Chapter 3

The nature of memory for music performance skills

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Although most studies of memory for music performance focus on dimensions of musical structure, recent studies suggest that motor factors of performance are also represented. Brain imaging measures collected during mental practice or listening tasks suggest that both motor and auditory cortical areas are active during musical thought processes. Four types of behavioural study with performers reveal motor-based representations: performers' musical interpretations, transfer of learning from one musical task to another, mental practice effects, and anticipatory movements. These sources of evidence implicate distinct motor and non-motor (melodic) information in performers' memory for music. Implications from these behavioural tasks suggest that an accurate auditory and motor representation underlies successful performance from memory.

Introduction

Theories of memory often cite music performance as an example of expert memory, and many studies have examined the factors that influence performers' memory (for review see Palmer (1997) and Gabrielsson (1999)). Music performance can be depicted as a cognitive skill with large memory demands, or as a motor skill with large physical execution demands. Cognitive dimensions of performers' memory for music are often described in terms of musical structure, such as harmony, tonality, phrasing, and meter (Palmer 1997; Gabrielsson 1999; Palmer and Pfordresher 2003). Motor aspects of performance are measured in physical dimensions such as fluency, speed, rhythmic precision, and hand coordination (Krampe and Ericsson 1996; Drake and Palmer 2000). Musicians' memory that allows them to perform a specific musical piece, referred to as 'memory for performance', is distinguished here from other memories of performance (by oneself or someone else).

Music performance is of much interest to psychologists precisely because it is demanding both cognitively and in terms of motor skills. Memory for music entails sequences on the order of thousands of pitch events that are produced at rates as high as 8–12 events per second, with less than 3% error (Palmer and van de Sande 1993; Repp 1996; Finney and Palmer 2003). In addition to categorical pitch events, listeners (infants as well as adults) remember fine expressive nuances of performances, including timing, intensity, and articulation information that distinguish different performances of the same music (Palmer *et al.* 2001). A more accurate conceptualization of the problem of describing memory for performance may be: what are the underlying features of music performance that are represented in memory? Which features are described in motor coordinates? How do factors such as maturation, musical acculturation, and training influence the representation of those features?

This chapter addresses these questions in the domain of piano performance. Piano is one of the most-often chosen instruments of study by children in North American schools (Johnson 1994). Piano has consistently been among the most-often performed instrument by amateur musicians in American households (Gallup Poll 1994, 2000) and piano performance is one of the most easily measured instruments with the advent of MIDI (music instrument digital interface). Thus, research in performance is based largely on measures of pianists' behaviours. Despite the rapid growth of research into piano performance during the past 20 years, less attention has been paid to the motor aspects of memory for performance (such as finger and hand movements) than to auditory (intensity, duration, etc.) or structural aspects (phrase structure, rhythm, etc.).

Motor representations of piano performance

The motor demands of piano performance are quite large, especially in terms of finger movements. One of the few models to attempt to capture aspects of motor difficulty is an ergonomic model of fingering in piano performance (Parncutt *et al.* 1997). This model, based on a series of rules, reflects specific ergonomic difficulties such as weak versus strong fingers and spans between finger pairs. Measures of the pianists' fingering consistency and performance accuracy for musical exercises correlated negatively with the model's predictions of fingering difficulty (Sloboda *et al.* 1998). The model compared favourably with performances that used the least difficult fingers; however, the model sometimes made predictions for simpler fingerings that were not preferred by the pianists.

Imagery techniques applied to brain organization also support motor and non-motor features of performers' memory for music. Pantev *et al.* (2001) found enlarged representations of the auditory and somatosensory cortex with musical practice. The somatosensory cortex showed neuronal changes specific to fingers used during practice. Pascual-Leone and colleagues (reviewed in Pascual-Leone

1995) found changes in cortical motor areas as non-pianists practised finger exercises; physical practice as well as a combination of mental and physical practice established those changes. With magnetoencephalograph (MEG) techniques, Haueisen and Knösche (2001) reported that pianists displayed motor activity in the contralateral primary motor cortex while listening to familiar music (music they had performed). In addition, functional magnetic resonance imaging (fMRI) measures in skilled violinists demonstrated activity in primary auditory regions while the violinists silently tapped the opening section of a violin concerto; the amateur violinists' fMRI results did not indicate auditory stimulation (Lotze *et al.* 2003). To address whether co-activation in auditory and motor cortical areas arises from years of joint auditory–motor practice or over shorter time spans, Bangert and Altenmüller (2003) used direct current electroencephalography (DC-EEG) with non-musicians who were trained to associate a purely auditory (passive listening) task with a purely motor (silent finger movement) task. One group had consistent mappings of auditory events to motor events, while another group learned with altered mappings. Only the consistent mapping group exhibited additional EEG activity in right anterior regions, which the authors took to indicate an audiomotor interface that developed in the first weeks of practice. Of interest is how far the behavioural changes following pairings of motor and auditory activity extend both in time and across tasks.

