Annu. Rev. Psychol. 1997. 48:115–38

MUSIC PERFORMANCE

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KEY WORDS: skilled performance, musical memory, sequence production, music perception, motor skills

ABSTRACT

Music performance provides a rich domain for study of both cognitive and motor skills. Empirical research in music performance is summarized, with particular emphasis on factors that contribute to the formation of conceptual interpretations, retrieval from memory of musical structures, and transformation into appropriate motor actions. For example, structural and emotional factors that contribute to performers' conceptual interpretations are considered. Research on the planning of musical sequences for production is reviewed, including hierarchical and associative retrieval influences, style-specific syntactic influences, and constraints on the range of planning. The fine motor control evidenced in music performance is discussed in terms of internal timekeeper models, motor programs, and kinematic models. The perceptual consequences of music performance are highlighted, including the successful communication of interpretations, resolution of structural ambiguities, and concordance with listeners' expectations. Parallels with other domains support the conclusion that music performance is not unique in its underlying cognitive mechanisms.

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0084-6570/97/0201-0115$08.00

INTRODUCTION

Music performance provides a rich domain for study of both cognitive and motor skills. Performers dominate many aspects of our musical culture today. Concert attendance and recording sales, for example, often reflect listeners' preferences for performers and abilities to distinguish among performances. Although public consumption of music tends to highlight performance differences, there are also strong commonalities across performances that reflect cognitive functions of grouping, unit identification, thematic abstraction, elaboration, and hierarchical nesting. Thus, music performance is based on both individualistic aspects that differentiate performers and normative aspects shared by performers. Both the commonalities and differences among music performances can be modeled theoretically in terms of general cognitive abilities.

The majority of studies focus on the performance of musical compositions for which notation is available, thus providing unambiguous performance goals. The focus has also been on piano performance, in which pitch and timing measurements are simplified. Common forms of music performance in the Western tonal tradition include sight-reading (performing unfamiliar music from notation), performing well-learned (prepared) music from memory or from notation, improvising, and playing by ear (performing music from aural presentation). Correlations among these abilities tend to be high and to increase with training (McPherson 1995, Nuki 1984), although some studies show differences in abilities across performers. For instance, accompanists perform better than soloists on some sight-reading tasks (Lehmann & Ericsson 1993). Although there are few studies of long-term changes in performance ability, diary and interview studies suggest that differences in performance levels across individuals are largely a function of experience and practice (Ericsson et al 1993, Sloboda et al 1996).

Psychological studies of music performance aim to develop theories of performance mechanisms (what cognitive or motor constraints influence performance). A second aim is to explain the treatment of structural ambiguities (in what contexts do ambiguities arise, what kinds of choices do performers make). A third aim is to understand relationships between performance and perception (how are listeners influenced by performance aspects). During a performance, musical structures and units are retrieved from memory according to the performer's conceptual interpretation, and are then prepared for production and transformed into appropriate movements. The following sections of the review—Interpretation, Planning, and Movement—focus on these components of performance. Topics that are covered elsewhere include stylistic performance conventions, expertise and skill development (Ericsson & Lehmann 1996), sight-reading and improvising (Sloboda 1985b), and social and evaluative aspects of performance (Gabrielsson 1997). This chapter reviews only those perceptual studies that address performance issues.

Serial Order and Timing Issues

Speaking, typing, and performing music are among the most complex forms of skilled serial action produced by human beings. Seminal theories of motor control (Bernstein 1967, Lashley 1951) often use music performance as the ultimate example of human motor skill. Based on capacities such as the trilling speed of concert pianists (on the order of 16 notes/s), Lashley (1951) suggested that successive elements of this kind of activity must be centrally linked; a centrally controlled mechanism determines movements in a predetermined order. This open-loop (motor program) theory is based on two types of evidence: There is little time for feedback to affect the planning of the next movement (Keele 1968), and some skills can be performed in the absence of kinesthetic feedback (Keele & Summers 1976, Lashley 1951).

The control of complex, temporally structured behaviors such as speech production or music performance embodies two problems: the serial order of sequence elements, and their relative timing. The serial order problem arises from the fact that chain-like organization of behavior is inadequate to explain certain serial order effects in sequence perception and production. For instance, strong constraints on the order of words within phrases and of phonemes within words must be met for speech to be acceptable. Musical and linguistic sequences that are well-formed in their serial order, however, are often not understandable unless additional constraints hold on the relative timing of the individual sequence elements. Music performed without accurate temporal control is considered deficient because it lacks the property of rhythm, in which the timing of elements is influenced by the timing of other (adjacent and nonadjacent) elements (Vorberg & Hambuch 1978). The domain of music performance is ideal for developing models of timing mechanisms because it offers theoretical consensus on the nature of the temporal relationships that must be present for a sequence to be considered accurate. Questions of serial order, relative timing, and how rhythm (temporal patterning) constrains the planning and production of musical sequences are addressed below.

Methodological Issues

Several methodological issues influence the interpretation of research in music performance. First, the wealth of data from a single performance (roughly 3000 pieces of information in one second of digital audio sound recorded at a low sampling rate) results in problems of separating signal from noise. Carl Seashore (1936, 1938), one of the first to conduct psychological studies of music performance, developed a piano camera system to record only gestural (movement-based) data from hammer and foot-pedal movements, greatly reducing the amount of data necessary to capture essential performance aspects. Current computer music technology relies heavily on movement-based information and records only event onsets, offsets, and their relative intensities from electronic- or computer-monitored musical instruments.

