level above the beat (i.e., to downbeats) and for that reason alone might have been tracked more accurately. However, the data suggest this was not the case; participants seemed to track all beats in non-congruent positions equally well.

Responses to the post-experiment questionnaire revealed that some participants tapped along with the beat of one rhythm while perceptually tracking the beats of the other rhythm, based either on specific meter (2/4 or 6/8) or registral placement (high or low). Indeed, some individual participants showed large differences in their hit percentages for A- and B-rhythms, suggesting that they preferentially focused on (and perhaps synchronized with) one or the other. A combined motor-perceptual strategy may qualify as polymetric perception in our definition, namely as tracking of two independent beats. However, it may not entail completely divided attention because tapping along with one rhythm may require little attention and thus frees up attentional resources for the other rhythm. We did not wish to prohibit movement in this and the following experiments because it is natural to move along with rhythms and because the absence of any movement is difficult to prove. Movement may be a significant aid in tracking the beats of polymetric rhythms, and six out of our eight participants reported using some sort of synchronization strategy at least some of the time.

Participants did not evince any consistent preferences of attending to the high or low registers, and any preferences of attending to the A- or B-rhythm seemed idiosyncratic. The different phase relationships of the rhythms likewise did not impact performance. The only consistent effect of the structure of our materials was the better performance in the A-high + B-low condition than in the A-low + B-high condition in Block 2. This result could be due to an implicit association of high pitch with a fast tempo, and of low pitch with a slow tempo (see Boltz, 2011). Such an association is plausible not only because small organisms often move faster and emit higher sounds than do large organisms, but also because pitch and rhythmic periodicity are both frequencies that range from low to high, albeit on different time scales, and therefore may be associated. As the beats of our A-rhythm had a faster tempo than those of our B-rhythm, when the two rhythms were combined, the beats of the A-rhythm may have been easier to track at a high pitch than at a low pitch in the DA condition, and the opposite for the beats of the B-rhythm. Interestingly, this effect became significant only with repeated exposure to the rhythms.

Performance in the DA condition improved with practice, which suggests that the ability to divide attentional resources between two rhythms could be trained. Although our participants were expert musicians, they were not specialists in complex contemporary music (except perhaps for the two composer-pianists, who performed rather well in the experiment), and except for a few very specific idioms, polymetric passages are infrequent in the standard classical repertoire.[11] Our participants were also not experts in the performance of non-Western music where such patterns are more frequent (e.g., music from the African diaspora). Moreover, when such passages do occur in Western music, musicians may not deal with them by dividing their attention in the way that our DA condition demanded. For example, orchestral musicians are much more likely to focus on their own part and try to ignore the other parts, using the conductor as a reference to stay coordinated with the rest of the ensemble. The observed improvement with practice may also have reflected increasing familiarity with the specific rhythms we used and their combination, in particular the composite beat pattern. While effects of training and previous musical experience are worthy of further research, we did not pursue them in the following two experiments but rather focused on reducing the potential facilitating role of the composite beat pattern.

Experiment 2

The purpose of this experiment was to make it more difficult for participants to use a strategy of using the composite beat pattern to track the beats of the two rhythms. We used the same rhythms but modified the phase relationships by using a shorter delay between the two rhythms (half of the common unit, i.e., a "sixteenth note"). This resulted in two different composite rhythms and a more complex composite beat pattern. It also had the consequence that beats (and tones more generally) never coincided, which facilitated data

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[11] Exceptions include the cadential hemiola pattern of three duple rhythmic groups in the time of two triple measures and accompaniment textures based on simple polyrhythms such as 3:2 and 4:3.

analysis in some respects: Beats and non-beats no longer occurred in congruent or non-congruent positions; instead, they occurred in (eighth-note) positions that were specific to each rhythm's metric grid. We also presented the rhythms at a faster tempo than in Experiment 1. The rapid alternation of tones in different registers was expected to lead to stronger auditory segregation of the two rhythms (Bregman, 1990), which might facilitate the tracking of independent beats if that is possible.

METHOD

Participants. The 10 participants in this experiment included 8 of the musicians who had participated in Experiment 1 and the two authors, who are experienced amateur pianists with formal music training (ages 35 and 65, respectively).[12] Several months elapsed between the two experiments.

Stimuli and design. The same two rhythms as in Experiment 1 were superimposed, but modifications were made to the rate of presentation and the phase conditions. The beats in Experiment 1 were on the slow side relative to a preferred beat period of about 500 ms (van Noorden & Moelants, 1999), and we thought an acceleration of the rhythms would strengthen beat induction. The smallest interval within a rhythm (an eighth note) corresponded here to a basic IOI of 300 ms, so that the basic beat periods were 600 and 900 ms, respectively, in the A- and B-rhythms. The tempo was randomly changed on each trial by a scaling factor of -13.3, -6.7, 0, 6.7, or 13.3%. There was no in-phase condition, and in the two out-of-phase conditions, A-first and B-first, the second rhythm was delayed by a basic duration of 150 ms, equivalent to a sixteenth note, so that the two rhythms were interleaved. Consequently, there were 26 different probe positions, with the even-numbered probe positions (starting with 0) pertaining to the leading rhythm, and the odd-numbered probe positions pertaining to the lagging rhythm. By "pertaining to" we mean that the probe could coincide with a beat only in that rhythm, though participants were not necessarily aware of that. Diagrams of the second half of the trial (the "test period") for each of the two phase conditions are shown in Figure 5; they include all event onsets and probe positions, with beat designations.

