Quantitative and Subjective Assessment of

Rhythmic Performance Abilities in a Musically Untrained Sample

by

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ABSTRACT

Rhythmic synchronization abilities have been extensively studied in experimental research, but individual differences in these abilities are only beginning to be understood. Ecologically valid measurement of such individual differences, focusing on cross-culturally universal musical behaviors, will be essential to evaluating hypothesized evolutionary signaling functions of musical abilities. In this study, 46 male, right-handed, musically untrained subjects produced rhythmic output by drumming on electronic drums pads connected to a computer. They completed paced and unpaced isochronous tapping tasks and simple pattern synchronization tasks, and improvised creative musical performances (with and without a metronomic beat). Reliable estimates were produced of individual differences in two domains of untrained performers' rhythmic accuracy abilities (synchronization and continuation). Subjects' objective synchronization accuracy was significantly correlated with the rated rhythmic accuracy and creativity of their improvised performances when paced by a metronome. The results suggest that rhythmic accuracy and rhythmic creativity are somewhat overlapping abilities, and might both constitute reliable indicators of neurophysiological functioning.

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Introduction

Adaptationism and human creative abilities

The application of adaptationism to generate and test evolutionary hypotheses about animal behavior—originating in 1970s sociobiology—has revealed the design and information content of many behavioral and morphological signals in non-human animals (Andersson, 1994). Direct application of the methods of sociobiology to human behavior proved difficult, however, until a cognitive approach to evolutionary hypothesis testing was outlined (Barkow, Tooby, & Cosmides, 1992). Because the superficial appearance of functional design in human behavior, particularly when it satisfies a consciously accessible goal, may often be a result of exapted learning mechanisms (Andrews, Gangestad, & Matthews, 2002), a clear specification of the modular function of universal cognitive adaptations—such as the types of input that are used, the computational processes performed, and the specific types of behavioral output or motivational states (leading indirectly to adaptive behaviors) produced by the proposed units of cognitive function—has been a key element of rigorous hypothesis testing in evolutionary psychology.

Adaptationist hypotheses of the origins of creative and artistic abilities have been particularly difficult to test through specification of design details. As sexually attractive, apparently wasteful extended phenotypes, these modes of behavior suggest a function in signaling phenotypic quality for mate attraction (Miller, 2000a). Several studies have demonstrated a relationship between developmental stability (a phenotypic outcome partially reflecting genetic quality, measured in humans as a composite of the left-right asymmetry of bilateral traits) and general intelligence (e.g., Furlow, Armijo-Prewitt, Gangestad, & Thornhill, 1997; Prokosch, Yeo, & Miller, 2005; Bates, 2007; but c.f. Johnson, Segal, & Bouchard, 2008). The possibility that creative displays may convey valid information about phenotypic quality to conspecifics as part of a sexually selected signaling system has been investigated in the behaviors of both signalers and receivers: rated creativity of individual's output prompted by creative writing tasks is moderately predicted by general intelligence (Miller & Tal, 2007), creativity in short-term sexual partners is increasingly preferred over wealth by women in the fertile window of the ovulatory cycle, during which many indicators of genetic quality tend to be more strongly favored (Haselton & Miller, 2007); and activating mating goals in men promotes a switch to more creative uses of verbal ability (Griskevicius, Cialdini, & Kenrick, 2006).

For identifying candidate behaviors and generating predictions for the specific functional design of cognitive mechanisms underlying creative intelligence signals, however, the standard criteria used in evolutionary psychology may not be applicable (Miller, 2000b). A signal of developmental stability as reflected in mental fitness may not show a complex fit between its functional design and the ancestral information structure, but rather a conspicuously complex precision that provides a valid index of many different cognitive abilities. If the empirical fact of a positive manifold between mental abilities—the existence of the *g* factor (Jensen, 1998)—is explained by general effects of individual differences in developmental stability, over developmental time, on the efficient functioning of all cognitive modules, then any behavior that produces a reliable index of intelligence must do so by revealing individual differences in the functioning of a large number of cognitive modules. Supporting this causal hypothesis of general intelligence, recent studies have found that the *g*-loadings of cognitive tests are strongly predicted by the extent to which they tap the functions of diverse regions of the brain (Colom, Jung, & Haier, 2006), and by the strength of the relationship of each test with developmental stability (Prokosch, Yeo, & Miller, 2005).

From this perspective, the cognitive approach to evolutionary psychology becomes intractably complex when applied to the generation of cognitive ability signals. The signal content of a putative intelligence display, such as musical performance, could not be traced to the efficient function of any small, easily defined set of cognitive abilities. Conversely, a signaling behavior that did not rely on individual differences in a very large number of cognitive abilities would be unlikely to evolve, because it would necessarily have a weak relationship with genetic quality (mediated by a low *g*-loading), and would cause insufficient selection pressure for conspecifics to evolve signal responses. Rather, if human displays have evolved to signal diverse differences in cognitive ability, these must contain an index of many abilities, each honestly conveyed by the complex details of the signal content. The creative use of multiple modes of expression may produce such "embodied index" signals. Because of the complexity of information content in such signals, quantitative measurement of such signals is difficult; researchers must investigate signal content indirectly, relying on relationships between the signaler phenotype and the behavioral effects of putative signals on receivers, including ratings of display quality.

Another causal perspective on general intelligence may produce more clearly testable hypotheses about the functional design of specific cognitive adaptations for intelligence signal production. The relationships between diverse human cognitive abilities may be partially explained by individual differences in low-level neurological functions that affect the efficiency of multiple systems, possibly including differences in neural oscillation rate (i.e., the minimum time between neural excitatory potentials). Jensen (2006) has argued in support of this view, based on evidence that tasks requiring different sets of specific, elementary cognitive abilities can produce highly intercorrelated, *g*-loaded results if response time is measured. Psychometric intelligence is correlated (r = -0.49) with choice reaction time in a simple 4-choice task, and correlated (r = -0.31) with simple response time to stimulus events in a representative population sample (Deary, Der, & Ford, 2001). Recent findings suggest that tasks precisely measuring the resolution of time discrimination abilities may tap general intelligence even more strongly (Rammsayer & Brandler, 2007). Accuracy of the production of equally-spaced time intervals in a finger-tapping task has also been recently found to be moderately correlated with intelligence (Madison, Forsman, Blom, Karabanov, & Ullén, 2007). Variability in intelligence as revealed by reaction time tasks is still correlated with developmental stability (Thoma, Yeo, Gangestad, Halgren, Davis, Paulson, & Lewinee, 2006), so a signal indexing individual differences in reaction time or time discrimination abilities could contain valid information about phenotypic and genetic quality.

