Journal of Experimental Psychology:
Learning, Memory, and Cognition
1993, Vol. 19, No. 2, 457–470

0278-7393/93/$3.00

Units of Knowledge in Music Performance

Caroline Palmer and Carla van de Sande

The units of knowledge that form cognitive plans for music performance were examined in production errors. In Experiment 1, pianists performed multivoice homophonic music (containing strong across-voice associations) and polyphonic music (containing strong within-voice associations). Pitch errors reflected more chordal (across-voice) units in homophonic performances and more single-note units in polyphonic performances. Error instructions were harmonically and diatonically related to their intended pitches more often than chance, which demonstrates retrieval-based influences on planning. In Experiment 2, pianists conceptualized one of several voices as melody. Both the melody and the voice controlled by outer right-hand fingers (a common location of melody) contained fewer errors, which implies that there are conceptual, retrieval-based, and articulatory influences on units of knowledge that contribute to planning music performance.

Many aspects of skilled music performance make it a particularly interesting cognitive capacity. Music performance reflects a communication of structure among composers, performers, and listeners, which suggests the existence of some shared musical knowledge. In addition, music performance is a highly complex parallel behavior; for instance, skilled pianists can produce 15–20 individual note events per second with each hand (simultaneously), and the cognitive demands can be large. Perhaps the most interesting aspect of this musical skill is the apparent flexibility (ability to generate different but functionally equivalent actions) and fluency (smoothness and consistency) seen in well-practiced behavior. A paradox that arises here is that fluency tends to reduce errors in skilled performance, whereas the flexibility of generating novel combinations of events can lead to an increase in new types of errors. A popular explanation offered for this paradox is that skilled production involves the advance construction of one or more cognitive *plans* or internal representations of the behavior to be produced (Lashley, 1951; MacKay, 1982; Norman, 1981). Plans are responsible for fluency and flexibility; the ability to form plans increases with practice. Furthermore, if these internal representations co-exist, then the potential for competition arises, which sometimes results in the wrong plan (or portions of it) being performed. Thus, errors in skilled performance are thought to reflect multiple internal representations of the behavior (Garrett, 1975; Norman, 1981).

Several accounts of skilled production assume that errors result from a co-occurrence of more than one plan or component at some point in processing. For instance, some types of errors (such as anticipations and perseverations) reflect influences of information intended for earlier or later in a sequence (Lashley, 1951). In language production, speech errors often involve related sounds or meanings, which may arise from the computation of similar components during planning (referred to as computational simultaneity; cf. Garrett, 1975). Some theories of language production posit the assembly of higher order (earlier) components (such as a semantic representation) before lower order (later) components (such as a phonological representation; cf. Fry, 1969; Garrett, 1975). In accordance with this view, an internal buffer stores the earlier planned components, which are retrieved during planning of the later components. Speech errors thus may involve similar elements because similar units are caused to co-occur in the buffer. Music production errors may likewise provide insights about the musical elements that contribute to, or compete in, the planning of a particular sequence of events.

We address here the specific problem of the units of knowledge that contribute to the cognitive organization of music performance. What musical structures and units are retrieved from memory, organized, and executed in skilled performance? We draw from production errors, or breakdowns resulting in unintended output, as evidence of the units that constitute planning in music performance. Studies of production errors in other skilled behaviors have posited conceptually distinct units at multiple levels of planning. For example, letters, digraphs, and word units are proposed to be part of mental plans that account for production errors in skilled typing (Gentner, Larochelle, & Grudin, 1988; Shaffer, 1978) and phoneme, syllable, and word units are proposed in language production (Fromkin, 1971; Fry, 1969; MacKay, 1982). The multiple types of units supported by production errors are thought to reflect memory retrieval, organization, and articulatory (motor) influences on planning, as well as conceptually distinct categories of items.

In Western tonal music, individual pitches, chords, and keys have been posited as conceptually distinct units of knowledge, which reflect levels of melodic, harmonic, and tonal structure, respectively. Most perceptual models consider individual pitch events to be the primary units (pro-

Caroline Palmer and Carla van de Sande, Department of Psychology, Ohio State University.

This research was supported in part by Grant 1R29-MH45764 from the National Institute of Mental Health to Caroline Palmer. We thank Lola Cuddy, Gary Dell, Susan Holleran, Mari Jones, Mark Schmuckler, and three reviewers for comments on an earlier draft and David Butler and Korinthia Klein for assistance with the stimulus materials.

Correspondence concerning this article should be addressed to Caroline Palmer, Department of Psychology, Ohio State University, 1885 Neil Avenue, Columbus, Ohio 43210. Electronic mail may be sent to cpalmer@magnus.acs.ohio-state.edu.

cessed first), and chords (simultaneously sounded pitches) and keys (specific patterns of intervals among a set of pitches) to be secondary units, built from individual pitches. For instance, a spreading activation model of pitch relationships reflects individual note (pitch) units at a primary (lowest) level, from which chords and keys are formed on the basis of the strength of their links to units at other levels (Bharucha, 1987; Bharucha & Stoeckig, 1986). Nodes corresponding to individual pitches are initially activated, and through excitatory and inhibitory connections between nodes, the activation spreads to parent chords and then to keys. Music-theoretic and psychological accounts of pitch relationships also suggest that hierarchical relationships hold among notes, chords, and keys on multiple dimensions, including pitch chroma, diatonicity, the harmonic circle of fifths, and parallel and relative relations between major and minor keys (Krumhansl, 1990; Krumhansl & Kessler, 1982; Lerdahl, 1988; Shepard, 1982). These accounts assume that essentially the same mental processes operate on each type of unit. Thus, we might predict that planning of music performance reflects influences of the same distinct units, with individual notes as primary units and with the same processes affecting each type of unit. The experiments reported here test these predictions by examining the size and contents of production errors during music performance.

There are difficulties, however, in applying these assumptions from perceptual models to music performance: First, they do not incorporate conceptual or artistic interpretations. Performers have significant latitude in their interpretation of the structural significance of musical events; they can weight some units more or less heavily, depending on their particular conception of a musical piece. Also, articulatory properties (motor commands produced for a specified sequence of successive events) may influence performance plans; for example, two perceptually related musical events may be distinguished by their ease of motor production. For instance, keyboard performances of musical scales suggest a greater range of articulatory control for the right hand than for the left hand (MacKenzie & Van Eerd, 1990). Thus, accounts of the mental plans underlying music performance must consider production constraints in addition to perceptual constraints.

One prediction that follows from the communicative demands on music performance is that production errors reflect some correspondence between the composer's specification of musical structure and the performer's conceptual representation of it. For instance, both homophonic and polyphonic piano compositions contain multiple simultaneous voices or parts, but the interrelationships among the voices are quite different in each; the performer's conception of the music may reflect these differences. Homophonic compositions usually contain one important or primary voice, a melody, and several secondary voices with similar rhythmic or harmonic properties that support the melody and form strong across-voice associations. Most 19th-century Western tonal music is written in the homophonic style. Polyphonic compositions tend to contain multiple voices of *(roughly) equal importance* with different rhythmic properties and thus have stronger within-voice than across-voice associations. Much of J. S. Bach's contrapuntal music demonstrates the polyphonic style. Homophonic and polyphonic music are often considered opposite compositional styles (Apel, 1972). (Many musical pieces may lie on a continuum between these styles.) We investigated the correspondence between composers' and performers' conceptions of musical structure in Experiment 1, by comparing production errors for performances of the two compositional styles. If production errors reflect influences of compositional structure on the mental planning of a performance, then they may differ in content for homophonic and polyphonic music.

Another prediction of the communication perspective is that errors reflect the relative importance of musical events according to the performer's conceptualization of the piece. This prediction stems from work in musical interpretation and its effects in skilled performance. The role of interpretation in Western tonal music is to allow each performer to decide the relative importance of musical events; the performer emphasizes some events at the expense of others to communicate particular constituent structures. Many researchers have studied the timing and intensity characteristics of piano performances that serve to emphasize the performer's intended musical structure (cf. Clarke, 1985; Gabrielsson, 1987; Palmer, 1989; Repp, 1990; Shaffer & Todd, 1987). However, errors as an index of interpretation have received less attention. If interpretations determine the contents of mental plans, then their experimental manipulation should lead to systematic changes in errors that reflect changes in the relative importance of musical events. We investigated how musical interpretation influences the planning of music performance in Experiment 2 by comparing performances in which the same pianist is instructed to emphasize different interpretations of musical structure for the same musical piece.

