INTRODUCTION

Music performance is considered one of the most complex human activities. It involves not only hundreds of muscles, coordinated to produce the desired musical result, but also a variety of cognitive mechanisms, including complex emotional and analytic processes (Zatorre et al., 2007). The study of music performance has yielded important insights into brain processes, including neural plasticity (Schlaug et al., 1995; Schlaug, 2001; Münte et al., 2002; Schneider et al., 2005), motor control (Slobounov et al., 2002; Watson, 2006), rhythmic control (Ramsayer and Altenmüller, 2006; Repp and Doggett, 2007; Goebi and Palmer, 2009), and emotional communication (Gabrielsson and Juslin, 1996; Juslin, 1997; Juslin and Laukka, 2003). The information acquired through systematic studies is invaluable in its contribution to our understanding of brain mechanisms underlying music perception and performance. However, such studies are limited in their ability to simulate the atmosphere of a concert performance, or to systematically follow the long period of training required to master a musical piece. Hence, it may be beneficial to obtain additional information by studying the strategies employed by professional concert artists to optimize their practice routines and their performance under stressful conditions. Such strategies enable them to confront many of the physiological constraints dictated by the muscular and central nervous system. In this short note, we highlight some key properties of these strategies and their possible relevance to studying other complex human activities.

DISTRIBUTING CONTROL OVER TIME SCALES

Performing virtuoso musical pieces often involves extremely fast motor action. In piano playing, for example, a pianist may play at a speed of 30 notes per second (Rumelhart and Norman, 1982), surpassing visual reaction times (Lashley, 1951). Many other human activities, such as speech, competitive gymnastics, driving a car, typing, as well as many other activities involve extremely fast serial motor actions. Lashley, in a seminal article published in 1951, observed that the time differences between the components of fast sequential action do not allow separate conscious planning of each component. He concluded that the ability to perform fast sequential motor actions can be explained only by the existence of a single motor plan encompassing the whole sequence. This hierarchical movement planning theory is also supported by evidence showing that the process of learning complex serial movements typically involves formation of “chunks” of movements (Miller, 1956). The process of learning a task is habitually associated with a reduction in movement variability and a decreasing involvement of cognitive control (Cohen and Poldrack, 2008). This state, commonly termed automaticity, enables an individual to perform a task without reduction in performance in the presence of a concurrent competing task (Logan, 1979).

The time scales involved in music performance suggest that both automatic and non-automatic processes are involved. While fast passages may involve time scales of tens of milliseconds (Rumelhart and Norman, 1982), musical phrases, sections, and whole movements typically involve time scales of seconds, minutes, and longer. In performing such musical excerpts, the performer may consciously follow various structural levels of the piece using known nomenclature such as “exposition,” “first theme,” or “second theme,” etc. Hence, musicians must rely on both implicit and explicit memory processes during music performance, enabling them to play fast passages, relying on automaticity, while simultaneously dedicating their intellectual and emotional resources to higher level processes.

Concert performances may involve high levels of stress. If musicians begin to doubt their knowledge of a musical text, they may consequently doubt their ability to automatically execute sequential motor action required to play the same musical text. Such hesitation may drive the performer to use alternative motor planning strategies, namely, online movement-by-movement planning. Since fast passages cannot be executed using on-line motor planning, the ultimate outcome of this strategy may be a failure to perform the musical passage in a successful manner, leading to growing anxiety, which, in turn, increases the uncertainty in both explicit and implicit memory abilities. The final outcome of this Performance Vicious Cycle (PVC) is a faulty performance, which, at times, may even reach full interruption of the musical performance.

Diverse strategies are employed by musicians to overcome such incidents. Those habitually comprise cognitive behavioral treatment (Kendrick et al., 1982; Harris, 1987; Nagel et al., 1989), various relaxation techniques (Sweeney and Horan, 1982; Niemann et al., 1993), pharmacological methods, such as beta blockers which reduce sympathetic activation by stress (Neftel et al., 1982; Nube and Musicybog, 1991), or even hypnosis (Stanton, 1994). The efficacy of all these methods is debatable (Kenny, 2005). The reason for this may be that most of the reported interventions attempt to affect the general state of mind of the performing musician, but do not try to directly affect mental processes during the performance of specific pieces of music.
A more direct approach for a performer to avoid the PVC is by developing “mental scripts” which include the exact series of desirable mental events during a musical performance. These scripts should not include any reference to fingering or other fast-scale motor action, but rather focus on large time-scale events, such as musical phrases. Thus, the performer can actively avoid interfering with automaticity. These mental scripts should be continuously repeated, in order to acquire automatic control of the desired mental process, in a similar fashion to the music practice routines, which use constant repetition to produce faultless and automatic motor control. By employing this method, musicians may reach a relatively high state of certainty in their ability to maintain their technical and mental achievements, earned through long years of practicing.