Despite the reduction of information, problems with separating the signal—performance expression—from random noise fluctuations remain. Performance expression refers to the large and small variations in timing, intensity or dynamics, timbre, and pitch that form the microstructure of a performance and differentiate it from another performance of the same music. Musicians can replicate their expressive patterns of timing and dynamics for a given musical piece with high precision (Gabrielsson 1987a, Henderson 1936, Seashore 1938, Shaffer & Todd 1987), and attempts to play without expression significantly dampen these patterns but do not remove them altogether (Bengtsson & Gabrielsson 1983, Palmer 1989, Seashore 1938), which suggests that some variations are intentional. Expression is often analyzed according to the deviation of performed events from their fixed or regular values as notated in a musical score (Gabrielsson 1987a, HG Seashore 1936). However, performance can be expressive without reference to a score (as in musical improvisation). Expression can also be analyzed relative to the performance itself; for instance, expression within a unit such as a phrase is the pattern of deviations of its parts with respect to the unit itself (Desain & Honing 1991). Consequently, measurements of performance expression sometimes differ across studies, which makes comparisons difficult.

A second methodological problem is determining which performances should be considered representative, given the large variations that can occur among competent performances of the same music. There are few objective criteria for performance success; most experimenters opt for a recognized level of performer expertise. Large samples of famous performers are hard to find, however, and exploratory (nonexperimental) methods or case study methods are often used. A similar representativeness problem arises in choice of musical stimuli. Because of complexity issues, experimenters often use simplified or reduced musical compositions. For these reasons, the domain of music performance relies heavily on converging evidence from both small and large sample studies conducted with different musical stimuli.

INTERPRETATION

Music performance is often viewed as part of a system of communication in which composers code musical ideas in notation, performers recode from the notation to acoustical signal, and listeners recode from the acoustical signal to ideas (Kendall & Carterette 1990). Each performer has intentions to convey; the communicative content in music performance includes the performers' conceptual interpretation of the musical composition. Western tonal music has developed a notation that represents pitch and duration information fairly explicitly but intensity and tone quality only approximately. Other relationships, such as group boundaries, metrical levels higher than the measure, and patterns of motion, tension, and relaxation are unspecified or only implicitly specified in notation. Thus, ambiguities in musical notation allow a performer considerable freedom in deciding how to interpret the music's content. Interpretation refers to performers' individualistic modeling of a piece according to their own ideas or musical intentions. Differences in interpretation can account for why the same musical score is performed differently by different performers or why the same performer may perform a piece differently on separate occasions.

As in other art forms, there is no single ideal interpretation for a given musical piece; every performance involves some kind of interpretation or analysis (Cone 1968, Levy 1995, Meyer 1973). The field of music analysis offers various explanations for the content of a given composition. For instance, a piece can be viewed as a hierarchy of part/whole relationships, as a linear course that follows the harmonic tension, or as a series of moods that result in a unity of character (Sundin 1984). However, music analysis does not indicate how a performer actually produces a desired interpretation (Dunsby 1989). One goal of interpretation is to convey the meaning of the music. Definitions of musical meaning abound, but several theorists define it as having major components that relate to structure, emotion, and physical movement (Gabrielsson 1982, Meyer 1956), which contribute to performers' interpretations.

One function of interpretation is to highlight particular structural content (Clarke 1987). Some experimental work evaluates the effects of individual performers' structural interpretations on performance expression. Nakamura (1987) compared musicians' performances of a baroque sonata with their notated interpretations of musical dynamics (patterns of intensity changes). Performers' notated intentions generally corresponded to changes in sound level. Listeners' perceived dynamics matched performers' intended dynamics fairly well, even when underlying acoustic changes were not identifiable. Palmer (1989) compared pianists' notated interpretations of phrase structure and melody with expressive timing patterns. Onsets of the melodic voice preceded other voice onsets in notated simultaneities (termed melody leads), and slowing in tempo was greatest at phrase boundaries. Expressive timing patterns decreased when pianists attempted to play without interpretation, and these patterns increased in exaggerated interpretations, similar to other findings of modulations in expressive level (Kendall & Carterette 1990, Seashore 1938). Further studies indicated that the expressive timing patterns increased from novices to experts, increased during practice of an unfamiliar piece, and changed across different interpretations of the same piece performed by the same pianist (Palmer 1988).

Interpretations of structural content affect both the expressive marking of individual events and the likelihood that events will be correctly retrieved and produced. Error analyses (based on comparison with the notated score) of piano performances with different phrase structure interpretations indicated that pitch deletions tended to occur within phrases and perseverations at phrase boundaries, which suggests that interpretations strengthen phrase boundaries relative to other locations (Palmer 1992). These findings were replicated in later experiments, which also indicated that melodic interpretations increased the likelihood that melodic events were correctly retrieved and produced relative to nonmelodic events (Palmer & van de Sande 1993, 1995).

Another function of interpretation is to highlight particular emotional content of the music. An extreme view holds that the structure of music is isomorphic to the structure of moods or feelings; music should sound the way moods feel (Langer 1953). Gabrielsson (1995) compared performers' interpretations of emotional content with their use of expression. Flute and violin performances of the same music interpreted with different emotional characters indicated general patterns of change in expression. Performances of happy and angry emotions were played with faster tempo and larger dynamic range, whereas soft and sad emotions were performed with slower tempo and smaller dynamic range. Tone onsets were abrupt in the angry version and more gradual in the sad version. Related patterns of performance expression were found in violin performances of a Beethoven theme with tender or aggressive interpretations (Askenfelt 1986). Later experiments replicated these patterns, and most of the emotion categories were accurately conveyed to listeners (Gabrielsson & Juslin 1996). The emotional content of music has also been examined recently in terms of narrative, with emphasis on dramatic characterization, thematic content, and conceptions of large-scale structures (Schmalfeldt 1985, Shaffer 1995).

