Sequence Memory in Music Performance

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ABSTRACT—*How do people remember and produce complex sequences like music or speech? Music provides an example of excellent sequence memory under fast performance conditions; novices as well as skilled musicians can perform memorized music rapidly, without making mistakes. In addition, musical pitches repeat often within a melodic sequence in different orders, yet people do not confuse the sequential ordering; temporal properties of musical pitches aid sequence memory. I describe a contextual model of sequence memory that is sensitive to the rate at which musical sequences are produced and to individual differences among performers. Age and musical experience differentiate adults' and children's memory for musical sequences during performance. Performers' memory for the sequential structure of one melody transfers or generalizes to other melodies in terms of the sequence of pitch events, their temporal properties, and their movements. Motion-analysis techniques provide further views of the time course of the cognitive processes that make sequence memory for music so accurate.*

KEYWORDS—*sequence learning; memory retrieval; motor learning; music performance.*

Music is one of the most complex sequential behaviors that people produce. People of varying musical experience can hum tunes lasting several minutes, with little practice. How are they able to do this? Musical sequences contain pitch events that must be produced in a particular order; like speech, the meaning will change if the units (tones) are reordered. Yet musicians can produce long melodies from memory with few errors (Finney & Palmer, 2003). Musical sequences are complex on many dimensions: Musicians must remember the patterning of finger, hand, or foot movements, as well as the patterning of pitches and durations. The pitch sequence is important, but it is not the only important dimension. For example, the first five notes in "Mary Had a Little Lamb" and "The First Noel" are identical, yet most listeners do not confuse these two melodies. That is because the time between tone onsets (forming musical durations) differs between them. Thus, the timing of music is necessary for distinguishing musical sequences in memory.

Musical sequences can also be remembered in terms of how they are performed. For example, trombonists, clarinetists, and guitarists perform the same melody with different sequences of finger, arm, and hand movements. Which sequential aspects (pitch, motor, timing, etc.) are most important for performers? Are the sequence dimensions represented in memory independently? These questions are the focus of research on typing, handwriting, sports, and other sequential behaviors (cf. Schmidt & Lee, 1998); only music performance requires a hierarchy of prespecified times for when each sequence event must be produced (rhythms), and thus offers a good testing ground for understanding the time course of sequence memory.

MEMORY FOR MOTOR AND PITCH SEQUENCES

One approach is to examine how sequence memory transfers or generalizes from one performance to another. In an experiment using a transfer paradigm, pianists practiced one melody and then, as quickly as possible, performed a second melody that was the same as or different from the first melody in terms of either the motor sequence (the sequence of hand and finger movements) or the pitch sequence (e.g., A B C E). Comparisons of the amount of time the musicians took to perform the second melody relative to the first melody indicated both motor and auditory transfer of the melodic information (Palmer & Meyer, 2000). The more similar the two melodies were in the required hand and finger movements or in their pitch sequence (melodic-contour and interval information), the greater the transfer—that is, the faster they could perform the second melody. Most importantly, the two types of information had independent effects on the results. Novice child pianists were more dependent on motor information (hand and finger positions) than were skilled pianists; skilled pianists relied more on the sequence of pitches than on

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the sequence of motor movements (Palmer & Meyer, 2000). Thus, performers preserved pitch- and motor-sequence information independently, and the importance of the two sequence dimensions changed with age and experience.

Are motor sequences encoded as memory for when events should be produced? Motor-control research has focused on whether sequences of effector movements (limb movements) are encoded separately from timing information about the movements (Schmidt, 1975). For example, pianists may encode a musical sequence in terms of finger orderings, or in terms of the arrival times for each keypress. When the rhythmic sequence (patterning of keypress times) and the motor sequence (patterning of fingers to be used) were manipulated separately between two melodies that pianists performed in a transfer-of-learning task, the finger sequence transferred between melodies independently of the rhythmic sequence; the more similar the sequences were in their patterns of musical durations or finger movements, the more quickly pianists were able to perform the second melody (Meyer & Palmer, 2003). This research suggests that motor movements are not preserved in memory simply as a pattern of temporal information for when to move effectors, but instead as a sequence of finger orderings that is remembered independently of their timing. These findings extend what we know about effector-independent sequence representations from tasks like handwriting or typing to music performance, in which events must be performed not only in a certain order but also at precise times.

INDIVIDUAL DIFFERENCES IN SEQUENCE MEMORY

How do individual differences influence performers' sequence memory? Music performance is a skill in which individual abilities differ widely, compared with other skills like handwriting or talking. Highben and Palmer (2004) compared performers' memory for auditory information (the sequence of sounded pitches) with motor information (the sequence of finger movements) by removing auditory or motor feedback during performance. The feedback that pianists received during normal practice was replaced in the experiment with instructions to imagine the missing feedback: how the piece sounded or how the finger movements felt. After performers practiced with a musical score under reduced-feedback conditions, pianists performed from memory under normal-feedback conditions (i.e., with all feedback). Independent tests of auditory-imagery ability and motor-imagery ability were collected as well.

