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TRANSFER OF LEARNING IN SKILLED SEQUENCE PRODUCTION: 
THE MOTOR-INDEPENDENCE OF TEMPORAL REPRESENTATIONS 
IN PIANO PERFORMANCE

DISSERTATION

Presented in Partial Fulfillment of the Requirements for 
the Degree Doctor of Philosophy in the 
Graduate School of The Ohio State University 

By 
Rosalee K. Meyer, M.A.

*****

The Ohio State University 
2001

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Two forms of temporal structure (meter and rhythm) and motor movements are manipulated in music performance to identify the components of performers' sequence representations. A transfer of learning paradigm, in which one variable changes or remains the same from training to test, was used in three experiments to identify whether meter (periodic accent structure) and rhythm (duration pattern of events) are motoric or abstract (non-motoric) components of mental representations for piano performance. Sixteen skilled adult pianists performed short musical sequences ten times, and then performed test sequences that contained the same or different temporal structure and motor movements four times as quickly as possible. The difference between the sequence duration of the last training trial and the mean sequence duration of the four test trials was taken as a measure of transfer of learning. In all experiments, the serial ordering of pitches was held constant from training to test.
In Experiment 1, pianists performed a musical sequence and then transferred to a sequence with the same or different meter and same or different motor movements (hand and finger assignments). The results suggested that sequence representations include both an abstract metrical component and a motoric component that do not interact. In Experiment 2, pianists performed a musical sequence and then transferred to a sequence with the same or different rhythm and same or different motor movements. The results indicated that sequence representations include both a rhythmic component and a motoric component that do not interact. In Experiment 3, pianists performed a musical sequence and then transferred to a sequence with the same or different rhythm and same or different meter. The results suggested that representations of meter and rhythm are independent in music performance.

These findings suggest that temporal structure (meter and rhythm) is an important component of sequence representations for music performance, and does not interact with motor movements. A motoric component of sequence representations in music performance was also identified; this component may contribute more when increased temporal
and motor demands are made on performers. Finally, meter and rhythm are independent in performance, contrary to predictions from models of music perception that predict an interaction.
To A.W.R.
I would like to thank my advisor, Caroline Palmer, for her encouragement, enthusiasm, patience, and immeasurable amounts of time; I consider myself very fortunate to have such an organized, intelligent, and caring adviser. I wish to thank the members of my dissertation committee, Dr. Richard Jagacinski, Dr. Neal Johnson, and Dr. Mari Jones, for their cooperation and comments. Thanks also go to Pete Tender for his assistance and time with the Boesendorfer Concert Grand Piano at Ohio State University and the pianists who participated. I would also like to express my gratitude to my lab mates for their good humor and help; thanks go to Grant Baldwin, Danielle Brink, Zeb Highben, Melissa Jungers, Annalisa Ventola, and Tim Walker. A special, heartfelt, and very sincere ‘thank you’ goes to Steven Finney and Peter Pfordresher for making late nights and early mornings (respectively) at the lab both
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INTRODUCTION

Although theories of sequence production have addressed the serial ordering problem, or how to produce elements within an action in the appropriate order (Dell, 1986; Lashley, 1951; Levelt, 1989; MacKay, 1987), few theories have addressed how to produce elements in the desired order at the desired time. Skilled sequence production in domains such as speech and music requires that the performer produce the elements of the action in the correct order and at the correct time. For example, a musical melody can become unrecognizable if the individual notes are played in the correct serial order but not with the correct durations (Jones & Ralston, 1991; Peretz & Hebert, 1995). Language production makes similar timing demands on speakers; speech can become unintelligible if the durations of segments are altered (cf. Tajima, Port, & Dalby, 1997).

In music performance, the temporal demands on the performer go beyond producing the correct serial ordering of pitches; some temporal goals are explicitly notated, and
hypotheses from theories of temporal structure in music can be compared to hypotheses from theories of sequence production. These characteristics make music performance an ideal domain in which to study issues concerned with timing in sequence production.

One question that arises in sequence production is whether the components of mental representations of performance are abstract, conceptual, and separate from the specific motor commands necessary to produce the sequence. Many researchers have assumed that representations of timing in sequence production are abstract and conceptual (MacKay, 1987; Rosenbaum, 1985), whereas others have suggested that sequence timing and motor movements are closely related to each other (Sundberg & Verillo, 1980; Todd, 1995; Treffner & Turvey, 1993). Conceptual (non-motoric, abstract) representations have received some experimental support in language production and music performance (MacKay & Bowman, 1969; Palmer & Meyer, 2000), but these studies did not include representations of temporal structure (the desired timing pattern of elements within a sequence). Assumptions that representations of timing are conceptual and non-motoric have not been experimentally tested in complex tasks such as music performance.
The goal of the present research is to investigate the role of two forms of temporal structure in performers' representations of musical sequences: meter and rhythm. Meter is a hierarchical, periodic accent structure in music, and rhythm refers to the relative timing of events within a sequence. The relationship between these two temporal structures and their implementation in motor movements in music performance has not been closely investigated. Three experiments are reported here that address the following issues in music performance: 1) whether sequence representations of meter are conceptual or motoric, 2) whether sequence representations of rhythm are conceptual or motoric, and 3) whether sequence representations of meter and rhythm are independent of each other.

The introduction reviews the relevant literature addressing the motor-independence of representations in sequence production. Then the role of temporal structure, including meter and rhythm, in sequence representation is considered, as well as the relationship between meter and rhythm in music. Finally, an overview of the three experiments is presented.
Motor-independence of Representations in Sequence Production

Sequence representations, or psychological structures and processes that allow us to use past experience in behavior, have been incorporated in many motor learning and sequence production theories (Ivry, 1996). Motor programs are one example of sequence representations that predict separate coding of conceptual and motor knowledge. Motor programs are abstract representations of an action that exist independently of any specific effector system (Ivry, 1996; Keele, 1981). As an example of a motor program consider handwriting; handwriting samples by the same person written with different effectors (dominant, non-dominant hands and feet) are similar, even though different muscles are used for each signature (Bernstein, 1967). This implies that a representation of how to write one’s name exists independently of the motor movements necessary to execute the action (Bernstein, 1967; Ivry, 1996).

Sequences have also been represented independently of the motor movements necessary to produce the sequence via connections between nodes. Node Structure Theory (MacKay, 1987) accounts for speech production and perception, and can be generalized to extend to other sequence production domains. The theory posits that sequences are represented by
three different types of nodes that each represents different kinds of information. Conceptual nodes represent concepts and propositions; phonological nodes represent the phonological expression of the concepts; and muscle movement nodes represent the activation of articulators. Conceptual nodes represent word meanings, whereas motor nodes represent movements of speech articulators. For example, to produce the phrase "Cognitive Psychology", nodes representing the concept of cognitive psychology, nodes representing the morphemes within "cognitive psychology", nodes representing the phonemes of the words "cognitive" and "psychology", and nodes representing the motor movements necessary for producing the utterance all become activated. Because motor movements are represented in nodes separate from those representing concepts, MacKay's theory predicts that motor movements are independent from abstract concepts for skilled producers (MacKay, 1987).

MacKay and Bowman (1969) found evidence from a transfer of learning study to support the prediction from Node Structure Theory that representations of conceptual meaning of sentences are abstracted from the movements needed for production. German-English bilingual speakers repeated sentences with either normal or scrambled syntax as quickly
as possible. After practice, speakers translated the
practice sentence as quickly as possible. Direct
translations of the practice sentence with normal syntax
showed positive transfer, whereas direct translations of
sentences with scrambled syntax showed no transfer. These
results suggest that transfer (change in response on a novel
task due to a prior task) occurs because of conceptual
learning (arising from sentence structure) rather than motor
learning, because the sentences with normal syntax had a
greater conceptual (meaning) component than the sentences
with scrambled syntax.

Cohen, Ivry, and Keele (1990) also suggested that
representations of sequence structure are conceptual and not
motoric. In a transfer of learning paradigm, participants
produced cyclically repeating five-event sequences by
pressing keys corresponding to positions of three visual
signals. The structured sequences contained one unique
position and two repeated positions; examples of structured
sequences are 12323 and 32121, in which the numbers
symbolize the effector (producing muscles) position (for
instance, 1 = right index, 2 = right middle, 3 = right ring
finger). Mean reaction time (per individual) from the
presentation of a visual signal to key press decreased as
participants learned the sequence structure. At test, participants performed the task with the same or different effector (three fingers or arm position) and the same or different sequence structure as during training. Participants showed positive transfer when the sequence structure remained the same, regardless of whether they used the same or different effector. Positive transfer, indicated by no increase in reaction times at test, occurred only when the sequence structure remained the same from training to test; in the case, the effector had no effect on transfer. These results suggest that representations of sequence structure are conceptual and not motoric.

The distinction between conceptual and motoric representations has also been investigated in piano performance. Palmer and Meyer (2000), using a transfer of learning design similar to that of MacKay and Bowman (1969), required that skilled adult pianists perform a short musical piece 10 times as quickly as possible during training. After training, pianists performed another short musical piece with either the same or different conceptual (pitch order) component with either the same or different motor (hand and finger) movements. Transfer sequences with the same melodic but different motor components were learned more quickly
than transfer sequences with the same motor but different melodic components; these results suggested that, as in MacKay and Bowman (1969), learning was primarily in terms of conceptual, rather than motoric, aspects of the representation.

However, MacKay and Bowman (1969), Cohen, Ivry and Keele (1990), and Palmer and Meyer (2000) did not investigate whether the conceptual aspects of the representation include temporal information. The learning of when to produce elements (timing) may be conceptual or motoric in nature. Whether representations of temporal structure are abstracted from movements or motoric in nature is the focus of the experiments proposed here. These previous studies also relied on a variety of dependent variables, which may have influenced the findings. The experiments discussed here rely on the differences in sequence durations between training and test trials as a measure of learning.

The Role of Temporal Structure in Sequence Representation

Research on the production of hierarchically organized sequences has implications for the performance of temporal structures such as meter and rhythm in music performance. For example, researchers have investigated the produced
timing patterns of hierarchically structured finger tapping sequences. These sequences are abstract configurations of rules such that lower level units can be recursively rewritten in terms of successively higher level rules. (Jones, 1981). Rules developed by Restle (1970), including R (repetition), T (transposition), and M (mirror), can be applied to a small alphabet, for example, 1, 2, 3, 4, 5, and 6, to create hierarchically structured patterns. For example, N(1) creates the pattern 12; (R(N(1))) creates 12 12; N(R(N(1)))) creates the pattern 12 12 23 23; and C(N(R(N(1)))) creates 12 12 23 23 65 65 54 54.

Povel and Collard (1982) studied the relationship between hierarchical sequence structure and performance timing in a serial tapping task. Sequences with different hierarchical and non-hierarchical structures were constructed using Restle’s rules (1970); the sequences were composed of the numbers 1 through 4, corresponding to the index, middle, ring and little fingers, respectively. The components of each sequence were predicted to have different interonset intervals (times between successive responses), depending on the hierarchical structure of the sequence. Participants memorized the sequence, and then produced six repetitions of the sequence without errors. Different
interonset patterns were found for stimulus patterns with the same motor movements, but different hierarchical descriptions of structure. Longer interonset intervals occurred at locations of deeper hierarchical structure (more nodes to be traversed), not at locations of more difficult finger movements in tapping the patterns. Greater intersubject variability in interonset patterns was found for nonhierarchical sequences than hierarchical sequences. Povel and Collard’s (1982) findings suggest that hierarchically structured sequences are easier to produce, and the hierarchical structure is reflected in the latencies of the produced elements.

Rosenbaum (1987; Rosenbaum, Kenny, & Derr, 1983) found results similar to those found by Povel and Collard (1982); Rosenbaum additionally proposed that representations of hierarchically structured sequences (consisting of a nested pattern of responses) are motor-independent. His model, based on a theory of memory retrieval (Johnson, 1978), claimed that motor programs are executed in a way that depends on the hierarchical structure of the sequence. The hierarchically structured motor program is decoded or “unpacked” during execution. Events that require larger portions of the hierarchical tree to be traversed before
becoming activated will have longer interonset intervals. Hierarchical sequences, such as MmMmIiIi and ImIImMiMi, where M and m denote the right and left middle fingers, respectively, and I and i denote the right and left index fingers, were created to test this hypothesis. Participants memorized and performed repeating hierarchical sequences, as quickly as possible. The time (in ms) between successive responses, or interonset intervals, were measured. As predicted, interonset intervals increased with the number of nodes to be traversed based on a hierarchical description of the stimuli. The findings supported Rosenbaum's model, but do not address whether hierarchical structures specified within motor programs are abstract or motoric.

Johnson and Migdoll (1971) investigated the effects of the grouping structure on sequence representations. They argued that two responses are identical only if their grouping organizations are the same; hence learning SBJ FQLZ and SB JFQ LZ involves learning two different letter strings, even though the order of the letters are identical. Participants learned random letter sequences grouped as 3-4 or 2-3-2 (i.e., SBJ FQLZ or SB JFQ LZ), and then learned a second list of random letter sequences. The second list differed from the first in one of four ways; it was either
1) the same letters with the same grouping 2) the same letters with the different grouping 3) different letters with the same grouping or 4) different letters with the different grouping. Participants recalled the first list after learning the second list. Johnson and Migdoll (1971) found that when the grouping had changed between the first and second lists but the letters were the same, recall of the first list was impaired. These results suggest that grouping organization is an important part of the sequence representation. Simply having the serial order of units identical to each other is not enough for transfer to occur; the abstract structural organization must be similar as well. The following sections review relevant literature on the role of two temporal structures in music performance, meter and rhythm.

