Auditory Metrical Coordination of Attention on a Visual *n*-back Task

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Abstract

The *n*-back task is a working memory task that requires participants to decide whether a stimulus in a sequence matches the one that appeared *n* items ago. Items are presented sequentially at a steady rate; the task has an inherent visual rhythm. Findings about rhythmic attentional allocation in a metric (accented) rhythm were extended to the *n*-back task. A simultaneous auditory rhythm was found to coordinate attention metrically on the *n*-back task, resulting in increased attention on strong beats. Participants showed faster response times to targets landing on strong beats, relative to those landing on weak beats. Participants also responded more quickly when exposed to subdivided rhythms in which auditory beats were presented at a rate twice that of the task stimuli, than when exposed to a slower rhythm. Results suggest that some auditory rhythms raise the attentional salience of *n*-back stimuli, especially on strong beats. Participants with more musical experience demonstrated higher detection rates in the *n*-back, suggesting that musical experience strengthens cognitive structures relevant to the task.

Keywords: attention, mental recall, meter, music cognition, *n*-back, oscillation, periodicity, reaction time, rhythm, temporal expectancy, working memory

Auditory Metrical Coordination of Attention on a Visual *n*-back Task

Music and speech are two important examples of behaviors that are structured in time. Many events in our environment occur with regularity, such as the dripping of a faucet, or the beat of a song. Events that occur at regularly spaced intervals can be described as rhythmic. A great deal of research has investigated how we perceive and synchronize ourselves with rhythmic periodicities. It has been demonstrated that a rhythmic context influences the processing of future events by synchronizing internal cognitive rhythms that focus attention on future points in time (Large & Jones, 1999; Large & Palmer, 2002). The extent to which our behavior and cognitive activity are controlled by internal rhythms is unknown, and intriguing. The reported commonalities of rhythmic behavior in music, speech, and ambulation imply that attention can be applied rhythmically, at regular intervals (Jones, Kidd, & Wetzel, 1981). The rhythmic coordination of attention is a cognitive process that underlies the perception of melodic changes (Jones, Boltz, & Kidd, 1982) and lexical cues (Pitt & Samuel, 1990), among others.

Research on rhythmic attending has been applied most often to musical contexts. There is a large body of research that examines and refines Jones's and her colleagues' theories in light of how people tap along to and perceive music. Tapping studies require participants to tap along to auditory rhythms. By measuring how closely the taps correspond with beat presentation, we can get an idea of how well participants' internal rhythms are synchronized with the external rhythms. An experimenter can manipulate levels of metric hierarchy, accent structure, the expressiveness of the music, and so on, measuring the effects on the participants' level of synchrony with the beat (Jones & Pfordresher, 1997; Drake & Bigand, 2000). These studies have shed light on the behavior of internal rhythms, and how they help us perceive and attend to rhythmic structure.

The current research extends findings about rhythmic attention to a non-musical context. Instead of testing the effects of an auditory rhythm on responses to other auditory stimuli, I test the effects on a popular working memory and attention task, *n*-back. In the *n*-back task, stimuli are presented at a steady pace, lending the task an inherent visual rhythm. It is a prime candidate to test the attentional effects of an auditory rhythm on a task unrelated to music or speech. However, at this point there has been no research on the effects of a simultaneous auditory rhythm on *n*-back performance. This study is the first to connect the *n*-back task with the extensive body of research on rhythm perception.

Kirchner (1958) was the first to use the *n*-back task, in an experiment testing the effects of aging on very short-term retention. Using an apparatus first designed and described by Welford (1952) for the purpose of studying serial learning, Kirchner had participants observe a row of 12 small lights, above a row of 12 associated keys. The lights would come on in a random sequence, and following each light activation, participants were instructed to press the key where the light had gone out *n* positions before. At the 2-back load, for example, Kirchner's task required participants to store two pieces of information while waiting for a third piece to appear. This would cue participants to compare this third piece to the first piece, looking for a possible match. After doing this comparison, participants would drop the first piece in preparation for future pieces of information. Kirchner assumed that this continual task of information manipulation measured participants' short-term memory retention abilities. He found that older people had lower accuracy and higher error rates than younger people, especially as *n* increased.

Anticipating the work of later theorists (Kahneman, 1973; Baddeley & Hitch, 1974), he thought that there must be some central system, with limited resources, that organizes this interchange of incoming and outgoing streams of information. He proposed that *n*-back was able to provide a performance measure for this central system.

The concept of working memory describes a limited-capacity system that retrieves, stores, and manipulates information, integrating it with long-term memory (Baddeley & Hitch, 1974). *N*-back has emerged as a commonly used measure of working memory performance (Kane, Conway, Miura, & Colflesh 2007). In modern versions of *n*-back, participants view a continuous stream of stimuli (letters, most commonly) and are instructed to press a key when they see a letter that matches the letter they saw *n* letters ago (known as a target). With a 3-back load, for example, the sequence “T, F, J, B, M, J” should elicit a correct response on the second “J” (typically, the task load is not increased beyond 3-back, because the difficulty of the task has a floor effect on performance). Participants must maintain and update their mental representation of the target items while responding to each item and dropping now-irrelevant items from memory (Kane, Conway, Miura, & Colflesh 2007). It has been widely used in neurophysiological studies of working memory involving continuous brain scanning, as it requires that participants continually engage in manipulation of working memory stores (Pesonen, Hämäläinen, & Krause, 2007). Research on correlations between *n*-back scores and scores on other working memory span tasks have found that, as Kirchner believed, *n*-back is not simply a test of short-term memory storage; rather, it requires more demanding cognitive processes that involve executive control and attention (Conway et al., 2005). Because *n*-back demands that executive attentional processes be engaged at regular points in time (with each letter presentation), it will be useful to examine the task in light of theories of rhythmic attending.

According to Jones (1986), a rhythmical approach to attention assumes that we attend to events in space and time in a rhythmical fashion. Attending is guided by internal rhythms that are set in motion, or synchronously driven by the ongoing temporal character of our environment. Jones' approach to attention draws on the work of Kahneman (1973) in assuming a limited-capacity system of attention. Kahneman's model of attention incorporates a central processor that constantly evaluates the demands of each task and adjusts attention accordingly, applying it to various cognitive processes, enhancing their efficiency. Attention can be thought of as a nonspecific mental resource that may be higher or lower at different points in time; a useful phrase for describing the relative level of attention at a point in time is "attentional energy." Large and Jones (1999) extended Kahneman's concept of attention and made it more specific. They proposed that internal rhythms can provide a rhythmic pulse that targets the allocation of attentional energy at different points in time. When conditions in the environment lead to a higher level of attention, the level of attentional energy at that moment is higher, raising the salience of events at that time.

The temporal structuring of auditory events coordinates perception by focusing attention on when a future event is likely to occur (Large & Jones, 1999), a phenomenon known as focal attending. When auditory events are presented at constant intervals, a rhythmic structure can be perceived, organizing notes and syllables. Thus, external rhythms create internal rhythms that guide the attending of future events. When notes are presented at a steady pace, the listener automatically expects future notes at specific times. Internal rhythms allocate higher levels of attention at times when an event is expected to happen. Large and Jones (1999) originally observed that with isochronous sequences (i.e., rhythms with equal spaces between beats), listeners were better at judging the temporal and melodic characteristics of a rhythmically expected tone, relative to a rhythmically unexpected tone. Accuracy was greater when the tone was close to the expected point in time. This finding has been interpreted as evidence for the entrainment of attending rhythms to external environmental regularities. Dynamic attending theory is the name that Large and Jones give their proposed system of attending rhythms.