Performance from memory showed significant effects of removing motor or auditory feedback during practice; pianists' memory for the music, based on pitch errors, was worst when both types of feedback were unavailable during learning. There were important individual differences in how each type of feedback affected performance: Pianists who scored high on the aural-imagery test performed best from memory following the removal of auditory feedback during practice, compared with pianists who scored low. Musicians' aural-imagery skills were predictive of how much they relied on auditory feedback during learning to perform a novel melody. Removing motor-feedback did not differentiate pianists; all pianists scored high on motor-imagery skills. These findings confirm that an accurate auditory image is important for successful performance from memory (McPherson, 1997), and individual differences exist in the extent to which memory for musical sequences is encoded in motor movements and in auditory images (Highben & Palmer, 2004).

ROLE OF WORKING MEMORY

How much of a musical sequence is available in memory during performance? Despite anecdotal accounts such as that of Mozart's ability to remember an entire choral chant after one hearing, most psychological studies indicate that there are strict limits on the amount of sequence information available in memory during performance. Serial-ordering errors (sequence events that are produced in the wrong order, such as ABCD being reordered as A*DCB*) often tell us which sequence events are active in memory at a given time. For example, a speech error such as "He brought the *store*" instead of the intended "He brought the *book* to the *store*" indicates that "store" was available three words earlier than its intended sequence location. Drake and Palmer (2000) found that child and adult musicians' pitch-ordering errors tended to arise from sequence events within a range of 3 to 4 pitches, with older musicians' errors reflecting events farther away than younger musicians. One correlate of age that may account for these differences is working memory: a temporary store of information necessary for ongoing complex tasks. Palmer and Pfordresher's (2003) measures of pitch-ordering errors in music performance also spanned 3 to 4 events on average; in performances at faster tempi, the range was smaller, and at slower tempi, the range was larger. Furthermore, two pitches tended to be substituted for each other if they shared the same stress or metrical accent, analogous to similarity-based principles that affect speech errors and other memory lapses (Dell, Burger, & Svec, 1997).

Palmer and Pfordresher (2003) proposed a quantitative model of sequential-memory retrieval that predicts which sequence events musicians can remember during performance. The model's predictions are shown in Figure 1; the black bars indicate the model's predictions for how active or accessible each tone is at the time at which the performer is producing the circled tone. The model is based on two common memory processes: interference and decay. The graded descent in event strength indicates that nearby events are more accessible than events farther away from the tone currently being produced. The rate of decrease is related to tempo: the faster the performer plays, the less time available for retrieval and the steeper the graded descent. The model also predicts that the greater the performer's working-memory capacity, the less steep the graded descent in memory strength. The peaks within that graded descent, shown in Figure 1, indicate that

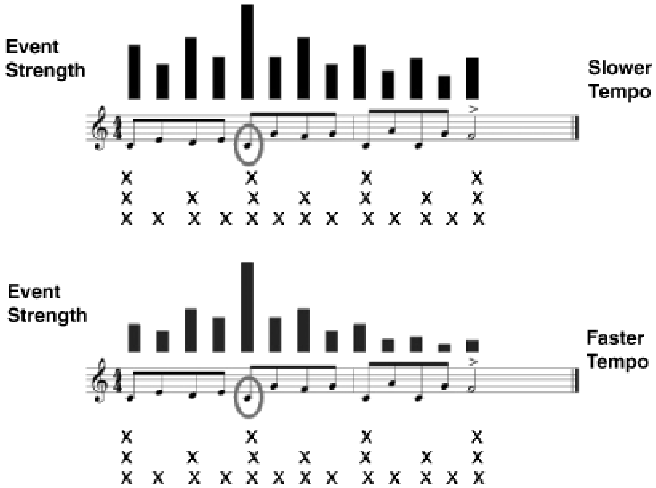

Fig. 1. Predictions of memory retrieval strength for past, present, and future sequence events during performance of a melody at two rates (slower tempo = 2 tones per second; faster tempo = 5 tones per second) by a performer with large working-memory capacity (high initial activation = .95). Bars indicate amount of memory strength for the different sequence events at the time at which the circled note is performed. *X*s indicate metrical accent strength (the more *X*s, the more accent). Based on Palmer & Pfordresher (2003).

events that are metrically similar to the current event are more strongly activated. The grid of *X*s depicts a hierarchy of metrical accent attributed to each musical event, based on music-theoretical depictions of Western tonal music. The more *X*s, the greater the accent. The current event—the circled tone in Figure 1—has strong metrical accent and is similar to other events with strong metrical accent, giving rise to the peaks or increased memory access. Thus, memory errors in this model arise from both decay and similarity-based interference.