**Representations of Meter in Sequence Production**

Meter (periodic accent placement) in Western tonal music is a hierarchical structure of alternating strong and weak beats (the temporal periodic unit of a composition) that form accents (Cooper & Meyer, 1960; Lerdahl & Jackendoff, 1983). Meter is a hierarchical structure; beats with larger periods occur at higher levels and beats with
smaller periods occur at lower levels. When beats at different metrical levels align, they create metrical accents.

Palmer and Krumhansl (1990) found evidence that listeners have implicit knowledge of the hierarchical levels in meter. First, an analysis of musical compositions composed in four different meters indicated that musical events were distributed differentially across metrical positions. Strong periodic components in the distribution of musical events in the notated score were found that differed across the four meters and corresponded to the hierarchical levels of metrical accent predicted by Lerdahl and Jackendoff (1983). In an experimental study, listeners rated how well a probe tone (a single tone) fit in a given metrical context established by a repeating beat that created one of four meters. Listeners rated probes that occurred at strong beats as good fits and probes that occurred at weak beats as poor fits; more musically experienced listeners differentiated more metrical levels than less experienced listeners. Additionally, listeners' hierarchical structures matched those found in the frequency
analysis of the distribution of note onsets in musical compositions. These findings indicated that listeners have learned the hierarchical structure of meter.

Jones and Yee (1997) also found differences between musically experienced and inexperienced listeners. Participants heard sequences consisting of 15 IOIs; sequences were either strictly isochronous, strictly rhythmic, isochronous with some timing irregularity, or rhythmic with some timing irregularity. Participants had to detect a small time change, which occurred in one of two possible locations in the sequence. Musically experienced listeners were more accurate and needed smaller time differences to detect the time change than less experienced listeners. Musically experienced listeners were also more likely to report subdividing (using lower metrical levels) than others. This result, similar to that found by Palmer and Krumhansl (1990), provides evidence that listeners represent meter as a hierarchical structure.

Meter is a meaningful temporal structure for performers as well as for listeners. This is illuminated in a study by Sloboda (1983). Skilled pianists performed short musical pieces in which metrical barlines were shifted. None of the performers recognized the metrically modified pieces as
containing identical notes during post-experiment questioning. Analyses revealed that notes at stronger metrical positions were played longer and louder than the notes at weak metrical positions. In a perceptual study, listeners judged which metrical version they heard of the performances (shifted or non-shifted). Their judgements of which version they heard were more accurate for the performances with larger interonset intervals and velocities at metrical accents than for other performances. These results suggest that meter influences the production of events in music performance. However, these results also point out that consistent differences in IOIs and intensities do not always occur in performance of different meters, and listeners vary in their reliance on these cues.

Although evidence from perceptual studies has demonstrated listeners' knowledge of meter (Palmer & Krumhansl, 1990); evidence from performance studies have not shown strong effects of meter on interonset intervals and intensities (Sloboda, 1983; Drake & Palmer, 1993). Whereas listeners' representations of meter may be conceptual because no motor response is required, it is possible that performers' representations of meter are motoric. Many researchers have proposed a close relationship between
timing and movement in music (Kronman & Sundberg, 1987; Sundberg & Verillo, 1980; Todd, 1995). Kinematic models of music performance propose that a strong analogy exists between the kinematic, physical characteristics of typical motor movements and the timing of music.

Sandberg and Verillo (1980) sought evidence of an analogy between musical and physical motion from analyses of ritards (gradual slowing of tempo) in keyboard music. The authors generated ritards that either fit or deviated significantly from their model. The model was based on regressions of event IOIs in pieces motor music, or music dominated by long sequences of short and equal note events. Model-generated ritards were rated more musically acceptable by listeners than model-conflicting ritards. The authors concluded that the timing of performances of motor music replicates a listener’s knowledge of physical motion because the occurrence in time of pitches in a ritard bears a similarity to the temporal pattern created by the sound of footsteps as one changes from a run to a walk. Performed sequence timing may bear a similarity to the timing of other movements, like walking, because the characteristics of the motor system and the body of the performer (producer) may influence timing in production.
Kronman and Sundberg (1987) analyzed the ritards studied by Sundberg and Verillo (1980). The authors adapted kinematic formulas of physical motion (velocity, distance) to describe the timing of musical motion (ritards) in piano performance. Their model was based on physical slowing and closely approximated the average ritard from Sundberg and Verillo (1980). The authors concluded that the close fit between the mean ritard and predicted ritard suggested that the musical motion of ritards is similar to physical deceleration.

Todd (1995) presents a more extreme kinematic model of timing in music performance. He states that changes in pitch and metrical accent over time generate the perception of musical movement, and that musical movement resembles the movement of a physical body/limb. Todd, similarly to Kronman and Sundberg (1987) adapted kinematic formulas of physical motion (velocity, acceleration) to describe the timing of ritards in piano performance. He argued that the relationship between timing and movement displayed in performance is the result of a sensory-motor feedback system (Todd, 1995). This sensory-motor feedback process consists of one system, related to the tactus, that represents actions such as foot tapping, and a second system, related
to the production of rubato (gradual expressive changes in tempo), that represents actions such as body sway. The feedback process identifies periodicities in the auditory signal near 600 ms as related to foot tapping and the tactus, and identifies periodicities near 5 s as related to body sway and rubato. Although this model has not been tested thoroughly (Todd, 1995), it raises a possibility not considered by most sequence production theorists, namely, that representations of meter (at least at the tactus level) are directly linked to movement.

Representation of Rhythm in Sequence Production

Another dimension of temporal structure in music that may influence sequence representation is rhythm. Psychologists have defined rhythm as temporal patterning (Martin, 1972; Shaffer, 1982) or simply the relative timing of events (Rosenbaum, 1991). For the purposes of this paper, rhythm will be defined as the pattern of durations (event onset-to-onset) that arises from a series of tone onsets in a musical sequence. It is important to notice that rhythm is not exclusive to music. Rhythmic behavior does not necessarily entail strict temporal regularity (as it is commonly found in music notation), but it also includes the
rhythmic patterns that may be at the heart of language (Martin, 1972), action (Lashley, 1951) and attention (Jones, 1976; Large & Jones, 2000).

Some psychological theories of sequence production have suggested that rhythm and motor movements are separate and independent in sequence representations. Motor programs include abstract information about timing; this information is input to a motor system, which produces a temporally structured output. According to proposals of generalized motor programs (Schmidt, 1975; Vorberg & Wing, 1996), centrally stored patterns specify the relative timing of commands in sequence production. The timing of events in the stored pattern is multiplied by a rate parameter value to generate the performed time intervals. This multiplicative rate parameter predicts proportionality in event interonset intervals across production rates, which is called relational invariance (for a review see Gentner, 1987). In general, experimenters have failed to observe strict relational invariance in music performance (Repp, 1994; Desain & Honing, 1994; Meyer & Palmer, 1996).

However, evidence from tapping tasks has been found to support the notion that generalized motor programs include timing information. Summers (1975) presents evidence that
rhythm is a stored part of sequence representations. In a transfer of learning study, participants pressed keys in response to repeated patterns of light presented in a fixed schedule (either 500 ms-500 ms-100 ms or 100 ms-100 ms-500 ms). At transfer, participants were asked to produce the sequences as quickly as possible without regard to the learned time pattern, but the rhythm persisted in their production of the sequence. Summers concluded that the timing of the rhythmic pattern was an important part of the stored representation of the sequence. However, from this evidence alone, one can not say whether the representation was conceptual or motoric.

It is possible that rhythm is not independent of representations of motor movements. Treffner and Turvey (1993), among others (Kelso, 1995), propose that rhythmic behavior is constrained by characteristics of the motor system that are describable by nonlinear dynamical oscillators. Component frequencies of bimanual movements form rhythmic patterns called resonances; these rhythms can be simple (1:1, 1:2) or complex (2:3, 2:5). The Farey tree, a hierarchical structure of ratios generated from a 1:1 ratio, predicts the difficulty of producing rhythms of different rational ratios. Ratios with wider resonances
allow more stable behavior than narrow resonances; simple rhythms have wider resonances, and hence, their performance is less variable and more stable than performance of complex rhythms.

Treffner and Turvey (1993) investigated predictions generated by the Farey tree. In one task, participants manipulated a drumstick in synchrony to an isochronous sequence. Participants attempted to tap at the rate of the first sequence while simultaneously hearing a second rhythm that was a ratio of the first. For example, if the first sequence was one tone per second, the second sequence would be two tones per second to produce a simple ratio of 1:2. The behavior of participants matched the predictions of the Farey tree: as the rate of the second sequence changed, participants shifted to a different ratio while attempting to tap at the rate of the first sequence and this ratio tended to be a simple, neighboring ratio from the Farey tree. These results suggest that rhythmic timing and movement may interact; dynamics of the motor system may affect sequence timing.

Shaffer, Clarke, and Todd (1985) propose that representations of meter are conceptual, whereas representations of rhythm are motoric. According to the
authors, a two-level mechanism controls timing in music performance; at an abstract (non-motoric) level, a central timekeeper operates to control the tactus level (most prominent metrical level), and at the other level motor procedures specify movement patterns that define rhythms (Clarke, 1997; Shaffer, 1982). The authors assumed that if a timekeeper were operating at the tactus (most prominent metrical level), then metrical levels below the tactus would negatively covary (alternating long-short IOI pattern), because they were not under direct control of the timekeeper, whereas the tactus and higher metrical levels would not negatively covary. In one pianist's performances of Satie's Gnossienne No. 5, the authors did not find evidence of negative covariance at any metrical levels; they concluded that there were not enough metrical levels in the music to verify at which level a timekeeper was operating.

In another analysis, they found that for small groups of notes (4 to 8 notes), the variability of the groups was greater than the variability of the assumed tactus. Shaffer, Clarke and Todd (1985) concluded that a central timekeeper paced the performance at the level of the tactus and that a motor procedure constructed the rhythmic pattern for the groups of notes. If Shaffer et al.'s
conclusion is correct, then perhaps the timekeeper underlying the performance of meter is a conceptual aspect of sequence representation, whereas the motor procedures underlying the performance of rhythm are a motoric aspect of sequence representation. Experiments 1 and 2 of this thesis test this possibility.

Representations of Meter and Rhythm in Sequence Production

A final question is whether different temporal structures within music interact in sequence representation. Some music theorists have suggested that meter and rhythm do not function independently of each other in music. Musical rhythm arises out of, among other things, the metrical structure (Lerdahl & Jackendoff, 1983), and rhythm is closely tied to meter in music composition and performance (Shaffer, Clarke, & Todd, 1985; Clarke, 1987). Other theorists claim that meter functions as a rule system that generates appropriate rhythms (Longuet-Higgins & Lee, 1982; Shaffer, Clarke, & Todd, 1985). Music-theoretical proposals that rhythm and meter interact are consistent with perceptual theories that predict a perceptual interaction between meter and rhythm (Longuet-Higgins & Lee, 1982; Parncutt, 1994; Povel & Essens, 1985).
Parncutt’s model (1994) of pulse salience accounts for the perception of meter as a function of the rhythmic patterns in music. Cyclically repeating rhythms were presented to listeners at six different tempi; listeners tapped to the underlying beat of the rhythmic sequences. The results suggested that the relative salience of events at different metrical levels, as measured by when listeners tapped, depended on the rhythmic pattern and the tempo. The model accounts for these findings by assigning a phenomenal accent to each event of the rhythmic sequence; the amount of accent depends on the tempo and duration of the IOI within the rhythm. The amount of accent, along with a pattern matching routine, leads to a perception of pulse and eventually a prediction of a perceived meter. Hence, meter perception is dependent on rhythm (via IOI).

Rhythmic patterns influence the perception of beat in Povel and Essens’ (1985) model. The model assumes that listeners fit or find the best clock grid for a temporal pattern; the clock that conflicts least with the perceived stimulus provides the “best fit” and is perceived as the beat. Participants listened and tapped to rhythmic sequences until the sequences were memorized. Then, participants produced the sequences from memory. Rhythmic sequences that
were predicted to strongly induce a clock were learned after fewer repetitions and were produced from memory with fewer errors than rhythmic sequences that were predicted to only weakly induce a clock. This finding demonstrated that rhythmic patterns that strongly fit a simple meter (event onsets align with metrical accents) are more accurately reproduced than rhythmic patterns that do not strongly fit a meter.

Longuet-Higgins and Lee (1982) describe a model of meter perception in which the initial rhythm of a musical sequence generates an initial perception of meter. The model simulates meter perception by using only the relative lengths of IOIs and seeking a “good fit”. After each new IOI of a rhythmic sequence is introduced, the listener may expand the current metrical unit, move the initial downbeat, or have the current metrical interpretation confirmed. As the sequence progresses, the initial perception of meter affects rhythm perception, and the event durations influence the perception of meter; meter and rhythm interact in the perception of the sequence.

Much research on the perception of rhythm and meter has been conducted, but less research has been conducted on the performance of rhythm and meter. Some evidence from
performance suggests that the accentuation of rhythmic grouping, which segments a sequence based on changes in event duration, dominates the accentuation of metrical structure, which segments a sequence based on higher-order regularities in the sequence. Drake and Palmer (1993) investigated the relationship between rhythmic, metrical, and melodic accent structures in music performance. Three accent structures (rhythmic, metrical, and melodic) were manipulated in three experiments. Pianists performed pieces containing only one accent structure, pieces containing coinciding (important events from accent structures all occur at the same points in time) or conflicting (important events from accent structures are displaced in relation to each other) accent structures, and a sonata containing coinciding and conflicting accent structures.