Musical experience enhances both performers' use of expression to emphasize interpretations and listeners' ability to identify interpretations and expressive aspects of performance (Geringer & Madsen 1987, Johnson 1996, Palmer 1988, Sloboda 1985a). Listeners without musical experience do pick up some interpretive aspects. Nonmusician listeners were able to discern general differences among mechanical (inexpressive), expressive, and exaggerated levels of performance as accurately as musician listeners (Kendall & Carterette 1990). Some evidence suggests that type of musical experience matters: All musician listeners were influenced by expressive timing cues when asked to choose the intended phrase structure in piano performances, but only listeners with piano training were influenced by expressive timing cues (melody leads) when choosing among melody interpretations (Palmer 1988, 1996b). Although these studies address the sufficiency of expressive features to convey performers' interpretations, they do not address how necessary they are (see section below on Perception of Performance Expression).

PLANNING

Planning and memory retrieval processes in music performance reflect multidimensional relationships among melodic, harmonic, and diatonic elements. In Western tonal music, individual pitches, chords, and keys are posited as conceptually distinct units of knowledge, that reflect levels of melodic, harmonic, and diatonic structure, respectively. Some compositional structures, such as homophonic music, emphasize across-voice (chordal) associations between melody and accompaniment, whereas others, such as polyphonic structure, emphasize within-voice (single-note) associations among multiple important voices. Analyses of piano performances indicated that chord errors occurred more often in homophonic styles and that single-note errors occurred more often in polyphonic styles, which suggests that the relevant musical units change across different musical contexts (Palmer & van de Sande 1993, 1995). Knowledge of diatonic and harmonic structure influences performance as well. Mistakes were more likely to originate from the key of the piece than from another key and to be of the same chord type as what was intended (Palmer & van de Sande 1993). Child singers' pitch errors were also likely to be harmonically related to intended events (Moore 1994), and pianists' errors during sight-reading of pieces in which deliberate pitch alterations had been placed indicated tacit knowledge of likely melodic and harmonic relationships (Sloboda 1976).

Theories of skilled performance often assume that people prepare complex sequences for production by partitioning them into shorter subsequences (cf van Galen & Wing 1984). Phrase structure is one feature that influences the partitioning of musical sequences; evidence from performance timing and errors suggests that musical sequences are partitioned during planning into phrase segments (Palmer & van de Sande 1995). Errors that replaced intended pitches in piano performances were more likely to originate from the same phrase as the intended event than from different phrases. Interacting elements rarely crossed phrase boundaries, similar to findings in speech errors (Garcia-Albea et al 1989, Garrett 1980). Segmentation during performance planning is also influenced by relationships among musical accent structures. Adult pianists' and children's abilities to reproduce melodies were increasingly disrupted the more that melodic, metrical, and rhythmic grouping accents were shifted out of alignment in the performed tunes (Drake et al 1991).

Both structural relations and the serial distance between sequence events influence the range over which performers can plan, presumably because of limitations on memory capacity. Supporting evidence is seen in eye-hand span tasks, in which pianists reproduced briefly presented musical sequences. The mean eye-hand span was 7–8 events beyond the location at which the notation disappeared, and it tended to extend only to phrase boundaries (Sloboda 1974, 1977). However, eye-hand span measures may reflect effects of both memory capacity and anticipatory eye movements. Range of planning in memorized piano performances (with no notation) was affected by both serial distance and structural relations among sequence elements (Palmer & van de Sande 1995). Errors and timing measures indicated that the planning of current elements was affected by elements that spanned larger serial distances in the absence rather than in the presence of intervening phrase boundaries, similar to interactions of distance and structural constraints in language production (Garcia-Albea et al 1989). These findings suggest two possible invariants in the planning of complex serial behaviors in many domains: the co-occurrence during planning of elements that share structural features, and constraints of structural boundaries on serial distances over which elements are concurrently planned.

Syntax of Musical Structure

The performance of music is also constrained by style-specific syntactic properties that transcend individual interpretations. Many theories of Western tonal music have meter and grouping as their primary syntactic elements (Cooper & Meyer 1960, Lerdahl & Jackendoff 1983). Meter refers to periodic features: the regular alternation of strong and weak beats. Positions of metrical accents form hierarchical levels, with different periodicities represented at each level. Meter provides a temporal framework in performance for when to do what, as supported by evidence that only those rhythmic patterns that can be accommodated to a metrical framework are correctly reproduced (Povel 1981, Povel & Essens 1985), and the same duration pattern is performed with different expressive timing when placed in different metrical contexts (Clarke 1985). Grouping refers to the segmentation of a sequence into smaller subsequences that also form hierarchical levels, based largely on pitch relationships (Lerdahl & Jackendoff 1983). Some metrical and grouping levels are more salient than others. Tactus refers to the most salient periodicity or metrical level, which corresponds to the rate at which one might tap a foot to the music (Fraisse 1982), and phrases are thought to be the most salient level of grouping structure. Events at the most salient levels are commonly emphasized in performance (cf Repp 1992b, Todd 1985) and may be most precisely or consistently produced and perceived (see section below on Timekeeper Models).

