Time Course of Retrieval and Movement Preparation in Music Performance

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ABSTRACT: Music performance requires that musicians represent many different kinds of sequence structure: musicians must remember which pitch to produce, when to produce it, and how to produce it (with what movements). The time course of item retrieval and movement preparation processes during music performance are considered. Serially ordered stage models of retrieval, in which item retrieval ends before movement preparation begins, are compared with interactive cascade models, in which the time course of both processes overlap, permitting interaction. Evidence from transfer of learning paradigms, production errors, and anticipatory movements, as measured in motion capture, are described. This early evidence suggests different time courses for item retrieval (slower, earlier) than for movement preparation (faster, later) with significant temporal overlap during music performance.

KEYWORDS: performance; motor planning; memory retrieval; stage models; cascade models

Most research on the brain functions that support music focuses on perception. Although live music performances are the stimulus for most music perception, our understanding of the neural mechanisms underlying music performance is just beginning. The research reported here addresses two lines of study on the time course of brain processes during music performance: one on memory retrieval, and one on movement preparation. Music performance requires that musicians represent many different kinds of sequence structure: musicians must remember which pitch to produce, when to produce it, and how to produce it (with what movements). Music contains pitches that repeat within a melody in different contexts; the mapping of musical pitches to the movements that produce them is not one-to-one. FIGURE 1 shows the pitch sequence of a simple melody and the right-hand finger sequence that a pianist might use to produce it. In this example, the pitch E is produced with finger 3 as well as with finger 1; likewise, finger 3 produces the pitch G as well as the pitch E. When one adds rhythmic and timbral complexity to the process, music performance becomes a complex sequencing task.[1] The objective of this paper is to discuss how memory retrieval functions and movement preparation combine in music performance.

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Pitch: C – ***E*** – D – ***E*** – F – ***E*** – A – G – F
Finger: 1 – ***3*** – 2 – ***3*** – 4 – 1 – 4 – ***3*** – 2

FIGURE 1. Sequencing demands of piano performance in pitch memory and finger movements: a piano melody with right hand fingering.

One important sequencing issue is the time course of memory retrieval and movement processes. Although musical events unfold in time, the brain processes that support them do not necessarily occur in the same order. Theoretical models of the time course of mental processes in such domains as object recognition, speech production, and word recognition have indicated several general classes of models. One possibility is that item retrieval and movement preparation are independent stages of processing and are serially ordered. Stage models assume that multiple processes are accessed in a serial manner, one after the other, and that processing at an early stage must be completed before a subsequent stage can begin, permitting no feedback from the later to the earlier stages.[2] A schematic for this class of model is shown in Figure 2a; process B (movement preparation) cannot affect process A (item retrieval) in this view, because B is serially ordered after A. In Sternberg's[3] original description of reaction times in psychological tasks that appear to be additive combinations of various factors, each factor reflects the operation of discrete stages; each processing stage must finish before the next begins. Stage models of production processes in speech propose that phonological (sound) processes associated with words cannot begin until the word to be spoken is done being selected from memory.[4,5] A stage model would predict that, as in Figure 2a, pitches are retrieved from memory before movement preparation can begin in music performance, and movement preparation cannot affect pitch retrieval.

Another possibility is that item retrieval and movement preparation are distinct processes that overlap temporally and thus offer the possibility for interaction. In this view, depicted in Figure 2b, process B (movement preparation) begins after process A (item retrieval), but overlaps in time with process A. As a result, some information from process B may affect process A. Cascade models of word recognition propose that multiple processes are activated at least partially in parallel, and later and earlier stages of processing can interact.[6,7] McClelland's[6] cascade model accounts for factor additivity in reaction times in terms of a series of N stages that operate at the same time (not sequentially), with the output of one stage serving as input to another stage. The cascade class of models allows that, as depicted in Figure 2b, movement preparation would overlap and allow interaction with item retrieval in music performance.

The distinction between serially ordered and cascade models is debated in speech production, with regard to how words are selected from memory and when phonological processes (including information that defines sound production) begin. One major view holds that speech production is strictly serial, with phonological encoding beginning only after a lexical item has been selected.[4,5,8] Latencies to name pictures support the temporal separation of lexical selection and phonological

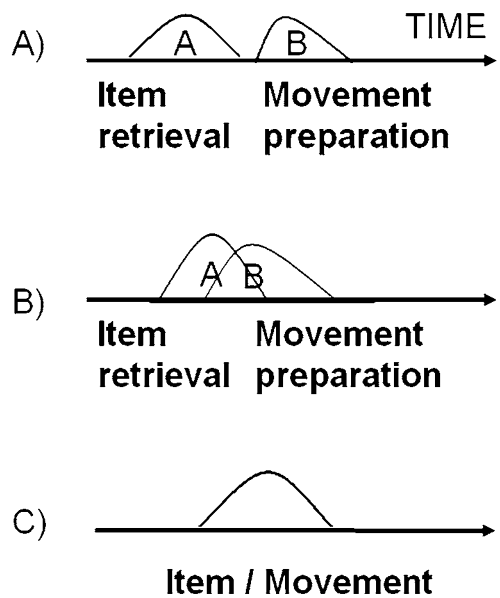

FIGURE 2. Time course of item retrieval and movement preparation. (**A**) Serial stage models; (**B**) cascade models; (**C**) single model.

processes. Another widely held view proposes that although phonological forms are activated after lexical nodes, activation from the lexical level can serve as input to the phonological level before lexical selection has taken place.[9–11] Speech production errors provide evidence that phonological similarity influences lexical retrieval, supporting temporally overlapping processes that interact.