Music Production Errors

Despite the prevailing view that production breakdowns provide rich information about cognitive planning processes (Norman, 1981), there is little documented evidence of errors in music performance; primarily caused by methodological limitations. Deviations from the musical notation are expected in Western tonal music as part of a performer's artistic license, and it is often difficult to distinguish these artistic deviations from actual errors. For example, the variability of timing and velocity measures in keyboard performances often increases with playing speed (MacKenzie & Van Eerd, 1990). Therefore, most references to musical errors refer to pitch events, because pitch is relatively fixed by the compositional notation of Western tonal music. Sloboda (1985) described some pitch errors in sight-read piano performances in which more likely events (those in the key of the piece) were substituted for less likely events (that were actually typesetting mistakes in the musical notation). Palmer (1992) reported a small collection of pitch errors in well-practiced piano performances, in which performers' interpretations of the phrasal relationships among musicalelements influenced the likelihood of different error types at phrase boundaries. Thus, some limited evidence suggests that errors reflect multiple relationships among the events planned in music performance.

There are several advantages to studying errors in the domain of music performance. First, computer-monitored musical instruments allow error detection that is free of perceptual biases, that can arise in acoustic domains. Second, we can avoid some of the sampling biases that arise from error collection methods in other domains, by controlling the frequency of occurrence of musical events in a piece. Also, errors are fairly commonplace in piano performance; the demands of producing many events quickly are so great that errors appear even in highly skilled performances (cf. Palmer, 1992). Finally, the metrical and rhythmic structure of Western music performance require that musicians continue (instead of stopping) when an error is made, which provides naturalistic conditions for study of uninterrupted errors (those in which the performer's intent is unambiguous).

We examined pitch errors in piano performance in two experiments. Pianists' performances are collected on a computer-monitored acoustic piano that allows precise measurement of frequency, timing, and hammer velocity (correlated with intensity) for each key pressed. As in other experimental studies of production errors (Baars, Motley, & MacKay, 1975; Dell, 1986; Ellis, 1980), we attempted to separate errors that were due to failures of planning from those that were due to failures of input (i.e., failures that occur during perception or learning of what is to be performed). Although interesting, perceptual and learning errors do not necessarily reflect failures of planning because the performer's intent may have been successfully enacted. For this reason, we used two types of musical stimuli: well-learned (familiar) music that the performer has memorized, and short musical excerpts that are easily sight-read (unfamiliar music performed from notation).

We adopted an error coding scheme similar to that used in speech error research (Dell, 1986; Garrett, 1975; Stemberger, 1982), with modifications for the musical domain. A summary of the coding scheme is shown in Figure 1. First, the question of what units of knowledge form plans can be addressed by evaluating the size of pitch errors; they can involve one note event or multiple simultaneous notes (referred to here as a chord). The co-occurrence of more than one plan is often reflected in the units that interact in an error: the target, an intended event, and the intruder, an unintended event that replaces the target. The intruder can reflect different sources of planning: contextual (from the immediately surrounding musical context as in a misordering), or noncontextual (not from the immediate context). Different error types can indicate the particular planning processes likely to compete: A substitution involves an intruder replacing a target; an addition involves an intruder being added (without replacing a target); a deletion involves a target being deleted; and a shift involves the movement of a target to a neighboring location. Finally, contextual errors can reflect the range of influence of different plans in the type of movement, including forward movement (an event performed too early; anticipations), backward movement (an event performed too late; perseverations), or both (events switching neighboring locations; exchanges). The computation of similar components during planning may also be reflected in other target–intruder relations, such as harmonic similarity (sharing the same chord type) and diatonic similarity (sharing the same key). Thus, we coded pitch errors for additional target–intruder relations, which are described more fully in Experiment 1.

Experiment 1: Influences of Compositional Structure

We examined the influence of compositional structure on the size of units planned in music performance by presenting pianists with two types of musical compositions:

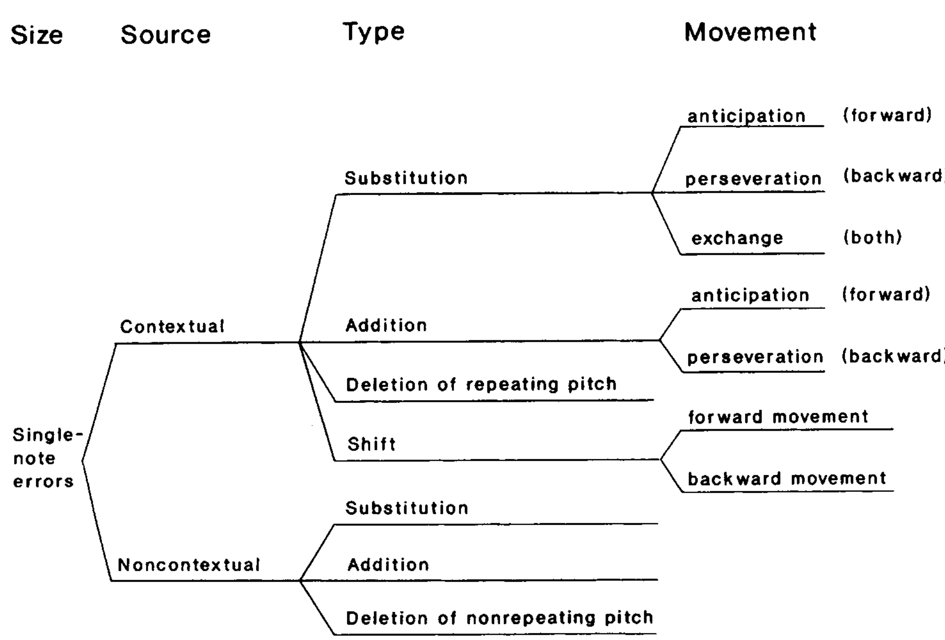

Figure 1. Pitch error coding scheme for single-note errors. (The same coding scheme was repeated for errors of chord size and note/chord combinations.)

homophonic and polyphonic, each containing three simultaneous voices or parts. The homophonic compositions contained one melody and two accompanying voices of secondary importance. Thus, homophonic structure emphasized across-voice associations, and errors should reflect associations among simultaneous voices (chords). The polyphonic compositions contained two melodies and a third (less important) voice. Thus, polyphonic structure emphasized within-voice associations, and errors should reflect associations among elements within the voices (single notes). Our hypothesis was that compositional structures should influence performers' conceptual representations of the music, which in turn should be revealed in distinctive error patterns. Homophonic performances should display more chord errors, and polyphonic performances should display more single-note errors, despite the equivalent number of chords and single-note elements in the two compositions. In addition, the compositional structures may affect pianists' conceptions of similarity among simultaneous musical elements. Because homophonic structure emphasizes across-voice associations, error targets and intruders may be harmonically similar (of the same chord type) more often in homophonic than in polyphonic performances.

The relative importance of different voices may provide another compositional influence on planning performance. Both homophonic and polyphonic compositions contain multiple voices, some of which are more important than others. If performers' conceptual representations reflect the compositional emphasis given to different voices, then error patterns may also reflect voice emphasis, with fewer errors in melodic (most important) than in nonmelodic (less important) voices. We examined the effects of voice emphasis on errors by comparing performances of pieces containing different numbers and locations (in frequency range) of melodies. Skilled pianists memorized short homophonic and polyphonic pieces and then performed them at a faster speed to induce a higher error rate, a common method in studies of experimentally elicited errors (Dell, 1986; Ellis, 1980; Levitt & Healy, 1985). All pitch errors were collected on the computer and were analyzed for compositional influences.

Method

Subjects. Sixteen skilled pianists (aged 18–34 years) from the Columbus, Ohio, community participated in the experiment. The pianists had a mean of 15 years (range = 8–23 years) of private instruction and a mean of 18 years (range = 12–26 years) of playing experience. All of the pianists were comfortable with sight reading and memorizing short pieces. None were familiar with the pieces used in this study.

Materials. Examples of the musical stimuli are shown in Figure 2. The musical pieces were constructed as follows: Two simple melodies of the same length were composed, one in the high-frequency range (in the key of E-flat major, shown in Figure 2) and one in the low-frequency range (in the key of A major). These melodies will be referred to as primary melodies. A two-voice homophonic and polyphonic accompaniment was then created for each primary melody (in the lower frequency range for the high-frequency melody and the higher frequency range for the low-frequency melody). The homophonic accompaniment consisted of two nonmelodic voices with equal numbers of note events. The polyphonic accompaniment consisted of a nonmelodic voice and a melodic voice, or secondary melody (marked in Figure 2). The secondary melody was constructed so that it had approximately the same number of note events as the primary melody it accompanied, as well as the same amount of change in pitch range and note durations. Each piece was constructed so that it had the same total number of chords (nine) and approximately the same total number of note events (range = 31–34); thus, the likelihood of a single-note or chord error was equivalent across stimuli. This yielded a total of four stimulus pieces, two homophonic and two polyphonic, each of which contained three voices.