Changes in intensity (loudness), interonset intervals, and articulation were compared in relation to each type of accent. Rhythmic grouping accent structures were marked most by changes in intensity, interonset intervals, and articulation. The relationship between the metrical and rhythmic structures was independent of other accent structures, but variations in timing and intensity corresponding to rhythmic grouping accents dominated in the
presence of conflicting accent structures. The authors concluded that performers may emphasize rhythmic accents more than other accent structures.

**Timing, Movement and Serial Order**

The previous discussions of the relationships between timing and movement in sequence production have not considered the role of serial ordering mechanisms. The relationship between timing and movement does not directly address the question of how events are placed in their appropriate order. Most sequence production and timing theorists have assumed that serial ordering takes place at a conceptual level, and that the serial ordering is preserved from the conceptual level to implementation at a motor level (MacKay, 1987; Wing & Kristofferson, 1973; Vorberg & Wing, 1996).

MacNeilage (1970) pointed out the distinction between solving the serial order problem at a motor level versus a conceptual level. MacNeilage was primarily interested in phonemic invariance; the large amount of variation of both the vocal tract configurations and the acoustic correlates leads to the question of how speakers produce perceptually constant phonemes. According to MacNeilage, the variability in vocal tract configurations and the produced acoustic
correlates presents a difficulty to speech production theories. He presents two views of phonemic invariance: one view states that phonemic invariance lies in the motor commands (Liberman, Cooper, Harris, MacNeilage, & Studdert-Kennedy, 1967), whereas the other view states that the invariance lies in an idealized “target” position of the vocal tract position (Lindblom, 1967; Ladefoged, 1967). If the units that are produced are phonemes, and the phonemes must be strung together in the correct order, is it the conceptual targets representing the phonemes that must be ordered, or the motor movements necessary to produce the phonemes? Also, solving the serial ordering of conceptual units doesn’t solve the serial order of motor movements. MacNeilage suggests that a serial ordering mechanism that orders conceptual units only will not solve the problem of how we make a motor transition from one unit to another. Hence, the serial ordering of motor movements must also be accounted for in sequence production models.

Although less research on the production of serial ordering and timing in music performance has been conducted, some evidence from piano performance suggests that the performance of pitch contents (what) and duration contents (when) may not be independent. Drake and Palmer (1999)
analyzed sight-read performances from novice and expert pianists. Pitch and timing errors were identified in the performances. Pitch errors were events whose pitch component differed from the notated pitch; duration errors were events whose performed interonset interval differed from the notated duration by more than 50%; and joint pitch-duration errors were events for which both the pitch and duration components were in error. Drake and Palmer (1999) computed the probability of joint pitch/duration (P/D) errors based on the error rates for the separately occurring pitch (P) and duration (D) errors \([\text{prob}(P) \times \text{prob}(D)]\) to assess the independence of pitch and timing. P/D errors were observed more often than predicted for both novice and expert pianists. These findings suggest that the pitch and duration components interact at the individual unit level of performance. A serial ordering mechanism must account for more than ordinal information; it must also include the temporal information of events (the when as well as the what) to account for these results.

The role of serial timing has been left aside in previous sections of the introduction, but evidence from Drake and Palmer suggest that serial order and timing may interact at the individual note level. In music performance,
the timing of movements and the serial order are often
correlated. For example, keypresses by the thumb followed by
the little finger with the right hand produces an ascending
sequence of pitches, and keypresses generated by the little
finger followed by the thumb produces a descending pattern
of pitches. To address the role of timing and motor
movements in sequence representation independently of the
serial order problem, the experiments reported here hold the
serial order of pitches constant; in all three experiments,
the pitch orderings in the musical sequences remain the same
from training to test. Figure 1 demonstrates this concept:
numbers under each musical example represent assigned finger
movements (1=thumb, 5=little finger); the serial ordering of
pitches in examples 1 and 2 are the same, but the hand and
finger movements are different. The independent manipulation
of meter, rhythm, and hand and finger assignments while
serial order is held constant allows evaluation of the
components of mental representations without the possible
confounding factor of serial ordering.

Overview of Experiments

Three experiments that utilize a transfer of learning
paradigm address two issues. The first issue is whether
sequence representations of meter and rhythm are abstracted
from motor movements; the second issue is whether sequence representations of meter and rhythm interact. Transfer of learning paradigms measure the change in response on a novel task as a function of experience on a prior task (Underwood, 1983). Two classes of transfer have been identified, specific transfer and nonspecific transfer. Specific transfer is transfer that can be attributed to specific relationships between two tasks (Underwood, 1983); different experimental paradigms use specific transfer as a dependent variable (usually either timing or error measures) to study learning. Nonspecific transfer is transfer that cannot be attributed to specific similarity relationships between the two tasks (Underwood, 1983); warmup effects and learning-to-learn are two examples of nonspecific transfer. Warmup effects, caused by the development of strategic adjustments by the learner, are transitory and evident only over a short period of practice, whereas learning-to-learn effects are gradual, and evident over long-term practice (Underwood, 1983).

In each experiment, skilled pianists train on one musical sequence and then perform another sequence at test, under speeded conditions. Differences in total sequence durations from between training and test is the measure of
specific transfer in the current experiments. Use of a difference score as a measure of learning controls for nonspecific transfer by comparing learning to a baseline established by the end of training. Positive transfer refers to facilitation of performance; a small difference in sequence durations between training and test indicates greater positive transfer than a large difference in sequence durations between training and test. Negative transfer refers to interference or degraded performance in the novel task; sequence durations at test longer than the sequence durations at the beginning of training indicate negative transfer. These experiments are interested in specific relative transfer. Whether negative transfer occurs is not measured here; a control condition in which test trials are produced without training is necessary to test for negative transfer (Underwood, 1983).

In Experiment 1, the meter and the required motor (hand and finger) movements in musical sequences are changed from training to test to address whether meter is an abstract, conceptual component or a motoric component of sequence representations. Positive transfer should occur when either dimension remains the same from training to test. Independence between motor (hand and finger) movements and
meter in the amount of transfer is predicted. If representations of meter are independent of representations of motor movements, then changing the motor movements should not affect the transfer of meter, and vice versa. These results would suggest that meter representation is independent of the representations for motor movements in music performance.

In Experiment 2, the rhythm and motor movements of musical sequences are manipulated to study whether rhythm is an conceptual (abstract) component or a motoric component of sequence representations. Positive transfer should occur when either dimension remains the same from training to test. Independence between motor movements and rhythm in the amount of transfer is predicted, counter to prediction of an interaction by kinematic theories (Todd, 1995) and dynamic theories (Treffner & Turvey, 1993). If representations of rhythm are independent of representations of motor movements, then changing the motor movements should not affect the transfer of rhythm, and vice versa. These results would support the notion that representations of rhythm and motor movements in music performance are independent.
In Experiment 3, both meter and rhythm of musical sequences are changed from training and test in order to identify whether these aspects of sequence representation are independent of each other. An interaction between rhythm and meter is predicted, similar to the predictions of an interaction between rhythm and meter from perceptual theories of music perception. Positive transfer should be observed when rhythm and meter remain the same during test, but changing either rhythm or meter should lead to no transfer. This result would suggest that sequence representations of meter and rhythm are not independent.
CHAPTER 1

Experiment 1: Meter and Motor Movements

Experiment 1 investigated whether meter is a conceptual or motoric part of performers’ representations of musical sequences. Evidence has been found to suggest that sequence representations are conceptual and non-motoric for skilled producers (Cohen, Ivry, & Keele, 1990; MacKay & Bowman, 1969; Palmer & Meyer, 2000), but the role of timing was not investigated. Also, the independence of timing structures, such as meter, from the production of movements has implications for theories that predict an interaction between motor movements and timing (Todd, 1995; Treffner & Turvey, 1993).

Experiment 1 used a transfer of learning paradigm in which the serial ordering of the pitches remained the same during test, while motor movements and meter were either the same or different from training to test. Pianists were told to perform as quickly as possible, and transfer was measured by the difference in sequence duration of the last training
trial and the mean of the test trials. Musical sequences were designed to be interpretable in both 3/4 or 4/4 meter and could be easily performed with either the right or left hand; the ease in which the musical sequences could be performed was tested in a pilot experiment. Distractor pieces were also included to control for carryover effects during the experiment by altering any memory for motor movements from earlier stimuli between conditions.

Main effects of both meter and motor conditions were predicted; more transfer should occur when a variable remains the same than when it differs from training to test. However, if meter effects are independent of motor effects, then no interaction of these variables should occur. That is, changing the motor movements should not affect the transfer of meter and vice versa. An interaction between Meter and Motor variables, such that changing the hand and finger movements influences the production of meter, or vice versa, would suggest that meter representation is not independent of the representation of motor movements.
Method

Subjects

Sixteen skilled pianists from the Columbus, Ohio music community participated. Participants' mean age was 25.2 years (range of 18 - 48 years). The pianists had a mean of 13.3 years of piano instruction (range of 8 - 18 years) and a mean of 17.9 years of performing experience (range of 8 - 40 years) and reported being right-handed.

Materials

Simple melodies were developed on the basis of a pilot study with different performers where pianists rated the ease of performing various musical sequences in different meters with different hands. Stimuli that were rated as equally easy to perform in either hand and meter were included in Experiment 1 (see Appendix A for details). Four sets of eight isochronous (equal duration) sequences, each containing 13 quarter-note pitches, were chosen. Each set was composed in a different musical key (half were major and half were minor) so that each would be distinguishable melodically. An example of five stimuli from one set are shown in Figure 1.
Four sequences in each set were notated in the treble clef and four in the bass clef. Within each clef, two sequences were notated for the right hand and fingers, and two were notated for the left hand and fingers. In addition, two were notated in 3/4 meter, and two were notated in 4/4 meter. For each meter, one stimulus was notated to be performed by the right hand, and the other stimulus was notated to be performed by the left hand. The serial order of pitches was preserved in all stimuli within each set, but the finger movements were altered between stimuli across hands; therefore, changing the motor movements changed the finger movements, while the serial order of pitches remained the same.

Thus, each set of eight sequences contained all combinations of clef (treble, bass), hand and finger assignments (right and left) and meter (3/4 and 4/4). The clef in which the sequences were notated was altered from training to test so that the test stimulus was never visually identical to the previous training stimulus. Figure 1 shows one training stimulus and what the test stimulus could be. The remaining three stimuli for the set shown in Figure 1 are the same as stimuli two, three, and four from the figure, but notated in the bass clef.
Four filler "distractor" pieces were also composed for the purpose of reducing carryover effects between conditions. The distractors were 13-note isochronous pieces for two hands. Distractors were composed in different keys, and were also different from the keys of the test stimuli. Two of the distractors were in 3/4 meter and two were in 4/4 meter. Distractors used all five fingers in both hands.

**Equipment**

Participants performed on a computer monitored Boesendorfer SE Imperial Grand piano (1.25-ms resolution). Computer software determined key-press onsets and offsets and identified pitch errors by comparing the performance with the pitch information in the notated musical score.

**Design and Procedure**

Experiment 1 used a 2X2 within-subjects design with independent variables of motor movements (same or different hand/finger relationships from training to test) and meter (same or different meter from training to test). The two levels of the meter variable were meter-same and meter-diff (different), and the two levels of the motor movement variable were motor-same and motor-diff (different).
The four conditions were ordered within an experimental session according to a Latin square design, with a different stimulus set assigned to each condition for each subject. Each stimulus set appeared equally often in each condition across subjects. The following variables were balanced across subjects and conditions: whether the musical sequence was performed by the right or left hand, whether the sequence was notated in bass or treble clef, and which stimulus set was assigned to each condition. Furthermore, hand and finger assignments for melodies were counterbalanced across both conditions and performers. The dependent variables were total duration of sequence production (onset of last produced tone minus onset of first one) and pitch error rate per sequence and trial. Transfer of learning was measured as the difference between the sequence duration of last training trial and the mean sequence duration of the four test trials.

Participants completed the following procedure for each condition under instructions to perform as quickly as possible, to become familiar with the task: They first performed a distractor melody four times. Then, they began a training session by performing a musical sequence slowly until no errors were made (to ensure that any errors were
not due to perceptual or reading errors); all participants performed the training sequence without any errors within three pretraining trials. Then participants performed the same training sequence ten times during training. Then they performed one of the four related test sequences from the same stimulus set four times. For example, for the training sequence in Figure 1, the test piece would be either: sequence 1 for the Motor-same/Meter-same condition, sequence 2 for the Motor-diff/Meter-same condition (diff = different), sequence 3 for the Motor-same/Meter-diff condition, or sequence 4 for the Motor-diff/Meter-diff condition. The same procedure was repeated for the remaining three conditions, using a new distractor and new stimulus set for each condition.

Results

Sequence Durations

First, outliers were removed from the sequence duration data. Outliers were defined as sequence durations greater or less than three standard deviations from the mean across subjects, trials, and conditions. Twelve of 896 trials were
greater than three standard deviations from the mean (1.3% of all trials), and were distributed across all four conditions.