In music, melodic and temporal accents give rise to a sense of meter (Lerdahl & Jackendoff, 1983). Meter provides a rich structure that chunks words and phrases into groups, identifies stress patterns, and adds emphasis on certain notes. As opposed to a nonmetric, simpler rhythm, a metric rhythm can be represented by hierarchical trees in which stronger beats exist at higher hierarchical levels. Because of their richer structure, metric rhythms are easier to remember and reproduce than nonmetric rhythms (Essens & Povel, 1985). Lerdahl and Jackendoff (1983) conceptualize metrical structure as a grid of beats at various time scales. According to this notational convention, horizontal rows of dots represent levels of beats, and the spacing between the dots at a particular beat level represents the periods and phases of the beat levels. Metrical accents are indicated in the grid by the number of coinciding dots at a particular point in time. Points at which many beat levels coincide are called strong beats; points at which few beat levels coincide are called weak beats. This concept of beat strength, as the coupling of multiple beat levels, fits neatly with the multiple attending rhythms of dynamic attending theory (Large & Jones, 1999).

Dynamic attending theory posits that internal rhythms synchronize themselves with (i.e., they entrain to) environmental regularities. But they also entrain to each other. Thus, an attending rhythm may entrain to another one with half the period, forming harmonic subdivisions of beats. When these two rhythms align, each representing a different beat level, a strong beat is perceived. Using dynamic attending theory, we can understand the concept of meter as the perceptual result when attending rhythms are coupled together to form an accent structure, a pattern of perceived strong and weak beats. Large and Palmer (2002) adapt metrical notation to dynamic attending theory (Large & Jones, 1999), proposing that each beat level corresponds with a specific internal rhythm. When these internal rhythms coincide on strong beats, attention is enhanced. See Figure 1 for a visual comparison of Lerdahl and Jackendoff's metrical notation, and Large and Palmer's coupling of internal rhythms.

Metric rhythms coordinate attentional processes in music and speech by making accented events more perceptually salient (Boltz, 1993; Port, 2003). By inducing a sense of meter, Jones, Boltz, and Kidd (1982) primed participants with various rhythms, manipulating contextual regularity to guide attention toward tones. Participants listened to a nine-tone sequence with a STRONG-WEAK-WEAK accent structure, a WEAK-WEAK-STRONG accent structure, or no accenting. Participants then judged whether a transposed comparison pattern was identical to the preceding sequence in which the rhythmic context was established. In half of the trials, the pitch of one of the tones was altered. The listeners exposed to the STRONG-WEAK-WEAK context were better able to recognize melodic differences at the fourth note location, and listeners exposed to the WEAK-WEAK-STRONG context were better able to recognize melodic differences at the sixth note location. Once a rhythmic context was established, participants were better at recognizing melodic differences at times when a rhythmic accent was expected. These results support the hypothesis that attention can not only be rhythmical but metrical as well, increasing at accented points in time.

The present study induced internal metric expectations with an auditory metric rhythm, and examined the effects on performance in a 3-back task. I examined whether the metrical accent structures created by various rhythms would affect performance on a working memory task in which the letters to be recalled would be presented simultaneously with the rhythm. Dynamic attending theory posits that internal attending rhythms allocate different amounts of attentional energy at various points in time, depending on the level of accent. I tried to determine if the accent structure of the beat would affect performance on the 3-back task in a manner congruent with the predictions of Large and Palmer (2002). I predicted that the internal attending rhythms arising from a three-beat metric rhythm would create an accent structure that would increase attentional energy on strong beats, therefore increasing performance (measured by detection rates and response times) for target letters that landed on these accented notes. I also predicted that the three-beat rhythm would provide a timeline that would match the timeline of the 3-back task, chunking stimuli into discrete groups, and increasing performance overall.

The study consisted of two experiments. In Experiment 1, a simple STRONG-WEAK-WEAK rhythm was used. In this rhythm, beats coincided with letter presentations, and there were no intermediate beats between letters. Effects of the beat on performance were examined, as well as the effects of beat strength. This experiment also introduced priming conditions, cueing participants at the start of each experimental block to notice targets on strong or weak beats. Intermediate beats were left out of the rhythm because they were thought to interfere with memory rehearsal between letter onsets, affecting task performance.

Experiment 2 complemented Experiment 1 by using a faster, subdivided three-beat rhythm (STRONG-weak-WEAK-weak-WEAK-weak). This rhythm had intermediate beats landing midway between letters, thereby doubling the speed of the auditory rhythm, introducing a new, lower level of metric hierarchy, and making the rhythm more salient. It was important to test the effects of a faster rhythm, because the speed of the *n*-back task is necessarily slower than the speed necessary for rhythm perception. To prevent a floor effect on *n*-back performance, letters must be presented at a rate far slower than the minimum rate for auditory rhythm perception (Fraisse, 1982). I predicted that the auditory rhythm would be more salient if it was subdivided with intermediate beats, doubling the tempo of the rhythm without affecting the task. Additionally, the effects of a subdivided two-beat rhythm (STRONG-weak-WEAK-weak) on the 3-back task were tested. I predicted that the subdivided two-beat rhythm would fail to effectively chunk the task stimuli into groups, as the timeline of the rhythm would no longer match the timeline of the 3-back task. Therefore, I predicted that the presentation of the subdivided two-beat rhythm would negatively affect performance on the 3-back task.

In both experiments, I collected information on musical experience. Previous research (Repp & Doggett, 2007) has shown that in some contexts, musicians (people with greater musical experience than a comparison population) have a greater ability to synchronize with auditory rhythms than nonmusicians. It has been proposed that musicians are more sensitive to the structure of a rhythm and may have more robust mental representations (Drake & Botte, 1993). I predicted that rhythms would have a stronger effect on musicians than on nonmusicians, as they would be more sensitive to its presence.

General Method

Overview

In two experiments, participants performed a continuous matching 3-back task that required them to indicate whether the current letter matched the letter presented three letter trials ago. Participants were exposed to various rhythms that were synchronized with letter presentation.

3-Back Task

Task stimuli consisted of single capital letters (43 pixels high, Helvetica font) presented in the center of a computer screen, drawn randomly from a set of consonants (vowels were excluded due to phonological similarity, and the letter *X* was excluded because of visual association with targets). Letters were displayed onscreen for 500 ms, at regular interonset intervals (IOIs) of 1750 ms.

Participants were told to indicate when the letter they saw matched the letter presented three letter trials ago. These letters are referred to as targets. During the task, participants responded to targets by pressing a button with the index finger of their dominant hand. Participants were instructed to respond as quickly as possible, while minimizing errors. Response times (RTs) and accuracy measures were recorded.