Probably the most widespread structural characteristic of Western music is its hierarchical nature; both pitch and rhythm structures are represented in a series of levels, between which relationships of reduction or elaboration operate (cf Clarke 1988, Lerdahl & Jackendoff 1983, Schenker 1969). For instance, Schenker's (1969) music theory views the melodic and harmonic organization of a musical piece as a series of progressively more complex elaborations of a simple foundation, the background, from which the surface level or foreground (the note-to-note aspects of the musical score) is generated. These hierarchical levels not only embody music-theoretic principles but also have implications for perceptual and cognitive processes, such as the prediction that more important events are processed at deeper levels and thus memory should be facilitated for those events.

Improvisation tasks have been used to address hierarchical implications for music performance. Pianists' improvisations on a musical theme tended to retain from the theme only structurally important events from abstract hierarchical levels of reduction (Large et al 1995). A neural network model trained to produce reduced memory representations represented structurally important events more efficiently than others, by accounting for the musical reduction in terms of a recursive auto-associative mechanism. The network's weightings of relative importance corresponded with both the musical events retained across improvisations and the predictions of structural importance from a reductionist music theory (Lerdahl & Jackendoff 1983), which suggests that reduction may be a natural consequence of hierarchical encodings of musical structure (Large et al 1995). Schmuckler (1990) used an improvisation task to test performers' expectancies for which events would follow in open-ended musical fragments. Performers' improvised continuations reflected influences of both the contents of the musical fragments and the abstract tonal and metrical hierarchies typical of Western music (Krumhansl & Kessler 1982, Lerdahl & Jackendoff 1983). Other studies indicated a correspondence between the events most often produced in improvisations and listeners' ratings of how highly expected those events were (Schmuckler 1989). These findings suggest that music perception and performance are both influenced by the hierarchical properties of musical styles.

Structure-Expression Relationships

Many findings have established a causal relationship between musical structure and patterns of performance expression (Clarke 1988, Palmer 1989, Sloboda 1983). One of the most well-documented relationships is the marking of group boundaries, especially phrases, with decreases in tempo and dynamics (Henderson 1936). Patterns of rubato (tempo modulations) often indicate a hierarchy of phrases, with amount of slowing at a boundary reflecting the depth of embedding (Shaffer & Todd 1987; Todd 1985, 1989). The more important the musical segment, based on a hierarchical analysis of meter and grouping principles (Lerdahl & Jackendoff 1983), the greater the phrase-final lengthening. The greatest correspondence between expressive timing and intensity in performance is found at an intermediate phrase level (Palmer 1996a, Todd 1992), and performers' notated and sounded interpretations tend to differ most at levels lower than the phrase (Palmer 1989, Repp 1992b).

Metrical structure also influences performance expression. Metrical accents (events aligned with strong beats as implied by notated metrical information) are often emphasized by lengthened durations and delayed onsets in piano performance (Henderson 1936) and in vocal performance (Palmer & Kelly 1992). Pianists presented with the same melodies in different notated metrical contexts played events aligned with metrical accents louder, with longer durations, and with more legato (smooth) articulation (Sloboda 1983, 1985a). Listeners' subsequent judgments of meter for the different performances aligned with performers' metrical intentions most often for the most experienced pianists' performances (whose expressive markings of meter were clearer) (Sloboda 1983). When the different expressive cues were independently manipulated in computer-generated simulations, listeners most often chose the intended meter primarily on the basis of articulation cues. Loudness cues alone communicated meter also, but they were not present in all performances (Sloboda 1985a). In all, these findings suggest that there is no one set of necessary and sufficient expressive cues to denote meter.

One of the first types of musical structure for which systematic patterns of performance expression were documented is the duration patterns that form characteristic rhythms (Bengtsson & Gabrielsson 1977). An example is the Viennese waltz (based on a repeating pattern of three equal-duration beats with a metrical accent on the first beat), typically performed with a short first beat and a long second beat (Askenfelt 1986, Bengtsson & Gabrielsson 1977). Gabrielsson (1974) documented systematic deviations in the note durations and amplitudes of pianists' and percussionists' performances of repeating rhythmic patterns to a metronomic tempo; the first note of each measure was louder, and notated duration ratio relationships were increased. Listeners' ratings of similarity among these performed rhythms (Gabrielsson 1973a) and performances of polyphonic (multivoiced) rhythms (Gabrielsson 1973b) suggested that the expressive timing patterns can be grouped according to three factors: structure, motion, and emotion. Structure included meter, accent pattern, and simplicity (of duration ratios). Motion included rapidity (sound event density), tempo, and forward movement. Emotion included vitality, excitedness, and playfulness (Gabrielsson 1982). Factor analyses of the timing profiles from piano performances of a Mozart sonata replicated some of the same structure-expression relationships found with the simpler rhythm patterns, in which other types of musical structure were not present (Gabrielsson 1987a).

The mapping between structure and expression is modulated by several factors, however, including the musical context. Drake & Palmer (1993) examined whether accents associated with different musical structures affect performance expression independently or interactively. Three types of structure were systematically combined in melodies presented to pianists: meter, rhythmic grouping, and melodic accents (pitch jumps and contour changes). Performance expression corresponding to rhythmic grouping and meter remained the same when those two structures were presented separately or combined, and they remained the same when the two structures coincided or conflicted (Drake & Palmer 1993). Expression associated with melodic accents and sometimes metrical accents, however, was altered by the presence or absence of other accents. These findings suggest again that the mapping between particular musical structures and performance expression is not consistent across contexts.