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[12] The authors had also tested themselves in Experiment 1, but only in an earlier pilot version, so their data were not included there. Although the authors had some prior experience with the stimuli of the present experiment, the DA task seemed difficult enough to warrant their having a go at it.

Apparatus and procedure. The apparatus and task were the same as in Experiment 1. Again, each trial included an induction period followed by a test period, each of which corresponded to a full polymetric cycle of 3:2 measures and 6:4 beats, with a basic cycle duration of 3,600 ms (12 × 300 ms) and a basic total duration of 7,200 ms, not including the two final probe positions, each of which corresponded to a beat in one of the two rhythms, but was not marked by a tone. The experimental session consisted of two blocks of 104 trials each (2 registers × 2 phases × 26 probe positions), each block lasting about 20 min. The first block was always the SA condition. In contrast to Experiment 1, the "attend high" and "attend low" conditions were randomly intermixed in that block, and an instruction specifying the register to be attended was shown on the screen before each trial. The to-be-attended register was always the one corresponding to the probe location (even- versus odd-numbered). In other words, the probe never fell between eighth-note positions of the attended rhythm. The second block of trials was the DA condition. As in Experiment 1, participants had to report whether or not the probe fell on a beat in the attended rhythm in the SA condition, and in either rhythm in the DA condition.

RESULTS

Selective attention (SA) condition. Performance in the SA condition was not as impressive as in Experiment 1, suggesting that a concurrent rhythm leading or lagging by a sixteenth-note was a more effective distracter than a rhythm leading or lagging by an eighth note. The random sequence of "attend high" and "attend low" trials could also have played a role in lowering performance. Mean percent correct was 87.4 (range = 65.4-99.0), the mean hit percentage was 81.3, and the mean false alarm percentage was 6.5. The hit percentages were submitted to a 2 (rhythms) × 2 (registers) × 2 (phases) ANOVA, which did not yield any significant effects. We also conducted an analysis comparing long- and short-note beats. A 2 (rhythms) × 2 (beat note length) ANOVA revealed a significant main effect of beat note length, $F(1, 9) = 15.90$, $p = .003$. The mean hit percentage was higher for long-note (86.0) than for short-note (76.7) beats.

Divided attention (DA) condition. Participants performed significantly worse in the DA condition than in the SA condition, $t(9) = 5.06$, $p < .001$, with a mean DA score of 68.3% correct (range = 53.8-81.7). The mean hit percentage was 60.2, and the mean false alarm percentage was 23.6. This performance was also clearly lower than that in the DA condition of Experiment 1.
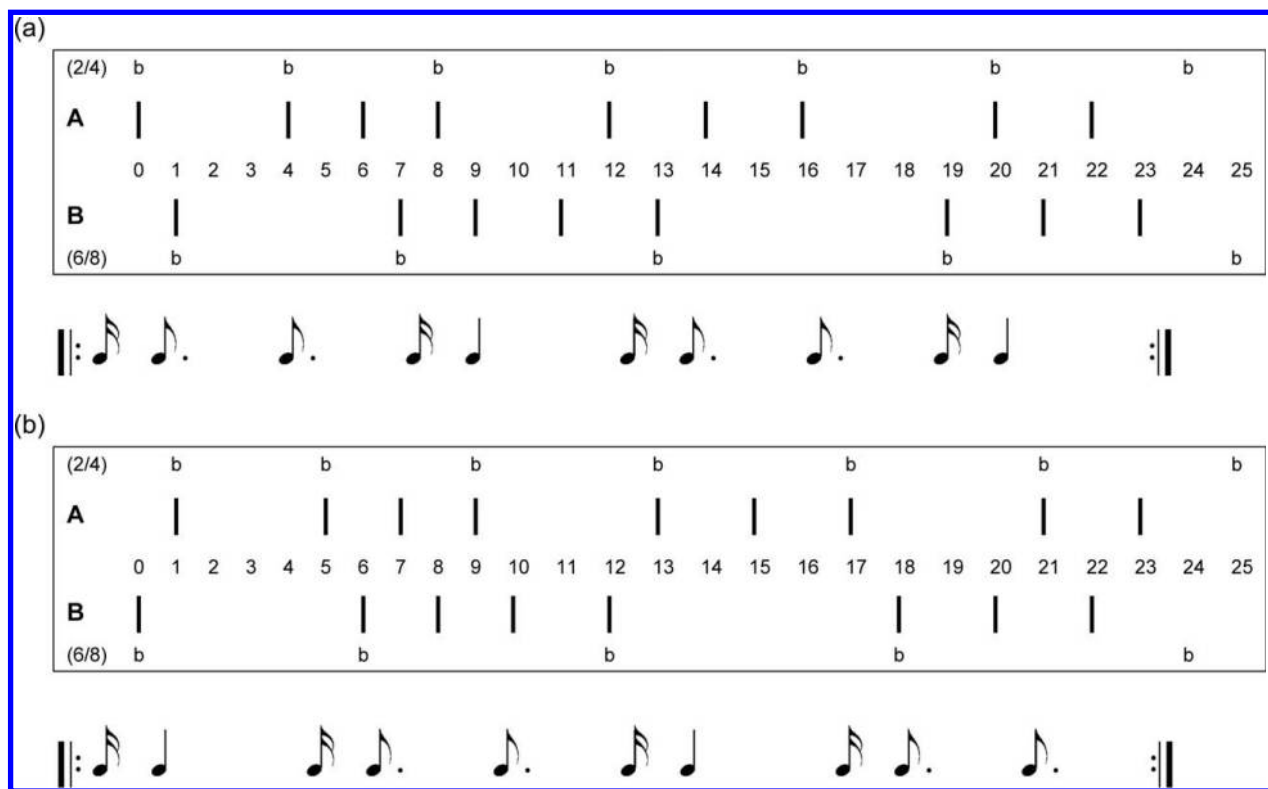
FIGURE 5. Diagrams of the test periods for each of the two phase conditions of Experiment 2, including all event onsets (vertical lines) and probe positions (numbered from 0 to 25), with beat designations ("b"). Diagram (a) shows the A-first condition, and (b) shows the B-first condition. The corresponding composite beat pattern is shown in musical notation below each diagram.