Auditory Stimuli

Participants wore Sony MDR-V700DJ headphones for the entirety of the experiment. In nonsilent conditions, an auditory rhythm was presented through the headphones. Participants were able to adjust the volume to a comfortable level. Isochronous rhythms were constructed, consisting of two or three different high-pitched, 50 ms tones. From highest to lowest, the tones were 779 Hz, 539 Hz, and 496 Hz. The higher tones were used to mark beats with stronger metric salience. In nonsilent conditions, a two-bar “count in” was played to acquaint participants with the rhythm before letters were presented. See Figure 2 for a graphic illustration of how the various rhythms in Experiment 1 and 2 were presented with the task stimuli.

Participants

Participants were recruited from the student population of Carleton College, and gave their informed and written consent to participate in the study. Experiment 1 and Experiment 2 were conducted on different weeks, and each experiment consisted of separate populations. Details on the individual populations are reported below. The study was approved by the Carleton College IRB committee. Participants completed the task in a single session lasting roughly 20 minutes. All participants reported normal hearing.

Procedure

Participants completed the experiment in 12 blocks of trials. Each block consisted of 33 letter trials. The first three trials of each block were never targets, and of the remaining trials, nine were targets. For blocks with a three-beat rhythm, five targets landed on strong beats and four landed on weak beats. Each participant was exposed to the conditions in counterbalanced, randomized order, with the constraint that all four conditions were sampled in every set of four blocks. A short break was provided between each block to allow participants to rest. Prior to the start of the actual task, participants completed a practice block of 66 letter trials, and were asked if they understood the task. All participants reported comprehension of the task following the practice block.

Lists of letters were counterbalanced between participants, and randomized within participants such that they never encountered the same series of letters. Presentation of the next letter was not dependent on the participant's response. The stimuli were generated and presented using PsyScope X software (MacWhinney, Cohen, & Provost, 1997) for Mac OS X on a 2006 15" MacBook Pro (Experiment 1) or a 2009 20" iMac (Experiment 2). PsyScope X was also used to record response data.

Data Analysis

Analyses focus on participants' sensitivity on the *n*-back task, as measured by *d'*. *d'* is a widely used measure of discrimination sensitivity (Macmillan & Creelman, 1991) that reduces noise by taking the participant's response bias (number of false alarms) into account. *d'* is equal to (z-score[hits / targets] - z-score[false alarms / possible false alarms]), in which "possible false alarms" represents the total number of trials that were not targets. *d'* is a useful measure because it incorporates "penalties" for false alarms; a participant's propensity for being "trigger-happy" with the button does not increase their *d'* score as it would increase simple accuracy rate (proportion of hits to misses). It is worth noting that most participants made only a small number of false alarms; bias corrections tended to be small. For each participant, *d'* values were computed using Microsoft Excel 2008 for Mac.

Additional analyses focused on RTs for correct responses, which were also computed using Microsoft Excel 2008 for Mac. In Experiment 1, participants responded by pressing a spacebar on a USB keyboard, which introduced some noise into the results, but was unlikely to introduce systematic noise that would affect data analysis. In Experiment 2, highly accurate RT data were collected with an ioLab Systems USB button box. Statistical analyses were computed using SPSS 16 for Mac.

Information regarding years of formal music training was collected and summed for each participant. For instance, a participant who had taken guitar lessons for four years and piano lessons for 11 years was given a musical experience score of 15 years.

Experiment 1

Participants were administered the 3-back task, and were informed to press a button immediately upon seeing a letter matching the letter presented three letters ago. On-screen presentation of letters coincided with the auditory presentation of beats in a three-beat rhythm. Because the three-beat timeline of the rhythm matched the three-letter distance tracked by participants in the task, target letters landed on beats with identical strength that of its match (i.e., a strong beat target referred to its match three letters ago, which also landed on a strong beat; see Figure 2A for a visual representation of the task). This would seem to present a mental framework around which to organize the task. I believed that the rhythm would provide a timeline to help chunk the 3-back task, providing more structure than when the beat is not present. Therefore, my first hypothesis was that participants would perform the 3-back task with greater accuracy when the task was accompanied by the auditory rhythm than when it was accompanied by silence.

The effects of beat strength were also examined. When a sense of meter is induced in listeners, more attention is placed on the strong beats than the weak beats. I induced a STRONG-WEAK-WEAK accent perception by constructing the rhythm with a higher tone on the downbeat (the first beat of the timeline) than on the other beats. I expected attention to be increased on strong beats, enhancing both letter storage and recall. When a letter is perceived with a strong beat, storage will be enhanced relative to weak beats. Three letters later, its matching target letter will also land on a strong beat, enhancing the process of recall and matching. My second hypothesis was that detection of strong beat pairs would be greater than detection of weak beat pairs because of increased attentional salience.

I also added priming conditions to the experiment. In some of the auditory beat conditions, the fourth letter of the experimental block was a target, which I believed would increase the likelihood of strong beat target detection. In other conditions, the fifth or sixth letter was a target, which I believed would increase weak beat target detection. Other conditions had no priming targets in the beginning. My third hypothesis was that priming conditions would strengthen responses to targets landing on the beat that the participant is primed to detect.

Previous research (Repp & Doggett, 2007) has shown that, compared with nonmusicians, musicians synchronize more accurately with very slow rhythms. At IOIs above 1600 ms, such as those in this experiment, musicians show greater synchrony when tapping along to the beat. This indicates a greater ability for "subjective rhythmization," the spontaneous perceptual grouping of successive rhythmic events, at slower tempos. As musicians are better able to perceptually group slow rhythms, the rhythm should be more salient for musicians than for nonmusicians. Therefore, my fourth hypothesis was that there would be an interaction between beat presence and musical experience: the presence of the beat would enhance task performance to a greater extent for musically experienced participants than for musically inexperienced participants. I also predicted an interaction between beat strength and musical experience: compared to nonmusicians, musicians would show even stronger performance for targets landing on strong beats than on weak beats.

Method

Participants. Undergraduates from Carleton College (14 males, 15 females, M_{age} = 20.2 years, age range: 18-23 years) were recruited from psychology courses, and were informed that two participants would be randomly selected to receive $50.

Self-reported musical experience (*M* = 7.90 years, *SD* = 5.76, range = 0 to 17) was fairly dichotomous, with 16 participants having zero to nine years of experience and 13 having ten to seventeen years of experience.

Materials and procedure. Two independent variables were manipulated within participants: Rhythm/prime condition (no prime, strong prime, weak prime, and silent), and for the nonsilent conditions, beat strength (strong and weak). The rhythm presented in the nonsilent conditions was a three-beat STRONG-WEAK-WEAK rhythm. Psychological research on rhythm measures time in milliseconds rather than beats per minute (bpm), and that convention will be used here. Tones were presented at 1750 ms IOIs, equal to the IOIs of *n*-back letter presentation. Tone presentation was always simultaneous with letter presentation.

In the strong prime condition, the fourth trial of the block (the first possible target landing on a strong beat) was a target, priming participants to notice targets landing on strong beats. In the weak prime condition, the fifth or sixth trial of the block was a target, priming participants to notice targets landing on strong beats. In the no prime condition, none of the first six trials was a target. In the silent condition, there was no auditory beat or “count in” period.

Participants pressed the spacebar on a Dell USB keyboard to indicate that they had detected a target.

