Acquisition and Loss of Skilled Movement in Musicians

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Although the relationship of music and medicine is measured in millennia, it is only within the past few years that it has developed genuine vitality. The change is due in large part to the recent recognition of a broad range of clinical problems affecting performing artists. The present issue of *Seminars* is persuasive evidence of the importance of these medical issues.

My own interest has a somewhat different origin: shortly after my daughter's 12th birthday, in what was to prove a pivotal moment in my career as a neurologist, I stopped to listen as she prepared Chopin's "Fantasie Impromptu" for presentation at a student piano recital. Although I had listened to her playing countless times before, I had never really watched her hands as closely as I did on this occasion. Startled that I could see nothing but a blur beyond the wrists, I asked myself the innocent question, "How does she make her fingers go so fast?"

That question, in various forms, has captivated observers and practitioners of instrumental music playing for a considerable time—at least since 1762, when C.P.E. Bach published his "Essay on The True Art of Keyboard Playing."[1] It certainly captivated Homer W. Smith, the eminent renal physiologist, who wrote *From Fish to Philosopher* in 1953.[2] Smith, possibly because of his personal acquaintance with pianist Simon Barere, had evidently come to the conclusion that pianists occupy one of the major summits of mammalian evolution: "the most intricately and perfectly co-ordinated of all voluntary movements in the animal kingdom are those of the human hand and fingers, and perhaps in no other human activity do memory, complex integration, and muscular co-ordination surpass the achievements of the skilled pianist." Smith counted the number of key strikes (6266) Barere had used in playing the Schumann C Major Toccata, Op. 7, and, based on a performance time of 4 minutes and 20 seconds, calculated an execution rate of 24.1 notes per second. He then estimated that "a speed of 20 to 30 notes per second may involve 400 to 600 separate motor actions—all effected by a competent musician with such automatism that he can give his attention to the over-all effects, rather than to the mechanical details."[2]

As it happens, the prospects for illumination of the neural regulation of highly skilled movement became considerably greater in the mid 1970s than they had been at any previous time, largely because of the exceptionally fertile collaboration of physiologists and psychologists studying brain and muscle activity in both primates and humans who had been trained to carry out stereotyped movements. The seed for this work had been planted by Paul Richer in 1895,[3] who had demonstrated something special about muscular activity associated with rapid movement.

Richer had taken a series of rapid sequence photographs of the quadriceps muscle during a kicking motion. After studying the photographs, he said this about the contraction of the muscle during the kick: "It is very energetic and short lasting. It launches the limb in a set direction and ceases long before the limb will have completed its course of action."[3] Because of the similarity of this kind of move and the firing of a gun shell, it was called "ballistic."

Despite the remarkable productivity of research on ballistic movement, much of which was

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done at the National Institutes of Health beginning in the mid-1960s, neurophysiologists have been both modest and wary about the applicability of this work to skilled human performance. C. G. Phillips, writing in 1977 about hand control in musicians, was emphatic: "Contemporary neurophysiology cannot investigate such complex performances."[4]

The daunting realities aside, the question continues to attract ardent followers, among whom music teachers are understandably the most devoted. As with Bach, thoughtful teachers have sought an objective basis for helping students to succeed with music study; there is an enormous professional literature on this subject, impressive even on the basis of a superficial acquaintance.[5-11] Moreover, as suggested by Max W. Camp, Professor of Music at the University of South Carolina, in his recent chronology of piano pedagogy, influential teachers have long sought to connect their teaching precepts with anatomic and physiologic principles.[12]

Despite this tradition, the best music teaching has remained intuitive or purely pragmatic, and usually highly individual. One hears often of the "methods" of highly acclaimed pedagogues, but serious analysis of such methods is virtually never undertaken, and the expertise of a noted teacher is rarely challenged. Camp refers humorously to the real world of pedagogy as being governed by the rule of apostolic succession.[13]

The work of Otto Ortmann[14,15] marked a significant departure from previous pedagogic scholarship; he possessed a sophisticated understanding of the anatomy of the upper extremity and based his conclusions about hand movement at the keyboard on a substantial body of original and meticulous research. Nevertheless, in 1989, 60 years after Ortmann published his second book, there is no discernible consensus among piano teachers that a science of musical performance would be useful even if it did exist. The ambivalence among music teachers about the relevance of science to their work, combined with that of scientists about the real prospects for developing a physiologic psychology of complex behavior, should remain a sobering influence for those impatient to know how pianists make their fingers go so fast.