If levels of ability in a few basic cognitive tasks—such as those tapping auditory stimulus interval size discrimination ability and reaction time differences—can provide valid intelligence information in a research setting, and communication of intelligence information can benefit signalers and receivers, then signaling systems may have evolved to allow the (usually imperceptible) differences in these abilities to be observed and acted upon. If so, the cognitive mechanisms allowing signalers and receivers to participate in this system might have clearly discernable, species-typical design features. The functional complexity of signaling adaptations that reveal and broadcast intelligence information by such a route might be easily discerned through evolutionary psychology's cognitive methodology, in contrast to the difficulties posed by signals for which an index of many systems must be embodied in signal content. Quantitative differences in signal quality could be directly assessed, because the signal would not be required to embody many types of information about diverse cognitive abilities. A full description of the information pathway in the signal system would be a realistic goal, including mapping the modular cognitive underpinnings of signal production, measuring the effects of individual differences in these cognitive abilities on quantitative signal traits, and determining whether those particularly informative features of the signal trait are preferentially attended to and acted upon by coevolved behavioral responses in signal receivers.

If highly specific cognitive abilities can be highly *g*-loading, might we expect to find cross-culturally universal human behaviors that reflect behavioral adaptations for signaling, showing special design to make these specific cognitive differences easily discernable to social partners and potential mates, perhaps even to have been broadcasted to entire ancestral communities?

Measuring evolutionarily relevant individual differences in rhythmic ability

Many musical behaviors show hallmarks of signaling selection, producing functionally designed signal modes to communicate honest information about performers' traits to conspecifics, possibly including social partners and potential mates (Miller 2000c), or members of competing groups (Hagen & Bryant, 2003). Rhythmic synchronization in particular may signal intelligence or other physiological abilities indicating quality, without requiring the complexity or flexibility of adaptations for signaling creative intelligence.

Very little is known about individual differences in rhythmic musical abilities except among professional musicians and music students. Strong predictors of musical performance outcomes in these two groups include general intelligence (Ruthsatz, Detterman, Griscom, & Cirullo, in press), “audiation” ability (i.e., the ability to produce accurate auditory mental imagery; Gordon, 1986), and the intensity and effectiveness of practice (Ericsson, Krampe & Tesch-Römer, 1993). However, individual differences that predict outcomes and rated abilities in these highly selected samples are of limited use for inferring the information content of musical performances in the ancestral environment.

Assumptions about the nature of selection pressures over the course of an adaptation’s evolution—the nature of its environment of evolutionary adaptedness (EEA)—are necessary for hypothesis formation in evolutionary psychology. In domains where details of selection pressures cannot be known with certainty, relevant features of the EEA cannot be assumed from general knowledge of the natural world; for the purposes of hypothesis formation, evolutionary psychologists assume that any cross-cultural human universal is likely to have been part of the ancestral environment. These human universals, particularly those for which the behavior has apparent implications for the fitness of the actor or conspecifics, suggest selection pressures and provide grounds for evolutionary hypothesis testing. Percussion, as a mode for musical display, exists in all known extant societies, and some evidence of prehistoric use of instruments for percussion exists in the archeological record (Fitch, 2006). Cross-culturally universal rhythmic percussion performance suggests a selection pressure on observers to act on any fitness information (including information about intelligence) that may be present in the behavior, which could initiate the elaboration of the cue into a signal (Maynard Smith & Harper, 2004).

To aid in building models of expected selected pressures on performers and listeners in the evolution of music, tests of individual differences used to evaluate adaptationist signaling hypotheses must be ecologically valid in a special sense—they must test abilities that were revealed by the natural expression of display behaviors over the course of its evolution. The information content of a signal can be assessed by various means, such as quantitative comparisons between measured aspects of the signal and tests of relationships between signalers' underlying traits and conspecifics' behavioral responses to a produced signal. Measurement methods that tap a wider or narrower range of individual differences than the natural expression of a display behavior, however, will result in inaccurate estimations of the information content of a signal. Evaluating candidates for signaling adaptations will therefore require the design of specific tests of signal production ability, tailored to the details of the expected ancestral forms of a given display behavior as extrapolated from cross-cultural human universals.

The best-validated and most popular measures of musical aptitude in current use, such as the Musical Aptitude Profile (Gordon, 1995), test subjects' ability to discriminate small differences between similar musical recordings (e.g., in pitch or tempo). They lack ecological validity as measures of a communicative skill for two reasons: first, because they require only evaluation of stimuli rather than production, and second, because they are based on forms of musical expression that were unavailable until the last few hundred years. The form of the test would be irrelevant if these tests were known to be highly correlated with display quality in cross-culturally universal performance modes, across a wide range of performance abilities, but there is no evidence that they are. Rather, they are designed and validated as predictors of general success in Western musical performance, which differs drastically from ancestral musical performance in the nature of the skills required, such as the fine motor learning involved in expert violin performance.

In addition to universal modes of performance, details of the social structure of musical performance gatherings may have been an important part of the selective environment in shaping musical abilities as signals. Among small-scale societies, musical performance is a much more broadly inclusive activity compared to musical performance in post-industrial societies. If music performance by group members with a wider range of ability is likely to have been the ancestral norm, then relationships between human rhythmic abilities and other phenotypic traits (such as intelligence and developmental stability) must be investigated across broad levels of ability, to begin to approximate the extent of ancestral information content. More typically, validations and applications of music ability testing have been among selected high-ability groups, such as in music education settings (Shuter-Dyson & Gabriel, 1981).