Results

Effects of rhythm presence. A paired-sample *t*-test was performed to compare performance between silent and nonsilent conditions. There was no significant effect for rhythm presence on *d’*, *t*(28) = -0.31, *ns*, or on RT, *t*(28) = -0.89, *ns*.

Effects of beat strength. In the nonsilent conditions, the effects of beat priming and beat strength were examined with a 3 × 2 (Beat priming [no prime, strong prime, weak prime] × Beat strength [strong, weak]) repeated-measures analysis of variance (ANOVA) for *d’* and RT. There was no main effect for beat strength on *d’*, *F*(1, 27) = 0.52, *ns*. However, there was a main effect for beat strength on RT. Participants responded faster to targets on strong beats (*M* = 693 ms, *SD* = 112) than to targets on weak beats (*M* = 731 ms, *SD* = 140), *F*(1, 27) = 11.49, *p* = .002. This enhanced response to strong beat targets indicated increased attentional salience on strong beats. Effects were consistent across participants, with 21 (72.41%) participants showing an enhanced response to strong beat targets.

Effects of beat priming, and interaction with beat strength. There was no main effect for beat priming on *d’*, *F*(2, 54) = 0.31, *ns*, or on RT, *F*(2, 54) = 0.47, *ns.*

There was no significant interaction between beat priming and beat strength on *d’*, *F*(2, 54) = 0.38, *ns*, or on RT, *F*(2, 54) = 0.02, *ns*.

Effects of musical experience, and interaction with rhythm presence and beat strength. Because of the bimodal distribution of years of musical experience, musical experience was encoded as a variable with two levels (*low musical experience* and *high musical experience*), and used as a between-subjects factor in the above repeated-measures ANOVA. The 16 participants with zero to nine years of musical experience were encoded as *low musical experience* (*M* = 3.31 years, *SD* = 2.66). The 13 participants with ten to seventeen years of musical experience were encoded as *high musical experience* (*M* = 13.54 years, *SD* = 2.47).

There was no main effect for musical experience on *d'*, *F*(1, 27) = 0.35, *ns*, or on RT, *F*(1, 27) = 0.02, *ns.* There was no interaction between musical experience and rhythm presence on *d'*, *F*(1, 27) = 0.07, *ns*, or on RT, *F*(1, 27) = 0.02, *ns*. Similarly, there was no interaction between musical experience and beat strength on *d'*, *F*(1, 27) = 0.04, *ns*, or on RT, *F*(1, 27) = 0.17, *ns.*

Discussion

My main goal in Experiment 1 was to assess the effects of an auditory three-beat metric rhythm on detection rates and RTs in the 3-back task. I found that neither measure of performance changed between the silent and nonsilent conditions. I also found no interactions between beat strength and beat priming conditions; early instances of a strong or weak beat target did not prime the participant to notice strong or weak beat targets later in the experimental block. There were no main effects of musical experience on performance. Nor did musical experience interact with beat presence or beat strength.

Most significantly, I found that participants in all rhythm conditions responded more quickly to targets that landed on strong beats. This supported my hypothesis that strong beats would increase the attentional salience of task stimuli, improving participants' storage and recall of letters. It could be argued that the findings of enhanced RT following strong beats simply replicate previous findings that when tapping along to a rhythm, the most salient position (i.e., the strongest beat) elicits the fastest response (Ladinig, Honing, Haden, & Winkler, 2009). Thus, faster RTs on strong beats may not necessarily indicate enhanced storage and recall on 3-back, but rather a response to the rhythm alone. However, it is important to note that participants' tendency to respond faster to strong beats did not increase the number of false alarms enough to decrease *d'* scores; they scored equally well on strong beats, indicating that they were not reflexively pressing the button in response to the accented beat. Although I found no effects on *d',* the effects on RT, accompanied by no decrease in *d'* scores, may indicate that strong beats raise attention on either letter storage or recall.

It is impossible to determine whether decreased RTs for strong beat targets is due to raised attention on the initial storage of the prime letter, or on the recall that occurs upon presentation of the target letter. This is because strong beat targets always referred back to strong beat primes and weak beat targets always referred back to weak beat primes. Experiment 2 addressed this methodological problem by introducing a beat condition in which the beat strength of target letters did not match the beat strength of the prime letter to which they referred.

The results from Experiment 1 would be even more meaningful if *d'* scores were affected by either beat presence or beat strength. To this end, I tried to find a way to increase the salience of the rhythm. The main flaw of Experiment 1 was the relatively long IOI between beats. A rate of 1750 ms IOI was used in order to optimize timing of the 3-back task. This is a very fast rate considering the difficulty of the task, and is near the lower limit for what is typically used for 3-back. Problematically, however, this rate is on the upper limit of temporal continuity for auditory rhythms—Fraisse (1982) proposed 1800 ms as the maximum rate of IOIs for subjective rhythmization. Around this upper limit, it is difficult to say that any sort of rhythmic processes are perceptually salient, and could modulate attention. Experiment 2 addresses this methodological problem as well.

Experiment 2

As in Experiment 1, participants were administered the 3-back task, accompanied by various auditory rhythms. To minimize the possibility that the slower rhythm from Experiment 1 was not rhythmically salient, a faster. subdivided version of the rhythm was created. This new rhythm added intermediate beats halfway between the presentation of each letter (STRONG-weak-WEAK-weak-WEAK-weak instead of STRONG-WEAK-WEAK). This addition subdivided the beat, adding another level of metric hierarchy, and also decreased the IOIs to 875 ms, half the IOIs of *n*-back letter presentation. I hypothesized that this new, faster rhythm would improve the salience of the rhythm and increase 3-back performance relative to the silent condition. See Figure 2B for a visual representation of how this rhythm lined up with the task stimuli.

I also tested the effects of a subdivided two-beat rhythm (STRONG-weak-WEAK-weak) presented at a constant rate of 875 ms IOI. This rhythm was thought to be metrically salient, but would have a two-beat timeline incompatible with the 3-back task. In the two-beat rhythm, a target landing on a strong beat refers to a letter that originally landed on a weak beat. This mismatch of beat strengths in target letter pairs is unlike the three-beat rhythms, in which strong beat targets always refer to a letter that originally landed on a strong beat. I hypothesized that this beat strength mismatch in the two-beat rhythm would decrease the ability of the rhythm to successfully chunk the task, and that performance would be least in the subdivided two-beat condition. See Figure 2C for a visual representation of how this rhythm lined up with the task stimuli.

Method

Participants. There was no overlap in participants between the two experiments; an entirely new population was recruited. Undergraduates from Carleton College (13 males, 16 females, M_{age} = 20.7 years, age range: 18-24 years) gave their informed and written consent to participate in the study. Participants were compensated for their time with baked goods.

As in Experiment 1, self-reported musical experience (*M* = 12.60 years, *SD* = 10.99, range = 0 to 41) was fairly dichotomous, with 14 participants having zero to nine years of experience and 15 having eleven to forty-one years of experience.

Materials and procedure. Two independent variables were manipulated within participants: Rhythm condition (silent, three-beat, subdivided three-beat, and subdivided two-beat), and for the nonsilent conditions, beat strength (strong and weak). The rhythms presented in the nonsilent conditions were either a three-beat rhythm with 1750 ms IOIs (STRONG-WEAK-WEAK), a subdivided three-beat rhythm with 875 ms IOIs (STRONG-weak-WEAK-weak-WEAK-weak), or a subdivided two-beat rhythm with 875 ms IOIs (STRONG-weak-WEAK-weak). Tones were presented simultaneously with letter presentation, and in the faster, subdivided rhythms, tones were additionally presented halfway between letters.