Interpretive influences on performance memory

The occasional errors that performers make (hitting the wrong key or chord) often display active memories for other to-be-performed events. For example, pitch errors tend to reflect tones intended for elsewhere in the same piece (Palmer and van de Sande 1993). Such performance errors also indicate motor features. Palmer and van de Sande (1993) documented pianists' errors in two-handed piano music; left-handed errors were more common than right-handed errors (regardless of the pianists' handedness), consistent with Peters (1985) findings of greater right-hand coordination skills among pianists. Harmonically related errors (a substituted pitch that arises from the same chord as the intended pitch) were more common than harmonically unrelated errors, even when their production required different hand or finger movements (Palmer and van de Sande 1993). Likewise, hand differences in errors occurred for both harmonically related and harmonically unrelated errors.

Do motor factors interact with non-motor features of memory for performance? Palmer and van de Sande (1993) asked pianists to perform the same music with different melodic interpretations. The melody or primary (most important) voice is not directly marked in musical notation, and performers often interpret the voice intended as melody as more important (Palmer 1989). The voice interpreted as melody was less likely to contain errors, even when pianists changed their melodic interpretation for the same musical piece. Performers also made more errors in parts controlled by the left hand, regardless of hand dominance. Motor factors (hands and fingers used) did not interact with interpretive factors (melody being emphasized) in the likelihood of errors in the pianists' performance, suggesting that interpretive and motor factors are represented independently in memory for performance (Palmer and van de Sande 1993).

Transfer of performance skills

Another source of evidence for motor dimensions of memory for performance is the conditions under which performers generalize what they know from one performance situation to another. In typical transfer of learning tasks, participants learn one task and then perform a second task. The ease with which they perform the second task is thought to reflect what was learned in the first task. The mirror symmetry of hand and finger movements in piano performance provides a convenient format in which to test transfer of motor learning. Consider the sequence of finger movements 5–4–3–2–1 in the right hand (where thumb is 1), used to press adjacent keys on a piano; this sequence becomes 1–2–3–4–5 when the same keys are pressed by the left hand. Thus, the same melody can be played with different hand and finger movements in piano performance. In addition, different melodies (different pitch sequences) can be performed with the same hand and finger movements. Although the transfer of musical skills to math, spatial reasoning, and other tests of intelligence has been studied (Rauscher *et al.* 1995; Schellenberg 2004), fewer studies have examined the transfer of learning from one musical task to another musical task. Are well-learned motor movements transferred from one melody to another? Palmer and Meyer (2000) measured the transfer of pianists' hand and finger movements from one practised melody to a novel melody. When the second (novel) melody required the same finger movements as the initial melody performed, pianists were able to play it more quickly. Comparisons across age and skill levels indicated that the more advanced performers showed the greatest transfer across motor movements, suggesting that they were able to generalize from one hand and finger set to another. The least skilled pianists showed no ability to generalize beyond the particular finger sequence learned.

Does knowledge of a set of motor movements transfer across temporally distinct patterns in music performance? For example, can a pianist performing one rhythmic pattern with a set of finger movements such as 1–2–3–4–5 generalize those same finger movements to produce a different rhythmic pattern as fluently as the first pattern? Using a similar transfer of learning task, Meyer and Palmer (2003) showed that pianists' finger movements did transfer across different rhythmic patterns: pianists could perform novel rhythms with the same finger movements as quickly as the first-learned rhythms. In addition, there was rhythmic transfer: pianists could perform well-learned rhythms with different hand and finger movements as quickly as with the first-learned movements. There was no interaction between rhythmic transfer and motor transfer; the times at which keys were pressed were remembered independently of the motor features that produced them. Similar findings were obtained when pianists transferred from one melody to another that differed in meter and motor movements. No interactions were observed among the temporal (meter and rhythm) and motor structures: retaining temporal structure from one melody to the next facilitated speeded performance more than retaining motor movements, and motor features played a smaller role in the transfer of knowledge across melodies. These findings are consistent with the general view that representations of timing in sequence production are not defined primarily in terms of motor features (MacKay 1982, 1987; Semjen and Ivry 2001), at least for performers with moderate to high levels of musical experience.