An initial four-way ANOVA on hit percentages that included condition (SA vs. DA) as a variable confirmed the difference between conditions, $F(1, 9) = 14.74$, $p = .004$. In addition, there were three significant interactions: Rhythm $\times$ Register, $F(1, 9) = 5.13$, $p = .05$, Rhythm $\times$ Phase, $F(1, 9) = 5.57$, $p = .04$, and Condition $\times$ Rhythm $\times$ Phase, $F(1, 9) = 9.79$, $p = .01$.

In a separate three-way ANOVA on the DA condition, the Rhythm $\times$ Register interaction only approached significance, $F(1, 9) = 4.46$, $p = .06$. Its pattern resembled that of the same interaction in Experiment 1: Participants performed better with A-high + B-low (65.4% hits) than with A-low + B-high (56.9% hits). However, the Rhythm $\times$ Phase interaction was significant, $F(1, 9) = 17.58$, $p = .002$. This interaction amounts to a main effect of leading versus lagging rhythm, with performance being worse for the former (53.7% hits) than for the latter (68.5% hits). However, this difference was entirely due to the A-first phase condition, where the A-rhythm yielded a much lower hit percentage than the B-rhythm (46.4 vs. 72.0), whereas there was little difference between the

two rhythms in the B-first phase condition (65.0 vs. 61.0).

A comparison of hit percentages for long-note versus short-note beats was also carried out. In contrast to the SA condition, however, no difference emerged in a 2 (rhythms) $\times$ 2 (beat note length) ANOVA on the DA condition. A three-way ANOVA on the SA and DA conditions combined yielded a significant Condition $\times$ Beat Note Length interaction, $F(1, 9) = 7.18$, $p = .03$, which confirms that the effect of beat note length was restricted to the SA condition.

Did participants perform better in the DA condition than one would expect under the null hypothesis that only one rhythm could be attended at a time? Here two possibilities need to be considered, which we will call Null Hypotheses 1 and 2, respectively. Null Hypothesis 1 is that, as in Experiment 1, participants make a guess whenever the probe does not coincide with a beat in the attended rhythm. This would occur both with probes that pertain to the attended rhythm (i.e., probes that fall on non-beat eighth-note positions within that rhythm) and with probes that pertain to the unattended rhythm

(i.e., probes that fall on either beat or non-beat eighth-note positions within that rhythm and therefore between eighth-note positions of the attended rhythm). In that case, the same calculations as in Experiment 1 apply (Equations 1 and 2). This null hypothesis assumes, however, that participants are unaware (or do not make use) of the fact that probes pertain to one or the other rhythm; they treat all probes as if they pertained to both rhythms. According to Null Hypothesis 2, by contrast, participants are conscious of which rhythm is being probed and/or of the relative duration of the delay between the two rhythms, and therefore do not guess when the probe falls on a non-beat eighth-note position in the attended rhythm. Rather, they will respond in that case with the same percentage of "yes" responses as in the SA condition, which is given by FA(SA). They will guess only when the probe pertains to the unattended rhythm, in which case the unknown percentage of "yes" responses will be G(DA). Because the observed false-alarm percentage in the DA condition, FA(DA), derives from non-beat probes in either rhythm, each of which is being probed on half of the trials, it follows that

$$FA(DA) = [FA(SA) + G(DA)]/2. \qquad (3)$$

The predicted hit percentage in the DA condition, H'(DA), includes proper hits (when the probe falls on a beat in the attended rhythm), which should be as frequent as in the SA condition, and fortuitous hits due to guesses (when the probe falls on a beat in the unattended rhythm), and therefore