Apparatus. Pianists performed on a computer-monitored Yamaha Disklavier acoustic upright piano. Optical sensors and solenoids in the piano allowed precise recording and playback without affecting the touch or sound of the acoustic instrument. The timing resolution was 2 ms for note events, with precision (measured by the standard deviation of onset-to-onset durations

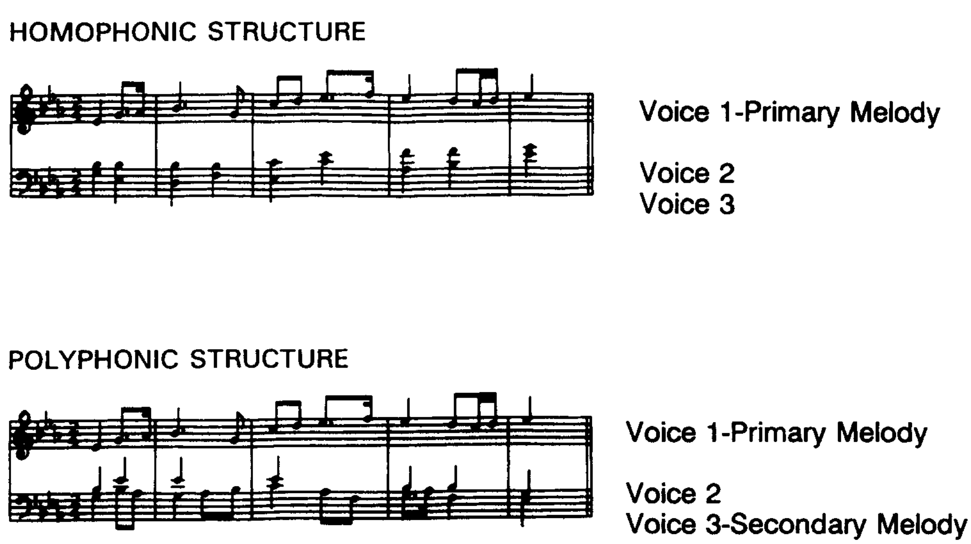

Figure 2. Experiment 1: Examples of homophonic and polyphonic stimuli composed from the same melody (Voice 1).

during recording) within 0.8% for durations in the range of the performances. The pitch, timing, and hammer velocity values (correlated with intensity) for each note event were recorded on the computer, which detected all incorrect pitch events according to the ideal values in the musical notation.

Procedure. The following procedure was repeated for each piece: Pianists practiced a piece until they had memorized it (usually less than 10 min). The musical notation was then removed, and recordings were made until the pianists were satisfied with at least four performances. These initial performances provided a measure of how well each pianist had learned the piece. Next, the pianists were instructed to practice the piece two times at approximately twice the speed of their initial performances. The subjects then performed the piece 10 times at the faster speed; these performances formed the test performances. Pianists were encouraged to continue if they made mistakes and were told that they could reexamine the musical notation at any time if they were unsure of their memory. (In this event, 10 additional speeded performances were recorded.) The pianists then performed the piece again at the (slower) speed of their initial performances and notated their fingering assignments. These last performances provided a measure of the retained memory for the piece over the course of the experiment.

Each pianist performed each of the four pieces. Order of stimulus presentation was determined by a Latin square design in which pieces with different primary melodies were alternated. The experiment lasted approximately 1.5 hours, and pianists were paid $8 for their participation.

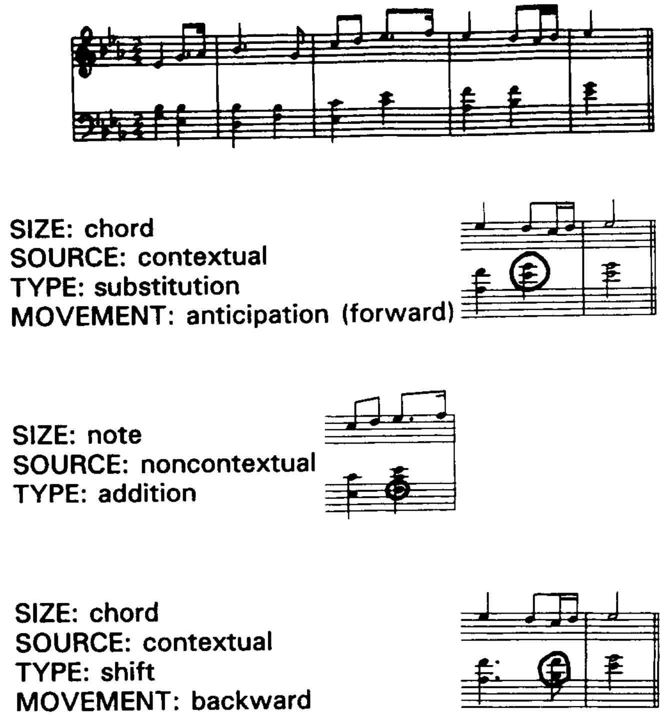

Figure 3. Experiment 1: Three pitch error examples and their coding in size (note/chord/both), source (contextual/noncontextual), type (substitution/addition/deletion/shift), and movement (forward/backward/both).

Results

Error coding. Examples of pitch errors in the test performances and their codings are shown in Figure 3. Error size was determined by comparing the number of incorrect note events performed (intruders) to the number of intended events in the musical notation that were in error (targets). If one target or intruder was in error (whether it was notated as a solitary pitch event or as part of a chord), then the error was coded as a note error. If two or more simultaneous targets or intruders were in error, then the error was coded as one chord error. If the target(s) and intruder(s) included both a note and a chord (as in a chord being substituted by or substituting for a single note), then the error was coded as a *note/chord error.* Source of error was coded as contextual (reflecting a misordering) if the intruder was from the context immediately surrounding the target (in any voice), as determined by the musical notation. Target–intruder relations were coded for harmonic similarity (coded same if intruder was one of three pitches [first, third, and fifth scale steps], from target chord type; if no target chord was present in the musical notation, then similarity was not coded) and for diatonic similarity (coded same if intruder was one of the seven pitches in the diatonic key of the piece). Voice emphasis was coded as primary melody, secondary melody (in polyphonic pieces), or nonmelody. Location of error target was coded as Voice 1 (highest frequency voice), Voice 2 (next highest), Voice 3 (lowest frequency voice), or combination of these (for chord errors).

An inherent problem in coding production errors is the ambiguity that arises from different possible codings of the same error. A common strategy, which we follow here, is to choose the simplest or most economical coding, in terms of the number of rules required. For example, the production of Pitch C in place of Pitch D was coded as a substitution rather than as a deletion plus an addition. The presence of simultaneous voices provided additional information for distinguishing among possible codings. If an error occurred in one of many simultaneous voices, then the consequences to the other voices were used to rule out some coding combinations, because the other voices often reflected the same (or different) processes. Remaining coding ambiguities, which formed less than 2% of the total errors, were divided equally among the possible coding categories.

Errors in the 10 test (speeded) performances that occurred in the same location in three or more of the four initial performances or in the last performance (normal speed) were not included in the analyses, because they may have reflected perceptual or learning problems. Errors in the locations immediately adjacent to these errors were also excluded, as were interrupted errors (those corrected midway through the error), because they could not be coded unambiguously. This resulted in a total of 283 included pitch errors; excluded errors formed less than 10% of the total errors. The number of errors in each performance was correlated with the mean rate at which it was performed (measured by the average quarter note duration) to ensure that the instructions to play quickly did not account for differences in error rates across subjects. The correlations were small and ranged from $r = -.32$ to .32 across stimuli ($p > .10$), which indicated that the number of errors was not simply a function of individual speed.

Order of stimulus presentation did not affect the number of errors or interact with other variables, and it was, therefore, removed from further analyses. Following other studies of experimentally elicited errors (Dell, 1986; Ellis, 1980; Levitt & Healy, 1985), all statistical analyses were conducted on the number of errors in each subject's test performances; error percentages are presented in all figures for comparison across conditions and experiments relative to chance estimates. Parametric tests (analyses of variance; ANOVAs) were conducted on the total number of errors, and nonparametric tests (sign and matched-pairs signed rank) were conducted on comparisons of specific error types (subsets). Errors were examined in terms of their size, source (target–intruder relations), and voice influences (melody and location).