Figure 2 shows the mean sequence durations of training and test trials for Experiment 1 after outliers were removed. An analysis of variance (ANOVA) on sequence durations by training trial (10) and condition (4) indicated a main effect of training trial, $F(9, 135) = 22.07, p < .01$. The total sequence durations of the training trials were examined for evidence of a power law relationship (Ivry, 1996; Newell & Rosenbloom, 1981) between practice and sequence duration. The correlation between training trial number and sequence duration averaged over subjects and performances indicated a significant negative relationship on both a linear-linear ($r = -.947, p < .001$) and log-log scale ($r = -.994, p < .001$). A significance test between dependent $r$'s (Cohen & Cohen, 1983) indicated that the log relationship was significantly larger than the linear relationship ($t(7) = 2.72, p < .05$). Individual subject correlations were greater for the log than the linear relationship for 12 of 16 subjects, and the correlations by subject (16) and condition (4) were greater for the log
relationship for 44 of 64 conditions. Thus, the data support a power law relationship between amount of training and sequence duration.

An ANOVA on sequence duration for training trials 9 and 10, alone, was conducted to ascertain whether or not sequence durations had reached an asymptote at the end of training. There was a significant difference between trials 9 and 10, \( F(1, 15) = 10.9, p < .01 \), suggesting that performers were continuing to improve. An ANOVA on the sequence duration of trial 10 by Meter and Motor conditions at training indicated no significant effects. Therefore, as in Palmer and Meyer (2000), the difference between trials 10 and the mean of the four test trials for each subject was taken as the measure of transfer.

Figure 3 shows the mean sequence duration of each of the ten training trials and the mean sequence duration across the four test trials for each condition. An analysis of variance (ANOVA) conducted on the difference between the sequence duration of the last training trial (trial 10) and the mean duration of the test trials indicated both a significant effect of motor condition, \( F(1, 15) = 11.34, p < .01 \), and a significant effect of meter condition, \( F(1, 15) = 7.39, p < .05 \). For comparison with previous measures
of learning on a logarithmic scale (Ivry, 1996; Newell & Rosenbloom, 1981), the previous ANOVA was repeated on log transformed sequence durations. The same effects were found; there was a significant effect of motor condition, $F(1, 15) = 12.49, p < .01$, and a significant effect of meter condition, $F(1, 15) = 9.63, p < .01$.

The data in Figure 3 suggest that changing the motor movements had a greater effect on transfer than did changing the meter. Planned comparisons also suggested a larger effect of motor than meter conditions; Table 1 shows the p-values of each comparison (significance = $p < .05$). There were significant differences between the Motor-same/Meter-same and Motor-diff/Meter-same conditions. Significant differences were also found between the Motor-same/Meter-diff and Motor-diff/Meter-diff conditions. These two comparisons suggest a large effect of altering the motor component at test. There were no significant differences between the Motor-same/Meter-same and Motor-same/Meter-diff conditions, or between the Motor-diff/Meter-same and Motor-diff/Meter-diff conditions. "Perfect" transfer (no significant change in sequence duration from training to test) was observed for the Motor-same/Meter-same condition only.
Analyses were conducted to test for differences in sequence duration within the test trials. An ANOVA on the sequence durations of the test trials by each condition (4) and trial (4) indicated main effects of condition, $F(3, 45) = 5.27, p < .01$, and trial, $F(3, 45) = 8.58, p < .01$, but no interaction. However, separate ANOVAs on the first two and the last two test trials reveal a change in the meter effect. The ANOVA on the difference between the sequence duration of the last training trial (trial 10) and the mean duration of the first two test trials (trial 11 and 12) indicated both a significant effect of motor condition, $F(1, 15) = 7.53, p < .05$, and meter condition, $F(1, 15) = 8.51, p < .05$. The same ANOVA on the last training trial and the mean duration of the last two test trials (trials 13 and 14) indicated a significant effect of motor condition, $F(1, 15) = 12.56, p < .01$, but a borderline effect of Meter, $F(1, 15) = 3.07, p = .1$. Together, these results suggest that the motor effect was larger and more robust than the effect of meter. Performers were able to adjust to a change in meter more quickly than they were able to adjust to a change in hand.
Additional tests were conducted on the effects of hand (Right or Left) used to perform, distractor stimuli, and order of the conditions. The difference between the sequence duration of the last training trial (trial 10) and the mean duration of the test trials by the hand used to perform the training stimulus (Right or Left) indicated a significant effect in the Motor-same/Meter-same condition only, \( t = 2.79, p < .05 \). In this condition, transfer was greater when performing the training stimuli with the right hand than with the left. No effects of distractor stimuli or condition order were found.

Timing

As performers practice a piece of music, performance may become less variable temporally. This reduction in variability may be due to learning either the motor movements or the required meter; a corresponding transfer in variability may also be observed, depending on the test condition. For example, as learning progresses, trial 10 may be less variable temporally than trial 1, and the amount of variability at trial 10 may be transferred if the motor and meter demands are the same in test as training.
To test this possibility, coefficients of variation (CV) were calculated for each performance. First, interonset intervals (IOIs) were computed for each performance. Pitch errors, the event before such errors, and the event after such errors were removed before computing the mean and standard deviation (SD) of IOIs within each performance. Coefficient of variation was computed by dividing standard deviation by the mean IOI of each performance. An ANOVA on coefficients of variation by training trial (10) and condition (4) indicated that there were no changes in variability (CV) across the ten training trials and no effects of condition. An ANOVA on the difference between the CV of the last training trial and the mean CV of the test trials was also conducted to be consistent with earlier measures of transfer used here; no significant effects of motor or meter conditions were found.

To investigate whether pianists performed the notated meter, velocities (a measure of loudness) were compared across position in the sequence for each meter. An ANOVA on interonset intervals by metrical position (strong or weak) and meter (3/4 or 4/4) indicated a main effect of metrical
position, $F(1, 15) = 13.78$, $p < .01$, such that notes at strong metrical positions were performed louder notes at weak metrical positions in both meters.

Errors

Pitch error rate was defined as the number of single note pitch errors divided by the number of opportunities for error (the number of pitches in the musical piece). The pitch error rate for all conditions and practice trials was .016, indicating that performance was close to perfect ($n = 180$). Figure 4 shows the mean error rate of each of the ten training trials and the mean error rate across the four test trials for each condition. An ANOVA on the pitch error rates of the training trials by trial (10) and condition (4) revealed no significant effects. An ANOVA on the difference between the mean error rate in the last training trial and the mean of the test trials also indicated no significant effects.

Duration errors were also considered. Individual events whose interonset intervals were greater or less than three standard deviations from the mean IOI across subjects and conditions were considered duration errors. Duration error
rate was defined as the number of individual event duration errors divided by the number of individual events minus one (number of durations) in the stimulus. The mean rate of duration errors for IOIs (not to be confused with sequence durations) was .012, indicating that performance was close to perfect (number of duration errors = 138 IOIs).

An ANOVA on the duration error rate by training trial (10) and condition (4) revealed a main effect of trial, $F(13, 195) = 2.09, p < .05$, with lower duration error rates over practice. An ANOVA on the difference between the duration error rate of the last training trial and the mean duration error rate in the test trials revealed no significant effects or interaction.

Rates of duration and pitch errors were summed for each pianist to yield a total error rate. An ANOVA on the total error rates of the training trials by trial (10) and condition (4) revealed only a significant effect of trial, $F(9, 135) = 2.63, p < .01$, with improvement over practice. An ANOVA on the difference between the mean error rate in the last training trial and the mean of the test trials indicated no significant effects.
A correlation between total sequence duration and the error rates within trials was computed to identify whether a speed-accuracy tradeoff occurred. The mean r between sequence duration and pitch error rates across conditions was 0.007 across the training trials (p = .85) and -0.035 across the test trials (p = .61). The mean r between sequence duration and total error rates across conditions was .061 across the training trials (p = .2) and -.035 across the test trials (p = .61). Hence, there was no speed-accuracy tradeoff.

Discussion

The findings from Experiment 1 indicated that both meter and motor movements are a part of performers' representations of musical sequences; changing either the meter or the hand and finger assignments at test increased performers' sequence durations from training to test. This suggests that representations of both meter and motor movements are important aspects of sequence representations in performance. Motor movements were independent from meter; changing one variable did not affect the production of the
other variable. The independence between meter and motor movements contradicts kinematic theories that predict an interaction between timing and motor systems.

Comparisons to Palmer and Meyer (2000) can be made regarding the relative importance of motor and timing components of performance. Palmer and Meyer (2000) found that changing the motor movements had no effect on performance when the serial order of pitches and the meter remained the same from training to test. By contrast, in the current study, changing the motor movements affected transfer when serial order and meter remained the same.

One reason for this may involve the relative difficulty of the stimuli. The metrical ambiguity of the stimuli and the required finger movements used here may have made this task more difficult than of Palmer and Meyer (2000). The stimuli in the current study had to be uncorrelated in metrical structure and required finger movements to allow them to be interpretable in two meters. Thus, the required finger movements differed across each metrical bar within a stimulus pattern. In contrast, the stimuli used in Palmer and Meyer were correlated in meter and motor movements; the finger movements repeated across each metrical bar and were less difficult. The number of unique finger transitions was
compared for the stimuli used in Palmer and Meyer (2000) and in Experiment 1. For example, for a 1-2-1-2 sequence in the right hand, the initial thumb-index finger transition is a unique transition, as is the next index finger-thumb transition, but the final thumb-index finger transition is not unique; hence, there are two unique finger transitions for this example. The stimuli in Experiment 1 had 10 unique finger transitions out of a possible 12 for the 13-note stimuli (range of 10 - 11 transitions), whereas Palmer and Meyer's stimuli had an average of 7 unique finger transitions out of a possible 11 for the 12-note stimuli (range = 4 - 9 transitions). Hence, the stimuli used here in Experiment 1 required a greater number of novel finger movements per stimulus than those used by Palmer and Meyer (2000) and therefore may have been more difficult motorically. However, mean interonset interval (IOI) and pitch error rates do not suggest that the stimuli in the current study were more difficult than those used by Palmer and Meyer (2000) whose mean IOIs were 190 ms within training trials, and 202 ms within test trials. In the current study, the mean IOIs were 184 ms within training trials, and 182 ms within test trials. Hence, the mean IOIs were quite similar
across the two studies. Pitch error rates were also similar across the two studies; both studies contained error rates near floor (under .05).

It is also possible that the experimental context of changing meters may have increased the importance of motor movements in performers’ representations. This suggests that temporal factors, such as meter and rhythm, which were not investigated in Palmer and Meyer (2000) increase the relative importance of motor movements in sequence representations. Rhythm, or the relative timing of event durations, is another temporal factor in music that may influence the importance of motor movements in performance. The relationship between motor movements and rhythm is investigated in the next experiment.
Experiment 2 investigated whether rhythm is a conceptual or motoric component of representations for musical sequences. Specifically, is rhythm abstracted from the motor movements necessary to produce it? Motor programming theories state that the timing information (such as the meter or rhythm) of an action is part of a motor program that exists independently of any specific effector system (Ivry, 1996; Keele, 1981; Summers, 1975; Vorberg & Wing, 1996). This predicts that representations of rhythm are conceptual and non-motoric.

Experiment 2 provided an additional test to Experiment 1 of the relationship between timing and movement, by manipulating the rhythm and the motor movements of each sequence without changing either the meter or the serial order of pitches. Experiment 2 used a transfer of learning paradigm in which the motor movements and rhythm are either the same or different from training to test. The musical
sequences used in Experiment 2 stimuli could be paired with
two different rhythms and could be easily performed with
either the right or left hand. Distractor pieces were also
included to control for carryover effects during the
experiment by reducing any motor memory carried over across
conditions.

Main effects of rhythm and motor were predicted; more
transfer should occur when a variable remains the same than
when it differs from training to test. Changing the motor
movements should not affect the transfer of rhythm and vice
versa, if rhythm effects are independent of motor effects.
However, an interaction between rhythm and motor variables,
such that changing the hand and finger movements influences
the production of rhythm, or vice versa, would suggest that
representation of rhythm is not independent of motor
movements.

Method

Subjects

Sixteen skilled pianists from the Columbus, Ohio music
community participated. Participants’ mean age was 20.9
years (range of 16 - 45 years). The pianists had a mean of
10.1 years of piano instruction (range of 7 - 14 years) and
a mean of 13.9 years of performing experience (range of 8 - 40 years). Fourteen subjects reported being right-handed, and two reported being left-handed. Two of the subjects from Experiment 1 participated in Experiment 2.

**Materials**

Simple melodies were created and selected, for the ease of playing different rhythms with either hand, based on a pilot study with different performers (see Appendix B for details). Four sets of eight musical melodies, each containing 19 pitches, were notated in 4/4 meter. Each set was composed in a different musical key; half were in a major key and half were in a minor key so that each would be distinguishable melodically. Each set of eight sequences contained all combinations of clef (treble, bass), hand and fingers (right and left) and one of two rhythms. Each set was designed to be used equally often in all four experimental conditions, which are described in the design and procedure section. See Figure 5 for an example of one training and four test stimuli from one stimulus set. Each rhythmic pattern was composed from a different combination of two different note values: for example, quarter-notes and eighth-notes. Every rhythmic pattern was based on a pattern of four beats (6 notes) that repeated three times per
sequence; hence every sequence was of equal notated
duration. The two rhythms within each set were related such
that quarter-notes were replaced with two eighth-notes, and
two eighth-notes were replaced by a quarter-note. This
manipulation allowed the rhythm to change from training to
test, while the total number of unique durations and
sequence length remained the same.