$$H'(DA) = [H(SA) + G(DA)]/2. \qquad (4)$$

From Equation 3 it can be derived that

$$G(DA) = 2 * FA(DA) - FA(SA), \qquad (5)$$

and substitution of Equation 5 into Equation 4 yields

$$H'(DA) = [H(SA) + 2 * FA(DA) - FA(SA)]/2. \quad (6)$$

The results are shown in Figure 6, which plots predicted against obtained hit percentages under the two null hypotheses. It can be seen that under Null Hypothesis 1 (upper panel) all but one participant performed better than predicted, but the difference fell short of significance, $t(9) = 2.15$, $p = .06$ (two-tailed), due to large individual differences. A one-tailed test may be justified, however, because there is no good reason to expect any participants' performance to be worse than predicted; in that case, $p = .03$. Under Null Hypothesis 2 (lower panel), however, there was clearly no significant overall
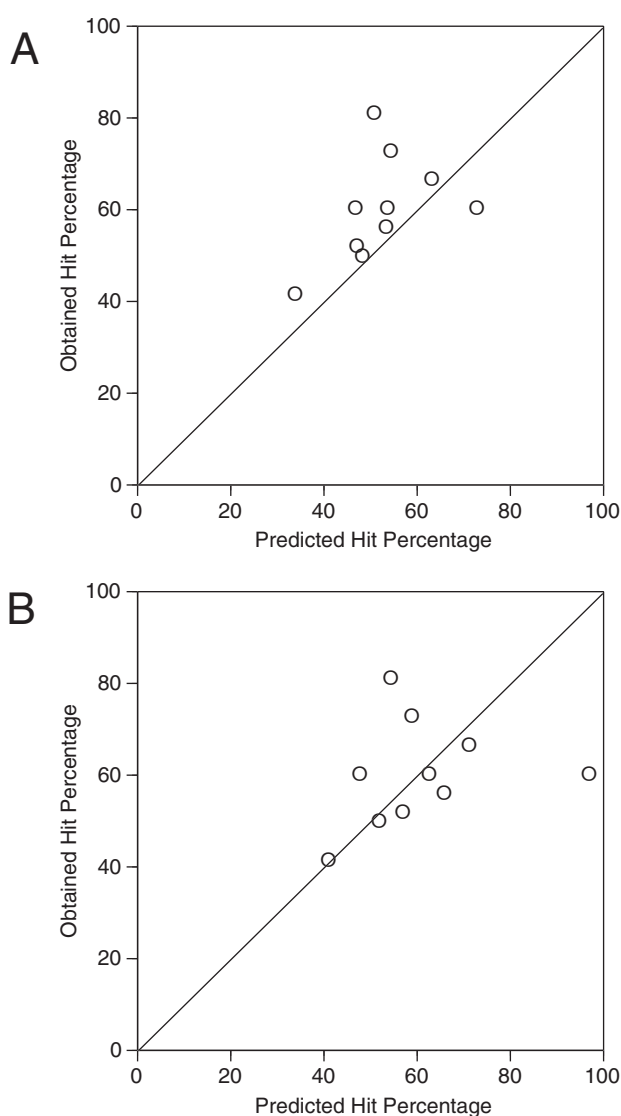

FIGURE 6. Predicted versus obtained hit percentages in the DA condition of Experiment 2 according to Null Hypotheses 1 (A) and 2 (B). Each data point is an individual participant.

difference between predicted and obtained hit percentages, $t(9) = -0.11$, although three participants (the authors not among them) still performed better than predicted. One participant clearly performed worse than predicted, and for her it can be concluded that she did *not* use the guessing strategy assumed by Null Hypothesis 2.

DISCUSSION

Our introduction of a different temporal relationship between the two rhythms, which created two distinct composite rhythms and a more complex composite beat

pattern, resulted in poorer performance than in Experiment 1, not only in the DA condition but also in the SA condition. Thus an interleaved rhythm seems to be a more effective distracter than a rhythm that shares the same sub-beat (eighth-note) pulse as the attended rhythm. Moreover, performance in the DA condition was only slightly better than predicted under Null Hypothesis 1. Thus, even if this null hypothesis is considered plausible, there was only limited evidence that divided attention to the different beats was possible in this experiment. Under Null Hypothesis 2, there was essentially no evidence of success in the DA condition, although it could still be argued that some individual participants could do the task. Of course, we do not know which guessing strategy (if any) the participants employed. (Two participants did report that if the probe fell on a non-beat eighth-note position in one rhythm, they knew it couldn't be a beat in the other rhythm, but their performance did not stand out in any way.) However, the most likely explanation for the lower hit percentages in this experiment is the greater complexity of the composite beat pattern, which was very difficult to use to track the beats of the two rhythms, especially given that each of the two phase conditions presented a different permutation of the composite beat pattern. The stimulus design of Experiment 2 may truly have forced participants to try to track two independent beats, and this seemed to be very difficult indeed.

Some structural variables had an effect on performance. Long-note beats provided an advantage only in the SA condition, which may be due to the long IOIs associated with long notes in each rhythm. In the DA condition, tones of the other rhythm usually occurred during long IOIs, thereby eliminating this variable as a factor. More interesting is the interaction between rhythm and phase, which was specific to the DA condition. We will return to this particular finding in the General Discussion.

Experiment 3

By aligning the rhythms of Experiment 2 in ways that resulted in a more complex composite beat pattern, we clearly impaired divided attention performance compared to Experiment 1. However, for some participants performance was still better than predicted on the basis of selective attention plus guessing. In Experiment 3, we maintained the composite beat pattern of Experiment 2 and instead changed the rhythms themselves, without changing their meter. One rather artificial aspect of Experiments 1 and 2 was the constant repetition of the

A- and B-rhythms both within and between trials. This is not representative of listening to music, where rhythms are more varied, even though repetition often occurs. In Experiment 3 we varied the rhythms both within and between trials.

METHOD

Participants. The participants in this experiment were 8 graduate students of the Yale School of Music (2 men, 6 women, ages 21-27), who were paid for their efforts, and the two authors (ages 36 and 66, respectively).[13] All students were regular participants in synchronization and perception experiments in the second author's lab, but only two had participated in Experiments 1 and 2. Their primary musical instruments were piano (2), violin (1), viola (2), flute (1), trombone (1), harp (1), and guitar (1), which they had studied for 13-21 years, and one pianist was primarily a composer.