Based on typical small-scale societies, the settings for musical performance in human ancestry can also be inferred to have been much more communal, lacking the clear boundary between performer and audience seen in many modern societies. Rhythmic performance in small-scale societies typically takes place among a large group of performers, each maintaining a common beat along with the overall group, with variations in modality (including percussion, singing, and dancing), and with individual creative variations at lower metrical levels (i.e., subdivisions of the common beat).

The cognitive psychology of synchronous rhythmic performance (reviewed in Repp, 2005, 2006) also suggests a species-typical rhythmic entrainment response that preferentially responds to auditory pulses, but individual differences in these abilities are only beginning to be understood. The size of individual differences, and the degree to which this variation is affected by stable cognitive differences (e.g., general intelligence or more specific cognitive abilities), by degree and type of musical training, and by other experiential factors, is unknown. One recent study, however (Madison et al., 2007), has found interval size consistency in unpaced tapping tasks to be moderately positively correlated with performance on Raven's Standard Progressive Matrices (Raven, Raven, & Court, 1998), a highly *g*-loaded cognitive test.

The present study examines rhythmic accuracy in a set of computer-controlled synchronization and continuation tasks administered on a set of electronic drum pads. Because no research has yet demonstrated that individual differences in these simple rhythm-production abilities relate in any way to individual differences in the quality of complex, real-life musical performances, this study also included a preliminary validation of the tests' utility in predicting the rated quality of improvised musical output by performers with little musical instrument training and no substantial drumming experience.

Method

Participants

60 right-handed male students in psychology courses at the University of New Mexico participated in individual sessions for course credit. The work was carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans, and under UNM Institutional Review Board approval.

Eight participants (13%) who reported having "learned to play" drums on a questionnaire were removed from analyses. In addition, 3 participants were removed from analyses due to procedural problems (one whose data was not recorded due to an error in software setup before the session, one for whom the left-right orientation of the headphones was accidentally reversed for all tasks, and one who told the experimenters that he did not complete several tasks because he misunderstood the task instructions). Three further subjects were excluded due to extreme outlying scores (z beyond $\pm$ 3.00) on the major rhythm task outcome measures. Removal of the above data from analyses left $N = 46$. 70% of these reported having learned a musical instrument, but most of these had taken fewer than 5 lessons and had never performed publicly.

Self-report items

A questionnaire was administered following the rhythm tasks described below. Participants were asked about their handedness, physiological information (hearing deficiencies, or any recent injuries to the hands or arms), family information, music experience and training, music consumption and preferences, self-rated rhythmic and musical abilities, and experiences with dance and other rhythmic behaviors. (Results of these exploratory questionnaire scales are not included in the present analyses.)

Apparatus

Participants sat on a padded chair without armrests that was adjusted to their preferred height. They completed the rhythmic performance tasks with wooden 16" drumsticks on a pair of Roland PD-8 electronic drum triggers ("drum pads"). The two drum pads were 9" in diameter, positioned roughly horizontally at the seated participants' elbow level, and spaced with the pad centers about 11" apart. Participants' taps on the drum pads were registered by a Roland TD-6 percussion sound module ("drum module") connected to the pads, which sent audible drum sounds to a pair of AKG K-66 headphones, and which sent performance information to a host PC (a 2.2 GHz processor running Windows XP with 512 MB of RAM). Figure 1 depicts the overall setup of the host PC and drum apparatus.

The equipment has limitations that are relevant to how the data were screened for analysis. The drum module senses participants' drumstick tapping by monitoring microphone-like sensors inside the drum pads. The system "triggers" (registers a tapping response) when a certain (experimenter-determined) threshold is met. A high threshold setting increases the risk of light taps failing to trigger, whereas a low threshold setting increases the risk of taps causing a "double-trigger" (producing two signals in quick succession) due to reverberations in the equipment, and of multiple drum pads registering a trigger when a single pad is struck. Drum module settings were adjusted to balance these risks.

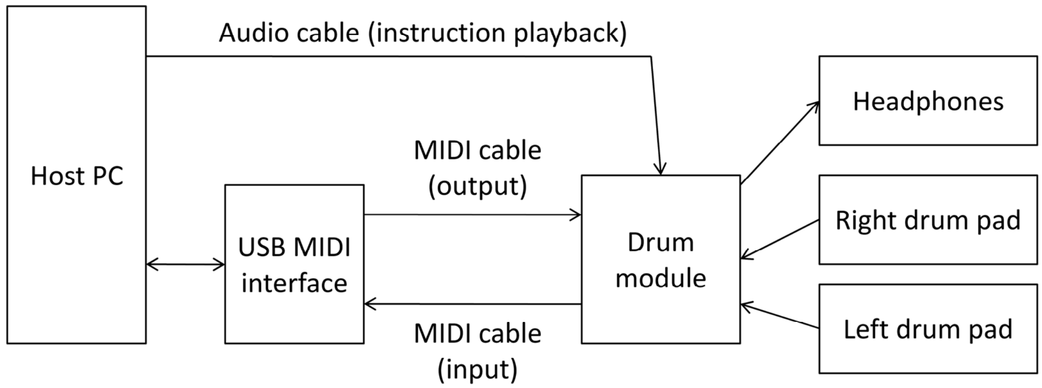

Figure 1. Rhythmic accuracy measurement and performance recording apparatus.

The study administration software in the host PC has two main functions: to receive and record signals from the drum module ("participant input"), and to send signals at appropriate times that the drum module translates into audible stimuli ("stimulus output"). Both input and output signals use the MIDI (Musical Instrument Digital Interface) protocol, which is based around small pieces of musical data (e.g., timbre, note, velocity, on/off commands) sent between computers and electronic instruments. "MIDI" can also refer to the type of cables used for this protocol, which provide one-way transmission of MIDI signals.