Performance expression also serves to differentiate among simultaneously occurring voices in multivoiced music. Voices can be distinguished by their intensity or timing. Early analyses of Duo-art (player piano) rolls indicated that pianists played tones comprising the melodic voice sooner than other tones notated as simultaneous (Vernon 1936). Recordings of wind, string, and recorder ensembles also indicated asynchronies among the voices for notated simultaneities, with a spread of 30–50 ms and a small relative lead (7 ms) of the instrument leading the ensemble (Rasch 1979). The amount of spread was larger for instruments whose rise (attack) time was longer, which suggests that musicians may adjust the asynchronies to establish appropriate timing of perceptual onsets. Measurements of both acoustic and electronic piano performances indicated a 20–50 ms lead of the melody over other voices (Palmer 1989, 1996b), longer than the 20 ms needed for listeners to determine the order of two isolated tone onsets (Hirsh 1959). As interpretations of the melodic voice changed across performances, the voice that preceded other notated simultaneities changed accordingly (Palmer 1996b). Melody leads may serve to separate voices perceptually. Experiments with simple tone sequences indicate that tones that are temporally offset tend to be perceived as belonging to separate streams (Bregman & Pinker 1978).

Do performers use a syntax or formal set of rules to generate expression? According to the view that musical structure is related to performance expression in terms of explicit generative principles, systematic patterns of expression result from transformations of the performer’s internal representation of musical structure (Clarke 1993, 1995). Three types of evidence support the view that structure systematically generates expression: the ability to replicate the same expressive timing profile with very small variability across performances (cf Henderson 1936, Seashore 1938), the ability to change an interpretation of a piece and produce different expression with little practice (Palmer 1989, 1996b), and the ability to perform unfamiliar music from notation (sight-read) with appropriate expression (Palmer 1988, Shaffer 1981, Sloboda 1983).

Structure-expression relationships have been formalized in computational models that apply rules to input structural descriptions of musical scores (Sundberg et al 1983a,b). In one model, three types of rules affect event durations, intensities, pitch tunings, and vibrato. Differentiation rules enhance differences among categories, grouping rules segment the music, and ensemble rules coordinate multiple voices or parts (Sundberg et al 1991). Another computational model of performance expression formalizes the inner pulses (reflecting individuality and viewpoint) of individual nineteenth-century composers (Clynes 1986); pulses defined at different levels of musical structure are applied similarly to all pieces by a given composer to generate performance expression (Clynes 1977, 1983). Perceptual judgments of model-generated simulations (Clynes 1995, Repp 1989, Thompson 1989, Thompson et al 1989) and comparisons with live performance expression (Repp 1990) provide some support for these models, but they indicate in general that piece-specific factors contribute to performance expression as much as the piece-transcendent factors captured by the models' rules.

The view that musical structure generates expression also predicts that performers should find it more difficult to imitate a performance that contains an arbitrary relationship between expression and structure than a conventional one. In fact, pianists most accurately imitated a performance that contained a conventional relationship between phrase structure and phrase-final lengthening, but they could also reproduce synthesized versions that contained distorted structure-expression relationships (Clarke 1993, Clarke & Baker-Short 1987). Reproduction accuracy worsened with increasingly disrupted structure-expression relationships, although accuracy improved over repeated attempts even for the most distorted timing patterns. Listeners' ratings of the quality of the performances decreased as the structure-expression relationship became more disrupted (Clarke 1993). Evidence that performers can imitate expressive timing patterns that have an arbitrary relationship to the musical structure suggests that performance expression is not generated solely from structural relationships (Clarke 1993).

Perception of Performance Expression

What perceptual functions do expressive aspects of performance serve? Performance expression can communicate particular interpretations and resolve structural ambiguities, as suggested by the studies reviewed above. Performance expression may also function to compensate for perceptual constraints of the auditory system. According to a bottom-up argument based on psychoacoustic mechanisms, musicians play some events louder or longer because they are heard as softer or shorter otherwise (Drake 1993). Listeners showed decreased detection accuracy for experimentally lengthened events placed right before a long duration in simple rhythmic patterns (Drake 1993), the same locations at which performers tended to lengthen events in richer musical contexts (Drake & Palmer 1993, Palmer 1996a). Similar findings have been noted for intensity changes. Under instructions to play melodic tones with equal intensity, pianists systematically intensified the second tone of each group of four tones (Kurakata et al 1993), contrary to predictions of metrical accentuation on the first tone of each group. Perceptual ratings of the same sequences indicated that the tones in original performances as well as simulated equal-intensity versions were judged to have equal intensities, compared with simulated versions of randomized or altered intensities (Kurakata et al 1993). These initial findings suggest that perceptual sensitivity to temporal and intensity changes is modulated by structural aspects of musical sequences, and performance expression may compensate for those modulations.