Stimuli and design. The A- and B-rhythms were elaborated by the addition of sixteenth notes. Moreover, the exact rhythms varied from trial to trial and also between the induction period and the test period of each trial. This variation was achieved by defining four rhythmic "cells" for each rhythm and concatenating random permutations of these cells. Immediate repetition of a cell could occur only across the boundary between two such permutations. Each cell corresponded to the duration of a quarter note in the A-rhythm, and to a dotted-quarter note in the B-rhythm; thus, one trial (induction period plus test period) comprised 12 cells (3 successive permutations) in the A- rhythm and 8 cells (2 successive permutations) in the B-rhythm. The rhythm construction was carried out on-line by customized MAX software. An example of a pair of rhythms is shown in Figure 7.

In all other respects, the design of the stimuli was identical to that of Experiment 2, except for a very slight slowing of the basic tempo to better accommodate the sixteenth notes. The basic duration of the eighth note was 310 ms, and variation in tempo from trial to trial occurred as in Experiment 2. Apparatus and procedure, too, were the same as in Experiment 2.

RESULTS

Selective attention (SA) condition. Participants achieved 81.8% correct in this condition (range = 69.2-100), with 80.6% hits and 17.0% false alarms. This performance is just slightly lower than in Experiment 2, mainly due to

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[13] One additional student discontinued the experiment because he felt unable to hear the B-rhythm in the 6/8 meter.

FIGURE 7. Sample pair of rhythms from Experiment 3.

the higher false-alarm rate. The hit percentages were subjected to a three-way ANOVA that yielded one significant effect, the Rhythm × Register × Phase interaction, $F(1, 9) = 7.75$, $p = .02$. The pattern of this complex interaction is difficult to describe and interpret, and we will not attempt to do this. We did not conduct any analysis of long-note versus short-note beats because, given the constant variation in the rhythms, locating these tones in each trial would have been cumbersome. (This also applies to the DA condition.)

Divided attention (DA) condition. Percent correct was 59.9 in this condition (range = 53.9-68.2), significantly lower than in the SA condition, $t(9) = 7.0$, $p < .001$. The mean hit percentage was 64.1, and the mean false alarm percentage an astonishing 42.0. This performance was clearly poorer than in Experiment 2, due to a false-alarm rate that was twice as high as previously. A three-way ANOVA on the hit percentages yielded no significant effects. A combined ANOVA on the hits in the SA and DA conditions yielded only a main effect of condition (SA vs. DA), $F(1, 9) = 22.70$, $p = .001$. The four-way interaction was almost significant, $F(1, 9) = 5.03$, $p = .05$, whereas the Rhythm × Register × Phase interaction was far from significance, suggesting that this complex three-way interaction was specific to the SA condition.

Predicted hit percentages were calculated under two null hypotheses, as in Experiment 2. The results are shown in Figure 8. Under Null Hypothesis 1, obtained hit percentages were slightly higher than predicted on average, but the difference fell short of significance, $t(9) = 1.70$, $p = .12$ (two-tailed), $p = .06$ (one-tailed). Under Null Hypothesis 2, obtained hit percentages were significantly *lower* than predicted, $t(9) = -3.21$, $p = .01$ (two-tailed).[14]

DISCUSSION

Experiment 3 provided even less evidence of participants' ability to track two independent beats than did Experiment 2. Although the beats of each rhythm could

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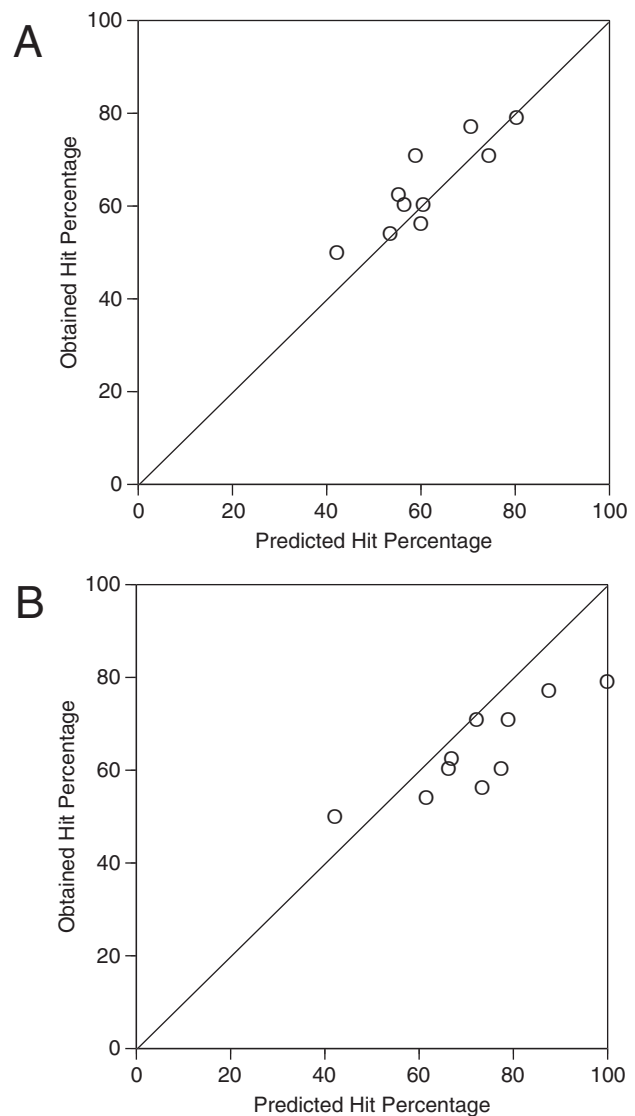[14] One prediction exceeded 100% and was set to 100%.