Unit size. Error percentages are shown in Figure 4 for each condition as a function of size. First, most errors (98%) involved one size unit (chord or note) rather than a mixture (note/chord error). Second, most errors (91%) involved single notes (whether from part of a chord or from a solitary notated event). Third, error size differed by compositional structure, as shown in Figure 4. A Wilcoxon matched-pairs signed ranks test on the number of note and chord errors indicated that there was a significant interaction between condition and size, with more chord errors in homophonic (13) than polyphonic (3) performances and more note errors in polyphonic (160) than homophonic (100) performances ($p < .05$), despite the equal chance estimates for note and chord errors across compositional structures.

Target–intruder relations. Target–intruder relations were examined first in contextual errors. Contextual errors made up 57% of the total errors, the greatest percentages of which were substitutions (31%) and contextual deletions (deletion of a repeating pitch, 31%). Of the movement errors (substitutions, additions, and shifts, which comprised 69% of the contextual errors), forward (early) movement was most frequent (52%), backward (late) movement next most frequent (37%), and bidirectional movement (exchanges) least frequent (11%). Thus, the instructions to perform quickly did not prevent the planning of upcoming events (forward movement) from contributing heavily to errors in both conditions.

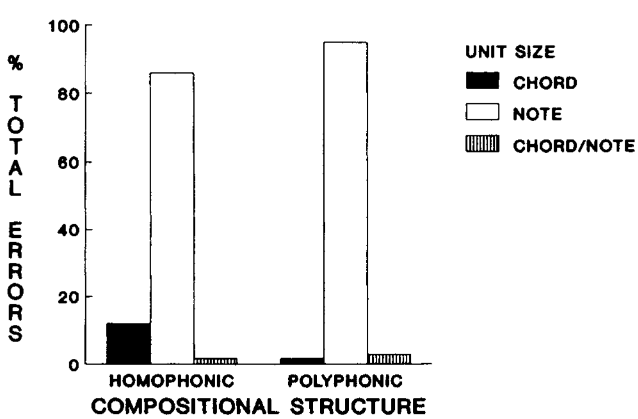

Figure 4. Experiment 1: Error percentages for each condition (compositional structure) by unit size.

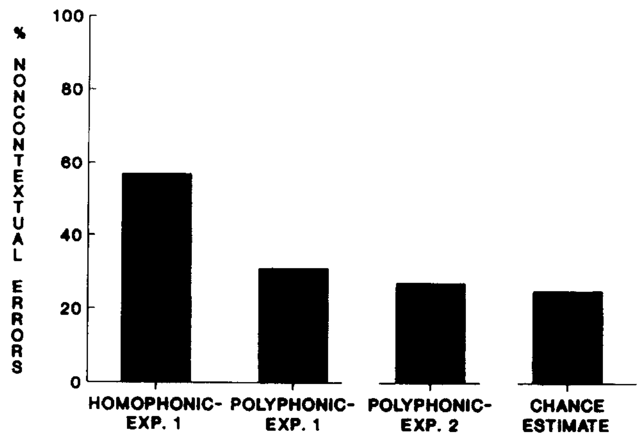

Figure 5. Percentages of harmonically similar noncontextual errors by condition. (First two bars, Experiment 1; third bar, Experiment 2; fourth bar, chance estimate.)

Target–intruder relations were examined next in noncontextual errors (those for which the intruders' source was undetermined). We expected that intruders and targets would be harmonically similar (of the same chord type) more often in the presence of stronger across-voice associations (homophonic compositions) than in the presence of within-voice associations (polyphonic compositions). By chance, 3 of the 12 possible intruder pitch values (across the entire frequency range) were of the same chord type as the target (3:12 is used here for chance estimate because the set of harmonically acceptable pitches differs for each chord and sometimes includes nondiatonic elements). Only those noncontextual errors with targets that had harmonic content that was unambiguously determined by the musical notation were included in the analysis (those for which the first, third, and fifth scale steps were present, or two were present and surrounding chords unambiguously defined the chord type). Figure 5 shows the error percentages of harmonically similar noncontextual intruders in each condition; 25 of 44 noncontextual intruders in homophonic performances were of the same harmonic content as the target (compared with the chance estimate of 3:12; sign test by subject; $p < .05$). Only 8 of 26 noncontextual intruders in polyphonic performances were of the same harmonic content as the target (compared with the chance estimate of 3:12; sign test by subject; $p > .05$). Although the difference between conditions in numbers of harmonically similar and dissimilar errors only approached significance (matched pairs signed ranks test; $p = .07$), harmonic similarity between targets and intruders was greater than chance in the homophonic condition but not in the polyphonic condition. Contextual intruders did not tend to be harmonically similar in either homophonic (18%) or polyphonic (27%) conditions.

Finally, target–intruder relations were examined for effects of diatonic key (set of seven pitches from which each piece is composed). The intruders of noncontextual errors were divided into two categories: those that were from the same diatonic key as the targets and those that were not.

(Total number of errors in this analysis is larger than in the harmonic similarity analysis because harmonicity was sometimes undetermined.) Of the 73 noncontextual intruders, 56 were from the same diatonic key; compared with the chance estimate of 7:12 (number of diatonic:chromatic pitches across the entire frequency range), the target–intruder similarity was significant (sign test by subject; $p < .05$), which indicates that the diatonic key context influenced the pitch value of intruders. Diatonic similarity of errors did not differ across homophonic and polyphonic conditions. The diatonic error effects could not be explained by a tendency to hit white or black keys on the keyboard; both black and white key errors were common (as expected for the key signatures of these stimuli, which were composed of 43% black keys), and they were equally frequent in the diatonic and nondiatonic error subsets.

Because the criterion for classifying contextual errors is strict (intruders must be from neighboring locations on either side of the error), the diatonic similarity bias seen in noncontextual errors may result from some noncontextual intruders actually being contextual (from farther away in the context and therefore diatonic). This explanation was tested by removing noncontextual errors from the reanalysis if their intruders occurred in the musical notation (as targets) within a window of half of a measure on either side of the error (the computed mean distance between any given pitch event and its reoccurrence in the stimuli). Of the 61 remaining intruders, 45 were from the diatonic key (compared with the chance estimate of 7:12; sign test by subject; $p = .10$), which suggested that the strict criterion for contextual errors did not account solely for the diatonic similarity bias.

Voice influences. The errors were next examined as a function of voice emphasis. Chord errors were divided among each voice involved (.33 per voice for 3 voices or .5 for two-note chord errors). A two-way ANOVA conducted on the number of errors for each subject by voice emphasis (primary melody, nonmelody [middle voice], and nonmelody2 [secondary melody in polyphonic performances]) and by condition (homophonic and polyphonic) indicated a significant main effect of voice emphasis, $F(2, 30) = 13.5$, $p < .01$, $MS_e = 2.2$. Errors were least common in the melody ($n = 44.5$; 16% of all errors) and most common in the middle voice (the voice that was never melody; $n = 162.5$; 57% of all errors). There was no main effect of compositional condition or interaction with voice emphasis, which suggests that melody is important in both compositional structures.

Because melodies in Western tonal music often occur in the mid- to high-frequency range, the melody advantage may reflect in part a location or frequency range advantage. Therefore, the errors were reexamined for the subset of voices in which the melody and frequency range were systematically varied across the stimuli (Voices 1 and 3). Figure 6 shows the error percentages across stimuli as a function of voice emphasis (melody or nonmelody) and frequency range (high [Voice 1] or low [Voice 3]). The chance estimates (expected number of errors for each voice) are not shown in Figure 6 because the comparison is drawn across stimuli (whose number of events in each voice differ); however, all stimuli contained at least as many melody events as nonmelody events, which made the chance estimates for melody errors higher than (predicted findings in the opposite direction of) the tests reported. A two-way ANOVA on the number of errors for each subject by voice emphasis (melody or nonmelody) and frequency range (high or low) indicated a significant main effect of voice emphasis, $F(1, 15) = 8.2$, $p < .05$, $MS_e = 3.4$, and a trend toward significance in effects of frequency range, $F(1, 15) = 3.4$, $p < .10$, $MS_e = 4.6$. There were fewer errors in the melody voice ($n = 44.5$) than in the nonmelody voice ($n = 76$), and there were fewer errors in the high-frequency voice ($n = 45$) than in the low-frequency voice ($n = 76$). There was no interaction between the variables, which suggests that both melody advantage and highest frequency (Voice 1) advantage contribute to the likelihood of errors, with events in relatively important voices and highest frequency locations less prone to error.