Four isochronous filler “distractor” pieces were also
composed. The distractors were 13-note isochronous pieces
for two hands in 4/4 meter. Distractors were composed in
different keys, and used different keys than those of the
test stimuli. Distractors used all five fingers in both
hands, to reduce any carryover of motor effects across the
test sequences.

Equipment

Participants performed on a computer monitored
Boesendorfer SE Imperial Grand piano (1.25-ms resolution).
Computer software determined key-press onsets and offsets
and identified pitch errors by comparing the performance
with the pitch information in the notated musical score.
Design and Procedure

Experiment 2 used a 2X2 within-subjects design with independent variables of motor movements (same or different hand and finger relationships from training to test, called Motor-same and Motor-diff, respectively) and rhythm (same or different rhythm from training to test, called Rhythm-same and Rhythm-diff, respectively). The dependent variables were total sequence duration and pitch error rate per sequence.

The same design and procedure was used as in Experiment 1. For example, for the training sequence in Figure 5, the test piece would be either: sequence 1 for the Rhythm-same/Motor-same condition, sequence 2 for the Rhythm-diff/Motor-same condition, sequence 3 for the Rhythm-same/Motor-diff condition, or sequence 4 for the Rhythm-diff/Motor-diff condition. Distractors preceded each condition, and stimuli from a new stimulus set were used for each of the four conditions.
Results

Sequence Durations

First, outliers were removed from the sequence duration data. Sequence durations greater than three standard deviations from the mean across subjects, trials, and conditions were considered to be outliers. Seven of 896 trials were greater than three standard deviations of the mean (0.78%), and were distributed across all four conditions.

Figure 6 shows the mean sequence durations of training and test trials for Experiment 2. An ANOVA on sequence durations by training trial (10) and condition (4) indicated a main effect of training trial, $F(9, 135) = 28.87, p < .01$. Sequence durations in training trials were examined for evidence of a power law relationship between practice and sequence duration. The correlation between training trial number and sequence duration averaged over subjects and performances indicated a significant negative relationship on both a linear-linear ($r = -.943, p < .001$) and log-log scale ($r = -.987, p < .001$). A significance test between dependent $r$'s indicated that the log relationship was significantly larger than the linear relationship ($t(7) = 59$).
The correlations conducted by subject were greater for the log than the linear relationship for 10 of 16 subjects, and the correlations by subject (16) and condition (4) were greater for the log relationship for 45 of 64 conditions. Thus, as in Experiment 1, the data support a power law relationship between amount of training and sequence duration for these rhythmically varying stimuli.

An ANOVA on sequence duration for just training trials 9 and 10 indicated no main effect of trial or interaction. Also, an ANOVA on the sequence duration of trial 10 by conditions revealed no significant effects. This suggests that sequence duration had reached an asymptote by the end of training. The difference between trial 10 and the mean of the four test trials was taken as a measure of transfer, to be consistent with Experiment 1.

Figure 7 shows the mean sequence duration of each of the ten training trials and the mean sequence duration across the four test trials for each condition. An ANOVA on the difference between the sequence duration of the last training trial and the mean of the test trials indicated both a significant effect of motor condition, $F(1, 15) = 14.39, p < .01$, and a significant effect of rhythm condition, $F(1, 15) = 7.99, p < .05$. The ANOVA was also
repeated on log transformed sequence durations. The same
effects were found; there was a significant effect of motor
condition, $F (1, 15) = 17.99, p < .01$, and a significant
effect of rhythm condition, $F (1, 15) = 7.93, p < .05$.

Figure 7 suggests that changing the rhythm increased
sequence durations more during test than changing the motor
movements. Planned comparisons, shown in Table 2, supported
these findings: There were significant differences between
the Rhythm-diff/Motor-same and Rhythm-same/Motor-same
conditions and the Rhythm-same/Motor-diff and Rhythm-
same/Motor-same conditions, ($p < .05$). Table 2 shows the $p$-
values for each comparison. “Perfect” transfer (no
significant change in sequence duration from training to
test) was observed for the Rhythm-same/Motor-same condition
only.

Analyses were conducted to test for differences in
sequence duration within the test trials. An ANOVA on the
sequence durations of the test trials by each condition (4)
and trial (4) indicated main effects of condition, $F (3, 45)$
$= 5.43, p < .01$, and trial, $F (3, 45) = 4.21, p < .01$. There
was also a significant interaction, $F (9, 135) = 2.5, p <$
$.05$, because the Rhythm-same/Motor-diff condition did not
asymptote during transfer in the same manner as the other

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three conditions. However, individual ANOVAs on the first and second half of the test trials revealed the same main effects as were found for the mean of the test trials. An ANOVA on the difference between the sequence duration of the last training trial and the mean duration of the first two test trials indicated both a main effect of motor, $F (1,15) = 14.6, p < .01$, and an effect of rhythm, $F (1,15) = 11.87, p < .01$. The same ANOVA on the last two test trials found the same effects of motor, $F (1,15) = 11.20, p < .01$, and rhythm, $F (1,15) = 5.2, p < .05$. These results confirm that both rhythm and motor movements facilitated transfer from one melody to another.

Additional tests were conducted on the effects of hand, distractor stimuli, and order of conditions. T-tests on the difference between the sequence duration of the last training trial (trial 10) and the mean duration of the test trials by training hand (Right or Left) indicated a significant difference in the Rhythm-diff/Motor-diff condition only, $t = 2.26, p < .05$. In this condition, transfer was greater when performing the training stimuli with the right hand than with the left. No other significant differences by training hand were found. No effects of distractors or order of conditions were found.
Timing

As in Experiment 1, the possibility of transfer of timing variability was investigated. Coefficients of variation were calculated for each performance; as before, pitch errors and the events immediately surrounding them were removed before the mean IOI and standard deviation were computed. The standard deviation was divided by the mean IOI of each performance to compute the coefficient of variation (CV). An ANOVA on the difference between the coefficient of variation of the last training trial and the mean CV of the test trials indicated no significant effects of either motor or rhythm condition. An ANOVA on the coefficients of variation by training trial (1-10) and condition (4) indicated a main effect of trial, $F(9, 135) = 5.38, p < .01$, but there was no systematic decrease in CV over trials. An ANOVA on the CVs by training (first 5, last 5 trials) indicated that the second half of the training trials were more variable, $F(1, 15) = 22.13, p < .01$. 

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Errors

Pitch error rates were computed as in Experiment 1. The mean pitch error rate was .014 indicating that performance was close to perfect (n = 223). Figure 8 shows the mean error rates for the ten training trials and across the four test trials for each condition. An ANOVA on the pitch error rates of training trials by trial (10) and condition (4) indicated no main effects or interaction. An ANOVA on the difference between the error rate of the last training trial and the mean error rate of the test trials indicated a borderline significant effect of motor condition, $F(1, 15) = 4.1, p = .06$, and a significant effect of rhythm, $F(1, 15) = 4.65, p = .048$. However, since the mean difference in error rate from training to test was minimal (.009), and there was no meaningful pattern in the mean amount of transfer across the four conditions, there may be too few errors to interpret these results.

Duration errors were also considered, and were identified as follows: For each performance (trial), the mean IOI of each duration category (eighth-, quarter- and dotted quarter-note) was computed. A threshold for each duration category was determined such that events that were
more than half way between the correct duration category and the next larger or smaller duration category were considered duration errors. For example, an eighth-note that was greater than 1.5 times the mean eighth-note duration for that trial would have been coded as an error, and a quarter-note less than .5 times the mean quarter-note duration would have been coded as an error. This method of identifying duration errors allowed some flexibility in the performed tempo without unduly increasing the number of events coded as duration errors.

Duration error rate was then defined as the number of duration errors divided by the number of events minus one (the number of durations) in the stimulus. The mean duration error rate was .011, indicating that performance was close to perfect (n = 184). Figure 9 shows the interonset intervals of a performance of the last training trial and the first test trial in the Rhythm-diff/Motor-same condition. The performed stimuli are notated in Figure 5; from the two figures, it is clear that the performer changed the rhythm pattern during test, and that the timing of the produced rhythm matched that in the notation. There were 35 duration errors in the test trials. Of these, 23 were cases in which the intended duration was replaced by a duration of
a note value longer than notated (for example, an intended eighth-note becomes a quarter-note), and the remaining 12 were shorter than the intended duration.

An ANOVA on the duration error rate by training trial (10) and condition (4) revealed no significant differences, and the mean of the last training trial was used to measure transfer. An ANOVA on the difference between the duration error rate of the last training trial and the mean duration error rate in the test trials indicated no significant effects of motor or rhythm condition. As with pitch errors, this result may have been due to the very low duration error rate overall.

A total error rate was computed by summing the pitch error rate and the duration error rate of each pianist. An ANOVA on the total error rates of the training trials by trial (10) and condition (4) revealed only a significant effect of trial, $F(9, 135) = 3.86, p < .01$, showing improvement over practice. An ANOVA on the difference between the mean error rate in the last training trial and the mean of the test trials indicated no significant effects.
A correlation between total sequence duration and the pitch error rate within training trials was computed to identify whether a speed-accuracy tradeoff occurred. Across conditions, the mean $r$ was 0.094 across the training trials ($p = .03$) and -0.037 across the test trials ($p = .59$). The mean $r$ between sequence duration and the total error rate was .10 across the training trials ($p = .03$) and -.045 across the test trials ($p = .52$). Hence, there was no speed-accuracy tradeoff.

Discussion

The findings from Experiment 2 indicate that both rhythm and motor movements are a part of performers' sequence representations of music; changing either the rhythm or the hand and finger assignments reduced transfer from one melody to another. These results suggest that sequence representations include both a motor component and a more abstract component representing the rhythm. The prediction made by motor programming theories that sequence timing is part of the motor program, and hence, abstract and non-motoric, were supported.
Motor movements also appeared to be independent from rhythm in performance; changing one variable did not affect the transfer of the other variable. The failure to find an interaction between timing and movement in either Experiment 1 or 2 provides support to theories of sequence production that include independent, non-interacting levels of timing and motor production. One cannot conclude that motor movements have no influence on timing, but it appears that for stimuli with simple integer ratio rhythms, such as those used here, independence between motor movements and rhythmic timing is observed. It is possible that timing and motor systems operate independently, but when the motor system implements the timing, the motor system is constrained such that the output of the timing system is changed. However, this may only be observed for complex ratio rhythms. Hence, empirical results indicating that the dynamics of the motor system influence timing (Treffner & Turvey, 1993; Kelso, 1995) are showing the predisposition of the motor system to produce simple ratio timing patterns.
CHAPTER 3

Experiment 3: Meter and Rhythm

Experiment 3 investigated whether meter and rhythm are independently represented in musical sequences. Meter and rhythm are two types of temporal structure that can be independently manipulated in musical compositions, but whether the psychological representation for each is independent of the other in music performance in unknown. Some theories of perception predict an interaction between the perception of meter and rhythm (Longet-Higgins and Lee, 1982; Parnscutt, 1994; Povel and Essens, 1985), but this may not be true in performance.

Experiment 3 used a transfer of learning paradigm in which the meter and rhythm were either the same or different from training to test, while the motor movements and serial order of the pitches remained the same. As in the previous experiments, each pitch sequence was composed to allow performance of two different rhythms and meters for the same serial ordering of pitches.

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Significant effects of rhythm and meter variables at test were predicted; more transfer should occur when a variable remains the same than when it differs from training to test. If rhythm is independent of meter effects, then changing the rhythm should not affect the transfer of meter, and vice versa. However, an interaction between meter and rhythm variables, such that changing the rhythm influences the production of meter, or vice versa, would suggest that representations of these temporal structures are integrated in music performance.

Method

Subjects

Sixteen skilled pianists from the Columbus, Ohio music community participated. Participants' mean age was 19.8 years (range of 18 - 25 years). The pianists had a mean of 10.3 years of piano instruction (range of 7 - 15 years) and a mean of 12.1 years of performing experience (range of 9 - 17 years). All subjects reported being right-handed and did not participate in previous experiments.

Materials

Simple melodies were created and selected based on a pilot study with different performers (see Appendix C). Four
sets of eight sequences, each containing 19 pitches, were chosen. Each set was composed in a different musical key, and half were major and half were minor so that each would be distinguishable melodically. Thus, each set of eight sequences contained all combinations of clef (treble, bass), meter (3/4 and 4/4), and rhythm. See Figure 10 for one training and four test stimuli from one stimulus set. All sequences were notated to be performed with the right hand, because unlike Experiments 1 and 2, motor movements were not manipulated in Experiment 3. The rhythmic patterns were composed of eighth-, quarter-, and dotted-quarter-notes, and were 12 beats long (three measures in 4/4 meter or four measures in 3/4 meter). The rhythmic patterns did not repeat within a sequence to prevent them from fitting one meter better than another, unlike those in Experiment 2, whose rhythms repeated in each metrical bar.

Four filler "distractor" pieces were also composed for this experiment. The distractors were 13-note isochronous pieces for two hands. They were composed in different keys, and were all different keys than the test stimuli. Two of the distractors were in 3/4 meter and two were in 4/4 meter. Distractors used all five fingers in both hands to reduce any carryover between conditions.
Equipment

Participants performed on a computer monitored Boesendorfer SE Imperial Grand piano (1.25-ms resolution). Computer software determined key-press onsets and offsets and identified pitch errors by comparing the performance with the information in the notated musical score.