The compensatory psychoacoustic explanation of performance expression can be contrasted with a top-down explanation that musical structure elicits expectations via listeners' internal representation of structure-expression rules (Repp 1992c). Listeners' detection of a single lengthened event in an otherwise temporally uniform (computer-generated) performance indicated that lengthening was more difficult to detect in places where it was expected to occur (at ends of structural units, strong metrical positions, and points of harmonic tension) (Repp 1992c). Furthermore, listeners' detection accuracy (percent correct per event location) for lengthened events was inversely correlated with a performer's natural use of expressive lengthening in the same musical piece. Detection accuracy also correlated with bottom-up acoustic properties of musical stimuli, including intensity and tone density characteristics inherent in the musical score. These findings were taken to reflect both top-down and bottom-up influences on the perception of performance expression (Repp 1992c). Further experiments replicated the detection findings for lengthenings and extended the detection paradigm to intensity changes (Repp 1995a). Although bottom-up and top-down explanations cannot be completely separated, the findings suggest that the structure given in a musical composition has inherent relational properties that constrain both perception and performance, rather than perception simply constraining performance or vice versa (Repp 1995a; see also Jones 1987).

Psychological tests of music-theoretic models of musical expectancy and tension-relaxation point to a similar explanation of the influence of compositional structure in perception and performance. Narmour's (1990, 1996) model of melodic expectancy predicts which events are most likely to occur in a given musical context. The more expected events are those that match their preceding contextual implications. Lerdahl's (1996) model predicts patterns of tonal tension and relaxation that arise from harmonic relationships across large musical sections. Both music theories are based on a combination of bottom-up (hard-wired) and top-down (acquired) processes that account for listeners' expectations. Perceptual experiments suggest that listeners can apprehend the music-theoretic predictions of melodic expectancies (Cuddy & Lunney 1995, Krumhansl 1995) and tension-relaxation (Krumhansl 1996) from just the categorical score information presented in computer-generated (expressionless) performances. Comparisons of the music-theoretic predictions with piano performance indicate that expressive cues emphasize melodic expectancies and tension-relaxation (Palmer 1996a). Unexpected events were played louder than expected events, and events with higher tension were performed with longer durations. These findings suggest that performers' and listeners' interpretations of certain structural relationships are constrained in similar ways by the musical composition.

MOVEMENT

After musical structures and units are retrieved from memory according to a performer's conceptual interpretation, they must be transformed into appropriate movements. Movement plays many roles in theories of music and its performance; for example, musical rhythm is often defined relative to body movement (Fraisse 1982, Gabrielsson 1982). Different views exist on the causal relationships between musical rhythm and movement in performance. For instance, movement can generate rhythm and timing, or rhythm and timing can generate movement (Clarke 1997). These two views are considered below.

Timekeeper Models

Movement generating timing is the motor control view: Structural information (such as a sequence's rhythm) may be the input to a motor system, which then produces some kind of temporally structured behavior, perhaps with the use of internal clocks or timekeepers. Internal clocks were proposed to account for behaviors such as the anticipation and coordination of gestures or acts, e.g. accompanying musical sounds with tapping. Accompaniment reflects a synchronization between perception and production that requires the anticipation of upcoming events. In music performance, motor systems are thought to construct the information for upcoming movements on the basis of internal clocks, which act as timekeepers by controlling the time scale of movement trajectories (Shaffer 1981). A clock constructs beats at an abstract level that provide temporal reference points for future movements. The primary role of an internal clock is to regulate and coordinate complex time series such as those produced between hands or between performers.

Evidence to support clock models comes mainly from reproduction tasks, in which subjects hear and then reproduce musical rhythms by tapping. People are more accurate at reproducing musical rhythms whose interonset intervals are based on 1:1 or 2:1 ratios than on other ratios (Essens & Povel 1985, Povel 1981). Both musicians and nonmusicians reproduce duration patterns most accurately when the durations are related in integer ratio relationships (Essens 1986). Early models of the temporal control of rhythmic sequences posited a single clock (Essens & Povel 1985, Povel & Essens 1985), whereas others contrasted multiple timekeepers (Vorberg & Hambuch 1984; for a review, see Jones 1990). Because reproduction tasks combine perceptual and motor processes, some models of reproduction timing attribute internal timekeeping to perceptual encoding (Povel & Essens 1985), whereas others attribute it to production mechanisms (Vorberg & Hambuch 1978).

At what hierarchical level of musical time does an internal clock operate? Most clock models exert their influence at the level of the tactus, or most salient metrical level in a musical sequence (Essens & Povel 1985, Parncutt 1994). Evidence from some tasks suggests that 600 ms may be the preferred pace of the tactus: People most often generate beat patterns around 600 ms in spontaneous rhythmic tapping tasks (Fraisse 1982), the typical interstep interval found in neutral walking is 540 ms (Fraisse 1982, Nilsson & Thorstensson 1989), and listeners most often use motion terms to describe rhythmic patterns whose interbeat intervals center around 650 ms (Sundberg et al 1993). Most internal clock models applied to music performance produce time periods greater than or less than the primary timing level by concatenating or dividing beat periods, rather than by positing additional clocks (Clarke 1997, Shaffer 1982).

A further implication of a motor system paced by an internal timekeeper or clock is that temporal variance in performed event durations may be attributable to the timekeeper or to the executing motor system. Early models of the timing mechanisms underlying tapping behaviors partitioned the temporal variance into lack of precision due to an internal timekeeper and due to motor response delays, based on covariance analyses of the interresponse intervals (Wing & Kristofferson 1973a,b). Extensions of this model were developed to test hierarchical organizations of timekeepers operating at multiple metrical levels or beat periods in single rhythms (Vorberg & Hambuch 1978) and in polyrhythms (Jagacinski et al 1988). Covariance analyses also allow comparison of whether the timing of event durations is constructed directly or indirectly; performed durations at the metrical level directly controlled by a timekeeper should be less variable than the durations of residual nested events within that level.