Mental and physical practice

Practice may be the single most important factor that influences memory for performance. Musicians' verbal reports of practice goals incorporate many levels of analysis, including structure, interpretation, and motor aspects of technique (Chaffin *et al.* 2003). Several studies suggest that deliberate rehearsal accounts for skill differences among music performers (Ericsson *et al.* 1993; Sloboda *et al.* 1996). More recently, comparisons have been made of the efficacy of physical practice with mental practice. When musicians practice the motor movements for performance in the absence of their physical instrument, they often make other overt movements such as drumming fingers on a tabletop or tapping feet under the table, suggesting that the motor features of performance are important for practice. If mental practice has effects on performance similar to those of physical practice, is it due to motor or non-motor components of mental practice? Are the thought processes underlying mental practice similar to those underlying physical practice?

Mental practice has been defined as the mental rehearsal of a specific task in the absence of actual physical movement (Coffman 1990; Driskell *et al.* 1994). Mental practice is distinguished from other mental techniques such as analytical study, general mental imagery, imitation, or self-arousal. Measurement of the effects of mental practice typically includes improvement in accuracy or time to complete a task relative to some control task (such as no practice or normal practice). Meta-analyses of mental practice effects (Feltz and Landers 1983; Driskell *et al.* 1994) indicate two consistent findings. First, normal (physical) practice exceeds mental practice alone, which exceeds no practice (Coffman 1990). Second, physical practice plus mental practice instructions exceed physical practice alone (Rubin-Rabson 1937; Ross 1985). These findings suggest that improvement with practice in general is due to two components: a physical (motor) component and a mental (non-motor) component. The meta-studies interpret differences among mental practice findings as indicating that tasks with greater cognitive requirements (memory, attention, symbol manipulation) show greater effects of mental practice than tasks with high-motor requirements (coordination, endurance, strength). Examples of tasks with a high cognitive load include maze-learning and card-sorting. Examples of tasks with a low cognitive load include balancing and dart throwing.

Two common theoretical explanations of the effects of mental practice include the cognitive (symbolic) hypothesis and the psychoneuromuscular hypothesis. The cognitive hypothesis states that the effects of mental practice apply to the cognitive components of a skill: those that can be represented symbolically or visuospatially (Feltz and Landers 1983). In contrast, the psychoneuromuscular hypothesis (which grew out of the ideomotor view) holds that the effects of mental practice apply to the physical components of a skill, such as low-gain innervation of muscles used in the physical enactment of the skill (Jacobson 1930; Shaw 1938). However, potential problems with studies of mental practice make conclusions difficult. Instructions to participants that define mental practice often vary or are absent. In addition, mental practice conditions are often accompanied by some kind of physical practice, either overt, such as foot-tapping (Wollner and Williamon 2004), or covert, such as movements of throat muscles (Jacobson 1932). As a result, the components of mental practice that are considered cognitive or motor are often determined *a priori* by experimenters.

Although the effects of mental practice have been examined in many behavioural tasks, fewer studies have compared types of mental practice in the context of music performance. Coffman (1990) showed that mental practice by pianists improved their performance compared with no practice. Pianists' mental practice with an auditory model showed advantages over mental practice alone (Lim and Lippman 1991; Theiler and Lippman 1995). Rubin-Rabson (1937) showed that analytical pre-study of the score often aided performers' memorization of unfamiliar music; this analytical study may have involved auditory or motor imagery (Lim and Lippman 1991). Mental practice may help musicians learning unfamiliar music by facilitating the creation of an auditory and/or motor image. Comparison of different practice conditions showed that listening to a performance was an effective aid to learning to perform unfamiliar music (Rosenthal 1984; Rosenthal *et al.* 1988). Not all studies show a facilitation of mental practice, however; Rosenthal *et al.* (1988) found that silent analysis (similar to mental practice, without explicit instructions) followed by sight-reading was no more effective than sight-reading alone.