Design and Procedure

Experiment 3 used a 2X2 within-subjects design with independent variables of meter (same or different meter from training to test, called Meter-same and Meter-diff, respectively) and rhythm (same or different rhythm from training to test, called Rhythm-same and Rhythm-diff, respectively). The dependent variables were total sequence duration (onset of last tone minus onset of first tone) and pitch error rate per sequence. The same design and procedure was used as in Experiment 1. For the training sequence in Figure 10, the test piece would be either: sequence 1 for the Rhythm-same/Meter-same condition, sequence 2 for the Rhythm-diff/Meter-same condition, sequence 3 for the Rhythm-same/Meter-diff condition, or sequence 4 for the Rhythm-diff/Meter-diff condition. Sequences from a new stimulus set were used for each condition, and a different distractor was performed four times before each condition.
Results

Sequence Durations

First, outliers were removed from the sequence duration data. Sequence durations greater than three standard deviations from the mean, computed across subjects, trials, and conditions, were considered to be outliers. Four of 896 trials were outliers (0.4%), and were distributed across three of the four conditions.

Figure 11 shows the mean sequence durations of training and test trials for Experiment 3. An ANOVA on sequence durations by training trial (10) and condition (4) indicated a main effect of training trial, $F(9, 135) = 55.48$, $p < .01$. The total sequence durations in the training trials were examined for evidence of a power law relationship between practice and sequence duration. The correlation between trial number and sequence duration averaged over subjects and performances indicated a significant negative relationship on both a linear-linear ($r = -.952, p < .001$) and log-log scale ($r = -.997, p < .001$). A significance test between dependent $r$'s indicated that the log relationship was significantly larger than the linear relationship ($t(7)$
The correlation averaged by subject was greater for the log than the linear relationship for 12 of 16 subjects, and the correlation by subject (16) and condition (4) was greater for the log relationship for 43 of 64 conditions.

An ANOVA on sequence duration for training trials 9 and 10 indicated a significant difference, $F(1,15) = 4.69, p < .05$, suggesting that performers were still improving in performance. An ANOVA on the sequence duration of trial 10 by Meter and Rhythm conditions indicated no significant differences. As in the previous experiments, the difference between trial 10 and the mean of the four test trials was used to measure transfer.

The mean sequence duration of the ten training trials and the mean sequence duration across the four test trials for each condition are shown in Figure 12. An ANOVA on the difference between the sequence duration of the last training trial and the mean duration of the test trials indicated a significant effect of rhythm, $F(1, 15) = 21.14, p < .01$, and a borderline significant effect of meter, $F(1, 15) = 2.499, p = .053$. The ANOVA repeated on log transformed sequence durations revealed similar effects. There was a
significant effect of rhythm condition, $F(1, 15) = 23.10, p < .01$, but no effect of meter condition, $F(1, 15) = 1.68, p > .1$.

Figure 12 suggests that rhythm had a larger effect than meter on performers' transfer. Planned comparisons among all pairs of conditions, shown in Table 3, also suggested a larger effect of rhythm than meter. There were significant differences between the Rhythm-same/Meter-same and Rhythm-diff/Meter-same conditions, and between the Rhythm-diff/Meter-diff and Rhythm-same/Meter-diff conditions. The Rhythm-same/Meter-same and Rhythm-same/Meter-diff conditions did not significantly differ, and neither did the Rhythm-diff/Meter-diff and Rhythm-diff/Meter-same conditions. "Perfect" transfer (no significant change in sequence duration from the end of training to test) was observed for both the Rhythm-same/Meter-diff and Rhythm-same/Meter-same conditions.

Analyses were conducted to test for differences in sequence duration within the test trials. An ANOVA on the sequence durations by test trials (4) by condition (4) indicated main effects of condition, $F(3, 45) = 8.34, p < .01$, and trial, $F(3, 45) = 17.51, p < .01$, but no interaction. However, separate ANOVAs on the first two and
last two test trials revealed different main effects. An ANOVA on the difference between the sequence duration of the last training trial and the mean duration of the first two test trials indicated both a significant effect of meter, $F(1, 15) = 6.93, p < .05$, and a significant effect of rhythm, $F(1, 15) = 16.26, p < .01$. The same ANOVA on the difference between the sequence duration of the last training trial and the mean duration of the last two test trials indicated only a significant effect of rhythm, $F(1, 15) = 20.67, p < .01$.

Similar to the findings in Experiment 1, the difference in transfer of meter between the first and last two test trials suggests that performers were able to learn to switch from one meter to another more quickly than they could learn to switch from one rhythm to another.

Additional tests were conducted on the effects of distractor stimuli and order of conditions. There were no significant effects of distractors or order of condition.

Timing

The possibility of transfer of timing variability was investigated. Coefficients of variation were calculated for each performance. Pitch errors and the events immediately
surrounding them were removed before the mean IOI and standard deviation were computed. Then, the standard deviation was divided by the mean IOI of each performance to compute the coefficient of variation (CV). An ANOVA on the coefficients of variation by training trial (1-10) and condition (4) indicated a main effect of trial, $F(9, 135) = 4.68, p < .01$; there was a gradual increase in CV over trials. There was also an interaction between trial and condition, $F(27, 405) = 1.56, p < .05$. There were no significant differences among CVs at trial 10 across conditions, and an ANOVA on the difference between the coefficient of variation of the last training trial and the mean CV of the test trials indicated no significant effects of either meter or rhythm condition.

Errors

Pitch error rates were calculated as in Experiments 1 and 2. The mean pitch error rate was .009, indicating that performance was close to perfect ($n = 149$). Figure 13 shows the mean error rates for the ten training trials and across the four test trials for each condition. An ANOVA on pitch error rate by training trial (10) and condition (4)
indicated a main effect of condition, $F(3, 45) = 3.18, p < .05$, and trial, $F(3, 45) = 2.9, p < .01$. An ANOVA on the pitch error rates of the last training trial by condition revealed no effects of condition. An ANOVA on the difference between the mean pitch error rate of the last training trial and the mean pitch error rate of the test trials also indicated no significant effects.

Duration errors were also considered. Duration errors were identified as follows: For each performance (trial), the mean IOI of each duration category (eighth-, quarter- and dotted quarter-note) was computed. Thresholds halfway between each duration category were determined, such that events whose observed durations were greater or less than half way to the next duration category were considered duration errors. For example, an eighth-note that was greater than 1.5 times the mean eighth-note duration for that trial or less than .5 times the mean quarter-note duration for that trial was coded as an error.

The duration error rate was defined as the number of single note duration errors divided by the number of events minus one in the piece. The mean duration error rate was .01, indicating that performance was close to perfect ($n = 175$), with no differences across conditions.
Figure 14 shows the interonset intervals of a performance of the last training trial and the first test trial in the Rhythm-diff/Meter-same condition whose stimuli are shown in Figure 10. Inspection of the notated and performed durations shows the accuracy of the performed rhythm during training and test. Of the 83 duration errors in the test trials, 50 were cases in which the intended duration was replaced by a duration of a note value longer than notated (for example, a notated eighth-note is performed as a quarter-note), and the remaining 33 were shorter than the notated duration.

An ANOVA on the duration error rates by training trial (10) and condition (4) revealed no effects of trial or condition. An ANOVA on the difference between the last training trial and the mean error rate of the test trials indicated no significant effects of meter or rhythm condition. Again, this result may have been due to the very low error rate overall.

Total error rate was computed by summing the pitch and duration error rates of each pianist. An ANOVA on the total error rates of the training trials by trial (10) and condition (4) revealed only a significant effect of trial, $F(9, 135) = 1.98, p < .05$, with improvement over practice. An
ANOVA on the difference between the mean error rate in the last training trial and the mean of the test trials indicated no significant effects.

A correlation between sequence durations and the error rates within training trials was computed to identify whether a speed-accuracy tradeoff occurred. The mean $r$ between sequence duration and pitch error rates across conditions was 0.043 across the training trials ($p = .40$) and 0.016 across the test trials ($p = .79$). The mean $r$ between sequence duration and the total error rates was 0.027 across the training trials ($p = .61$) and 0.053 across the test trials ($p = .45$). Hence, there was no speed-accuracy tradeoff.

Discussion

Experiment 3 investigated whether sequence representations of meter and rhythm interact with each other in performance, as some have claimed in perception (Longuet-Higgins & Lee, 1982; Shaffer, 1982; Shaffer, Clarke, & Todd, 1985). Consistent with the previous experiments, the findings of Experiment 3 indicate that rhythm and meter are both part of performers' sequence representations of music;
changes in either the rhythm or the meter from training to test increased sequence durations. However, the two have independent effects on transfer. The relative size of the effects suggests that rhythm is a more dominant representation in performance than is meter. Sequence durations during test reached an asymptote more quickly for a change in meter than a change in rhythm. It may be that performers find it easier to learn a new meter than to learn new motor movements or a new rhythm. Finally, no interaction between meter and rhythm was observed; changing one variable did not appear to affect the transfer of the other variable. Theories of music perception that predict an interaction between rhythm and meter (Longuet-Higgins & Lee, 1982; Parncutt, 1994) may not generalize to music performance, in which rhythm and meter appear to be independent.
The results from three experiments demonstrated effects of meter, rhythm, and motor movements; independence between temporal representations and motor representations; and independence between representations of meter and rhythm in music performance. These results extend previous research that investigated the cognitive and motor representations involved in skilled sequence production (Cohen, Ivry, & Keele, 1990; MacKay & Bowman, 1969) and the relationship between motor movements and timing (Shaffer, Clarke, & Todd, 1985), but did not investigate whether temporal structure is represented independently of motor movements. The findings from the current experiments suggest that metrical structure, rhythmic structure, and hand and finger movements are part of sequence representations in music performance.

Experiment 1 found that sequence representations include both a motoric component and an abstract (non-motoric) metrical component that do not interact with each
other. Pianists trained on one melody and transferred to a melody that required the same or different hand and finger movements and the same or different meter. The difference in sequence durations was smaller when meter was the same than different, and when motor movements were the same than different from training to test. A larger effect of motor movements was observed than of meter; greater differences in sequence durations from training to test were observed when the hand and finger assignments were changed than when the meter changed, at least for the rhythmically simple (isochronous) melodies used in Experiment 1. Also, there was no interaction between meter and motor movements; changing one variable did not affect the performance of the other variable at test. Finally, perfect transfer was observed when both meter and motor movements were the same, and the least amount of transfer was observed when both meter and motor movements were different from training to test.

Experiment 2 found that sequence representations in music performance include both a motoric component and an abstract (non-motoric), rhythmic component that do not interact. The difference in sequence durations from training to test was smaller when the rhythm was the same at test as at training, and when motor movements were the same at test.
as at training. A larger effect of motor movements was observed than of rhythm; greater differences in sequence durations from training to test were observed when the motor movements were changed than when the rhythm changed, at least when meter held constant across training and test. Most important, there was no interaction between rhythm and motor movements; changing one variable did not affect the performance of the other variable at test. Finally, perfect positive transfer was observed when both rhythm and motor movements were the same, and the least amount of transfer was observed when both rhythm and motor movements were different from training to test.

Experiment 3 found that representations of music performance include metrical and rhythmic components that do not interact with each other. The difference in sequence durations from training to test was smaller when meter was the same at test as at training, and when the rhythm was the same at test as at training. A larger negative effect of change was found with rhythmic than with metric changes; greater differences in sequence durations from training to test were observed when the rhythm was changed than when the meter changed, at least for the melodies performed by the right hand only, used in Experiment 3. Most important, there
was no interaction between meter and rhythm; changing one variable did not affect the performance of the other variable at test. Furthermore, perfect transfer was observed when both the rhythm and meter were the same and the least amount of transfer was observed when both rhythm and meter were different from training to test.

Although speeded performance conditions are unusual in musical behaviors, performers were able to complete the task. Experiments 2 and 3 required performers to produce rhythms as quickly as possible; nevertheless, the timing based on these simple ratio rhythms was correctly performed, as evidenced by the low duration error rate. Additionally, the rate of learning, measured by sequence duration over trials, fit a power law function in all three experiments; sequence durations decreased more rapidly at the beginning of training than at the end of training. This finding adds to the number of behaviors that follow the power law of practice (Ivry, 1996; Newell & Rosenbloom, 1981), and is evidence that participants were able to learn the melodies in all three experiments.

The findings from the three experiments have implications for psychological theories of sequence production and music-theoretic ideas on the relationships
between temporal structures in music. The following
discussion addresses these topics: 1) motor movements in
sequence representations, 2) meter in sequence
representations, 3) rhythm in sequence representations, 4)
independent representations of timing and motor movements,
5) the relationship between meter and rhythm in music, and
6) serial ordering and timing in sequence production.

Motor Movements in Sequence Representations

The transfer of motor movements across musical
sequences in Experiment 1 and 2 suggests that motor
movements are part of representations for sequence
production for skilled musicians. This finding differs from
previous studies that did not find a motoric component in
transfer of learning. Cohen, Keele, and Ivry (1990) found
that changing effectors did not change timing responses from
training to test, indicating that sequence representations
were not motoric. MacKay and Bowman (1969) found that speech
articulators changed at test did not affect the duration of
sentences produced by bilingual speakers. Translations of
sentences were produced as quickly at test as the original
(untranslated) training sentences, indicating that speakers’
representations were abstracted from the particular
articulatory movements used to produce the two languages. In
contrast, in these experiments, the sequence durations at
test were smaller when motor movements were the same than
different.