Participants pressed a button on an ioLab Systems USB button box. This yielded more accurate RT data than the USB keyboard used in Experiment 1.

Results

Effects of rhythm type. The effects of rhythm type and beat strength were examined with a 4 × 2 (Rhythm type [silent, three-beat, subdivided three-beat, and subdivided two-beat] × Beat strength [strong, weak]) repeated-measure analysis of variance (ANOVA) for *d'* and RT. The data for the silent condition was reproduced as a "dummy" variable to allow for analysis, despite the irrelevance of beat strength in this condition. There was a main effect for rhythm type on RT, *F*(3, 78) = 4.76, *p* = .004, but not on *d'*, *F*(3, 78) = 0.81, *ns*. *Post hoc* paired-sample *t*-tests were performed to compare performance between the four rhythm conditions. The subdivided rhythms (subdivided three-beat, and subdivided two-beat) that were expected to be more rhythmically salient than the nonsubdivided rhythm (three-beat), each produced faster RTs than both the silent condition and the three-beat condition. In the subdivided three-beat condition, participants showed significantly faster RTs than in either the three-beat condition, *t*(28) = 3.13, *p* = .004, or the silent condition, *t*(28) = 3.22, *p* = .003. In the subdivided two-beat condition, participants also showed significantly faster RTs than in either the three-beat condition, *t*(28) = 3.16, *p* = .004, or the silent condition, *t*(28) = 2.92, *p* = .007.

Effects of beat strength, and interaction with rhythm type. As in Experiment 1, there was no main effect for beat strength on *d'*, *F*(1, 26) = 1.32, *ns*, but there was again a main effect for beat strength on RT, *F*(1, 26) = 10.39, *p* = .003. Participants responded faster to targets on strong beats (*M* = 607 ms, *SD* = 134) than to targets on weak beats (*M* = 651 ms, *SD* = 141). This enhanced response to strong beat targets indicated increased attentional salience on strong beats. Effects were consistent across participants, with 21 (72.41%) participants showing an enhanced response to strong beat targets. See Figure 3 for a graph of RTs across beat type and beat strength conditions.

Effects of beat strength were examined for each individual beat type using *post hoc* paired-sample *t*-tests for RT. In the subdivided three-beat condition, participants showed significantly faster RTs on strong beats compared to weak beats, *t*(27) = 2.23, *p* = .034. To a less significant degree, this effect was repeated in the three-beat condition, *t*(27) = 1.95, *p* = .062, and in the subdivided two-beat condition, *t*(28) = 1.83, *p* = .079.

There was no interaction between beat strength and rhythm type on *d'*, *F*(3, 78) = 2.03, *ns*, or on RT, *F*(3, 78) = 1.41, *ns*.

Effects of musical experience, and interaction with rhythm type and beat strength. Because of the bimodal distribution of years musical experience, musical experience was encoded as a variable with two levels (*low musical experience* and *high musical experience*), and used as a between-subjects factor in the above ANOVA. The same numbers used to group participants in Experiment 1 were used in Experiment 2. The 14 participants with zero to nine years of experience were encoded as *low musical experience* (*M* = 4.04 years, *SD* = 3.49). The 15 participants with eleven to forty-one years of experience were encoded as *high musical experience* (*M* = 20.53 years, *SD* = 9.46).

Musical experience had a significant main effect on *d'* in all rhythm types, *F*(1, 26) = 6.69, *p* = .016. *d'* scores were higher for participants with high musical experience (*M* = 2.38, *SD* = 0.65) than for participants with low musical experience (*M* = 1.80, *SD* = 0.56).

There was no interaction between musical experience and beat strength on *d'*, $F(1, 27) = 0.02$, *ns*, or on RT, $F(1, 27) = 0.02$, *ns*. There was no interaction between musical experience and beat type on *d'*, $F(3, 81) = 0.38$, *ns*, or on RT, $F(3, 81) = 0.53$, *ns*.

A 3-way interaction between musical experience, rhythm type, and beat strength on *d'* approached significance, $F(2, 52) = 2.64$, $p = 0.081$. Further examination of the data revealed that in all rhythm conditions except the subdivided two-beat condition, musically experienced and musically inexperienced participants performed equally well on strong and weak beats (no interaction between musical experience and beat strength). In the subdivided two-beat condition, however, musically inexperienced participants showed decreased performance on weak beats, a tendency not displayed by musically experienced participants. However, this interaction was not statistically significant and did not warrant further *post hoc* testing.

Discussion

In both methodology and results, Experiment 2 was an improvement on Experiment 1. The primary finding from Experiment 1, that participants responded faster to strong beat targets than weak beat targets, was reproduced with more trustworthy RT data (due to the use of a button box with an internal clock).

The subdivision of the original rhythm, in order to double tempo and increase perceptual salience, was a success. Overall reaction times were significantly lower for the two subdivided rhythms, compared to the silent and nonsubdivided three-beat conditions. It is possible that this indicated a possible increase in levels of overall arousal when exposed to a fast rhythm. Effects of beat strength on RT were especially pronounced in the subdivided three-beat rhythm. All of these findings suggest that the perceptual salience of the rhythms were successfully increased.

However, there were no effects of beat type or beat strength on *d'* scores. It appears that although auditory rhythms have an effect on task RTs, it does not affect *d'* scores. There are several reasons why this may be the case. The first possibility is that *d'* is not a sensitive enough measure to display significant changes across conditions, with the current *N*. RT is a more sensitive measure than *d'*, and therefore is more likely to show significant effects.

The second possible reason for the lack of effect on *d'* is that the rhythm does not in fact facilitate performance on the task at all, and that the RT findings cannot be interpreted as supporting this notion. My finding that RTs were faster for strong beat targets could be interpreted as supporting my hypothesis that strong beats increase the attentional salience of task stimuli, improving participants' storage and recall, but it could also be argued that this effect is due to overall arousal, unrelated to the task. It is well documented that the most salient position (i.e., the downbeat) elicits the fastest response when tapping along to a rhythm (Ladinig, Honing, Haden, & Winkler, 2009). Thus, faster RTs on strong beats may not necessarily indicate enhanced performance on 3-back, but rather a response to the rhythm alone. However, it is important to note that participants' tendency to respond faster to strong beats did not decrease performance; they performed the task equally well, indicating that they were not reflexively pressing the button in response to the accented beat. Although I found no effects on *d',* my position is that the effects on RT, accompanied by no decrease in *d'*, indicate increased attention given to the task on strong beats.

The other question that Experiment 2 helped to address was the issue of whether the rhythm would facilitate stimulus storage or stimulus recall more strongly. The subdivided two-beat rhythm provided a way to test this. With the three-beat rhythms, targets always landed on a beat with equal strength to the letters to which they referred. So there was no way to test whether enhanced performance was due to the strong beat on the the prime letter or the strong beat on the target letter. With the subdivided two-beat rhythm, however, I was able to test whether performance was higher on weak-strong prime-recall pairs, or strong-weak prime-recall pairs. There was a strong trend towards faster RTs on the former pairs than the latter pairs, suggesting that the attention-enhancing effects of the strong beat were important upon letter recall and button response rather than during storage of prime letters.