The relevant pieces of information in the MIDI signals for recorded participant input are an instrument number (which is used to determine whether the left or right pad was struck) and a velocity number (which corresponds roughly to how hard the pad was struck, but which is also affected by the proximity of the strike to the sensors inside the drum pad). These MIDI signals are generated in the drum module and sent via MIDI cables to an Edirol UM-1SX USB MIDI interface connected to the host PC on a USB 2.0 port. Each time a MIDI signal is received by the PC, the administration software records the instrument and velocity values and attaches a "timestamp" (a number designating the time, in milliseconds from the start of the task, when the signal was received by the administration software). The timestamp is derived from the "multimedia timer" process built into Microsoft Windows XP, which has a higher resolution (approximately 1 millisecond) than the standard Windows timer.

During a study session, the software records performance data while simultaneously sending MIDI signals to the drum module at specified intervals to produce the audible stimuli to which participants must synchronize. Upon receiving these signals, the drum module plays the appropriate drum sounds (as described below) to the participant's headphones. The software keeps a record of the timestamp of these output events when each is sent to the drum module—this allows an evaluation of how precisely participants match the target beats with their performance in synchronization tasks.

The study administration program also automated the data collection process by playing pre-recorded instructions to participants before each task. These audio files were sent from the host PC to the "line in" jack of the drum module to be heard in participants' headphones.

Stimuli

Distinctive sounds were used for the right and left drum pads. The sound for the right drum pad had a "tom" quality and the sound for the left drum pad had a "snare" quality. These sounds were panned partially to their respective sides, and these respective timbres and channel placements were heard both as programmed stimuli and as feedback from participants' own taps. Both sounds had a supraliminal duration of approximately 210 ms. This configuration was selected to encourage a familiar sense of percussive musicality and variety to the stimuli and audio feedback.

Rhythmic accuracy tests

Three main types of rhythmic accuracy tests were used for each subject. First, *Isochronous synchronization* tests (i.e., requiring equal-interval performance; similar in procedure to tasks used in many experimental studies, e.g., Collier & Ogden, 2004) required participants to synchronize their tapping to an audible equal-interval beat as accurately as possible. The outcome from each of these 80-interval synchronization tasks was a set of 80 intervals delineated by the stimulus beats as midpoints, with performance timings recorded for comparison with the target timing.

The audible synchronization beats in each synchronization test continued until the end of 80 intervals, after which participants (as previously instructed) attempted to continue tapping at precisely the same tempo for another 160 beats without ceasing between the tasks. This second, unpaced performance task is usually referred to in experimental cognitive research as an isochronous serial interval production (ISIP) task, but is here referred to as a "*continuation*" test. The outcome from each continuation performance was a list of intertap interval (ITI) sizes that can be analyzed for long-term and short-term sources of inaccuracy in various ways.

Pattern synchronization tasks required participants to tap along as they heard a simple pattern of drum sounds. The stimulus for these tasks was similar to the synchronization period for the isochronous tasks above, except with every third or fourth stimulus tap dropped out. They were asked to tap on the audible beats and to refrain from tapping on the silent beats, to again be as temporally accurate as possible, and to start once they had "a sense of the pattern and rhythm." For this task, the audible stimuli continued for the entire recording period. Four variations on this task were performed, using combinations of two pattern types and two tempos. The outcome of these tasks included information on missed taps, spurious taps (i.e., those performed during silent portions of the stimulus pattern), and deviations from perfect timing for taps correctly performed during target beats.

Procedure and task variations

Each session began with a 90-second practice period. Instructions for this practice period were given to lead the participant to become accustomed to the feel of the pads and their threshold for activation, and to determine a comfortable way of holding the drum sticks. They were further instructed to see if they could make patterns of sound with the pads that sounded interesting to them, once they were comfortable with the apparatus. The drum module was initially set to a standard, moderate volume for each session, and each participant was requested to adjust this at will and to notify the study administrator if the auditory stimuli caused any discomfort. After the practice period, participants were given a brief, standard overview of the nature of the rhythmic task set, consisting of a description of the objectives of each task type and the tempo and pattern variations that will occur. Because the task administration progresses automatically, participants were encouraged to stop the tasks and retrieve the study administrator from the next room if any task's pre-recorded instructions were not fully clear.

First, four variations on the isochronous synchronization / continuation task set were performed, varying tempo and handedness (250ms intervals with the right hand, 500ms right hand, 750ms right hand, and 500ms alternating hands). The three right-handed tasks within this block were presented in all possible orders between participants, and the alternating-hands task was always presented fourth. These tasks were repeated following the pattern synchronization task set (below).

The first block of synchronization tasks described above was then followed by a set of more complex synchronization-only tasks requiring both synchronization with auditory beats and subdivision (i.e., tapping at precisely halfway between auditory beats) with the right or left hand and with alternating hands. These tasks were presented in a standard order across participants. Because of a programming error in the administration application that was undetected until the conclusion of the study, participant input data from these tasks are not available for analysis, and these tasks will not be discussed further.

Four variations of the pattern synchronization task were used for each participant: two audible beats then a skipped beat ("TT_"), at 250ms per beat and at 750ms per beat; and three audible beats then a skipped beat ("TTT_"), at 250ms per beat, and at 750ms per beat. The three- or four-beat patterns repeated 40 times for 250ms variations and 30 times for 750ms variations. These tasks were all performed with the right hand and right drum pad. The order of presentation between participants independently manipulated tempo order (250ms vs. 750ms first) and pattern-type order (TT_ vs. TTT_ first), so all possible orders were presented excepting those that would alternate the two pattern types across the trials (e.g., TT_ at 250, TTT_ at 250, TT_ at 750, TTT_ at 750). The block of the four initial synchronization/continuation tasks was then repeated in the same order for each participant following completion of the pattern synchronization tasks.

Improvised rhythmic creativity tasks

One major goal of development of these tests is to measure variation in rhythmic ability that substantially predicts performers' musical performance abilities as perceived by listeners. As a preliminary method of determining whether the quantitative measurements of rhythmic accuracy from the tasks above invoke the same cognitive abilities that are conveyed to listeners when a performer attempts to generate rhythmic music for recreational or entertainment purposes, participants were given a final set of tasks that asked them to improvise musical performances on the drum pads.