Music performance places large temporal and motor
demands on the performer. A motor component may be larger in
representations of music performance because music makes
greater temporal and motor demands on the producer than do
tapping tasks. A previous study of music performance did not
find a motor component in sequence representations of
skilled pianists (Palmer & Meyer, 2000). The transfer of
learning design used in Experiment 1 is quite similar to
that used by Palmer and Meyer (2000). At test, pianists
performed a short, isochronous musical piece with the same
or different melody (pitch ordering) component and either
the same or different motor (hand and finger) movements from
training (Palmer & Meyer, 2000). The motor movements at test
did not affect sequence duration, contrary to the findings
of Experiments 1 and 2, which showed that retaining motor
movements at test decreased sequence durations.

One explanation of the different experimental results
may lie in differences in motor and temporal demands made on
performers across the two studies. The metrically ambiguous
stimuli used in Experiment 1 made greater temporal and/or
motor demands on the performer than the isochronous, motorically repetitive stimuli used by Palmer and Meyer (2000). The metrical accent positions and required finger movements were uncorrelated in Experiment 1, to allow the same melody to be interpretable in two meters. In contrast, the melodies used in Palmer and Meyer (2000) were correlated in metrical accent positions and motor movements; the finger movements commonly repeated across each metrical bar, and hence, may have been both metrically and motorically simpler than the melodies used here. To verify this difference, the number of unique finger transitions between each pair of consecutive events within a piece were counted for each melody in both experiments. The melodies used in Experiment 1 had an average of 10 out of a possible 12 transitions (range =10 - 11 transitions), whereas Palmer and Meyer’s melodies had an average of 7 out of 11 possible unique finger transitions (range =4 - 9 transitions). Hence, the melodies used in Experiment 1 required a greater number of finger movements per melody than those used by Palmer and Meyer (2000).

Representations of motor movements may be used in situations in which complex temporal or motor demands are made on the performer. If temporal factors increase the
relative demands on motor movements in sequence representations, then rhythm may also increase the effects of motor movements in performance. Indeed, motor transfer was observed in the presence of rhythm changes in Experiment 2. Changes in rhythm increase the motor demands in part because changing the rhythm requires changing the time at which hands and fingers must move, even when hand and finger assignments are the same for two rhythms. Although no interaction was found between rhythm and motor movements (hand and finger assignments), it is possible that an interaction between rhythm and hand and finger movements occurs at shorter time spans than the total sequence duration (although there were no changes in timing variability).

Another explanation for the difference in observed motor transfer between Experiment 1 and Palmer and Meyer (2000) may be due to differences in skill level of the participants. Palmer and Meyer (2000) concluded that as pianists gain expertise, they differentiate the components of performance, and the relative importance of motor movements in sequence representations decreases. However, there was no significant difference in the amount of
experience between the advanced participants in Palmer and Meyer (mean = 18.3 years experience) and in Experiment 1 (mean = 17.9 years experience).

The finding of a motoric component as well as an abstract (non-motoric) component of sequence representations is consistent with physiological evidence of both effector-independent (abstract, conceptual) and effector-specific (motoric) pathways of learning and production in the brain. Grafton, Hazeltine, and Ivry (1998) found neural evidence identifying effector-specific and effector-independent neural systems involved in sequential movements produced by different effectors. Positron emission tomography measured cerebral blood flow of participants while they performed the same task as used by Cohen, Ivry, and Keele (1990). Activity in the inferior parietal cortex remained high during transfer, suggesting that this area had encoded the sequence at an abstract, effector-independent level during the learning phase. However, activity in the sensorimotor cortex shifted to a more dorsal location from training to transfer, suggesting effector-specific areas as well. Additionally, Grafton et al. (1998) suggest that the cingulate motor area plays a role in linking the abstract sequential representations with the relevant effector system.
The findings of transfer of meter across musical sequences in Experiments 1 and 3 suggest that meter is part of representations of sequence production for skilled musicians. This resembles findings from other transfer of learning studies that show the importance of structure in sequence representations. If meter is considered as a form of grouping (Cooper & Meyer, 1960) in these experiments, it bears a similarity to the grouping manipulation in Johnson and Migdoll (1971): in both experiments the order of the sequence events was identical, but only the grouping organization was altered. Johnson and Migdoll (1972) found that transfer occurred only when the grouping of random letter sequences remained the same from training to test. Cohen, Ivry, and Keele (1990) also found transfer of sequence structure. Reaction times did not change when the sequence structure remained the same at test, and increased when the sequence structure changed at test to a randomly ordered sequence, again demonstrating the importance of structure in sequence representations.

The findings of transfer of meter, which is a hierarchical form of sequence structure, are also consistent with findings from studies employing other paradigms that
demonstrated the importance of hierarchical structure in sequence learning (Povel & Collard, 1982). Rosenbaum, Kenny, and Derr (1983) found evidence that representations include the hierarchical (nested) structure of a sequence.

Participants produced hierarchically structured sequences as quickly as possible in a tapping task. The interonset intervals between produced events increased depending on the hierarchical description of the sequence, as predicted. The results from Rosenbaum et al. (1983) and the current experiments add to the evidence for hierarchical structures in sequence representations.

Skill level may reflect differences in flexibility in temporal organization for experts and novices; one of the hallmarks of skilled performance is fluency and flexibility (MacKay, 1982). The timing necessary to produce a notated meter or rhythm in music performance is difficult for novice performers to master (Drake & Palmer, 2000). Thus, experts may be much faster to impose a new metrical organization on a piece, and novices may demonstrate greater difficulty in learning a new metrical structure. It is possible that the smaller transfer effects observed for meter than for motor or rhythm dimensions across the experiments are attributable only to highly skilled participants; they were able to learn
a new metrical structure for the same musical sequence within the first two transfer trials. Performers may be more flexible at changing their conception of temporal organization of musical sequences than they are at learning new motor movements. Additional research that compares experts and novices over a greater number of test trials may illuminate the time course of learning temporal structures.

**Rhythm in Sequence Representations**

The transfer of rhythm across musical sequences in Experiments 2 and 3 suggest that rhythmic structure is part of representations of sequence production for skilled musicians. It is important to note that the manipulations of rhythm in Experiments 2 and 3 were slightly different from each other. In Experiment 2, the rhythm was repeated within each stimulus and changed in a systematic fashion in the rhythm-different condition, whereas this was not true for the stimuli used in Experiment 3. It is possible that different results may have been found for either experiment if different stimuli had been used, but the current experiments do show that rhythms are part of representations of sequence production.
This finding is similar to results from transfer of learning studies that demonstrated the importance of relative timing in sequence representations (Summers, 1975). In Summers' study (1975), participants produced either 500 ms - 500 ms - 100 ms or 100 ms - 100 ms - 500 ms cycling sequences in synchrony with visual cues. At test, participants produced the sequences as quickly as possible from memory and "that the maintenance of the correct timing between events was no longer important or necessary." (Summers, 1975 p. 233). The rhythm persisted in production, supporting the motor programming notion that timing is an intrinsic part of sequence representation.

The finding that differences between sequence durations were larger when the rhythm changed at test is related to the rhythm program hypothesis (Vorberg & Wing, 1996). The rhythm program hypothesis was proposed to explain the pattern of positive covariances of intercommand intervals (intervals between successive time points generated by timekeepers) observed in the production of rhythmic sequences (Vorberg & Hambuch, 1984). The rhythm program is a timekeeping component of a motor program that produces rhythmic timing; it operates only when explicit rhythmic timing demands are made on a performer (Vorberg & Wing,
1996), as is the case in music performance. A rhythm program, implemented as a hierarchy of adjustable timekeepers, specifies a hierarchical structure for every rhythmic figure (Vorberg & Wing, 1996, p. 248). Sequence durations increased when the rhythm changed in Experiments 2 and 3; one interpretation from the rhythm program hypothesis suggests that there is a sizeable cost to reassembling different hierarchical timekeepers when the rhythm changes.

**Independent Representations of Timing and Motor Movements**

The independence of temporal structure and motor movements in the transfer findings suggests that representations of timing and motor movements are independent at least for skilled producers. In Experiment 1, changing the motor movements at test did not affect transfer of meter, or vice versa. In Experiment 2, changing the motor movements at test did not affect transfer of rhythm, or vice versa. The failure to find an interaction between timing and movement has implications for theories of sequence production.

The failure to find an interaction between timing and motor movements is counter to the suggestions of kinematic models of music. Todd (1995) proposed that a sensory-motor feedback process identifies periodicities near 600 ms as
related to foot-tapping and the tactus, and identifies periodicities near 5 s as related to body sway and rubato. No interaction between motor movements and meter was found in the present experiment, suggesting that at some level, representations of temporal structure are independent from motor information.

Other models that are more explicit about rhythmic timing predict an interaction between timing and movement. Kelso (1995) argues that an intrinsic attraction exists to certain preferred relative phase relations between limbs. Relative phase, which measures the patterns of coordination between two limbs, can define various rhythms. For instance, producing a 1:4 ratio between hands would be equivalent to producing a \( \text{\textfrac{\text{\textfrac{\text{\textfrac{\text{\textfrac{\textfrac{1}{4}}}{4}}}{4}}}{4}}{4} \) pattern.

It is possible that the relationship between timing and movement is observable for ratio relationships more complex than the simple ratios used in Experiments 1 and 2. The Farey tree, described by Treffner and Turvey (1993), predicts greater variability for timing intervals that form complex ratios; for example a 1:2 ratio (common in music) would be more stable and less variable than a 3:5 ratio. Summers' (1975) finding that the rhythms produced under
speeded conditions were altered by performers to be closer to a 2-to-1 ratio coincides with predictions of Treffner and Turvey (1993). The relationship between rhythmic timing and motor movements may be more evident at an individual event level rather than across an entire sequence (i.e. IOIs rather than sequence duration). However, analyses of timing variability (CV) in all three experiments indicated no changes in variability that could be attributed to changes in timing or motor movements. Optimal performance in terms of low variability was observed for the simple ratio rhythms used here. Future research that investigates transfer of non-integer ratios and motor movements may provide additional information on the relationship between motor movements and timing.

The Relationship between Meter and Rhythm in Music

The independence of metrical and rhythmic transfer across musical sequences in two experiments demonstrates that representations of metrical structure and rhythmic structure are independent for skilled producers. This finding suggests that the temporal structures of meter and rhythm, which can be independently manipulated in music notation, are cognitively independent for performers.
Some models of music perception predict an interaction between meter and rhythm; these include models of meter perception by Parncutt (1994) and Longet-Higgins and Lee (1982), and Povel and Essens' model of beat perception (1985). In Parncutt's model (1994) of pulse salience and metrical accent in musical rhythms, the rate and IOI duration (rhythm) determines the amount of accent each event is assigned which determines the perception of pulse and meter. Hence, meter perception interacts with rhythm; if the rhythm is changed, the perception of meter will change. Povel and Essens' (1985) model assumes that listeners generate an internal clock while listening to a temporal pattern; a change in rhythm may change the internal clock that is chosen as having the "best fit" and becomes the perceived beat. The Longuet-Higgins and Lee (1982) model simulates meter perception by using only the relative lengths of IOIs. After each new IOI of a rhythmic sequence is introduced, the listener may expand the current metrical unit, move the initial downbeat, or have the current metrical interpretation confirmed. Different rhythms can lead the listener to different metrical interpretations. In
all of these models, meter and rhythm perception are not independent; the rhythm of the sequence is assumed to determine the perceived meter.

Some research has investigated how music performers emphasize meter and rhythm expressively. Drake and Palmer (1993) studied the relationship between rhythmic, metrical, and melodic accent structures in piano performance. Pianists performed pieces containing only one accent structure, conflicting accent structures, or both coinciding and conflicting structures. The authors found that the performance of metrical and rhythmic accents were independent of each other, and emphasis of rhythm dominated emphasis given to meter, similar to the findings in Experiment 3. The authors suggest that consistent and independent relationships between accent structures and the expressive cues that mark them may enhance the communication of accent structure to listeners.

Representations for musical sequences may be different for music in which meter and rhythm are correlated than when they are distinctly separate. Boltz (1998) systematically manipulated listeners' attention to the temporal and pitch properties of melodies; listeners attended to only the pitch dimension, only the duration dimension, both dimensions, or
were given no instructions directing their attention to any dimension. Then listeners’ subsequent memory of these structural dimensions was examined. Boltz (1998) found that temporal (meter and rhythm) and non-temporal (pitch) information are jointly encoded in the cognitive system when event structures coincided in the melodies, but independently coded when event structures conflicted. Boltz (1998) proposed that these results would hold for performers as well as listeners. It is possible that rhythm and meter are produced independently when they are not correlated in music (such as for the stimuli used in Experiment 3), but they may interact in performance when they are correlated in more naturalistic musical compositions. Future comparisons between listeners’ and performers’ representations of music with correlated and uncorrelated musical structures may offer a more direct method to test the similarities among music perception and production.

**Serial Ordering and Timing in Sequence Production**

One important outcome from these findings is that more than serial order is represented in sequence production. For example, sequence durations were longer when the meter changed at test, even though the training and test sequences required the same motor movements, the same rhythm, and had
the same pitch order. These findings suggest that performers adjusted their interpretation of the isochronous sequence even though the serial ordering and timing requirements remained the same.