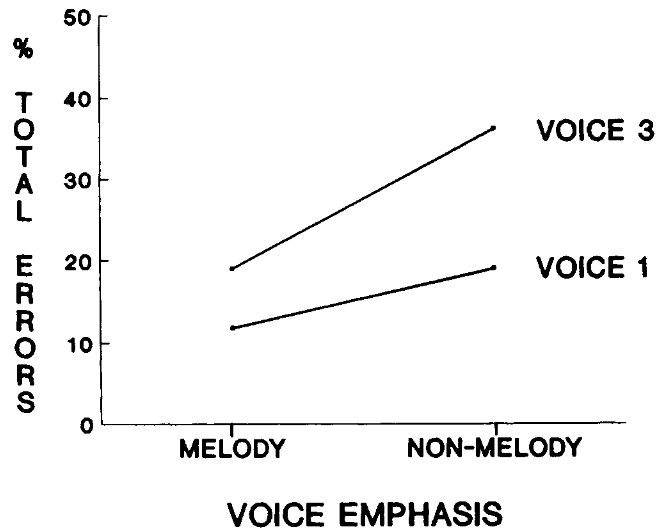

Figure 6. Experiment 1: Error percentages by voice emphasis (melody/nonmelody) and frequency range (Voice 1/Voice 3).

Melody-to-articulator mapping. We examined a collection of Western tonal piano music to test the possibility that the high-frequency advantage reflects some kind of articulatory advantage of hand or finger movements, by measuring how often the melody occurred in the high-frequency voice and how often it was controlled by the outer right-hand fingers. In multivoiced piano music, the melody can appear in any voice or frequency range and can be controlled by fingers on either hand. A skilled musician, experienced on viola and piano, who was unfamiliar with the goals of the experiment, analyzed a selection of 142 pieces from 19th- and early 20th-century piano repertoire. For each piece, the musician identified the melody and the hand and finger assignments controlling it. The melody was in the highest frequency range and was controlled by the right hand in 91% of the pieces. Of the 111 pieces containing two voices in the right hand, the melody was in the highest frequency range controlled by the outer right-hand fingers (Digits 3, 4, and 5) in 90% of the cases.

This analysis suggests that the mapping of melody to the high-frequency range controlled by the outer right-hand finger movements is highly consistent in Western tonal piano repertoire and may account for the lower error rates associated with movements controlled by those articulators.

Discussion

Pitch errors in piano performances demonstrated effects of compositional structure on the units planned in music performance. The size and contents of pitch errors differed across musical compositions: Although single-note errors were most prevalent in all performances, chord errors were more common in homophonic performances, and note errors in polyphonic performances. In addition, compositional structure affected similarity relationships among elements; target–intruder elements shared harmonic (chordal) content more often in homophonic performances (emphasizing across-voice associations) than in polyphonic performances (emphasizing within-voice associations). Finally, target–intruder elements shared diatonic (key) content more often than chance in both compositional structures. These findings implicate the same representational levels of melody, harmony, and tonality as posited for music perception, on the basis of note, chord, and key units, respectively. However, the production errors further indicate that different emphasis is given to each level, in accordance with the performer's conception of the compositional structure and the associations formed among musical voices.

Melodic importance and frequency range also influenced the contents of pitch errors, with the fewest errors occurring in the melody and in the highest frequency voice. The latter effect may be due to a well-learned mapping between melody and articulators (hand and finger movements) in Western tonal piano music; because the melody typically receives the most emphasis, performers may learn to control melodic-based movements better than other movements. However, the hand controlling the melody in these stimuli did not control any other voices, whereas the alternate hand controlled multiple voices. Thus, the melody advantage may actually be due to an articulatory advantage of fewer demands on the hand controlling the melody. Also, the choice of melody (and interpretation of relative importance) was uncontrolled in this experiment. The pianists may have interpreted the highest frequency voice as melody, regardless of the melody implied by the compositions. If so, the highest frequency advantage may actually be due to a conceptual (melodic) interpretation rather than to a well-learned articulatory effect. The next experiment addresses these potential confoundings.

Experiment 2: Influences of Melodic Emphasis

We examined the conceptual and articulatory effects on melodic emphasis by asking pianists to perform the same musical pieces according to different melodic interpretations. Performers of Western tonal music can often choose among multiple interpretations of the same musical elements, such as which voice is the melody or most important voice. If conceptualizations of melody enhance the subsequent retrieval, organization, and execution of those musical events in performance, then the number of errors should be lowest for the voice interpreted as melody (regardless of which voice that might be). In addition, we further investigated the articulatory effects on melodic emphasis by choosing pieces that contained multiple melodies located across the frequency range (controlled by different hand and finger movements).

This study was also designed to control for the potentially confounding variables of hand assignment and melodic voice. To control for hand assignments, we chose polyphonic pieces, half containing two melodies controlled by the same hand, and half containing two melodies controlled by different hands. Thus, the melody advantage, if obtained for all stimuli, could be attributed to a conceptual advantage rather than to a hand assignment advantage. Also, each pianist was instructed to conceive of a particular voice as melody in each performance, allowing us to determine whether the high-frequency advantage is actually attributable to a conceptual interpretation of melody. Because the polyphonic stimuli used in this experiment were longer than those in the previous experiment and the task of changing interpretations was demanding, pianists performed from the musical notation (rather than from memory).

Method

Subjects. Sixteen pianists (aged 21–59 years), from the Columbus, Ohio, community participated in the experiment. The pianists had a mean of 18 years (range = 14–30 years) of private instruction and a mean of 27 years (range = 15–55 years) of experience on piano. Seven of the pianists participated in Experiment 1. All of the pianists reported that they were comfortable with sight-reading and with performing various melodic interpretations.

Materials. The stimuli were chosen from the opening sections (the first three or four measures) of four three-part inventions by J. S. Bach (E-minor, A-major, D-minor, and F-major). Two of the four excerpts (E-minor and A-major) are shown in Figure 7. These four excerpts were chosen because they contain the entrance of three musical voices and allow at least two different interpretations of melodic emphasis.

Apparatus. Pianists performed on a computer-monitored Boesendorfer SE imperial concert grand piano. Optical sensors and solenoids in the piano allowed precise recording and playback without affecting the touch or sound of the acoustic instrument. The timing resolution was 1.25 ms for note events, with precision (represented by the standard deviation of onset-to-onset durations during recording) within 0.3% for durations in the range of the performances. All note events were recorded on computer, which detected all incorrect pitch events according to the ideal values in the musical notation.

Procedure. The following procedure was repeated for each of the four excerpts: Pianists practiced an excerpt until they were satisfied with their performance, and then five performances were recorded. The five performances provided a measure of how well the pianists had learned the excerpt. Next, the pianists were asked to perform the excerpt five times, emphasizing a particular voice as melody (in Figure 7, either the upper or middle voice). Then they were asked to perform the excerpt five more times, emphasizing an alternative voice as melody. These melodic interpretations formed the test trials, which were analyzed for errors. Pia-

Figure 7. Experiment 2: Examples of melody-interpretation stimuli. Three-Part Invention in [*top*] E-Minor and [*bottom*] A-Major by J. S. Bach. (Brackets indicate implied polyphony passage in A-major stimulus; vertical lines indicate sections of stimuli containing the two alternative melodies.)

nists were encouraged not to stop during a performance if they made mistakes. Finally, pianists were asked to indicate (a) their fingering assignments for the excerpt and (b) whether they were previously familiar with the excerpt.

All pianists performed the four excerpts in the same random order. Order of melody instruction was nested within excerpt, and a Latin square design determined the order in which the voices were presented as instructed melody across excerpts. The experiment lasted approximately 1.5 hr, and pianists were paid $8 for their participation.

Results

Only the section of each stimulus excerpt that contained the two instructed melodies was coded and analyzed for pitch errors (in Figure 7, the last two measures). Errors occurring in the same location in four or more of the five initial performances and in the test trials, as well as errors in adjacent locations and interrupted errors, were excluded from the analyses either because they could reflect learning problems or because they could not be coded unambiguously. This resulted in a total of 601 included errors. Of the 16×4 subject-stimulus combinations, in only 7 cases were the subjects familiar with the excerpts (they had performed it an average of 10 years previously). The errors of these subjects did not reveal any differences, and the analyses were conducted on all errors.

A two-way ANOVA conducted on the number of errors for each subject by stimulus excerpt (4) and by melody–instruction order within stimulus (first or second) indicated a significant main effect of both variables; errors were more common in some of the excerpts than in others, $F(3, 45) = 7.3$, $p < .05$, $MS_e = 33.6$, and in earlier rather than in later melody instruction performances, $F(1, 15) = 7.1$, $p < .05$, $MS_e = 10.0$; there was no interaction between the variables. Post hoc comparisons on the mean number of errors in each stimulus excerpt revealed significantly more errors for the A-major excerpt (shown in Figure 7) than for the others ($p < .05$); the total number of events was larger in this piece than in the others, which provided more opportunities for errors. The correlation between the number of errors in each performance and the mean rate at which it was performed (measured by the average quarter note duration) was not significant ($r = -.45$ to $-.13$, $p > .05$), which indicated that the number of errors was not simply a function of individual speed. Errors were again examined in terms of their size, source (target–intruder relations), and voice influences.