Following the set of quantitative rhythmic accuracy measures, each participant completed a set of three creative musical performance tasks. First, participants were given 30 seconds to improvise a short rhythmic pattern that would sound musically interesting and that they could repeat, and were then asked to continually repeat it as accurately as possible for a 60-second period. (The outcomes of this task were not rated for the present analyses, and will not be discussed further.)

For the next two improvised musical performance tasks, participants were instructed to perform in a way that “sounded musically interesting to them” and “would keep a listener entertained” for 90 seconds. The task (“unpaced performance”) was performed with no stimuli provided except auditory feedback from their own performance. The task was then repeated with a metronomic tick at 500 ms intervals (“paced performance”); for this task, participants were told that they would hear a steady “ticking sound,” and were asked to imagine that they were playing alongside this beat and to again play in a way that would again “keep a listener entertained” for the 90-second period. All data on timing and intensity of drum taps was recorded, but the primary output of interest for these tasks was an audio recording of the synthesized drum feedback produced in the performances.

Performance quality ratings

The sets of participant output data were translated into audio files by sending recorded MIDI signals from performances back through the drum module after the study and recording the synthesized audio output. Although the audio was reproduced from recorded MIDI signals, this process retained all information that contributed to the quality of the performance as the participant heard it while performing (note timings, timbre, panning, and velocity) and included ticking sounds in recordings from the paced task in which participants heard them.

Three members of the research team (Professor Geoffrey Miller, research assistant Zack Mendenhall, and the author) rated audio recordings of the results of the musical performance tasks on 18 adjectives regarding how the performance sounds (Accurate, Happy, Musically rhythmic, Original, Aggressive, Complexly structured, Creative, Entertaining, Expressive) and how the performer seems (Enthusiastic, Skilled, Musically trained, Intelligent, Able to keep a steady beat, Interested in the task, Talented, Physically well-coordinated, Physically strong). Adjectives were endorsed on a scale from 1 ("not at all") to 7 ("very much"). The order in which participants' recordings were presented to raters was randomly assigned for each of the three raters, with order independently randomized for the two recordings completed by each participant. All three raters were blind to the actual participant number associated with recordings as they rated them.

Data processing

A typical finding in synchronous tapping performance, when participants receive no auditory feedback from their own taps, is that participants' taps tend to slightly precede stimulus onsets, rather than producing an error distribution centered on the stimulus onset. Because this tendency is eliminated when participants receive auditory feedback from their own performances, as is the case in the present research (and in real-life musical performance), analysis of deviations without correction for the "mean negative asynchrony" is appropriate.

The raw recorded data required task-specific processing methods prior to the statistical analyses. Output data from these tasks were filtered along lines similar to those established in experimental rhythm studies to reduce the impact of equipment limitations (which can cause spurious or missed taps in the data) and to isolate "short-term" variance in interval sizes for continuation tasks.

Synchronization test data. Methods of data processing were similar between the isochronous synchronization and pattern synchronization test data.

Each recorded input event was sorted into one of a set of spans of time determined by the recorded timestamps of the study application's metronome ticks—the points at which each signal to play an audible drum sound was sent to the drum module during the session. These spans were designated as the time from one half-beat before the audible target stimulus to one half-beat after the stimulus. Within these spans of time, the performed tap that came closest in time to the target stimulus event (regardless of whether the performed tap precedes or follows the target) was recorded as the participant's attempt at that beat, and these attempts, once identified, were then compared with the timing of the recorded metronome ticks as the primary outcome measure (i.e., absolute deviation values).

For example, a small section of the "TT_" task at a tempo of 250ms could produce the results depicted in Figure 2. In this figure, six taps have been recorded from the participant across two repetitions of the "TT_" pattern, which have three beats each. The target stimulus drum sounds are metered out at 250ms intervals, and boundaries are drawn halfway between these metronome ticks (125, 375, and so on) regardless of whether the beat is silent (as in beat domains 3 and 6). The resulting list of correctly performed taps, used to calculate mean absolute deviation from target timing, would include only data points b, c, and e. (The participant would also have missed one beat, i.e., scored a "false negative" error, because there was no tap performed between 375 and 625 ms; and would have one "false positive" error, because there was a tap performed between 1375 and 1625 ms, but these error outcomes are not included in the present analyses.)

The main outcome measure for each of the synchronization tasks, in summary, was the mean of absolute deviations of performed drum taps from the target timing, within time intervals delineated by one-half of the interval size before and after each target timing point. Only the most accurate performed tap in each time interval was included in this mean, and (in pattern synchronization tasks) only data from time intervals that contained target beats were included in this mean.

For isochronous synchronization test data only, starting points were identified for each participant as the start of the first set of 5 intervals tapped in a row, and all data points after this point for each participant were used in calculating the participant's mean accuracy for each test. For pattern synchronization test data only, based on inspection of the typical starting points in performances, processing of the pattern synchronization task data began with dropping the first third of the recording period (i.e., the first 13 of 40 for 250ms tasks, and the first 10 of 30 patterns for the 750ms tasks); participants were instructed to begin when they had a sense of the beat, so this cutoff was selected (rather than starting from the point at which each participant began) to avoid including the

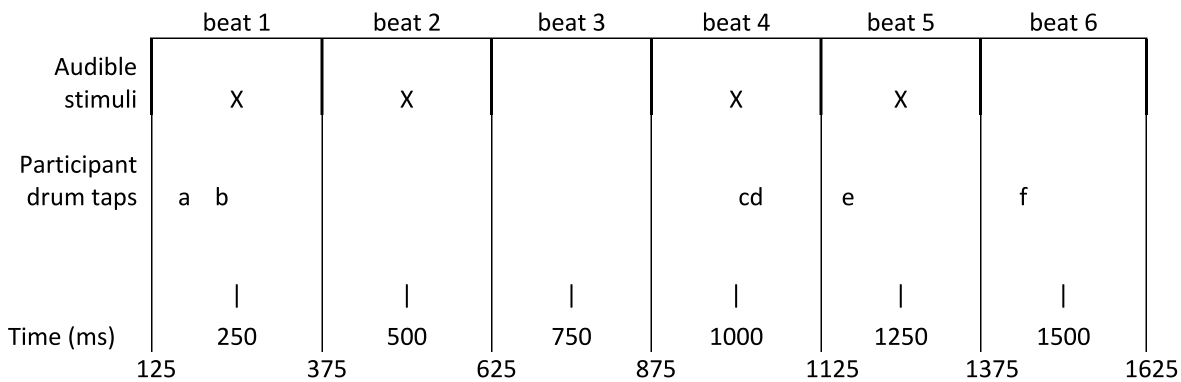

Figure 2. Example of the sorting procedure for performance data in six beats of the "TT_" task at 250ms.

commonly inaccurate early data points among these tasks produced by participants who began tapping earlier (possibly with a more unsure "sense of the rhythm").