Tests of hierarchical clock models operating at various metrical levels, based on covariance analyses, were applied to music performance. Comparisons of temporal variance in skilled piano performances indicated that timekeeping was most directly controlled (least variable) at intermediate metrical levels of the subbeat (below the tactus), the beat, or the bar (Shaffer 1980, Shaffer et al 1985). Further tests of solo piano performances indicated that timing was directly controlled at the beat level (above the level of individual notes), which allowed the two hands some temporal independence in coordinating note events below the beat level that differed in duration (Shaffer 1984). In extensions of covariance analyses, Shaffer (1981) concluded that separate timekeepers controlled the timing of individual hands in piano performance. Duet performances indicated that each pianist's timing had highest precision (least variance) at the bar level, which suggests how performers might coordinate in the absence of an external conductor (Shaffer 1984). Although covariance analyses rely on an assumption of constant global tempo that is rarely seen in music performance, these findings suggest that temporal precision in performance is influenced by the structure of the sequence—in particular, the salience of the beat level or tactus.

Performance timing can also exhibit stability at more abstract hierarchical levels, such as entire musical pieces. The durations of string quartets over repeated performances by the same performers were highly consistent (Clynes & Walker 1986). The standard deviation of the total piece duration (30–45 min) was about 1%, smaller than that of individual movements within the piece. If one movement was shortened, another compensated in duration, which suggests temporal control at a level higher than the individual movements. A related theory predicts that the performance tempos of successive sections of music form simple integer ratios, called proportional tempos (Epstein 1995). The various periodicities that comprise a performance display phase synchrony, particularly at structural boundaries. Like Clynes & Walker (1986), Epstein proposed oscillator mechanisms that track periodicities of tempo in performance and perception and specify relationships among successive movement durations and tempo changes in quantized steps. Similar mechanisms have been proposed in a model of rhythmic attending, based on internal referent periods (preferred attentional periodicities) that may be shared by performers and perceivers (Jones 1987). However, large-scale tempo measurements may reflect performers' memory for tempo (Levitin & Cook 1996) as well as timekeeper stability, and findings based on live performances (Clynes & Walker 1986) are limited by practical constraints such as concert hall rental periods. Nevertheless, these theories do suggest that a large range of periodicities influences the timing of music performance.

Motor Programs

Another theory of temporal control of performance stems from motor programming views. A motor program contains representations of an intended action and processes that translate these into a movement sequence (Keele & Summers 1976, Shaffer 1981). The basic idea is that a sequence of movements can be coordinated in advance of its execution. The goal of motor programming is to account for motor equivalence across contexts, the fact that the same sequence can be performed with different actions and retain its fluency, expressivity, and adaptivity. One view accounts for performers' ability to produce the same sequence in different ways with a single generalized schema that takes parameters (Rosenbaum et al 1986, Schmidt 1975). Changes in global tempo across performances of the same musical piece have been conceptualized in terms of a parameter change. If timing of music performance is relationally invariant across tempo changes, then a change in tempo amounts to multiplying all event durations by a constant value. Relational invariance would support the existence of a generalized motor program, in which a variable rate parameter accounts for performers' ability to produce the same sequence at different rates. Tests of relational invariance for speech, typing, and walking have produced mixed results (cf Gentner 1987).

Tests of relational invariance in music performance generally indicate that the relative durations of note events tend to vary across performances of the same music played at different tempi by the same performer (Clarke 1982, Desain & Honing 1994, MacKenzie & van Eerd 1990, Repp 1995b), although in some cases the relative timing patterns remain highly similar (Repp 1994). One hypothesis for the relative timing changes across tempi is that structural interpretation does not remain constant across performance tempo; for instance, the number of group boundaries increased with slower tempo in piano performances of the same musical piece (Clarke 1982). Lack of relational invariance suggests a failure of transfer of learning; practicing a pattern at a different rate than the intended performance rate might be counterproductive. These findings also warn against drawing structural conclusions based on performance data averaged or normalized across tempi.

Is the perception of musical structure invariant across tempo changes? Perceptual experiments with performed monorhythms (Gabrielsson 1973a) and polyrhythms (Handel & Lawson 1983) suggest that tempo changes do affect the perception of duration patterns. If performers use expressive timing to bring about a desired structural organization for a particular tempo, different perceptions might result for the same relative expressive timing pattern played at a different tempo. Repp (1995b) independently manipulated the amount of expressive timing (incremented in terms of a power function) and the global tempo (incremented in terms of total piece duration) of performances. Listeners gave higher ratings of aesthetic quality to the reduced expression at fast tempo and to the augmented expression at slow tempo for the same musical pieces, which suggests that listeners preferred the amount of expressive timing to change with tempo (Repp 1995b). Although these perceptual findings do not indicate the mechanisms controlling performance timing, they suggest that a perceptual analogue exists for the tempo effects on expressive timing documented in performance.

Kinematic Models

The view that rhythm generates movement is reflected in the notion that music performance and perception have their origins in the kinematic and dynamic characteristics of typical motor actions. For example, regularities observed in a sequence of foot movements during walking or running are similar to regularities observed in sequences of beats or note values when a musical performance changes tempo. A rhythmic framework may be transmitted from performers to listeners through sound (Shove & Repp 1995), as suggested by computational models of music performance in which the auditory system interacts directly with the motor system (Todd 1995). The kinematics of movement allow a common origin for performance and perceptual phenomena, based on similar kinematic properties applying across individuals. Consequently, aesthetically satisfying performances should be those that satisfy kinematic constraints of biological motion (Shove & Repp 1995).