Unit size. Errors were first examined as a function of size. All but one error (99%) involved one unit size (notes) rather than a mixture (note/chord). Thus, the within-voice associations of polyphonic music led to errors involving single-note units, as in Experiment 1.

Target–intruder relations. Target–intruder relations were first examined in contextual errors. Of the total errors 38% were contextual, the most common of which were shifts (45%) and additions (32%). Of the movement errors (substitutions, additions, and shifts, which composed 90% of the contextual errors), backward (late) movement was most frequent (69%), forward (early) movement was the next most frequent (30%), and bidirectional movement (exchanges) was the least frequent (1%). There were fewer contextual errors than in Experiment 1; however, there were also fewer opportunities for contextual deletions in these stimuli (because they contained fewer repeating pitches). The percentages of contextual errors as recalculated without contextual deletions, were 47% for Experiment 1 and 36% for Experiment 2.

Noncontextual errors were first examined for harmonic similarity between targets and intruders. The percentage of harmonically similar errors in this experiment is shown in Figure 5. Only 24 of 89 noncontextual intruders (27%) were of the same harmonic content as the target (compared with the 3:12 chance estimate, sign test by subject, $p > .05$). Targets and intruders did not tend to be harmonically similar, analogous to the findings for polyphonic performances in Experiment 1. The lower percentage of harmonically similar errors in this experiment suggests a possible influence of the task context; in Experiment 1, homophonic and polyphonic trials were mixed, whereas all trials in this experiment were polyphonic. Contextual errors in this experiment also tended to be harmonically dissimilar.

Diatonic similarity in noncontextual errors was tested by examining the number of intruders from the same diatonic key as the targets. Of the 122 intruders, 99 (81%) were from the same diatonic key; this proportion was compared with the chance estimate of 7:12 (sign test by subject, $p <$

.05), indicating that the diatonic key context again influenced the pitch values of noncontextual intruders.

Voice influences. Voice influences were first examined in error rates as a function of melodic emphasis. A two-way ANOVA on the number of errors for each subject by voice emphasis (instructed melody, alternate melody, and nonmelody) and by stimulus excerpt (1, 2, 3, and 4) indicated a significant effect of voice emphasis, $F(2, 30) = 8.3$, $p < .01$, $MS_e = 4.1$. Errors were least common in the melody (n = 122; 20% of all errors) and most common in the alternate melody (n = 303; 50%). There was also a main effect of stimulus excerpt, $F(3, 45) = 7.3$, $p < .01$, $MS_e = 5.6$, with more errors in Piece 2 (the A-major excerpt; n = 268) than in the other excerpts; there was no interaction of excerpt with voice emphasis.

The errors were next examined in terms of frequency range and hand assignments. In half of the excerpts, the two melodies were controlled by the same hand, and in the other half they were controlled by different hands (verified by performers' notated hand and fingering assignments). Figure 8 shows the error percentages for each excerpt as a function of voice emphasis, frequency range, and hand assignments. A three-way ANOVA on the number of errors for each subject by voice emphasis (instructed or alternate melody), frequency range (high or low), and hand assignment (melodies controlled by same or different hands) indicated a significant main effect of voice emphasis, $F(1, 15) = 13.8$, $p < .01$, $MS_e = 4.7$, and of frequency range, $F(1, 15) = 14.2$, $p < .01$, $MS_e = 5.3$. There were fewer errors in the instructed melody (n = 122) and in the highest frequency range (Voice 1; n = 114.5) than there were in the other voice. There was also a significant main effect of hand assignment, $F(1, 15) = 6.9$, $p < .05$, $MS_e = 8.7$, and a significant interaction of hand assignment with frequency range, $F(1, 15) = 14.8$, $p < .01$, $MS_e = 3.4$.

Both the main effect of hand assignment and the interaction with frequency range were primarily due to the larger number of errors in the low-frequency melody (Voice 2) controlled by the left hand in a particular section of Piece 2 (marked in Figure 7 with brackets). This section of Piece 2 contains an implied polyphony: a compositional technique of creating two lines in a single voice by using large frequency intervals between subsequent note events. The rapid succession of large frequency intervals often creates an auditory streaming effect, which results in the perception of two separate voices (cf. Bregman, 1990). If performers interpreted this section as containing two separate lines within Voice 2, then the error rates in Voice 2 should

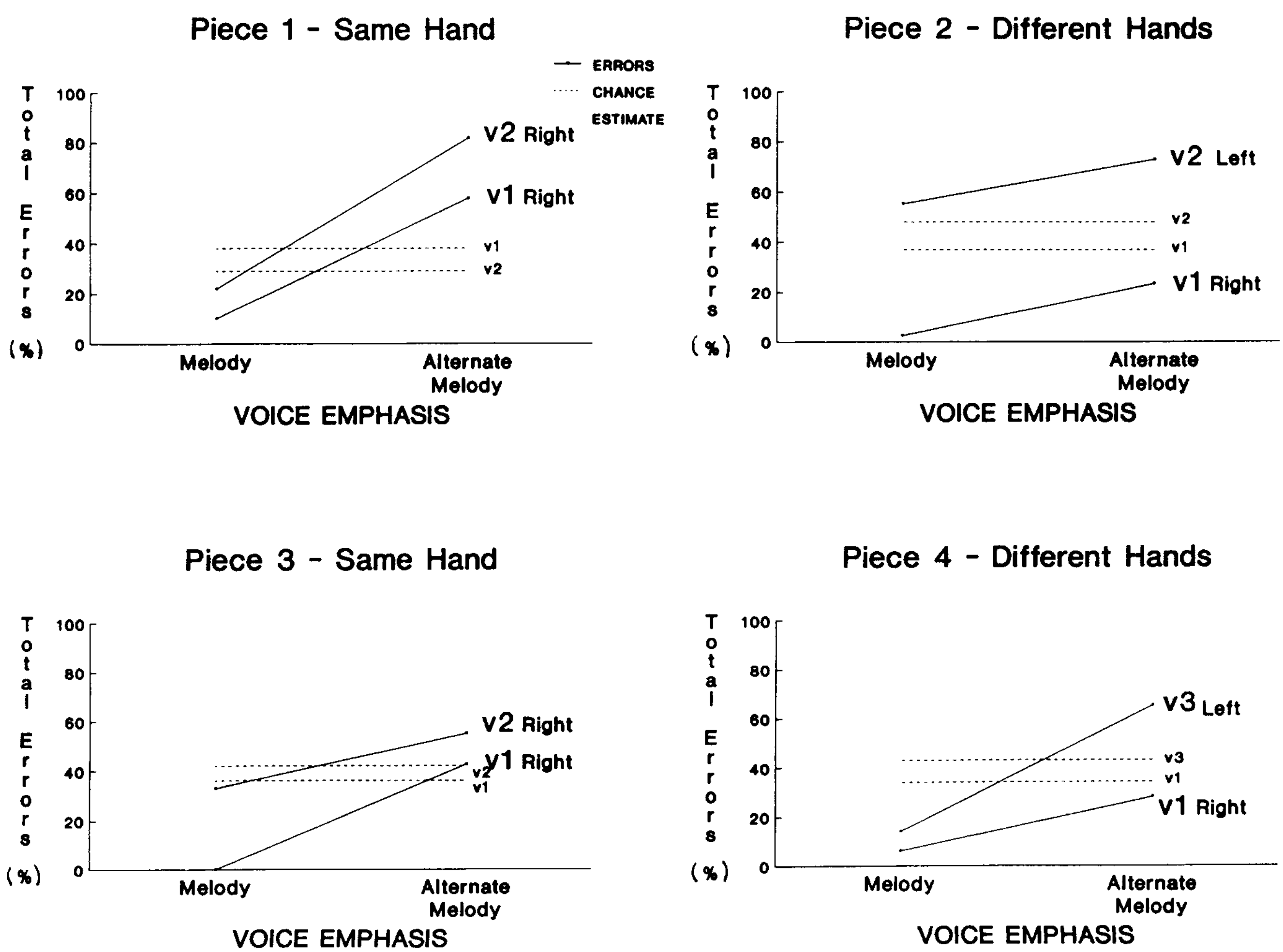

Figure 8. Experiment 2: Error percentages for each stimulus piece by voice emphasis, frequency range, and hand assignments.

increase in this section relative to other sections of the same voice (without implied polyphony), because of an interpretation of more parts of the voice as nonmelody. The errors were reanalyzed without the implied polyphony section to test whether this interpretation accounted for the interaction of hand assignment with frequency range. The same three-way ANOVA on the number of errors for each subject by voice emphasis, frequency range, and hand assignment without the implied polyphony section indicated significant effects of voice emphasis, $F(1, 15) = 15.1$, $p < .01$, $MS_e = 3.8$, and frequency range, $F(1, 15) = 8.5$, $p < .02$, $MS_e = 3.6$, with fewer errors in the instructed melody ($n = 86$; 18%) and the highest frequency voice ($n = 108.5$; 22%). There was no effect of hand assignment or interaction with frequency range, which suggests that the previous effects were indeed due to the implied polyphony section in Piece 2. Thus, the results indicate that in the absence of implied polyphony, the high-frequency voice advantage was not influenced by the number of melodies controlled by a hand.