Continuation test data. Data processing for continuation tasks began with isolating two lists of participant input events, corresponding to the synchronization period and the continuation period. The first 80 intervals were processed as described above; data from the subsequent continuation portion of each test (during which participants received no auditory stimuli except feedback from their own drum taps) were analyzed based on short-term changes in interval size.

The continuation period input was translated into intervals by subtracting successive input timestamps. The intervals were then filtered to compensate for the equipment limitations described above: intervals larger than 1.5 times the entrained target interval size were discarded from the interval list, and intervals smaller than 0.5 times the entrained target interval size are combined with the subsequent interval (under the assumption that a "double-trigger" is a likely explanation for the unusually short interval, in which case the first of a quick succession of taps would be the intended timing, and the second should be eliminated.) This process of adding smaller intervals produced summed intervals greater than 1.5 times the entrained target interval size in a few cases; these were filtered out a second time. These cutoff values were chosen based on visual inspection of the distributions of unfiltered interval sizes across tasks.

A substantial portion of the variance in these interval sizes in continuation tasks was accounted for by a long-term tendency to drift away from the target interval sizes (as is typically found when SMS tasks of this length are performed). The long-term drift typically present in continuation performance, as a source of variance, is less theoretically relevant to musical signaling than short-term deviations. Variability around a local, short-term mean tempo would be most perceptible to listeners, compared to interval variance across the entire task, deviations from a specified target interval size, or long-term trends. To control for long-term drift and isolate these short-term errors, deviations of each interval from the previous interval size (i.e., a lag-1 change score) were calculated, as by Madison et al. (2007). The sum of the absolute values of these lag-1 deviations formed the main outcome measure for each of the continuation tasks.

Results

Rhythmic accuracy estimates

In the data processing steps above, performance composites were formed for participants' performance on each of the 12 rhythmic accuracy tests. For synchronization tasks, these can be characterized as the mean, across the set of performed intervals, of the absolute deviation of each attempted tap during that interval from the target at its midpoint. For continuation tasks, these can be characterized as the mean, across the set of performed intervals, of the absolute deviation of each successive interval size produced from the previous interval size.

Participants showed a general tendency to increase error rates in proportion to target interval size among the interval sizes used in this study (250, 500, and 750 milliseconds), as has been found in previous rhythmic performance research using intervals shorter than about 1 second (Madison, 2004). Mean inaccuracy and variability between individuals in task summary scores were also found in this study to increase with interval size. To produce task outcomes with more closely equivalent means and standard deviations for multivariate analysis, each of the task outcomes was divided by target interval size in milliseconds, and multiplied by 100 as a convenient scaling factor (Table 1), yielding a mean percentage error.

These items were entered into a principal axis factor analysis that used direct oblimin rotation. Although the scree plot suggested up to 6 meaningful factors, the analysis was restricted to the first two factors for reasons of interpretability. The structure largely conformed to interpretation as a continuation ability factor (which explained 28.6% of the variance in scores) and a synchronization ability factor

Table 1

Distributions of Unadjusted Task Scores and Scores Adjusted by Target Interval Size (N = 46)

Task type	Absolute Deviation (Milliseconds) from Perfect Rhythm, Mean (s.d.)	Error in Rhythmic Accuracy as Percent of Target Interval Size, Mean (s.d.)
Isochronous continuation[a]		
250ms (trial 1)	14.82 (5.44)	5.93 (2.18)
250ms (trial 2)	14.13 (4.33)	5.65 (1.73)
500ms (trial 1)	24.29 (6.49)	4.86 (1.30)
500ms (trial 2)	24.16 (6.60)	4.83 (1.32)
500ms, alternating (trial 1)	33.87 (8.11)	6.77 (1.62)
500ms, alternating (trial 2)	29.88 (6.75)	5.98 (1.35)
750ms (trial 1)	34.62 (8.38)	4.62 (1.12)
750ms (trial 2)	33.57 (9.51)	4.48 (1.27)
Isochronous synchronization[b]		
250ms (trial 1)	34.96 (19.53)	13.98 (7.81)
250ms (trial 2)	33.75 (18.32)	13.5 (7.33)
500ms (trial 1)	51.32 (34.53)	10.26 (6.91)
500ms (trial 2)	36.55 (19.41)	7.31 (3.88)
500ms, alternating (trial 1)	52.66 (28.45)	10.53 (5.69)
500ms, alternating (trial 2)	43.68 (23.13)	8.74 (4.63)
750ms (trial 1)	78.55 (44.82)	10.47 (5.98)
750ms (trial 2)	67.44 (36.85)	8.99 (4.91)
Pattern synchronization[b]		
"TT_" at 250ms	36.05 (14.45)	14.42 (5.78)
"TTT_" at 250ms	33.13 (12.58)	13.25 (5.03)
"TT_" at 750ms	91.93 (33.95)	12.26 (4.53)
"TTT_" at 750ms	90.10 (39.19)	12.01 (5.23)

a. Distribution across participants of task mean of absolute lag-1 differences in interval size.

b. Distribution across participants of task mean of absolute target/attempt deviations.

(which explained 15.4% of the variance), except for several tasks; see Table 2. The second trial of isochronous synchronization at 500 ms and one pattern synchronization task ("TT_" at 250 ms) loaded slightly more highly on the continuation factor, but were included in the synchronization composite measure for simplicity of interpretation. Because the alternating-hands synchronization tasks were anomalous in that they loaded primarily onto the continuation factor (but did not load highly on either factor), these tasks were excluded from further analyses.