MUSICIANS AND ATHLETES

It has now been well over 10 years since I became interested in the neurologic basis of motor skills in musicians. Initially, it seemed to me—as it has to others—that there might be some advantage in considering musicians a special subset of athletes.[16] Indeed, there are many obvious similarities in all such activities related both to the development of skilled performance and to its exercise at the advanced ("competitive") level: learning begins at an early age and, especially in the early stages, usually takes place in a playful atmosphere; experiences with peers and with coaches, and family support, usually have a powerful effect on achievement; routines of stereotyped movement are rehearsed for extended periods of time, and pass through stages of increasing physical and strategic complexity. The serious performance situation (even for children) is a time of heightened physical and psychologic arousal, with flawless execution being not only the goal but often the only acceptable outcome. The process is often referred to globally as "talent development," and has been extensively studied at that level.[17,18]

This description of the process might be said to apply at the "macro" level; the most striking similarity on the "micro" level is that for both musicians and athletes (in the traditional usage) individual and sequential movements are usually directed toward an external target. It really does not matter whether the target is a golf ball or the key on an instrument, the control problem in physiologic terms seems on its face much the same: the problem of moving the body accurately at high speed to make contact with a target, or a succession of targets, whose distribution in space and time is predictable, seems the underlying experiential, biomechanical, and physiologic commonality in most cases.

FITTS'S RULE AND BALLISTIC MOVEMENTS

Since the mid 1950s, psychologists involved in human skills research have accepted Fitts's general formula describing movement toward a target.[19] In essence, the rule is that for ordinary movements, speed and accuracy are inversely related, that is, the faster a given move, the larger the target must be for the move to reach it consistently. What has also been accepted after a half-century of research on skilled movements is that ballistic movements do not follow this principle. For reasons that were not clear in 1950, and are still not clear, the learning of skilled movement invokes a novel form of neuromuscular control in which accuracy of trajectory is not degraded with increased speed of movement.

Despite the uncertainties, about 20 years ago the general character of an explanation began to emerge from the studies on brain activity in relation to voluntary movement to which I referred earlier. Interested in exploring sensory control of movement and its influence on learning, a number of investigators trained primates to perform patterned movements, mainly of the upper extremities, and then recorded activity of single cells in cortex, basal ganglia, all regions of the cerebellum, and nuclear structures in the brainstem. Simultaneous single unit electromyographic recordings of active muscles were also obtained. Studies were carried out on animals in a variety of learning and trained conditions, with a number of controlled stimulus and sensory alteration parameters, with and without both midcourse perturbations and end-point barriers. This approach made it possible to specify parameters of activation of single brain cells in relation to self-initiated and self-regulated movements and to study the temporal relationships between voluntary muscle activation and brain cell groups firing in relation to the resulting movements.[20–24]

In these paradigms, animals approach the problem by going through a trial and error process. The limb moves in small, discontinuous increments, with marked fluctuations in acceleration. Visual and proprioceptive information is required to succeed at this task. Once the move is learned so that it can be done accurately, and if the animal is rewarded for speed, it will come under a ballistic mode of control. There will be a marked increase in the speed of the move, disappearance of the fluctuations in acceleration, and quite remarkably, as Polit and Bizzi[25] at MIT demonstrated, a loss of the previous dependence on visual or proprioceptive feedback. Under conditions of ballistic control, the limb can be completely shielded from the animal's view, and deafferented, and neither accuracy nor speed will be compromised. Furthermore, the move can be perturbed, or interfered with, and it still will land on target.[25]

These studies, in the aggregate, established a number of facts about the central organization of skilled movement. Two seem especially germane to this discussion: first, it became clear that basal ganglia are involved not only in maintenance of posture, but in the initiation of limb movements, including skilled movements; second, it was found that lateral cerebellum is functionally and anatomically unlike intermediate and midline cerebellum with respect to both its afferent and efferent connections. Specifically, lateral cerebellum receives no direct spinal or proprioceptive input, and its output, by way of dentate nucleus, is primarily to motor cortex through the nucleus ventralis lateralis of the thalamus.

The possible significance of the latter finding, at least as it was understood in 1977, led Eccles[26] to make the following speculation:

> We can say that normally our most complex muscle movements are carried out subconsciously and with consummate skill. The more subconscious you are in a golf stroke, the better it is, and the same with tennis, skating or any other skill. In all these performances we do not have any appreciation of the complexity of muscle contractions and joint movements. All that we are conscious of is a general directive given by what we may call our voluntary command system. All the finesse and skill seems naturally to flow from that. It is my thesis that the cerebellum is concerned in this enormously complex organization and control of movement, and that throughout life, particularly in the earlier years, we are engaged in an incessant teaching program for the cerebellum. As a consequence it can carry out all of these remarkable tasks that we set it to do in the whole repertoire of our skilled movements in games, in techniques, in musical performance, in speech, dance and so on.