An indirect source of evidence for mental practice is the lack of any detrimental effect that removal of auditory feedback causes to performers once they have learned a musical piece well. Finney and Palmer (2003) measured the amount of time performers took to play a familiar piece from memory on a silent electronic piano; total performance durations were within 5% of the durations when the pianists played the same piece with normal auditory feedback. This result was not specific to well-learned pieces; after playing a novel musical piece 10 times, the removal of auditory feedback caused no change in the duration of the performance. However, when auditory feedback was removed during the initial practice session, pianists' later performances (with auditory feedback) were significantly slower and contained more errors (Finney and Palmer 2003). Thus, the absence of auditory feedback during practice of an unfamiliar piece did not affect pianists' accuracy while the music notation was in front of them, but the absence of auditory feedback during practice did impair their later performance from memory. Ross' (1985) study of trombonists indicated that normal practice conditions with both auditory and kinesthetic feedback present allowed musicians to correct and adjust their performances; that ability decreased as feedback was removed during practice. In sum, these studies suggest that pianists can substitute mental feedback for auditory feedback once they have practised the music sufficiently to form a mental representation.

Highben and Palmer (2004) contrasted mental and physical practice, in terms of auditory and motor feedback, to determine their role in how pianists learn to perform unfamiliar music. Comparisons were made of different types of mental practice by replacing auditory or motor feedback with instructions to imagine the missing feedback: how the piece sounds, or how the finger movements feel, during practice. In a 'normal' practice condition, pianists moved their fingers on the keys and heard themselves play over headphones during practice. In a 'motor only' practice condition, the pianists moved their fingers on the keys but auditory feedback was removed; they were told to imagine what the piece would sound like. In an 'auditory only' practice condition, motor feedback was removed (the pianists held their fingers in loose fists) and auditory feedback was present in the form of a computer-generated recording of the piece, and pianists were told to imagine what the finger movements would feel like. In a 'covert' practice condition, both motor feedback and auditory feedback were removed during practice (pianists held their fingers in loose fists during silence), and they were given both sets of instructions. Each participant performed in each condition with a different musical piece; a within-subject design was considered important to control for individual differences in mental practice abilities. After performers practised from a musical score, the score was removed, and pianists performed from memory under normal feedback conditions. Two independent measures of ability for mental imagery were collected: one for motor imagery and one for auditory imagery, for comparison with the effects of mental practice.

Both auditory and motor forms of practice facilitated pianists' subsequent performance from memory of unfamiliar music. Removal of auditory or motor feedback at practice caused significant memory deficits in later performance, despite the presence of both types of feedback at test. Physical practice conditions (in which auditory and/or motor feedback were present) led to better performance recall than conditions with mental practice. Recall was best following normal practice conditions, and worst when both auditory and motor feedback were removed during practice. Furthermore, pianists who scored higher on the test of aural skills performed better from memory following the absence of auditory feedback during practice, compared with pianists who scored lower on the test of aural skills. Thus, it is likely that performers with high aural skills were better able to use auditory imagery during learning than other performers (Highben and Palmer 2004). Whereas previous studies demonstrated the overall efficacy of mental practice in music performance (Ross 1985; Coffman 1990), Highben and Palmer's (2004) findings suggest specifically that auditory and motor forms of mental practice can aid the learning of unfamiliar music by performers. In addition, the presence of a motor component of mental practice that facilitates memory for performance indicates that explanations of the effects of mental practice based solely on symbolic, videospatial, or other cognitive (non-motor) forms of representation are not sufficient to explain memory for performance.

Individual differences in imagery abilities that are related to memory differences have implications for brain imaging studies as well as for behavioural studies. Most comparisons of methods of mental practice rely on cross-group comparisons (see Feltz and Landers 1983; Driskell *et al.* 1994), for which any correlated memory differences are not measured. The presence of individual differences suggests that within-subject designs—those that allow comparisons across all conditions within individual performers—combined with independent measures of behavioural correlates may be important controls for memory differences that result from differences in mental imagery abilities.