A composite measure of continuation accuracy was formed from the mean of the 8 continuation task outcomes (entrained at 250ms, 500ms, 750ms, and alternating hands at 500ms; with 2 trials at each tempo); these tests, taken as a scale, showed excellent reliability, $\alpha = .842$. A composite measure of synchronization accuracy was formed from the mean of the 10 non-alternating synchronization tasks (2 trials each of synchronization with audible beats at 250ms, 500ms, and 750ms intervals; and with the "TT_" pattern at 250ms and 750ms tapping intervals; and with the "TTT_" pattern at 250ms and 750ms tapping intervals), and also showed substantial reliability among the 10 tests, $\alpha = .783$. The relationship between these composited synchronization and continuation accuracy estimates approached significance ($r = .275$, $p < .07$).

Performance ratings

Ratings were obtained for 45 of the participants included in the above analyses. Interrater reliability across 3 raters ranged from $\alpha = .15$ to $\alpha = .73$ for the 36 ratings of each participant (Table 3). Separate principal axis factor analyses were conducted for our ratings of the paced and unpaced musical improvisation tasks. To locate adjective endorsements that load distinctly onto "accuracy" and "creativity" scales, items were

Table 2

Factor Analysis of Rhythmic Accuracy Measures: Pattern Matrix Loadings by Test type (N = 46)

Task type	Factor 1 ("continuation")	Factor 2 ("synchronization")
Isochronous continuation		
750ms, trial 2	**.78**	-.03
500ms, trial 2	**.72**	.11
250ms, trial 2	**.69**	.00
750ms, trial 1	**.65**	-.02
500ms (alternating), trial 2	**.64**	-.04
250ms, trial 1	**.64**	-.13
500ms (alternating), trial 1	**.59**	-.04
500ms, trial 1	**.56**	-.19
Synchronization		
Pattern ("TTT_"), 750ms	-.07	**.85**
750ms, trial 1	-.34	**.82**
750ms, trial 2	.32	**.65**
Pattern ("TT_"), 750ms	.28	**.58**
Pattern ("TTT_"), 250ms	.05	**.49**
250ms, trial 2	.37	**.47**
500ms, trial 2	.50	**.41**
500ms, trial 1	-.11	**.37**
Pattern ("TT_"), 250ms	.34	**.31**
250ms, trial 1	.01	**.26**
500ms (alternating), trial 1	.32	.09
500ms (alternating), trial 2	.26	.06

Table 3

Interrater reliability of performance ratings by task for 3 raters (N = 45)

Adjective endorsement	Unpaced Task (alpha)	Paced Task (alpha)
Accurate	.51	.68
Happy	.44	.29
Musically rhythmic	.56	.66
Original	.62	.52
Aggressive	.62	.30
Complexly structured	.51	.39
Creative	.65	.52
Entertaining	.48	.51
Expressive	.49	.33
Enthusiastic	.71	.63
Skilled	.52	.48
Musically trained	.57	.73
Intelligent	.43	.44
Able to keep a steady beat	.40	.54
Interested in the task	.47	.15
Talented	.45	.48
Physically well-coordinated	.52	.59
Physically strong	.44	.59

selected based on a to form composites based on the criteria that they load at least .6 on one factor and no more than .3 on any other factor (Tables 4 & 5).

For unpaced performances, items meeting these criteria and entered into a composite measure for the accuracy scale were *Able to keep a steady beat, Musically rhythmic, Accurate,* and *Musically trained*; and items composited as creativity were *Original, Expressive, Creative, Complexly Structured,* and *Entertaining*. For paced performances, items meeting these criteria for accuracy were *Able to keep a steady beat, Accurate, and Physically well-coordinated*; and those composited as creativity were *Creative, Complexly structured, Entertaining, Original, Enthusiastic, Intelligent, Happy, and Interested in the task*. Composites were formed by averaging adjective endorsements across the three raters and summing the z-scores of these 3-rater means. Among these four composite measures, the composites produced from the three raters produced moderately consistent between-task estimates of accuracy, $r = .576$, $p < .01$, and of creativity, $r = .423$, $p < .01$. Ratings of creativity and accuracy were also substantially correlated among ratings of each musical performance, both for the unpaced task, $r = .569$, $p < .01$, and the paced task, $r = .538$, $p < .001$.

The two sets of rhythmic accuracy test outcomes differed in their relationships with rated quality of the two corresponding types of improvised musical performance task. Measures of deviation from perfect synchronization with audible beats, composited across 10 tests, significantly predicted the paced performance task's rated accuracy, $r = -.434$, p < .01; and rated creativity, $r = -.449$, p < .01. Measures of short-term deviations in interval size in continuation tasks did not significantly predict ratings of

Table 4

Factor Analysis of Unpaced Performance Ratings: Pattern Matrix Loadings by Composite (N = 45)

Adjective endorsement	Factor 1 ("Creativity")	Factor 2 ("Rhythmic accuracy")	Factor 3 ("Intensity")
Creativity			
Original	**.94**	-.19	.08
Expressive	**.87**	-.10	.13
Creative	**.86**	.09	-.04
Complexly structured	**.82**	-.03	-.02
Entertaining	**.81**	.23	-.06
Talented	.66	.40	-.01
Skilled	.64	.42	.00
Interested in the task	.57	.13	.30
Intelligent	.50	.24	.24
Rhythmic accuracy			
Able to keep a steady beat	-.03	**.85**	-.05
Musically rhythmic	.11	**.84**	-.02
Accurate	.01	**.82**	.11
Musically trained	.24	**.68**	.03
Physically well-coordinated	-.05	.59	.51
Happy	.31	.36	.09
Intensity			
Aggressive	.15	-.18	.74
Physically strong	-.02	.17	.70
Enthusiastic	.45	.13	.47

Table 5

Factor Analysis of Paced Performance Ratings: Pattern Matrix Loadings by Composite (N = 45)