The chance estimates shown in Figure 8 (dashed lines) reflect the number of errors predicted to occur in each voice (on the basis of the percentage of events in each voice within an excerpt and the overall error rate for each excerpt). The dashed lines indicate that errors were less likely to occur by chance in one voice than in another. We compared the observed and expected numbers of errors among voices within each excerpt to determine whether the frequency range effects differed from the chance estimates. A Wilcoxon matched-pairs signed ranks test on the observed difference in number of errors between the two voices and the predicted difference, which was based on chance estimates, indicated a significantly larger observed difference for each excerpt ($p < .05$), except Piece 3. As shown in Figure 8, errors were significantly less likely to occur in the high-frequency voice (Voice 1), relative to chance estimates.

Discussion

Pianists' different melodic interpretations of the same music suggest that conceptualizations of melody influence the planning of musical elements in performance. Melodic elements were less prone to error, regardless of which voice (and which frequency range) was interpreted as melody. The highest frequency voice was also less prone to error, regardless of whether it was the melody. Because half of the musical stimuli contained the two melodic voices in the same hand and the other half in different hands, the melody advantage can be attributed to the performers' conceptions of relative importance rather than to an articulatory advantage for the melody. Also, pianists were instructed to conceive of a particular voice as melody in each performance, which allowed us to rule out the possibility that the high-frequency advantage was attributable to an interpretation of the highest frequency voice as melody. A tendency toward right-hand dominance would not explain the high-frequency advantage either; because the findings were unaffected by the presence or absence of other melodies in the right hand. Thus, the lower error rate in the high-frequency voice suggests an articulatory advantage for the outer right-hand fingers that cannot be accounted for by hand assignments alone and that appears to be independent of conceptual processes of melody interpretation.

The compositional influences found in Experiment 1, in which musical pieces were performed from memory, were replicated in this sight-reading task. Consistent with the finding that polyphonic compositions emphasize within-voice more than across-voice associations, errors in this experiment tended to contain single-note events, and target–intruder harmonic similarity was low. Finally, targets and intruders tended to be diatonically related (from the same key) in both experiments, as expected for these stimulus pieces that display the key relationships typical of Western tonal music.

General Discussion

We investigated the units of knowledge underlying music performance by examining the size and contents of production errors. Pitch errors made by skilled pianists implicated different types of units (notes, chords, and keys). Contrary to a strict perceptual hypothesis that individual notes always form the primary level of units, the likelihood of each unit type in production errors changed in different musical contexts. In Experiment 1, multivoiced (chord) errors were more likely in performances of musical compositions emphasizing across-voice associations, and single-voice (note) errors were more likely for compositions emphasizing within-voice associations. Harmonic (same-chord) errors were more likely for compositions that emphasized across-voice associations, and diatonic (same-key) errors occurred more often than chance in both types of compositions. Thus, the competing plans that formed production errors reflected multiple levels of musical structure, with different units at each level. Performers' conceptual interpretations influenced the contents of errors as well, with events interpreted as melody less likely to be in error in both experiments. Because music performance communicates composers' and performers' conceptions of musical structure, it is appropriate that both compositional style and performers' interpretations affected the relative importance of musical elements and their likelihood of error.

These findings suggest that retrieval processes during music performance may reflect the same relationships among levels of musical structure as do encoding processes during perception. For example, the different error sizes and sources of influence support the assumption that performance plans are constructed from multidimensional relationships among melodic, harmonic, and diatonic elements. Perceptual models of musical pitch also posit interrelations among melodic, harmonic, and diatonic dimensions, such as how closely related elements are on the circle of fifths or whether elements share the same diatonic key (Bharucha, 1987; Gjerdingen, 1989; Krumhansl & Kessler, 1982; Longuet-Higgins, 1978). The harmonic and diatonic relations found among error targets and intruders also fit well with proposals of how memory associations are formed among musical elements. Discrimination and recall tasks indicate that musical keys are strongly associated with their component chords, and musical chords with their component tones, such that diatonically and harmonically related elements are more often confused with each other than with unrelated elements (Cuddy, Cohen, & Miller, 1979; Krumhansl, 1990). These perceptual findings suggest that a chord's component tones are likely to be confused (and subsequently replaced) with diatonically and harmonically related tones, as reported in these production errors.

Articulatory processes also influenced performance planning, resulting in a reduced likelihood of error in the highest frequency voice controlled by outer right-hand fingers. Furthermore, this articulatory advantage appeared to be independent of conceptual processes of melody interpretation; the highest frequency voice was less prone to error, regardless of whether it was interpreted as melody. The highest frequency advantage persisted in the presence of additional voices controlled by the right hand, ruling out a simple explanation that is based on right-hand dominance. Our analysis of Western tonal piano music suggests that the high-frequency voice advantage may arise from a consistent, well-learned mapping of the melody to outer right-hand finger movements in keyboard performance. This melody placement may be correlated with a compositional bias toward placing the melody in the frequency range of the human voice (on keyboard instruments, the range typically controlled by the right-hand fingers). In fact, the articulatory advantage may have a perceptual analogue; some findings suggest that listeners are especially sensitive to the voice in the highest frequency range in polyphonic music performances (Gregory, 1990; Huron, 1989).

Domain Specificity in Planning: Is Music Different?

How do these conceptual, retrieval-based, and articulatory influences in music performance compare with planning of skilled behavior in other domains? Perhaps the broadest generality is the availability of knowledge about events other than those currently being produced. This is most apparent in the prevalence of contextual errors in music, speech, typing, and other skilled behaviors (Garrett, 1975; Lashley, 1951; Shaffer, 1976); many errors are accounted for by contextual elements that move a short distance, presumably because those elements are concurrently being planned. Another generality across domains is the distinct category information reflected in production errors. Interacting items in errors tend to come from the same category: Single notes interacted with notes, and chords interacted with chords in 98% of all production errors reported here. Similarly, in language production, substitutions nearly always involve elements from the same structural category (Shattuck-Hufnagel, 1979); for example, word substitutions tend to involve targets and intruders from the same syntactic category (Fay & Cutler, 1977; Garrett, 1975). These speech error patterns are thought to reflect category information as part of the speaker's representation of lexical items. The music production errors suggest that performers' knowledge about note, chord, and key categories constrains the information available during planning. Category information may influence the retrieval of elements by strengthening associations among those that share category membership while discouraging associations (and subsequent confusion) between categories.

Two more specific analogies between music and language production are found in production biases: namely, output and similarity biases (Dell, 1986). An output bias is a tendency for errors at one structural level to create output containing meaningful or frequently occurring combinations of elements at another level (Baars, Motley, & MacKay, 1975; Dell, 1986). An output bias often found in speech is that sound errors almost always result in permissible (meaningful) phonemes in the speaker's language (Fromkin, 1971; Garrett, 1975; Wells, 1951). A similar output bias is suggested by the interacting elements in music production errors. Intruders in noncontextual pitch errors tend to create diatonically acceptable elements (those of the same key as the musical context). The diatonic bias resembles the speech error bias because both result in "permissible" elements in that domain. A similarity bias is the tendency for interacting elements in errors to be similar on some perceptual or conceptual dimension (Dell, 1986; Fromkin, 1971). Similarity biases in speech often occur in sound and word errors, where interacting items are likely to be related in sound or meaning (Dell & Reich, 1981; Fay & Cutler, 1977; Fromkin, 1971). A musical parallel is seen in the noncontextual pitch errors whose interacting items tend to be harmonically related. (The harmonic similarity effect is stricter than the speech bias effects because musical elements were judged here to be harmonically related only if they were of the same chord type, not just if they were of a related chord).