IMPLICATIONS FOR LEARNING AND DISRUPTION OF MUSICAL SKILL

The most recent research on brain mechanisms in control of skilled movement suggests an arrangement somewhat more complex than what appeared to be the case in 1977, involving a highly complex set of relationships between cortex, basal ganglia, cerebellum, and thalamic nuclei, with considerable opportunity for flexible distribution of control throughout the system.[27] Moreover, research on spinalized cats in Edgerton's laboratory at the University of California, Los Angeles may well have relevance to a fully integrated model of motor control, since this work demonstrates conditions under which learning can take place even within isolated spinal cord.[28]

In all, the physiologic conceptualization is one that conforms remarkably well with one now being offered by psychologists who have become disenchanted with what used to be called the motor schema theory of learning. At a recent conference on Music and Child Development held at the University of Colorado in Denver, Michael Wade[29] described the state of current psychologic theories this way: "The centralization of control assumes that the 'executive' always dominates the variables below it, which in turn dominate the variables below them, and so on. While hierarchical organization allows for certain savings in the control burden borne by the executive, there is a cost to be paid in other areas. Coordination cannot be accomplished by means of a controlling executive, but must, in some way, emerge out of the natural compatibility between the animal and the environmental context in which the activity goes on. What we have in this view of motor skill is a *coordinated structure,* defined as a group of muscles spanning more than one joint, constrained to act as a functional unit. "

One way of looking at the lifelong music-learning experience is through the eyes of the student; another is through the eyes of the teacher; yet another is through the eyes of the psychologist or physiologist concerned with the neurophysiologic correlates of behavioral change, and, of course, one can approach the experience as a neurologist or a psychiatrist. None of these perspectives lacks essential information about the process, or provides all of what our understanding requires. In the context of this review, I would suggest that the learning process for musicians involves a transformation of both skill and subjective experience with at least the following essential features:

- The attainment of a high probability of stability in an ordered sequence of precisely targeted movements, which unfold under the influence of simultaneous internal and external cues—auditory, visual, tactile, kinesthetic, and verbal.
- The development of a quality of movement, perhaps best described as fluency, associated with modifications of muscle responsiveness, autonomic changes (such as altered skin temperature and conductance) and accompanied by a heightened sense of confidence by the performer in his or her ability to achieve whatever is intended.
- A shift of the performer's attentional focus away from the mechanical details of performance toward an internal mental state, which may be highly abstract, nonverbal, and personal, and which is usually associated with, or is capable of producing, highly sought-after emotional arousal.

The value of both the psychologic and the physiologic models for our understanding of the development of musical skill seems considerable; in addition, these models support a novel and clinically intriguing alternative to the currently favored theories concerning those most puzzling and resistant forms of skill loss, the task specific focal dystonias. These disorders are reviewed in this issue of *Seminars* by Jancovic and Shale. I have argued elsewhere that in certain cases they may stem not from any neurologic disease—central or peripheral—or from psychiatric disorder, but from inherent limitations in the capacity of the nervous system to control movement under special circumstances:

> In my view, motor control physiologists . . . challenge us to question the adequacy of our models of neurologic function and dysfunction in the case of musicians (and other skilled performers), who are almost certainly operating the nervous system at, or close to, the limits of its functional capacity. We are all accustomed to thinking of physical limitations in the realm of athletics, where a tradition of recording performance tells us how fast and how high the body can go. With respect to the body as an information processor, however, we are in a different situation.
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> It seems to me that musical study involves an evolution in physical and neurologic function toward what amounts to a virtual unitary physical and mental state. In this state, movement itself is information not only in the poetic sense, but in the physiologic sense. The brain as an information processor becomes critically dependent on the integrity not only of its own internal programs and processes, but on the biomechanical, auditory, and visual events that propel, follow, and, in effect, merge with internal events.
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> If the situation is at all like this, the musician's ability to perform probably becomes increasingly dependent upon the reliability not only of the separate components of his music-making and music-perceiving apparatus, but of the coordination and responsiveness of his perceptual-motor system as a whole. The disturbance of any of its biomechanical and control elements, or of their interaction, could then have extremely serious consequences in both the short and the long run. Put another way, the musician in full flight is an operational miracle, but a miracle with peculiar and occasionally unpredictable vulnerabilities.[30]

Although Eccles may not have been entirely accurate about the role of the cerebellum in his 1977 speculative remarks, he may nevertheless have provided a singularly useful clue to our understanding of both the success of skill learning and its vulnerability, by linking the lengthy rehearsal experience with its most valued outcome: the attainment of automatic, unconscious control of movement. One of the most striking features in patients with focal dystonia, particularly when the onset is sudden, is their utter disbelief when an arm or a hand no longer behaves as if it is theirs. Accustomed to feeling possessed of nearly magical bodily control, such an individual may rapidly become panic-stricken—especially if (as is so often the case) the disorder develops during a period of intense work on technically difficult material. If the person, alarmed and confused, further intensifies his or her efforts, the problem always gets worse, and almost invariably fails subsequently to improve.