Adjective endorsement	Factor 1 ("Creativity")	Factor 2 ("Rhythmic accuracy")	Factor 3 ("Intensity")
Creativity			
Creative	**.91**	-.05	.05
Complexly structured	**.88**	.05	-.04
Entertaining	**.76**	.21	.03
Original	**.73**	-.09	.20
Enthusiastic	**.71**	.08	.21
Expressive	.71	-.27	.34
Intelligent	**.67**	.18	.19
Happy	**.64**	.04	-.14
Interested in the task	**.63**	.18	.19
Rhythmic accuracy			
Able to keep a steady beat	-.15	**1.00**	.02
Accurate	-.06	**.92**	.04
Talented	.37	.68	-.02
Physically well-coordinated	.12	**.67**	.29
Musically trained	.35	.63	.09
Skilled	.49	.60	-.07
Musically rhythmic	.47	.50	-.10
Intensity			
Aggressive	.10	-.02	.79
Physically strong	.02	.17	.78

creativity, $r = -.245$, *n.s.*; and approached significant prediction of rated accuracy, $r = -.285$, $p < .06$.

These continuation outcomes did not significantly predict ratings on the paced performance task of accuracy, $r = -.266$, $p < .08$, or creativity, $r = -.231$, *n.s.*, and synchronization outcomes did not significantly predict ratings on the unpaced performance task of accuracy, $r = -.259$, $p < .09$, or creativity, $r = -.063$, *n.s.*

As a more direct comparison between similar continuation and synchronization tasks in prediction of task rating outcomes, composites were formed of the 6 isochronous, right-hand-only tasks performed as both continuation and synchronization (entrained at 250ms, 500ms, and 750ms, with 2 trials at each tempo). This resulted in a similarly reliable estimate of synchronization accuracy ($\alpha = .812$), but poorer reliability in the continuation accuracy estimate ($\alpha = .624$). These estimates were nonsignificantly correlated, $r = .168$. A similar pattern of prediction emerged: the 6-task synchronization test composite significantly predicted the paced performance task's rated accuracy, $r = -.381$, $p < .01$; and rated creativity, $r = -.385$, $p < .01$; but did not significantly predict ratings of unpaced task performance for accuracy, $r = -.116$, *n.s.*; or creativity, $r = -.021$, *n.s.* The 6-task continuation composite did not approach significant prediction of rated accuracy or creativity for either of the two performance tasks (all *p*s > .15).

Discussion

Rhythmic synchronization and continuation abilities as expressed in typical participants have been rigorously specified from an experimental cognitive perspective—such as the details of independent phase- and period-setting processes that determine and correct rhythmic timing, the expected degrees of inaccuracy in typical participants, and the effects of task demands and different input types on accuracy (Repp, 2005). The present study begins to investigate the nature of individual differences in rhythmic accuracy tests designed to be analogous to tasks in this paradigm.

Among the individual differences measured by rhythmic accuracy tasks in this study, two weakly related factors emerged, corresponding to synchronization accuracy and continuation accuracy, and scores on these factors related more strongly to ratings of musical performance tasks with similar demands—i.e., independent maintenance of a beat, versus continuous correction of a beat. The abilities invoked by these tasks, such as the keeping of a consistent internal timer on one hand and efficient detection and corrective responses to discrepancies in auditory feedback on the other, may covary weakly between individuals.

The quantitative differences in performers' synchronization and continuation accuracy tapped by these tasks may be a substantial component of differences between individuals in perceived performance ability during natural musical performance. If *g*-loaded cognitive abilities (such as accurate mental timekeeping; Madison et al. 2007) are conveyed to listeners by particular aspects of musical performance, the ways in which music perceivers attend to and interpret these aspects could be investigated as part of an adaptationist program of musical signaling. Because continuation accuracy measures were only marginally significant in predicting ratings of improvised musical performance, however, this combination of tasks may not convey to listeners the information about individual differences in intelligence carried by accurate continuation performance.

Several limitations to the ecological validity of these measures are present. First, the use of drumsticks may introduce task difficulties that would not be present in any environment in which membranophones were available for hand percussion. Perhaps more importantly, participants were unable to draw on the years of experience that would probably have been available to an ancestral percussionist for whom musical expression was a larger part of cultural life; these musicians could presumably use previously learned routines in creative performances. An ideal sample for measurement would be minimally selected for high levels of ability (in any stable cognitive and physiological individual differences that comprise rhythmic accuracy capacities), but would have substantial practice with musical percussion performance. This combination is unlikely to be available in college samples, but could be found in small-scale societies, and possibly also in specific Western subcultures where musical performance is encouraged with minimal selection for ability.

Another limitation of the measures is an incomplete sampling of all basic elements of musical synchronization ability. Two major categories of cognitive requirements for synchronized performance, missing from these measures, are subdivision and correction for externally-generated errors. The latter may be particularly relevant to the information content of rhythmic synchronization, because the degree of continued synchronization with an overall group beat formed by many performers, despite errors in that target beat (which will necessarily occur as a result of imperfection in others' performances), may conspicuously reveal reaction time, if, e.g., slow reaction time leads to perceptibly desynchronized performance compared to the overall group. Typical human performance tendencies in response to tasks where target intervals change over time have been investigated (e.g., Madison & Merker, 2005), but individual differences are not yet understood.

However, the abilities measured by these tasks are likely more relevant to understanding the information content of rhythmic accuracy as expressed in music in ancestral settings—i.e., are more ecologically valid for testing evolutionarily relevant individual differences—than any existing validated tests of music aptitude, such as the MAP (Gordon, 1995) or AMMA (Gordon, 1986). Continually revising these tasks to reflect cognitive abilities underlying accuracy and perceived overall quality of natural rhythmic performance in diverse populations will allow an increasingly accurate representation of the information content of musical rhythm performance. The pathways and uses of phenotypic information in the putative human musical signaling system can be investigated in a number of ways in future studies, including investigations of: (1) the correlations between ecologically valid musical ability tests, intelligence, and developmental stability; (2) the extent to which this phenotypic information is communicated to and acted upon by representative evaluators; (3) whether motivational priming produces quantitative differences in signal quality; and (4) whether quantitative manipulations of signal quality can produce predictable results in listeners' person perception processes as applied to the imagined performer.

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