A third possibility is that retrieval and execution are the same process. This single-process model, depicted in FIGURE 2c, might predict that the movements to be prepared are integrated with the items being retrieved. Evidence from transfer of learning studies suggests, however, that item retrieval and movement preparation are not integrated. Palmer and Meyer[12] showed that pianists who learn to perform a novel melody can generalize that knowledge to another novel melody independently for movement sequences and pitch sequences. Pianists performed a melody with one set of finger/hand movements. When asked to perform a second novel melody, their ability to perform was facilitated when either the finger sequence or the pitch sequence (or both) were the same as in the first novel melody. The degree of facilitation was independent for the movements and for the pitch items, inconsistent with an integrated process. Furthermore, child beginners showed less facilitation of the same finger movements across melodies than adults, indicating that the motor and pitch retrieval processes may progress at different learning rates.[12] Further studies indicated that movement dimensions and temporal dimensions (rhythm and meter) showed independent amounts of transfer from one novel melody to another in performance.[13] These studies suggest that movements and pitches are not retrieved in an integrated fashion.

This paper considers whether item retrieval and movement preparation in music performance can best be described by serially ordered stages or by cascaded processes. Is the time course of item retrieval and movement preparation sufficient to allow information from one process to influence the other? Item retrieval during music performance is considered in terms of when pitch information is available in memory, as evidenced in the occasional production errors that musicians make during well-learned performances. Palmer and Pfordresher's[14] model of memory retrieval during music performance describes specific predictions for the time course of retrieval. Then the time course of movement preparation is examined in terms of pianists' anticipatory finger movements, based on motion capture information. The final section returns to the classes of models that address how memory retrieval and movement preparation might combine to support sequencing in music performance.

TIME COURSE OF ITEM RETRIEVAL

Item retrieval during production is often examined in analyses of serial ordering errors: errors in which an event intended for elsewhere in the sequence is produced.[4] These errors are informative because they indicate what information from the sequence is available from memory at a given moment during production. Serial ordering errors are often caused by confusion among similar sequence events.[15,16] Serial ordering errors in speech and music reveal *distance*-based constraints on the accessibility of events during planning: an event is more or less accessible based on its separation (in number of events) from the current event.[14,17,18]

Palmer and Pfordresher[14] proposed a model of memory processes during sequence production, which predicts the time course of item retrieval during music performance. Events are considered accessible from memory, spanning from the current event being produced to nearby sequence events in the past and future, forming

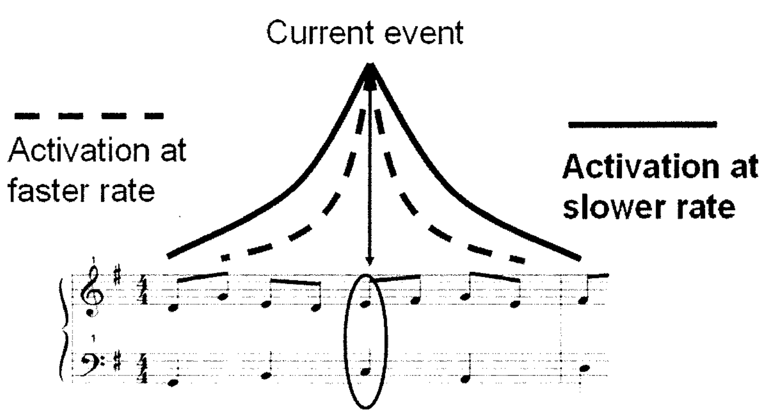

FIGURE 3. Range model predictions for temporal activation of pitch items during performance. (Based on Palmer & Pfordresher.[14])

a gradient of event activations across the sequence. Memory activations are determined in terms of the tempo at which the performance is produced and each event's distance from the current event produced. FIGURE 3 shows time-based predictions of the range model for item retrieval at the time the performer is producing the circled event in the melody; the gradient of activation above the score indicates how active sequence events are in memory during a slow tempo performance (the solid line) and a fast tempo performance (the dashed line). The range model predicts that items nearby in serial order will be more accessible during memory retrieval at slower tempi than at faster tempi; also, items that are metrically similar will be more accessible during retrieval.