Additionally, the results from Experiment 2 demonstrated a robust effect of musical experience on *d'* scores. Musically experienced participants were better at the task in all conditions; notably, they were better at the task even when the beat was not present. For whatever reason, it appears that the musical participants possess greater skill at cognitively challenging tasks such as *n*-back. To understand why the musical participants were better at *n*-back, it may be useful to consider the nature of sight-reading (reading and producing a piece of music at first sight).

When sight-reading, musicians look ahead of where they are playing. Using an eye tracker, an experimenter can measure the distance between the note that a musician is looking at, and the note that a musician is playing. This distance, known as the eye-hand span, increases with the musical experience of the performer. For less skilled piano players, the eye-hand span is about half a beat, while for experienced piano players it is closer to two beats (Truitt, Clifton, Pollatsek, & Rayner, 1997). The increased eye-hand span in experienced musicians indicates stronger abilities in the kind of cognition involved in sight-reading. Sight-reading involves recalling, processing, and executing previously seen notes, while storing new ones. This is very similar to the processes used during the *n*-back task, in which participants recall, process, and match previously seen letters, while storing new ones. The process of storing and manipulating notes within the eye-hand span is not dissimilar from the process of storing and manipulating letters in *n*-back. It is intuitive that participants who may have increased sight-reading abilities should show stronger performance on the *n*-back task.

Since the task itself, aside from rhythm conditions, did not vary between Experiment 1 and Experiment 2, it is curious that musicians did not also show stronger performance in Experiment 1. I attribute this to population differences between the experiments. For one thing, the participants in Experiment 2 were more musically experienced in general. There was also a greater disparity in Experiment 2 between the average musical experience for the *low musical experience* and *high musical experience* groups, which may have exaggerated differences.

Although I did not collect highly specific data on what kind of musical experience participants may have had, because of the similarities between *n*-back and sight-reading, I propose that the population in Experiment 2 may have been more experienced sight-readers. A greater ability to sight-read among the Experiment 2 population might explain why this effect appeared in Experiment 2 and not in Experiment 1. If an average participant in Experiment 1 reported themselves as musically experienced but had only played improvisationally, they would lack the sight-reading abilities that might enhance their performance on *n*-back.

After the conclusion of the experiment, I informally asked all of my participants whether they classified themselves as an “experienced sight-reader.” A cursory inspection of the data did not reveal differences in the two populations’ self-reported sight-reading ability. But self-report is likely not a useful way to measure sight-reading ability. Future research would do well to examine the relationship between performance on the *n*-back task and sight-reading performance as measured by an objective, reliable test such as the Watkins-Farnum Performance Scale (Watkins & Farnum, 1954). Future studies might also see if there are other cognitive tasks in which musicians or sight-readers tend to excel. It would be interesting to see what sort of cognitive skills are gained during musical training.

Summary and Concluding Discussion

This study suggested that an auditory rhythm does have effects on performance in the *n*-back task. Relative to silence, fast rhythms lowered overall RTs. Additionally, targets landing on strong beats were detected more rapidly than targets landing on weak beats. To understand just how an auditory rhythm can coordinate attentional processes, it may be of interest to speculate on what is going on in the brain when we are exposed to an auditory rhythm. The oscillatory rhythms proposed by Large and Jones (1999) represent a useful theoretical construct that is analogous to certain kinds of observed brain function that may correspond with rhythmic attention.

Large and Jones (1999) modeled attentional focus as a system of internal oscillators. These oscillators are theoretical constructs that model the internal rhythms that place attention to regularly expected events. They argue that oscillators apply expectancy pulses (timed increases in attentional energy) for auditory events, facilitating a listener's response to information. The attentional energy applied by a system of oscillators facilitates perception of melodic changes, perception of time, and speech perception (Boltz, 1993; Barnes & Jones, 2000; Pitt & Samuel, 1990). Rather than being an all-or-none affair, attention can be greater or less at different points in a rhythm, depending on the states of attentional oscillators (Jones, Kidd, & Wetzel, 1981) (see

Figure 2 for graphs of metrical percept, illustrating the amount of attentional energy applied at each point in the rhythms of the current study).

Attending rhythms can entrain not only to external rhythms, but to each other. Meter is the perceptual result of the entrainment of attending rhythms to each other in a hierarchical fashion (London, 2001). Large and Palmer (2002) describe a computational system that models metric perception as the combination of internal oscillators that guide expectancy pulses. Different oscillators entrain to different metrical levels. Oscillators also entrain to each other, preserving phase and period relationships characteristic of hierarchical metrical structures. When listeners are exposed to an isochronous beat, the strongest oscillatory patterns occur at the stimulus frequency. But oscillations are also observed at harmonic ratios (e.g., 2:1 and 3:1) slower than the stimulus frequency, and subharmonic ratios (e.g., 1:2 and 1:3) faster than the stimulus frequency. Multiple harmonic oscillators track different periodic components, or levels of beats (Large & Palmer, 2002). In a typical 3/8 rhythm (a time signature consisting of three eighth-notes in a measure), there may be an oscillator responding at the start of each measure (the downbeat), and other oscillators responding at an eighth-note or sixteenth-note level. These oscillators entrain to the music as well as to each other. For a listener exposed to a piece of music, beat strength is maximized when a larger number of oscillators respond at the same time. For instance, the downbeat occurs when the measure, eighth-note, and sixteenth-note oscillators respond simultaneously (see Figure 1, and imagine that each horizontal row of dots represents the state of a simplified “on-off” oscillator). Consequently, events on the downbeat are more perceptually salient than events on the next sixteenth-note, when only the one sixteenth-note oscillator responds.

It is important to clarify the metaphorical status of these oscillations; are internal oscillations merely a theoretical model to describe cognition of rhythmically occurring events, or do they exist as physical neural oscillations? The theory of internal oscillators came out of behavioral observations, rather than electroencephalographic studies, but the concept is not purely a processing metaphor (Jones, 1976). Perceptual rhythms are a fair approximation of processes within the central nervous system, and are tied to measurable biological phenomena; we can observe oscillations in the brain that correspond to the proposed attentional oscillators. In a rhythmic tapping task, the neural dynamics of entrainment were studied by measuring magnetoencephalographic brain wave responses (Thaut, 2003). Consistent engagement of distinct neural circuits in the cerebellum across rhythmic tasks suggest a cerebellar role in the temporal organization of music perception. Temporal information processing may be coded on a cellular level in the oscillatory timing patterns of synaptic networks in the auditory system. These oscillations may subsequently entrain other brain areas via neural resonance.

Large and Snyder (2009) propose a resonance model of rhythm perception, seeking to identify a neural correlate of oscillatory behavior. They hypothesize that the perception of pulse and meter result from rhythmic bursts of neural activity in response to musical rhythms. The theory of neural resonance to rhythmic stimuli holds that internal temporal patterns are intrinsic to the physics of the neural systems involved in perceiving, attending, and responding to auditory stimuli (Large & Snyder, 2009). Listeners experience auditory events in relation to these oscillations. Neural oscillations also can resonate at higher orders; this hierarchical nesting of oscillations is similar to the metric grid described by Lerdahl and Jackendoff (1983), and is likely associated with meter perception (Large & Palmer, 2002).