Kinematic models were first applied to the large decelerations in performance tempo that commonly occur at the ends of pieces, called the final ritard. Pianists' final ritards were modeled in two parts—a variable timing curve followed by a systematic, constant decrease in tempo (called linear tempo) (Sundberg & Verrillo 1980). The "motor music" used in the studies, which contains a regular sequence of events with short durations, may create associations for listeners with experiences of physical motion (Kronman & Sundberg 1987). Feldman et al (1992) modeled both ritards and positive accelerations that occurred throughout performances. Based on modeling fits to the timing of a few ensemble performances, cubic polynomial models were chosen to minimize the jerk or jumpiness in connecting points of tempo changes (ritards) to the constant tempo that preceded them. Repp (1992b) modeled the expressive timing of a short melodic gesture in piano performances of a Schumann piece, finding a best-fitting quadratic polynomial. The three parameters represented a positive constant that corresponded to overall tempo, a negative linear coefficient that corresponded to vertical and horizontal displacement of the parabola, and a positive quadratic coefficient that corresponded to degree of curvature. Synthesized performances for the same melodic segment based on altered parameter values were played for listeners, who preferred timing profiles that fit the original parabolic functions (Repp 1992a).

Although most models of motion in performance address timing, some apply to dynamic (intensity) changes as well. Some measurements of performance suggest a coupling between expressive timing and dynamics in singing (Gjerdingen 1988, Seashore 1938) and piano performance (Gabrielsson 1987a, Palmer 1996a), in which tempo and intensity increase and decrease together over a musical section such as a phrase. Todd (1992) proposed an underlying kinetic energy model for performance expression, in which intensity is proportional to the square of musical velocity (number of events per unit time). Contrasting the fit of different parabolic models to intensity and timing patterns in piano performances, Todd settled on a model with constant acceleration (linear tempo). Like Sundberg & Verrillo, Todd (1992) proposed that musical expression induces a percept of self-motion in listeners.

The notion that performance expression has its origins in the kinematic and dynamic properties of motor actions was extended in a general framework of perception and performance (Todd 1995). A linear tempo model equivalent to Kronman & Sundberg's (1987) was fit to the expressive timing of piano performance segments, which were identified by changes in the sign of acceleration. Todd (1995) proposed an auditory model of rhythm performance and perception, based on a time-domain process that computes temporal segmentation of onsets (low-pass filters) and a frequency-domain process that computes a periodicity analysis (bandpass filters). In addition, a sensory-motor feedback filter has two periodic components: the tactus (a filter centered at 600 ms), modeling beats, and body sway (a filter centered at 5 sec), modeling large-scale body movements. Performers' body and limb movements can specify some aspects of music performance, as evidenced in observers' ratings of performances based on visual information only from point-light displays (Davidson 1993, 1994). Todd's (1995) model requires further testing to eliminate potential overfitting of data, and its identification of line segments can be problematic. The model's advantage is that it is a purely bottom-up segmentation method that requires no input structural markers, as are required by several of the kinematic models discussed above.

Arguments against kinematic models suggest that physical notions of energy cannot be equated with psychological concepts of musical energy (Desain & Honing 1992). An alternative explanation suggests that tempo changes in performance are guided by perceptual rather than kinematic properties. For instance, large tempo changes cannot occur too quickly, because the rhythmic categories that occur within the region of tempo change will not be perceived intact (Desain & Honing 1992). Rhythm identification and discrimination tests suggest that categorical distinctions underlie the perception of rhythmic structure, and performers use expressive timing to separate durational categories of note events even more when the events' absolute durations are converging at fast tempi (Clarke 1985). Thus, tempo changes in performance may operate in a noncontinuous, stepwise fashion across absolute durations to retain the perception of intended rhythmic categories (Desain & Honing 1992), which is another explanation for why relational invariance may not hold across tempo changes. Although this explication is not yet fully developed, it incorporates perceptual constraints and sensitivity to musical structure in explaining the control of movement in music performance.

CONCLUDING COMMENTS

Scientific study of music performance has witnessed tremendous growth in the past ten years, due to both technological advances and theoretical interest from the related fields of psychoacoustics, biomechanics, artificial intelligence, computer music, music theory, and music education. Performance studies now draw on concepts from music theory, and structural parallels from psycholinguistics are often fruitful. Distinctions between the psychological mechanisms proposed for music perception and performance are becoming blurred. For example, listeners' (and performers') abilities to track the beat and recover categorical information in continuously varying performances are now active issues for researchers in both perception and performance. Music performance offers a well-defined domain in which to study basic psychological constructs underlying sequence production, skill acquisition, individual differences, and emotional response, all of which will be the focus of future research directions. Finally, interdisciplinary approaches to this domain are growing, in part because current findings document music performance as a seemingly unique human ability that is not unique in its underlying cognitive mechanisms.

ACKNOWLEDGMENTS

Preparation of this chapter was supported in part by NIMH grant R29-MH45764. I gratefully acknowledge the comments of Eric Clarke, Peter Desain, Carolyn Drake, Henkjan Honing, Richard Jagacinski, Mari Riess Jones, Bruno Repp, and John Sloboda, and the aid of Peter Knapp, Rosalee Meyer, Brent Stansfield, and Timothy Walker in preparing this manuscript.

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