FIGURE 8. Predicted versus obtained hit percentages in the DA condition of Experiment 3 according to Null Hypotheses 1 (A) and 2 (B). Each data point is an individual participant.

be tracked reasonably well when selective attention was focused on that rhythm, the increased number of false alarms suggests that beat induction was not as effective with variable as with repetitive rhythms. Divided

attention to two beats seemed nearly impossible with variable rhythms.

Structural factors (rhythm, register, phase) seemed to play no role in the DA condition and only an obscure role in the SA condition. One interesting finding, however, is that Null Hypothesis 2 overpredicted the hit percentages in the DA condition. This suggests that the majority of participants did not adopt the guessing strategy assumed under this null hypothesis, which depends on an assessment of each probe as pertaining to either the attended or the unattended rhythm. Since this may also have been the case in Experiment 2, the DA results of that experiment may seem somewhat more positive in hindsight. However, it is quite possible that the variability of the rhythms in Experiment 3 and the fact that they contained some sixteenth notes, together with the sixteenth-note offset between rhythms (a mere 155 ms on average), impeded recognition of which rhythm a probe pertained to. This problem may then have been specific to Experiment 3.

General Discussion

The present research is one of the first attempts at studying polymetric perception empirically. The three experiments presented were designed to investigate musicians' ability to divide their attention between two contrasting rhythms, each of which presented a distinct and unambiguous meter. Experiment 1 suggested that our participants could in fact track two different beats simultaneously, albeit not perfectly, and thus provided some evidence supporting polymetric perception. In Experiment 2, however, the evidence for such an ability was limited, and in Experiment 3 it was basically absent.

These conclusions rest on the premise that participants, in addition to trying hard to track the beats of the two rhythms, made guesses when the probe fell in non-beat positions. We estimated this unknown guessing rate from the observed false-alarm rates, assuming that participants' guesses would not depend on whether the unattended rhythm contained a beat or a non-beat in the probed position. It is possible that the assumptions underlying our null hypotheses are not correct. For example, if participants had not engaged in guessing at all, all three experiments would provide strong evidence for an ability to track two beats independently. However, false alarm responses need to be explained, and guessing is the most straightforward explanation. This does not mean that participants were consciously aware that they were guessing; rather, they were just uncertain about which response to give and sometimes said "yes," which amounts to a guess. Therefore, we

believe our Null Hypothesis 1 to have been appropriately conservative, even if it led to somewhat disappointing conclusions. Null Hypothesis 2 seems to have been less realistic, as it significantly overpredicted performance in Experiment 3.

The main difference between Experiment 1 on the one hand and Experiments 2 and 3 on the other hand was in the way the two rhythms were aligned: They shared a common eighth-note pulse in Experiment 1, whereas their eighth-note pulses alternated in Experiments 2 and 3. This difference resulted in different composite beat patterns: The pattern in Experiment 1 was relatively simple and resembled a slow 2:3 polyrhythm, whereas the one in Experiments 2 and 3 was more complex, due to the component beats being always out of phase (by at least a sixteenth note). Although the composite beat patterns were the same in the different phase conditions of each experiment, they started at different points. With the simple pattern of Experiment 1, our participants (being highly trained musicians familiar with 2:3 polyrhythms) could have discovered the identity of the composite beat pattern across the three phase conditions, but in Experiments 2 and 3 that seems much less likely. One plausible conclusion from the results, therefore, is that participants did not track two independent beats but rather integrated them into a composite beat pattern when they could do so, and then relied on this (probably incomplete) pattern when making their probe judgments. If they had been able to track the beats of the two rhythms independently, they should have performed as well in Experiment 2 as in Experiment 1, for the rhythms were the same. Indeed, they should have done better in Experiment 2 because the tempo was faster, which was expected to strengthen beat induction. Clearly, however, the temporal relationship of the two beats mattered.

COMPOSITE RHYTHM AND COMPOSITE BEAT PATTERN

What have we accomplished by using complex rather than simple polyrhythms, as used in many previous studies? As we have argued, one of the main differences between simple and complex polyrhythms is that the latter consist of superimposed rhythms rather than merely pulse trains, thereby offering more readily perceptible metric hierarchies. When participants are asked, for example, to "tap along with the beat" of a simple polyrhythm, they are encouraged to reduce the rhythmic surface to a periodic series of event onsets, a single beat, rather than to divide their attention between different beats. In contrast, when presented with complex polyrhythms, listeners are encouraged to differentiate between beat and non-beat metric

FIGURE 9. Hypothetical metric interpretations of the composite rhythm of the in-phase condition in Experiment 1; the 2:1:1:2 composite beat pattern can be interpreted as (a) a triple measure with duple subdivisions or (b) a duple measure with triple subdivisions (dashed and solid bar lines represent beats and measures, respectively; the accent marks represent the composite beat pattern).

positions (not always marked by auditory events) in at least two different rhythms heard simultaneously.