Likewise, the rhythmic effects in Experiment 2 have implications for the role of serial order in music performance. The difference between sequence durations was larger when rhythm changed at test, even though the training and test sequences required the same motor movements, had the same meter, and had the same pitch order. These findings suggest that timing is an important aspect of representations of sequence production; performers had to adjust the timing of events, even though the serial ordering of pitches was the same. Drake and Palmer (1999) found related evidence that temporal and pitch information are represented together in music performance. Jointly occurring pitch and duration errors were observed more often than predicted for both novice and expert pianists. If pitch and duration components interact at the individual unit level of performance, as these results suggest, then a serial ordering mechanism in performance must account for both the temporal and pitch information of individual events.
In sum, three experiments separately manipulated temporal structure and motor movements in a transfer of learning task in music performance. The findings indicate that temporal structure and movement are important dimensions of sequence representation. Serial order was constant across training and test in the current experiments; how these findings generalize to sequence production in which serial order changes is an interesting issue for future study. Finally, additional research on the relationships between serial order, temporal structure, and movement in sequence representations for integer ratios more complex than those used here may provide further insight into the role of motor-independence in representations of music performance.
LIST OF REFERENCES


APPENDIX A

A pilot study was conducted to select the stimuli for Experiment 1. The pilot study was conducted to ascertain which melodies were metrically ambiguous (equally interpretable in either 3/4 or 4/4 meter), motorically ambiguous (equally playable with either hand), and relatively easy to perform. Skilled pianists were asked to perform and rate how easy or difficult each stimulus was to perform. Based on the pianists' ratings in this pilot study, four sets of stimuli were selected for Experiment 1.

Method

Subjects

Eight skilled pianists from the Columbus, Ohio music community participated. Participants' mean age was 18.88 years (range of 18 - 19). The pianists had a mean of 7.88 years of piano instruction (range of 5 - 12 years) and a mean of 10 years of performing experience (range of 7 - 14 years). None of the pianists participated in Experiment 1.
**Materials and apparatus**

Seven sets of simple melodic stimuli were composed. Each of the seven sets consisted of a unique melody notated in 3/4 and 4/4 meter for each hand, producing 28 (7x2x2) stimuli. All stimuli were notated in treble clef. Participants performed on a computer-monitored acoustic Yamaha Disklavier piano.

**Design and Procedure**

Pilot Experiment 1 used a within-subjects design with stimulus set (7 sets), meter (3/4 or 4/4), and hand (right or left) as the independent variables. The dependent variable was the rating pianists gave to each sequence. Sequences were presented in a pseudo-random order (no stimuli from the same set was presented twice in a row). A different random order of stimuli was presented to each pianist.

Pianists were told that they were participating in a study that investigated factors that made music easy or difficult to perform. Participants first completed a short questionnaire about their previous musical experiences. Then the experimenter read the instructions; the pianists were told to perform each piece and then rate how difficult it was to perform with the notated hand and meter on a scale from 1 (very hard) to 7 (very easy). Participants were
encouraged not to give their rating until they felt very comfortable with the stimulus; all participants performed each stimulus without any errors within three trials. The experimenter recorded the performer’s rating on an answer sheet and presented the next stimulus.

Results
An Analysis of Variance (ANOVA) on the pianists’ ratings by stimulus set (7), meter (3/4 and 4/4), and hand (right and left) revealed a main effect of stimulus set, \( F(6, 42) = 3.61, p < .01 \). Tukey post-hoc comparisons on the stimulus ratings revealed that one stimulus was significantly easier to perform than the others; this stimulus set was removed from consideration. Tukey post-hoc comparisons on the non-significant interaction between stimulus set and hand identified the stimulus sets that were significantly easier to perform with one hand than another; two more sets were removed from consideration. The remaining four sets, which had no significant differences in ratings, were in different keys, half were major and half were minor, and therefore were chosen for use in Experiment 1.
As in Experiment 1, a pilot study was conducted to select the stimuli for Experiment 2. The pilot study was conducted to ascertain which stimuli were rhythmically ambiguous (equally interpretable with two different rhythms), motorically ambiguous (equally playable with either hand), and relatively easy to perform. To select stimuli for Experiment 2, pianists were asked to perform and rate how easy or difficult each stimulus was to perform.

Method

Subjects

Eight skilled pianists from the Columbus, Ohio music community participated. Participants' mean age was 22.86 years (range of 19 – 33). The pianists had a mean of 9.08 years of piano instruction (range of 6 – 14 years) and a mean of 14.25 years of performing experience (range of 10 – 19 years). None of the pianists participated in Experiment 2.
**Materials and apparatus**

Eight sets of simple melodic stimuli were composed. Each of the eight sets consisted of a unique melody notated with two different rhythms, and each rhythm was written for each hand, producing 32 (8x2x2) stimuli. All stimuli were notated in treble clef. Participants performed on a computer monitored Yamaha Disklavier piano.

**Design and Procedure**

Pilot Experiment 2 used a within-subjects design with stimulus set (8 sets), rhythm (2 rhythms), and hand (right or left) as the independent variables. The dependent variable was the rating pianists gave to each sequence. Sequences were presented in a pseudo-random order (no stimuli from the same set was presented twice in a row). A different random order of stimuli was presented to each pianist.

The same procedure was used as the pilot for Experiment 1. The pianists were told to rate how difficult each stimuli was to perform with its notated hand and rhythm on a scale from 1 (very hard) to 7 (very easy). Participants were encouraged not to give their rating until they felt very comfortable with the stimulus; all participants performed
each stimulus without any errors within three trials. The experimenter recorded the performer’s rating on an answer sheet and presented the next stimulus.

Results
An Analysis of Variance (ANOVA) on the pianists' ratings by stimulus set (8), rhythm (2), and hand (right and left) revealed a main effect of stimulus set, $F(7, 49) = 3.28, p < .01$. Tukey post-hoc comparisons identified the stimulus sets that were significantly different from the other sets; the most difficult set and the easiest set were removed from consideration. Four sets in different keys (half major and half minor) which had no significant differences in ratings were chosen for use in Experiment 2.
APPENDIX C

As in the previous experiments, a pilot study was conducted to select the stimuli for Experiment 3. The pilot study was conducted to ascertain which melodies were metrically ambiguous (equally interpretable in 3/4 or 4/4), rhythmically ambiguous (equally playable with either rhythm), and relatively easy to perform. To select stimuli for Experiment 3, pianists were asked to perform and then rate how easy or difficult each piece was to perform.

Method

Subjects

Eight skilled pianists from the Columbus, Ohio music community participated. Participants' mean age was 22.88 years (range of 18 - 42). The pianists had a mean of 10.38 years of piano instruction (range of 8 - 14 years) and a mean of 16.13 years of performing experience (range of 10 - 38 years). None of the pianists later participated in Experiment 3.
Materials and apparatus

Eight stimuli sets of simple melodies were composed. Each stimuli set consisted of one melody notated with two different rhythms, and each rhythm was written for each hand, producing 4(2x2) stimuli per set. All stimuli were notated in treble clef. Participants performed on a computer-monitored acoustic Yamaha Disklavier piano.

Design and Procedure

Pilot Experiment 3 used a within-subjects design with stimulus set (8 levels), meter (3/4 and 4/4), and rhythm (2 rhythms) as the independent variables. The dependent variable was the rating pianists gave to each sequence. Sequences were presented in a pseudo-random order (no stimuli from the same set was presented twice in a row). A different random order of stimuli was presented to each pianist.

The same procedure was used as the pilot for Experiment 1. The pianists were told to rate how difficult each stimuli was to perform with its notated meter and rhythm on a scale from 1 (very hard) to 7 (very easy). Participants were encouraged not to give their rating until they felt very comfortable with the stimulus; all participants performed
each stimulus without any errors within three trials. The experimenter recorded the performer's rating on an answer sheet and presented the next stimulus.

Results

An Analysis of Variance (ANOVA) on the pianists' ratings by stimulus set (8), meter (3/4 and 4/4), and rhythm(2) revealed a main effect of stimulus set, $F(7, 49) = 3.04, p < .05$. Tukey post-hoc comparisons identified the stimulus sets that were significantly different from the other sets; the sets rated the easiest and most difficult to perform were removed from consideration for Experiment 3. Tukey post-hoc comparisons on the non-significant interaction between stimulus set, rhythm, and meter revealed that there were no significant differences in mean rating between any stimuli. The stimuli sets with the smallest range of ratings (most similar ratings within a set) were chosen such that each set was from a different key and half were major and half were minor.
Table 1. P-values of planned paired comparisons in Experiment 1.

Table 2. P-values of planned paired comparisons in Experiment 2.

Table 3. P-values of planned paired comparisons in Experiment 3

Figure 1. Example of training and test stimuli from Experiment 1.

Figure 2. Mean sequence durations in training and test trials for Experiment 1.

Figure 3. Mean sequence durations in training trials and the mean sequence duration across the four test trials for each condition for Experiment 1.

Figure 4. Mean error rates in training and test trials for Experiment 1.

Figure 5. Example of training and test stimuli from Experiment 2.
Figure 6. Mean sequence durations in training and test trials for Experiment 2.

Figure 7. Mean sequence durations in training trials and the mean sequence duration across the four test trials for each condition for Experiment 2.

Figure 8. Mean error rates in training and test trials for Experiment 2.

Figure 9. Interonset intervals of a performance of the last training trial and the first test trial in the Rhythm-diff/Motor-same condition.

Figure 10. Example of training and test stimuli from Experiment 3.

Figure 11. Mean sequence durations in training and test trials for Experiment 3.

Figure 12. Mean sequence duration in training trials and the mean sequence duration across the four test trials for each condition for Experiment 3.

Figure 13. Mean error rates in training and transfer trials for Experiment 3.

Figure 14. Interonset intervals of a performance of the last training trial and the first test trial in the Rhythm-diff/Meter-same condition.
Table 1. P-values of planned paired comparisons in Experiment 1.
Table 2. P-values of planned paired comparisons in Experiment 2.
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Table 3. P-values of planned paired comparisons in Experiment 3.
Training:

Test:
1. Motor-same/Meter-same

2. Motor-diff/Meter-same

3. Motor-same/Meter-diff

4. Motor-diff/Meter-diff

Figure 1.
Figure 3.

Sequence Duration (ms)

1000

1500

2000

2500

3000

1  2  3  4  5  6  7  8  9  10

Training Trials

Mean Test

Motor-diff/Motor-diff
Motor-diff/Motor-same
Motor-same/Motor-diff
Motor-same/Motor-same
**Figure 4.**

Error Rate

Training Trials

Mean Test

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

1 2 3 4 5 6 7 8 9 10

Training Trials

Mean Test
Training:

```
Left hand: 1 3 1 3 4 5 1 3 5 3 4 2 1 2 3 5 3 4 5
```

Test:

1. Rhythm-same/Motor-same

```
Left Hand: 1 3 1 3 4 5 1 3 5 3 4 2 1 2 3 5 3 4 5
```

2. Rhythm-diff/Motor-same

```
Left Hand: 1 3 1 3 4 5 1 3 5 3 4 2 1 2 3 5 3 4 5
```

3. Rhythm-same/Motor-diff

```
Right hand: 5 3 5 3 2 1 5 3 1 3 2 4 5 4 2 1 3 2 1
```

4. Rhythm-diff/Motor-diff

```
Right hand: 5 3 5 3 2 1 5 3 1 3 2 4 5 4 2 1 3 2 1
```

Figure 5.
Figure 6.

Sequence Duration (ms)

Training Trials     Test Trials

1  2  3  4  5  6  7  8  9  10  1  2  3  4

- Rhythm-diff/Motor-diff
- Rhythm-same/Motor-diff
- Rhythm-diff/Motor-same
- Rhythm-same/Motor-same
Figure 7.

Sequence Duration (ms)

Training Trials

Mean Test

- Rhythm-diff/Motor-diff
- Rhythm-diff/Motor-same
- Rhythm-same/Motor-diff
- Rhythm-same/Motor-same
Figure 9.

![Graph showing event numbers for training and test trials. The x-axis represents event numbers, ranging from 1 to 18. The y-axis represents IOI (ms), ranging from 0 to 800. The graph is divided into two sections: one labeled 'Training (trial 10)' and the other labeled 'Test (trial 11).']
Training:

![Musical notation]

Right hand: 4 1 2 3 4 5 3 4 3 2 1 4 3 2 5 4 2 1 2

Test:

1. Rhythm same-Meter same

![Musical notation]

Right Hand: 4 1 2 3 4 5 3 4 3 2 1 4 3 2 5 4 2 1 2

2. Rhythm diff-Meter same

![Musical notation]

Right Hand: 4 1 2 3 4 5 3 4 3 2 1 4 3 2 5 4 2 1 2

3. Rhythm same-Meter diff

![Musical notation]

Right hand: 4 1 2 3 4 5 3 4 3 2 1 4 3 2 5 4 2 1 2

4. Rhythm diff-Meter diff

![Musical notation]

Right hand: 4 1 2 3 4 5 3 4 3 2 1 4 3 2 5 4 2 1 2

Figure 10.
Figure 11.

Sequence Duration (ms)

Training Trials

Test Trials
Figure 12.

Sequence Duration (ms)

1 2 3 4 5 6 7 8 9 10 Mean Training Trials Test

- Rhythm-diff/Meter-diff
- Rhythm-diff/Meter-same
- Rhythm-same/Meter-diff
- Rhythm-same/Meter-same
Figure 14.

A graph showing the interval of time (IOD) in milliseconds (ms) for events in Training (trial 10) and Test (trial 11). The x-axis represents Event Number, ranging from 1 to 18, and the y-axis shows IOD values from 0 to 800 ms. The graph displays two separate clusters of event data points, with Training showing a pattern of higher IOD values at certain event numbers, and Test showing a more consistent pattern with peaks at certain event numbers.