Output and similarity biases are important to theories of production because they reflect diverse sources of knowledge (often beyond the behavior being produced) that can influence a particular outcome. Spreading activation models of language account for these influences by feedback between activated lower level nodes (such as phonemes or letters) and higher level nodes (such as words) that share these elements. This feedback increases their associations and the likelihood that an intrusion will resemble the target or create another permissible element (Dell, 1986; McClelland & Rumelhart, 1981). Harmonic and diatonic similarity in music production errors might likewise be accounted for by feedback between levels; individual pitches may activate the correct chord or key, which then activates other (incorrect but associated) constituent pitches in that chord or key (as in Bharucha's, 1987, spreading activation model of tonal perception). Thus, harmonically and diatonically related pitch intruders would be more likely to occur than unrelated intruders, because of associations formed among notes, chords, and keys according to inclusion properties (the pitches comprising each chord and key). This account also fits with the prediction that discrimination errors tend to occur between nearby elements in a similarity-ordered perceptual space, made by geometric models of the psychological distance among musical elements (Krumhansl & Kessler, 1982; Lerdahl, 1988; Shepard, 1982).

There are important distinctions between music performance and language production that are problematic for both spreading activation and geometric models. First is the fact that musical units lack fixed meaning: For example, the diatonic and harmonic relatedness of musical elements are redefined for each context in which they appear. A second distinction is the role of melodic interpretation; performers' conceptions of melody determine each element's relative importance and subsequent likelihood of error. One explanation is that selective attending or monitoring for melodic errors in performance, which can then be corrected before execution, account for the melody advantage, similar to editor-based models proposed for language production (cf. Baars, Motley, & MacKay, 1975). However, an attentional explanation suggests that performers would be better at monitoring the melodic events in homophonic (one-melody) than in polyphonic (multiple-melody) performances; this prediction was not supported by the current findings. A more parsimonious explanation of the melody advantage is that conceptual prominence enhances the retrieval and organization of some events that are intended to be performed simultaneously over others. Melodic elements may be retrieved first, and then accompanying chordal elements retrieved together in homophonic compositions and separately (in order of decreasing importance) in polyphonic compositions. This ordering would account both for the melody advantage (items retrieved first may be less often confused with other items) and the enhanced likelihood of chord errors in homophonic performances (items retrieved together may be more likely to err together).

We began with the assumption that music performance reflects the communication of musical structure among composers, performers, and listeners. Production errors indicated different influences of conceptual (melody interpretation), compositional (across- and within-voice associations), and articulatory processes (hand and finger movements) in planning music performance. In addition, the size, harmonic dimension and diatonic dimension of production errors suggest that retrieval of musical elements from memory reflects multiple structural levels and units. These findings may not be unique to the domain of music; cognitive organizations with these properties may serve to ensure that retrieval matches encoding, which may make communication possible between performers and listeners.

References

Apel, W. (1972). *Harvard dictionary of music* (2nd ed.). Cambridge, MA: Harvard University Press.

Baars, B. J., Motley, M. T., & MacKay, D. G. (1975). Output editing for lexical status from artificially elicited slips of the tongue. *Journal of Verbal Learning and Verbal Behavior, 14,* 382–391.

Bharucha, J. J. (1987). Music cognition and perceptual facilitation: A connectionist framework. *Music Perception, 5,* 1–30.

Bharucha, J. J., & Stoeckig, K. (1986). Reaction time and musical expectancy: Priming of chords. *Journal of Experimental Psychology: Human Perception and Performance, 12,* 403–410.

Bregman, A. (1990). *Auditory scene analysis.* Cambridge, MA: MIT Press.

Clarke, E. F. (1985). Structure and expression in rhythmic performance. In P. Howell, I. Cross, and R. West (Eds.), *Musical structure and cognition* (pp. 209–236). San Diego, CA: Academic Press.

Cuddy, L. L., Cohen, A. J., & Miller, J. (1979). Melody recognition: The experimental application of musical rules. *Canadian Journal of Psychology, 33,* 148–157.

Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review, 93,* 283–321.

Dell, G. S., & Reich, P. A. (1981). Stages in sentence production: An analysis of speech error data. *Journal of Verbal Learning and Verbal Behavior, 20,* 611–629.

Ellis, A. W. (1980). Errors in speech and short-term memory: The effects of phonemic similarity and syllable position. *Journal of Verbal Learning and Verbal Behavior, 19,* 624–634.

Fay, D., & Cutler, A. (1977). Malapropisms and the structure of the mental lexicon. *Linguistic Inquiry, 8,* 505–520.

Fromkin, V. A. (1971). The nonanomalous nature of anomalous utterances. *Language, 47,* 27–52.

Fry, D. B. (1969). The linguistic evidence of speech errors. *Brno Studies in English, 8,* 69–74.

Gabrielsson, A. (1987). Once again: The theme from Mozart's Piano Sonata in A Major (K. 331). In A. Gabrielsson (Ed.), *Action and perception in rhythm and music* (pp. 81–104). Stockholm, Sweden: Royal Swedish Academy of Music.

Garrett, M. F. (1975). The analysis of sentence production. In G. H. Bower (Ed.), *The psychology of learning and motivation* (pp. 133–177). San Diego, CA: Academic Press.

Gentner, D. R., Larochelle, S., & Grudin, J. (1988). Lexical, sublexical, and peripheral effects in skilled typewriting. *Cognitive Psychology, 20,* 524–548.

Gjerdingen, R. O. (1989). Using connectionist models to explore complex musical patterns. *Computer Music Journal, 13,* 67–75.

Gregory, A. H. (1990). Listening to polyphonic music. *Psychology of Music, 18,* 163–170.

Huron, D. (1989). Voice denumerability in polyphonic music of homogeneous timbrese. *Music Perception, 6,* 361–382.

Krumhansl, C. L. (1990). *Cognitive foundations of musical pitch.* New York: Oxford University Press.

Krumhansl, C. L., & Kessler, E. J. (1982). Tracing the dynamic changes in perceived tonal organization in a spatial representation of musical keys. *Psychological Review, 89,* 334–368.

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–136). New York: Wiley.

Lerdahl, F. (1988). Tonal pitch space. *Music Perception, 5,* 315–350.

Levitt, A. G., & Healy, A. F. (1985). The roles of phoneme frequency, similarity, and availability in the experimental elicitation of speech errors. *Journal of Memory and Language, 24,* 717–733.

Longuet-Higgins, H. C. (1978). The perception of music. *Interdisciplinary Science Reviews, 3,* 148–156.

MacKay, D. G. (1982). The problems of flexibility, fluency, and speed–accuracy trade-off in skilled behavior. *Psychological Review, 89,* 483–506.

MacKenzie, C. L., & Van Eerd, D. L. (1990). Rhythmic precision in the performance of piano scales: Motor psychophysics and motor programming. In M. Jeannerod (Ed.), *Attention & performance XIII: Motor representation and control* (pp. 375–408). Hillsdale, NJ: Erlbaum.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review, 88,* 375–407.

Norman, D. A. (1981). Categorization of action slips. *Psychological Review, 88,* 1–15.

Palmer, C. (1989). Mapping musical thought to musical performance. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 331–346.

Palmer, C. (1992). The role of interpretive preferences in music performance. In M. R. Jones & S. Holleran (Eds.), *Cognitive*

bases of musical communication (pp. 249–262). Washington DC: American Psychological Association.
Repp, B. H. (1990). Patterns of expressive timing in performances of a Beethoven minuet by nineteen famous pianists. *Journal of the Acoustical Society of America, 88,* 622–641.
Shaffer, L. H. (1976). Intention and performance. *Psychological Review, 83,* 375–393.
Shaffer, L. H. (1978). Timing in the motor programming of typing. *Quarterly Journal of Experimental Psychology, 30,* 333–345.
Shaffer, L. H., & Todd, N. (1987). The interpretive component in musical performance. In A. Gabrielsson (Ed.), *Action and perception in rhythm and music* (pp. 139–152). Stockholm: Royal Swedish Academy of Music.
Shattuck-Hufnagel, S. (1979). Speech errors as evidence for a serial order mechanism in sentence production. In W. E. Cooper & E. C. T. Walker (Eds.), *Sentence processing: Psycholinguistic studies presented to Merrill Garrett.* Hillsdale, NJ: Erlbaum.
Shepard, R. N. (1982). Geometrical approximations to the structure of musical pitch. *Psychological Review, 89,* 305–333.
Sloboda, J. A. (1985). *The musical mind.* Oxford, England: Clarendon Press.
Stemberger, J. P. (1982). *The lexicon in a model of language production.* Unpublished doctoral dissertation, University of California, San Diego.
Wells, R. (1951). Predicting slips of the tongue. *Yale Scientific Magazine, 26 (3),* 9–30.

Received February 24, 1992
Revision received July 6, 1992
Accepted July 8, 1992 ■