One important question raised by our study concerns the roles of the composite rhythm and the composite beat pattern in tracking two different beats simultaneously. As we have seen, studies on the production and perception of simple polyrhythms generally show that composite rhythms (which in simple in-phase polyrhythms also constitute the composite beat patterns) are likely to be used as an aid in polyrhythmic performance. Thus, we might speculate whether expert musicians, who have learned to use composite rhythms in the performance of simple polyrhythms might use this knowledge to infer the composite beat pattern underlying a complex polyrhythm and use this composite beat pattern to track the competing beats of a polymetric structure. One possible motivation for participants' recourse to a composite beat pattern in tracking the beats of a complex polyrhythm is the efficiency gained by not dividing attentional resources. Thus, in the context of the stimuli used for Experiment 1, the simple composite beat pattern of 2:1:1:2 together with the recurrence of coinciding beat positions could have encouraged participants to adopt a strategy that involved matching the surface rhythms with the composite beat pattern. And, despite the large pitch separation, participants may still have formed an integrated representation of the two rhythms. Figure 9 presents two hypothetical metric interpretations of the composite rhythm for the in-phase condition of Experiment 1. (The A-first and B-first out-of-phase conditions presented permutations of the same composite rhythm.) In this figure, the component beats of the composite beat pattern implied by our design are marked with accents, and dashed and solid bar lines represent the hypothesized metric groupings (beats and measures, respectively), with congruent beats corresponding to the downbeats. It should be noted that if the composite rhythm was in fact perceptually integrated into a single

metric framework, only those component beats that correspond to the beats of the meter would be perceived as such. Here, one might argue that the triple measure with duple subdivisions (Figure 9a) would be preferred based on the higher number of component beats aligned with relatively strong metric positions, but this was not supported by our experimental findings.

From studies on simple polyrhythms, we also know that one common outcome from entrainment is that the beats of one of the rhythms (i.e., one of the pulse trains) will be interpreted as the unifying tactus for the composite rhythm. In our experiments, we found surprisingly little consistent advantage for one or the other rhythm in either the SA or DA condition. This could either mean that if there was a preference for the beats of one rhythm over those of the other, this preference was idiosyncratic (as suggested by participants' reported strategies and some participants' performance), or that our participants did divide their attention more or less evenly across the two rhythms, but that their ability to identify beat positions was to some degree compromised in the process (less so in Experiment 1 and more so in Experiments 2 and 3). There were two notable exceptions to this finding. The first involved a significant Rhythm × Register interaction for hits in Block 2 of the DA condition of Experiment 1. This interaction showed a higher performance when the rhythms were in the combination A-high + B-low, a result that we explained by the preferred association of faster beats with higher register and slower beats with lower register, a preference that seemed to have become manifest with more exposure to the stimuli. The second, and more intriguing finding, rests in the significant interaction between rhythm and phase in the DA condition of Experiment 2.

In Experiment 2, we strived to present participants with polymetric structures that did not include congruent beat positions, and also yielded a more complex composite beat pattern. The resulting two phase

FIGURE 10. Hypothetical metric interpretations of the composite rhythms of the A-first (a) and B-first (b) conditions in Experiment 2 (dashed bar lines represent measures and accent marks represent the composite beat pattern); both metric interpretations start with a sixteenth-note anacrusis. Only (a) is supported by experimental results.

conditions (A-first and B-first) also had the advantage of presenting two contrasting composite rhythms. Figure 10 presents metric interpretations of these two rhythms that will help clarify the possible influence of the temporal structure of the composite rhythm on the relative perceptual salience of the component beats of the underlying composite beat pattern (shown with accent marks below each rhythm). Both interpretations are based on the alignment of relatively longer IOIs and component beats with relatively strong metric positions. As represented by the repeat signs, in a given trial, each composite rhythm was heard twice, with the underlying composite beat pattern (1:3:3:1:4 for A-first and 1:4:1:3:3 for B-first) being cycled through four times.

As suggested by the dotted bar lines in Figure 10a, the hypothetical metric interpretation of the A-first composite rhythm rests on a dotted-eighth note beat (an interbeat interval [IBI] of 450 ms) that is exposed very close to the beginning (positions 1-3 in Figure 5a), and is subsequently subdivided in a "consonant" 2:1 duration ratio (positions 4-6), thus providing an entire measure of 6/16 without cross-accentuation. (Note that the reverse pattern is found two measures later.) This interpretation was supported by our experimental finding of a significant interaction between rhythm and phase in the DA condition, which showed a higher hit percentage for the lagging than for the leading rhythm, a difference that was entirely due to the A-first condition. This finding suggests that in the A-first condition, the B-beats were more salient, a finding that supports the interpretation of a metric integration of the composite rhythm in favor of the B-rhythm. In contrast, the hypothetical metric interpretation of 2/4 for the B-first condition (Figure 10b), which rests on a greater salience of the A-beats, was not supported by our experimental findings. Here, a relatively long IOI (positions 1-4 in Figure 5b, which corresponds to a quarter note, an IBI

of 600 ms) also occurs toward the beginning of the composite rhythm of the B-first condition, but this time-span failed to act as a unifying tactus, possibly due to the subsequent event onsets, which result in a more "dissonant" (i.e., syncopated) subdivision pattern. The design of our two experiments does not allow us to test the statistical significance of the differences in hit percentages between individual probe positions, but the observations afforded by the analysis of the composite rhythms and composite beat patterns in light of some of our experimental findings suggest that the experimental testing of the relative perceptual salience of specific beat positions within a complex polyrhythm might be a fruitful methodological approach for future research on polymetric perception.