According to what might be called the "medical" model of occupational cramp, or focal dystonia, the breakdown of function must reflect either central or peripheral nervous system disease: subtle entrapment neuropathies or early partial dystonias are believed to underlie the functional change. Although such pathologic conditions are almost certainly present in some cases, there are ample reports in the literature of severe dystonias lacking demonstrated pathologic changes, and, to my knowledge, medical or surgical treatments rarely reverse the problem.

Recently, there have been reports of musicians with what seem likely to have been focal dystonia being significantly helped by retraining.[31,32] What is most intriguing about these reports, whether they are to be believed or not, is that they represent the work of two music teachers who were, until recently, unknown to each other, and they advocate quite specific and essentially identical strategies for teaching movement at an instrument. One teacher (Dorothy Taubman) teaches piano, and the other (Patrick O'Brien) teaches guitar. I have had the opportunity of interviewing and examining (without electrophysiologic study) one pianist and one guitarist who have been retrained by Taubman and O'Brien, respectively, after developing what must have been a bona fide focal dystonia. Each required months of lessons concentrating on rebuilding a "healthy" movement strategy on the instrument before movements began to become normal, and both are playing again without evidence of dystonic movement on the instrument or in other activities. The pianist, a successful concert artist in his late teens and early twenties, had received extensive medical and neurologic evaluation incident to his disability (he is, in fact, himself a physician) and his judgment is that the only medical treatment that made the slightest difference was propranolol, which diminished his tremor slightly, although not enough to permit him to play the piano. His conclusion is unequivocal: retraining at the piano made the dystonia go away.

The apparent coincidence of teaching strategies to "fix" dystonia becomes the more arresting when one examines the specifics in relation to what has already been reviewed here concerning physiologic models for skill development. The underpinning of both strategies includes three disarmingly simple rules:

- Key strikes and string plucks should not be powered by flexion of the distal interphalangeal joint, since this action cannot be done without involuntarily extending the metacarpophalangeal joint, thereby producing simultaneous cocontraction of forearm flexors and extensors.
- Extreme abduction of the fingers should be avoided, because this "ties up" the interossei and impedes them from functioning as "in-the-hand" finger flexors.
- Simultaneous flexion and extension of individual fingers is to be avoided, again to reduce the risk of agonist-antagonist cocontraction in the forearm.

Why, it must be asked, might these particular rules make a difference? The answer, of course, will depend on careful study under controlled conditions. However, when one considers both the real biomechanics of skilled musicianship (as described, for example, by Homer Smith), and the dominant theme of ballistic control research—precise regulation of agonist-antagonist interaction—the most likely answer seems literally to jump off the page. Success at a high level of musical skill must be utterly dependent on the capacity of the control system to maintain agonist and antagonist activity in strict reciprocal balance. Any contrary condition, whether it be motor or sensory malfunction (central or peripheral), or simply the springing of a trap unwittingly laid by the rehearsal of movements incompatible with the agonist/antagonist ballistic paradigm ("faulty technique"), could put the system (meaning the hand and arm) out of commission. The final misery in this situation—its normal tendency toward irreversibility—may simply reflect the paradoxical consequence of the distraught musician practicing in an abnormal or disabled condition, thereby effectively locking in an end-stage, chaotic ballistic program (possibly at the spinal level) that can only degrade further each time the movement is attempted again. Perhaps this is going too far, but sick software has a certain appeal here as a metaphor for the pathophysiology.

CONCLUSION

It may well be that musical performance is not amenable to investigation by the techniques of contemporary neurophysiology, as Phillips concluded 12 years ago. George Moore, on the other hand, is more encouraging:

> Not for several decades have scientists seriously investigated the biological bases of music making. It is not recognized as a legitimate area of scientific research, nor can any agency be identified as having any interest in its becoming so. Yet now may be an ideal time for study to resume. We enjoy certain advantages today that our predecessors did not. First, we know a great deal more now about the detailed anatomy of the body, especially the nerves, muscles and bones employed in instrumental performance, and about the lips and vocal tract which are the instruments of singers. Second, we know far more today about the psycho-physiology of sensation and perception, about the physiology of neuromuscular control, and about the hierarchical control of movement and the learning processes associated with it. Third, much progress has been made in understanding the physics of musical instruments, the relation between the structure of instruments and the sounds they make, and the relation between certain purely physical aspects of playing and their acoustic consequences. Finally, we enjoy a technological advantage, possessing a wealth of instruments and computers for measuring, recording and analyzing the component processes of musical performance.[33]

Moore's own work with cellists indicates that important, and surprising, results await those willing to invest in such inquiry.[34]

I would propose, further, that musicians represent a sizable and richly varied population of individuals available for study (particularly when they are impaired), within which there is limitless opportunity for advancement of our understanding of complex human behavior.

We have much to offer one another.

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