Anticipatory behaviour in music performance

One of the hallmarks of memory for performance is anticipatory planning: the preparation of events prior to their execution (Rosenbaum 1991). Anticipatory behaviour is evidenced in occasional errors that reveal events intended for the future, and also in movements during the production of correct events that reveal trajectories toward future events. Studies of speech and music performance show anticipatory behaviour in the types of errors people make (such as a speaker producing 'I took the store . . . ' instead of the intended 'I took the car to the store' (Garrett 1980)). One of the main factors influencing anticipatory behaviour is practice. Drake and Palmer (2000) compared the anticipatory behaviours of child and adult pianists of various skill levels. The percentage of anticipatory pitch errors (compared with perseveratory errors, or produced pitches that were intended for earlier in the sequence) increased with both age and experience (Palmer and Drake 1997; Drake and Palmer 2000). Practice effects on anticipatory behaviour are found in many domains. Speech errors suggested that with more practice, speakers were more likely to anticipate a phoneme that was intended for later in the utterance (Dell *et al.* 1997). As the overall error rate decreased, speakers' percentages of anticipatory errors increased. Palmer and Pfordresher (2003) also found a consistent increase in anticipatory behaviour with practice in piano performance, and a general relationship between overall error rate and anticipatory behaviour: as pianists' pitch error rates decreased, the percentage of anticipatory errors increased. Furthermore, pianists' pitch errors were likely to span sequence distances of three or four events, termed the 'range' of planning: the faster the performance, the smaller the range over which anticipatory behaviour was evidenced (Palmer and Pfordresher 2003).

Analyses of finger movements in piano performance also display evidence of anticipatory behaviour. One of the earliest studies of musical motion (Ortmann 1929), using photographic techniques, documented finger movements during piano performance. Ortmann's records indicated anticipatory interactions among finger movements (movement of the second finger before the third finger strikes a key), as well as anatomical measures (arm weight, finger length, hand position) relevant for piano performance (such as the role of forearm bone length on rotation during production of tremolo). Ortmann (1929) documented general principles that are still the focus of movement research today: there are multiple routes to reach any key on the piano (the degrees of freedom problem), and the way in which each key is struck is influenced by the ways in which preceding and subsequent keys are struck (co-articulation).

Current techniques of measuring motion rely on optoelectronic systems. One type includes active markers or sensors that are placed on joints with wires and emit infrared signals 'captured' by cameras. Another motion capture technique uses passive markers that reflect light generated from a separate source that is detected by cameras. Both systems pinpoint the three-dimensional coordinates of each marker at each point in time. Engel *et al.* (1997) used an optoelectronic

Fig. 3.1 Picture of reflective markers on a pianist's right-hand fingers and piano keys. (From Palmer and Dalla Bella 2004.)

system to measure the degree of anticipatory behaviour of fingers as pianists performed short musical excerpts that began with the same pitches but diverged in the middle of the excerpt. Pianists' finger motions changed about 160–500 ms prior to the point of notated divergence in the musical score. Because performances differed in tempo, they were normalized with respect to time and anticipatory times were not reported in number of events.

Palmer and Dalla Bella (2004) measured anticipatory movements in piano performance of simple melodies performed at a range of specified tempi. Pianists' finger motions were recorded with a Vicon-8 system with passive 3 mm markers placed on a pianist's right hand, as shown in Fig. 3.1, and 14 cameras placed around the pianist recorded light reflected from the markers. This system, also applied to violin bowing (Visentin and Gongbing, 2003), has the advantage of requiring no wires on the pianists' hands. An example of a pianist's trajectory of motion of the fifth finger of the right hand is shown in Fig. 3.2, during a performance of the simple melody shown at the top. The position, velocity, and acceleration graphs below refer to the position of the marker placed on the tip of the fingernail (the finger position of greatest motion) in the vertical plane (height above the keyboard). The top panel shows the finger height; minimum values indicate where the piano key was pressed. The middle panel shows the velocity of the finger motion, and the bottom panel shows the acceleration. In this melody, the pianist's fifth finger pressed the keys on note events 6, 8, and 10. The pianist's trajectories of motion indicated changes in velocity and acceleration patterns of each finger prior to its arrival on a key. The key arrival (indicated by minimum finger height, top panel) is marked by peak finger acceleration (bottom panel). Anticipatory motion is evidenced in the finger heights (top panel) during the event prior to arrival on a key (events 6, 8,10).