The resonance model proposed by Large and Snyder arose in part from their previous work on gamma band activity (GBA) as a possible neuroelectric correlate of pulse perception and expectation (Snyder & Large, 2005; Snyder & Large, 2004). They investigated evoked (phase-locked to the stimulus) and induced (following the evoked response) GBA in response to metric rhythms that included missing tones. Participants listened to a rhythm composed of alternating loud-soft tones. Induced GBA peaks occurred around tone onset with a latency not significantly different than 0 ms, whereas evoked GBA peaks occurred following tone onset with a latency significantly longer than 0 ms. When tones were omitted, induced GBA remained present, while evoked GBA was diminished. Additionally, induced GBA differs in power in response to strong and weak beats, suggesting sensitivity to metrical structure (Zanto, Snyder, & Large, 2006). The occurrence of induced GBA peaks around tone onset, its persistence in the absence of tones, and its sensitivity to meter, suggest that induced GBA may be a neural correlate of rhythmic expectancy, and physical evidence of the theoretical oscillations proposed in dynamic attending theory (Large & Jones, 1999).

An intriguing and unexpected result of this study was the improved performance displayed by musicians relative to nonmusicians. This result begs further questioning regarding cognitive structures that may be enhanced by musical training. It appears that sight-reading engages similar cognitive skills as *n*-back, namely the execution of previously stored information while simultaneously processing and storing new information for future execution. A future study might correlate performance on *n*-back with performance on the Watkins-Farnum Performance Scale (Watkins & Farnum, 1954), a popular measure of music sight-reading ability.

The success of this experiment suggests that there may be future success in applying an auditory rhythm to other non-musical contexts. One possible experiment would be to present a metric rhythm alongside a steadily presented Stroop task (Stroop, 1935), and see if attention would be increased for words presented on a strong beat, helping participants to inhibit their automatic response. Findings about metric coordination of attention have been applied to speech and music, but rarely to cognitive tasks. Seldom has the question been asked, do we think rhythmically? This is an area of research that is wide open, and ripe for exploration.

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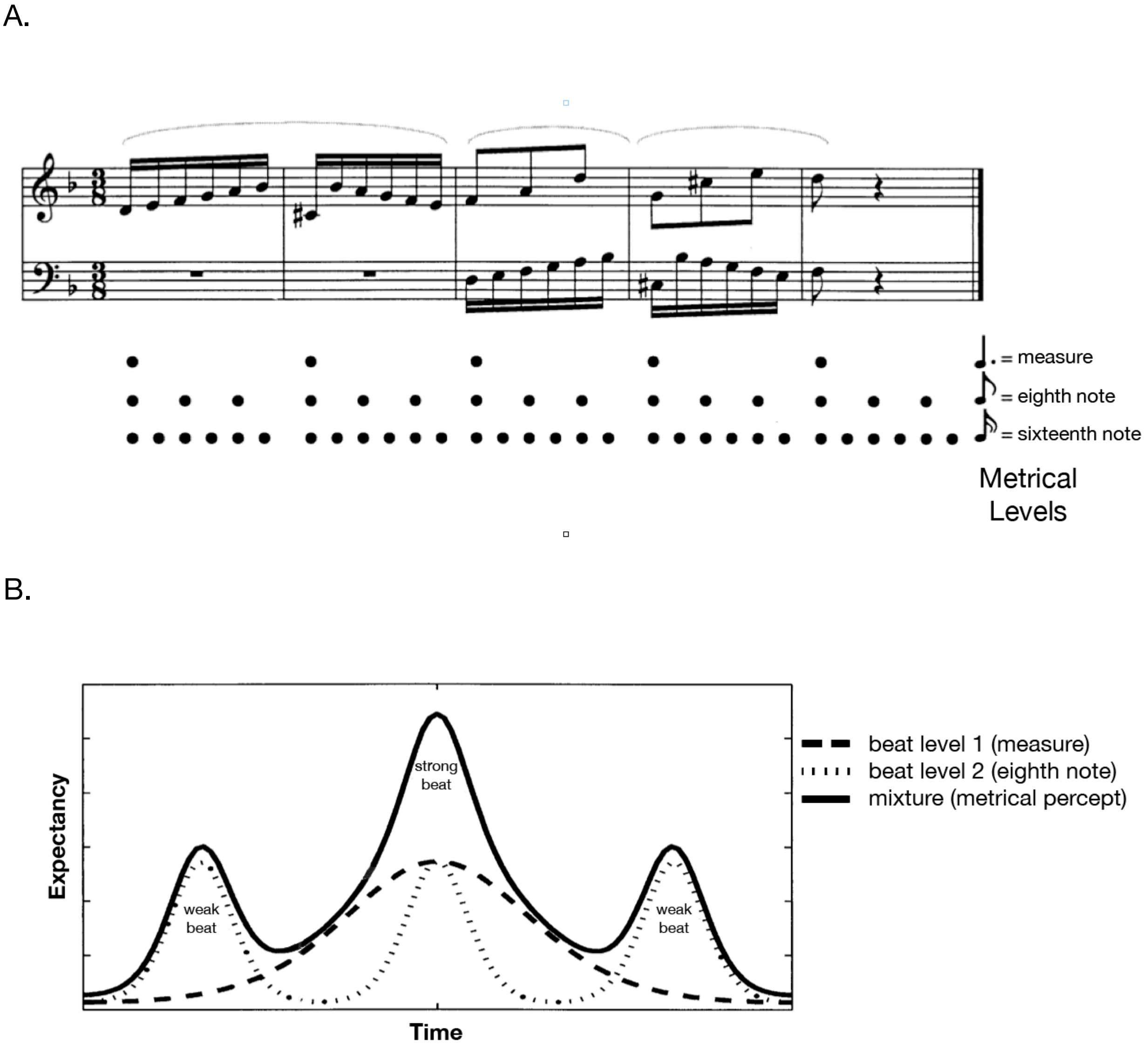

Figure 1. This example demonstrates how metrical grid notation corresponds directly with internal rhythms that drive meter perception. (a) Metrical grid notation indicates beat strength via metrical stress patterns in the opening section from 2-part invention in D-minor, by J.S. Bach. (b) Beat expectancy levels, based on a mixture of two oscillations. Adapted from “Perceiving temporal regularity in music,” by E. W. Large, and C. Palmer, 2002, *Cognitive Science, 26*, p. 1.