Analyses of serial ordering errors in piano performances supported the model's predictions; pitch errors were more likely to arise from nearby sequence positions.[14] Most important, the gradient of activation was steeper for fast tempo performances than for slow tempo performances of the same music by the same performers; errors tended to reflect sequence events from a larger range at slow tempi (four events) than at fast tempi (three events), consistent with the model's predictions. This range of three to four events is consistent with models of working memory that posit an attentional constraint on elements that must be retained temporarily during ongoing tasks[19] (Cowan, 1998). The effects of production tempo on item retrieval suggested that pitches were available 400–700 ms prior to their production.

Further studies extended these findings to novice child performers, who showed a smaller serial range of planning than advanced child performers (three to four events).[20] The role of auditory feedback in performance also supports a memory retrieval constraint of three to four items. Altered feedback presented to pianists over headphones during a performance tended to disrupt a pianist's memory when that feedback corresponded to pitches within three events from the past or future; pianists tended to produce pitches that compensated for that feedback (i.e., when they heard an event from the past, they produced an event from the future, and vice versa).[21] Overall, these experiments suggest that items from three to four events around the current event are accessible in memory during performance, and that performance tempo stretches or shrinks that range.

TIME COURSE OF MOVEMENT PREPARATION

When is the next movement prepared in music performance? Do the same serial or temporal constraints apply as during item retrieval? Recordings of finger movements during piano performance, made with motion capture techniques, provide information to address the time course of movement preparation. Anticipatory movements can be measured in terms of how early fingers begin their trajectories toward keypresses. Using a Vicon motion capture system with passive reflective markers on pianists' fingers and the piano keyboard, Dalla Bella and Palmer[22] captured the finger motion of performances of melodies at different tempi. Fourteen cameras positioned around the pianist recorded light reflected from each 3 mm marker, placed on the joints of pianists' fingers and on the edge of the electronic piano keys. From memory, pianists performed simple melodies at different tempi that required little or no hand repositioning. The goal was to determine whether finger trajectories toward keypresses began at different times when the same performer played the same melody at fast or at slow tempi.

Analyses of the finger motion in the height plane (upwards from the piano keys) showed the most change in motion across the tempo conditions. Measures of variance in each finger's velocity and acceleration one, two, and three events prior to the finger's arrival on a key indicated that finger trajectories began to change one to three events prior to a keystroke. By four events prior, the finger motion was equivalent to that of other fingers that were not producing keystrokes (a control condition). Thus, the serial distance over which finger trajectories showed movement preparation was within that of the item retrieval (three to four events prior). The movement preparation was constrained by the tempo: finger accelerations changed in variance only one event prior (150 ms) to the keypress at the fastest tempi, and up to 3 events prior (500 ms) at the slower tempi.[23]

CONCLUSIONS

Evidence from production errors and motion capture in music performance indicated temporal overlap in the time course of item retrieval and movement preparation, with item retrieval (three to four events, 400–700 ms prior to an event) preceding movement preparation (one to three events, 150–500 ms prior). Although more evidence is necessary to address the roles of important performance factors, such as individual differences in working memory, performer expertise, and instrument differences, this early evidence is most consistent with the class of cascade models. At the least, the evidence argues against serially ordered processes in which movement preparation does not begin until item retrieval is complete.

Cascade models are popular in modeling many psychological tasks. Behavioral evidence consistent with cascade models suggests that stimulus identification does not need to be complete before response preparation can begin,[24,25] and that perceptual object identification is not completed before semantic representations can be formed.[26] Cascade models are also prominent in neurophysiological modeling,[27,28] based on evidence from single-cell studies that indicates significant temporal overlap of target-related spike activity at different neural sites.[29,30]

What are the advantages of a cascade model? One advantage may be to accommodate different timescales of neural processes. Item retrieval in word recognition, speech production, and music performance tasks is relatively slow (300 ms) compared with movement preparation (150 ms); reflexive muscle stiffening (30 ms) is even faster. If faster processes have to wait for slower processes to finish, as in stage models, then fast and accurate performance typified by music performance might not be possible. Cascade models also make it possible that more easily executed items may be more easily remembered, if information from process B informs process A.

Study of the time course of mental processes in music performance is in its infancy, in part because of the recent development of time-sensitive measurement techniques that do not disrupt performance. This early evidence suggests that item retrieval is an early, slow process, whereas movement preparation is later and faster. The time course of these processes suggests significant overlap. Further evidence is necessary to examine possible feedback among the cascaded processes. Interaction among processes may be evidenced in production errors and the movements that accompany them. When the wrong item is retrieved, how early does the finger producing that event alter its trajectory, compared with production of the correct event? Can incorrect trajectories be adjusted after item retrieval? Techniques, such as motion capture and imaging with musical instruments, make it possible to address memory retrieval and movement preparation in music performance, a domain in which brain processes are pushed to their temporal limits. Yet performers excel.

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