The model's predictions were tested in pianists' performances of music at different rates. Pitch-ordering errors were more likely to arise from events nearby in the sequence, consistent with the model's predictions of a graded descent of activation. The faster performances showed a steeper graded descent than the slower performances did. Also, the more metrically similar two events were, the more likely they were to be confused in their sequential ordering (Palmer & Pfordresher, 2003). These findings support growing evidence that people's memory for sequence events is encoded in terms of contextual cues about the relationship between other sequence events. An important implication is that performers can access other sequence events that are related to whatever they are currently doing.

Does sequence memory during production change with experience or age? Studies of language development suggest that changes in speech abilities are accompanied by age-related changes in working-memory capacity (cf. Gathercole, 1999). Experiential influences on memory are notoriously difficult to tease apart from maturational effects, in music as in speech; however, the age at which performers begin to learn a musical instrument varies greatly (compared with the age at which people begin to learn a language), allowing us to separate, at least partially, the influences of experience and age. When musicians' sequential errors were examined in terms of the performers' age and performing experience, age and experience both predicted the children's and adults' performances, but age contributed above and beyond musical experience (Palmer & Pfordresher, 2003). Older pianists (ages 22–40) remembered tones that spanned greater sequential distances than those remembered by younger pianists (ages 9–16). Furthermore, independent measures of working memory predicted the span of adult performers' sequential errors (Palmer & Schendel, 2002). Working-memory influences on music performance appear to be driven in part by maturational factors, consistent with Gathercole's (1999) view of phonological development. An interesting prediction of this model is that age-related memory improvements should enable people to remember elements farther apart in a sequence.

ANTICIPATORY MOTION

One of the hallmarks of memory for action sequences is advance preparation of events prior to their execution. Anticipatory behaviors, the primary evidence for advance preparation, include ordering errors that reveal events intended for the future (such as the speech error "I *tr*acked the trunk" instead of the intended "I *p*acked the trunk") and movements that reveal trajectories toward future target locations. Anticipatory behavior increases with practice in many domains (Dell et al., 1997; Schmidt & Lee, 1998), including music performance (Drake & Palmer, 2000). The percentage of total pitch errors that were anticipatory (compared with perseveratory errors, or pitches that were intended for earlier in a sequence) increased with practice, as well as with musicians' age and experience (Drake & Palmer, 2000). Anticipatory behavior is related to the overall accuracy of performance; with more practice, people produce fewer errors and larger proportions of those errors are anticipatory. A positive relationship between overall level of performance and anticipatory behavior, first modeled in speech errors (Dell et al., 1997), was replicated in music (Palmer & Pfordresher, 2003), suggesting a domain-general relationship between practice and anticipatory behavior in sequence memory during production.

Sequential movements also display anticipatory behavior. For example, pianists tend to anticipate trajectories toward upcoming keypress locations in wrist and finger movements (Engel, Flanders & Soechting, 1997). Anticipatory motions are captured with optoelectronic systems, in which markers placed on joints are recorded with cameras. Pianists' finger movements display consistent changes in velocity and acceleration specific to certain sequence locations (Palmer & Dalla Bella, 2004). Each finger trajectory showed anticipatory motion upwards (above the key that was about to be pressed) 1 to 2 sequence events prior to pressing a particular key. However, each finger trajectory began to change up to 3 events before that finger struck a piano key; by

4 events prior, the velocity and acceleration trajectories were similar to the finger "at rest" (with no upcoming key to press; Dalla Bella & Palmer, 2004). If finger trajectories toward movement goals require some information about the arrival location prior to the execution of the movement, then it is not surprising that the anticipatory motion (1–3 events earlier) occurs within the timeframe of the memory retrieval (3–4 events earlier) described above.

FUTURE DIRECTIONS

Music performance provides an excellent example of finely timed cognitive processes that underlie sequential abilities, and current findings offer several promising areas of research in the cognitive bases of sequential skills. Motor-skills research in other domains focuses on whether hand and arm movements are remembered independently of their timing; one focus for future research will be to determine whether the motor and temporal dimensions of sequences such as handwriting and typing are combined independently. Another current direction in studies of motor control as well as of skill acquisition is whether individual differences in the weighting of motor and temporal dimensions of complex sequences such as language and music develop with experience, as reported here in music performance.

The relationship between memory and motor processes is already a focus of psychological science; current techniques in motion analysis allow us to address whether the time course of anticipatory motion follows that of memory retrieval, as described here in the context of music performance. In addition, memory research in language acquisition is beginning to focus on similar age- and experience-related individual differences in working memory to those seen in music performance. A focus on individual differences in motor and memory processes may reveal the cognitive capacities that serve as the signatures of skill development in a wide variety of sequential behaviors that humans produce so well.

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