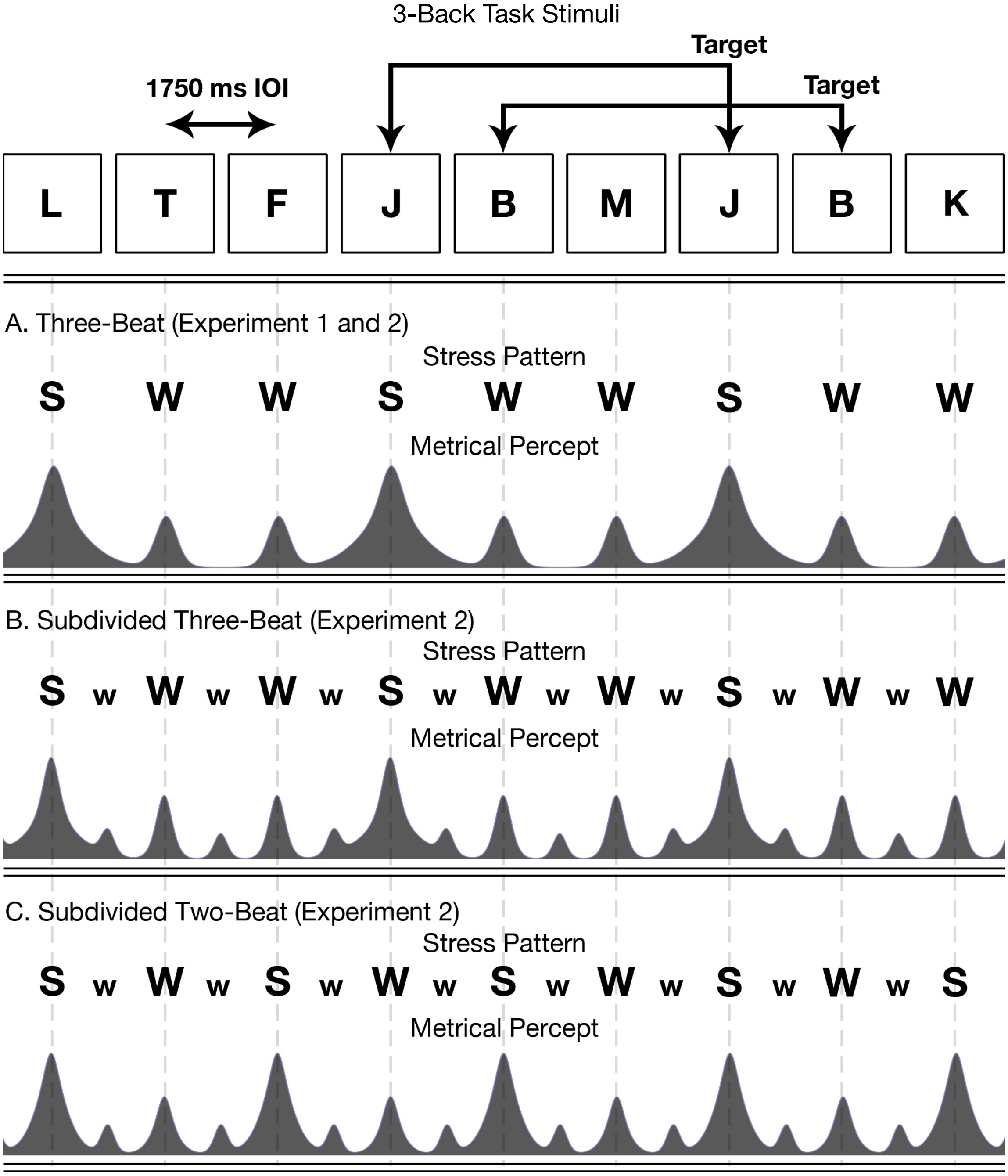

Figure 2. Illustration of the 3-back task. The three rhythms used in the study are displayed as a series of strong and weak beats, and as a profile of predicted metrical percept (Large & Palmer, 2002). The metrical percept profile represents the amount of attention allocated on each beat. (a) The nonsubdivided three-beat rhythm used in Experiment 1 and 2. (b) The subdivided three-beat rhythm and (c) the subdivided two-beat rhythm used in Experiment 2.

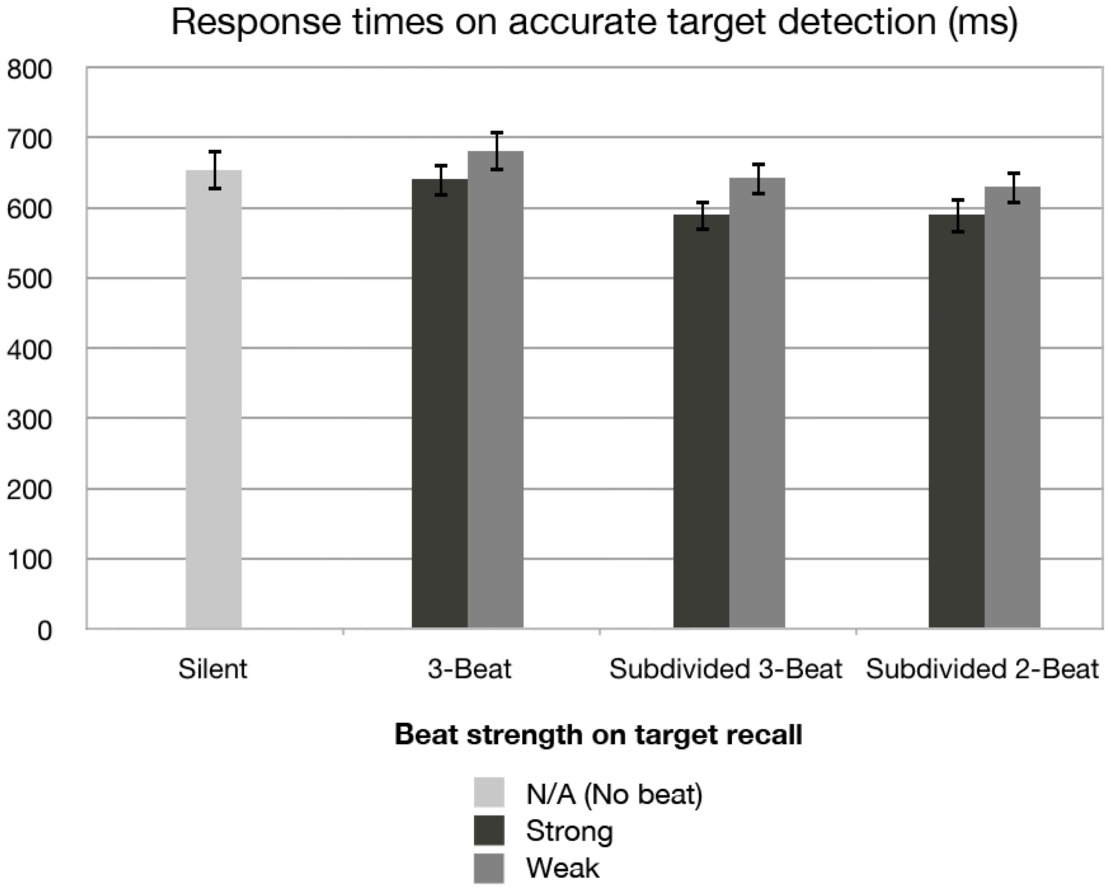

Figure 3. Mean response times (ms) for correct target detections in Experiment 2 ($N = 29$). A repeated-measures ANOVA revealed a main effect of both beat strength and rhythm type on RT. *Post hoc* paired-sample t-tests showed that strong beat targets were detected more rapidly than weak beat targets in the subdivided three-beat rhythm. Additionally, *post hoc* paired-sample t-tests showed that all targets (on both strong and weak beats) were detected more rapidly for the two subdivided rhythms, relative to both the silent condition and to the nonsubdivided three-beat rhythm. Error bars represent standard errors.