PARTICIPANTS' REPORTED STRATEGIES

As noted earlier, we collected information on strategies used by our participants in the three experiments and for each of the two attention conditions through a post-experiment questionnaire. Although caution is necessary when taking participants' introspective comments into account, we report some of the trends noted as these might offer pertinent information about common strategies used for tracking competing beats as well as insight into possible factors to consider in designing future experiments. Most participants reported using some form of synchronization either to one or both rhythms or to one or both underlying beats in both attention conditions, although it appeared to have been a more common strategy in the DA task. Forms of synchronization were varied and included both external (e.g., head nodding to one beat while listening to the other, finger or foot tapping, mouthing of one rhythm while conducting the other, or eye blinking) and internal (e.g., feeling the rhythms, keeping the beat in head, or imagining a high-pitched tone on the beat) synchronization.

Interestingly, although some participants reported tapping the composite rhythm (an "integrative" strategy), strategies involving some form of divided synchronization (i.e., tapping along one rhythm while focusing on the other) were much more common, suggesting that divided attention might be successfully supported by systematically matching different beats to different motor or perceptual systems. Some participants also reported strategies that are best classified as "analytical," that is, responding "Yes" or "No" based on some specific feature of the polymetric structure. For example, in Experiment 2, a few participants reported a strategy that involved rejecting probes that fell on the eighth note following a beat position, as these corresponded to non-beat positions. Other analytical strategies involved retrospective attending, suggesting that some participants might have been able to retain beat percepts in short-term memory.

As suggested by the finding of a practice effect in the DA condition of Experiment 1, the kind of divided attention called for in performing this task would also seem to require some amount of training, especially when considering the predominance of music written with a single, isochronous, underlying beat in the Western tradition. In one participant's words: "I think it would be possible for me to have performed better in this experiment with some practice – it doesn't seem impossible, it is just that my ears aren't trained to hear that way." Participants' post-experiment responses also suggest that at least some types of external synchronization (e.g., tapping the composite rhythm) might be detrimental to polymetric perception, as it would lead one to match probes to taps rather than dividing one's attention between two underlying beats, and that more passive forms of synchronization might be more successful. As reported by another participant: "[I] tried tapping to one and focusing on the other, [but] found that that complicated things, [so I] tried to feel the downbeats internally, mostly." Indeed, such "internal" synchronization seems to have been encouraged by the design of Experiment 3, since participants could not predict the rhythmic patterns.

Conclusions

What are the implications of our research for polymetric perception? There is no question that tracking two different beats simultaneously would present a perceptual challenge to most listeners. Our participants were highly trained musicians (in the Western musical tradition), and although our results show that they could track different beats under certain conditions,

they rarely performed with perfect accuracy. On the other hand, it would appear that practice and training might enhance listeners' ability to divide their attention and track different beats. Thus, skills that have become second nature to experienced musicians (e.g., tapping to the beat of the music) might facilitate strategies involving some form of divided synchronization.

Our findings suggest that there are structural factors that influence task performance, such as polymetric configuration, phase relationship, and beat note length. Significant differences between various structural factors in the DA condition could theoretically point to perceptual advantages of some beat positions over others, or of the beats of one rhythm over those of another. Future studies could include a more systematic investigation of these factors. However, the effects of various structural factors in our three experiments were not large enough to account for our participants' performance in the DA tasks.

Finally, the results of this study also suggest that a more systematic investigation of metric percepts using polymetric structures is in order. In the current music-analytical literature, it is common to reject the possibility of polymetric perception in favor of integrated models of metric perception, based on the evidence gathered mostly through experiments on the perception and production of polyrhythmic, rather than truly polymetric stimuli. Given the widespread use of metric dissonance by composers within the Western tradition, and the large repertoire of non-Western and contemporary musical practices that use polymeter as a compositional technique, music analysts would benefit from a better understanding of the perceptual challenges and possibilities afforded by polymetric structures. The results and methodology presented here suggest possible avenues for future research. In addition to a more systematic exploration of polymetric configurations and structural factors (especially the role of tempo) on polymetric perception, an exploration of empirical methods allowing a more direct access to (poly)metric entrainment (including the role of composite beat patterns in polymetric perception) would appear to be crucial.

In closing, we might be reminded of Handel's (1984) reflections on the use of polyrhythms to study rhythm. Following his exposition of the advantages of the (then) recent adoption by many researchers of a hierarchical model of meter, the author notes: "The essential difficulty with hierarchical tree representations is the restriction to one musical line. This inevitably leads to a conception of rhythm as the segmentation into repeating units and to an emphasis on the metric regularizing

component of rhythm." (p. 468) He then discusses the challenges involved in interpreting meter in polyphonic passages, especially when these include rhythmic lines that are dissonant with each other. In emphasizing the nature of *rhythmic* perception as "the interplay among levels," Handel also opens the door to a more profound questioning of the nature of *metric* (and possibly polymetric) percepts. In much of the music mentioned in the introduction, the use of dissonant rhythmic lines is systematic rather than incidental. Following in Handel's footsteps, we might suggest that there may be much to gain from the use of polymetric structures to study meter.

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