As shown in Fig. 3.2, the pianist's fingers reached peak amplitudes usually within one event prior to a keypress. However, the trajectories of each finger

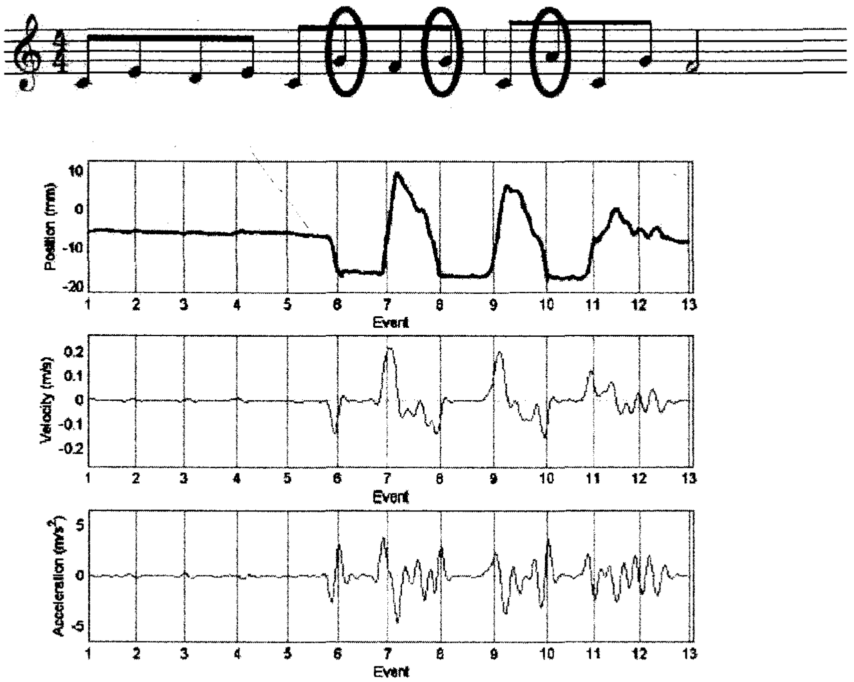

Fig. 3.2 Height of a pianist's fifth finger above the keyboard in terms of position (top panel), velocity (middle panel), and acceleration (bottom panel) during a single performance of the melody shown at the top, at a moderate tempo (120 beats/min). Vertical lines indicate the time of each keypress (as recorded on a MIDI keyboard).

began to change in velocity and acceleration one to three events prior to the anticipated arrival at the key by that finger; by four events prior, the trajectories showed the same amount of change in velocity and acceleration as when the finger had no upcoming keypress (resting level) (Dalla Bella and Palmer 2004). This anticipatory behaviour in finger trajectories is consistent with findings of memory retrieval occurring three to four events before the keypress (Palmer and Pfordresher 2003); finger trajectories toward keypresses must require some information about the arrival location prior to the execution of the movement. Furthermore, the faster the tempo, the less time there is for anticipatory movements, consistent with the memory retrieval model. Although statistical (morphometric) techniques that identify consistencies in shape and structural time patterns have not yet been applied to musical movement, motion capture techniques offer promise for rigorous measurement of co-articulation properties (how finger movements are influenced by subsequent and preceding fingers) and other shape/time constancies in musicians' movements that were first identified long ago (Ortmann 1929).

Summary

Research in music performance is beginning to document the nature of memory for the motor aspects of performance. Performers' hand and finger movements, as well as conceptual intentions, are encoded in memory for performance and tend to have independent effects on pitch accuracy. Performers' memory for melodies (specific pitch sequences) and finger/hand movements generalize in transfer tasks; furthermore, motor and melodic information transfer independently. Skilled performers show more transfer of learning across melodies that require different motor movements than do novices. Mental practice shows evidence of motor components that facilitate memory for performance. Finally, motion capture techniques for measuring music performance are beginning to document the time course of anticipatory movements.

One ramification of these findings is that memory for performance is flexible; performers can apply what they know about motor movements to different performance situations, and behavioural and neural changes result—as seen in the plasticity with which non-musicians learn aural–motor associations. Flexibility of motor movements is essential for the interpretive nature of music performance; otherwise, significant additional practice would be necessary before a musician could perform a familiar piece with an alternative interpretation. A second ramification is that performers differ in their individual abilities, as evidenced in interpretive effects on memory, in transfer of learning from one melody to another, and in mental practice benefits. Mental practice is appropriate for the study of brain states, measured in EEG, fMRI, and MEG studies, because of its avoidance of motion 'artefacts'. Scientific interest in applying imaging methods and motion capture techniques to music performance suggests that answers may soon be found to the interesting question of how motor aspects of music performance are represented in memory.

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