The same approach may potentially apply to other forms of complex sequential activities, such as sports, dance, and even speech. The reason why certain competitive gymnasts succeed more than others in producing perfect drills is not necessarily only due to physiological superiority, but also to the employment of mental scripts which do not allow the PVC to begin. This line of thought can be tested in studies examining other forms of fast sequential motor action. Mental scripts fitting specific tasks can be developed, rehearsed and then tested under stressful conditions to examine the ability of the subject to maintain automaticity. Such mental scripts should involve deliberate thinking in relatively slow time scales. The scripts could be related to the task (for example, naming the finger number, simultaneously with the beginning of a finger-tapping sequence), or completely unrelated to the task (reading or mentally rehearsing a certain text). Next, the ability of the subjects to maintain rapid and accurate sequence tapping can be examined, with and without the employment of mental scripts.

MENTAL CONTROL OF BIMANUAL COORDINATION

The ability of humans and primates to coordinate the movements of both limbs has been the focus of scientific research for decades. Several general conclusions regarding the nature of bimanual movements have been established and replicated in various empirical studies. One of the most common observations is that spontaneous bimanual hand movements tend to be similar, spatially (with a preference for mirror movements) and temporally (phase-locked) (Kelso et al., 1979; Kelso, 1984; Franz, 1997) Furthermore, symmetric movements are more natural than parallel movements, which are, in turn, easier to perform than unrelated movements. Corresponding to the behavioral observations, it has been found that brain activation for parallel movements is greater than for symmetric movements (Sadato et al., 1997; Stephan et al., 1999). These findings may suggest that parallel movements are more computationally demanding than symmetric movements.

Interestingly, professional pianists show different activation patterns than naive individuals for bimanual movements. Complex bimanual finger movements in professional pianists result in less brain activation than in naive individuals (Haslinger et al., 2004). Moreover, brain activation for parallel movements is not larger than for symmetric movements in pianists. These functional differences could have structural underpinnings. Indeed, differences between musicians and non-musicians were found in brain structures associated with bimanual movement. Increased corpus callosum volume (Schlaug et al., 1995) and reduced transcallosal inhibition (Ridding et al., 2000) were shown in professional musicians. Since inter-hemispheric connections were found to be highly important for bimanual movement (Serrien et al., 2001; Johansen-Berg et al., 2007; Muetzel et al., 2008), increased inter-hemispheric connectivity could account for higher efficiency in certain bimanual movements in musicians.

However, the unique brain activation patterns in pianists could be also attributed to different strategies employed by musicians to cope with non-symmetric bimanual movements. When practicing bimanual passages, pianists have to choose between mastering each hand alone first, or, alternatively, practicing both hands together from day one. In choosing between these two strategies, pianists employ an intuitive knowledge that certain bimanual movements are easier to execute as a unit, while other movements may involve two discrete motor plans which are combined later to produce coordinated movement. To illustrate how effective this can be, let us perform the following simple experiment: position your left hand close to the body, and then move it forwards, backwards, forwards and finally backwards again. Now, position your right arm in a forward position (away from the body), and move it backwards (toward the body) then forward (away from the body) then backwards and finally forward again. Now, try to perform the movements you rehearsed for each hand simultaneously (i.e., both hands together). You will probably find this drill uncomfortable to perform at first. Now, let’s try a different approach: hold your hands in the following starting position: the right hand away from the body, and the left hand close to the body. Now move your hands in a rowing movement, so that the hands perform symmetrical movements (it is also possible to think of this movement as a “karate” movement). You will probably find this strategy easier and faster to accomplish (see Figure 1 for illustrated instructions).

In choosing between a unified-bimanual motor scheme and two independent learning processes for each hand, pianists unconsciously enter the years-long discussion confronting two different theories of bimanual movement. The first theory suggests a “generalized motor program.” This theory was originally proposed by Schmidt (1975), who suggested that bimanual movement is governed by a unifying motor plan (a “generalized motor program”), rather than a combination of discrete plans for each component of the movement (Schmidt, 1975). The second theory, proposed by Marteniuk et al. (1984), suggests that bimanual movements are governed by two independent motor plans for each limb (“inter-hemispheric cross talk”), unified to produce a common movement (Marteniuk et al., 1984).

Single-neuron recordings in macaque motor cortex (Donchin et al., 1998) showed that neurons in each hemisphere control the motion of both limbs. Later work of the same group (Rokni et al., 2003) suggested that inhibitory cross-callosal effects act to decorrelate the unimanual and bimanual representations, suggesting that bimanual representations
tasks. By designing mental scripts and the participants during execution of the action. Experimental paradigms involve mental control of complex motor performance can serve as an by employing ready-made mental scripts. ble and dramatically improve performance by employing ready-made mental scripts. Hence, music performance may suggest that multiple coding exist for the same bimanual movements. Hence, pianists may choose the optimal coding for bimanual movement using mental control during practice. This proposition is relatively simple to check in controlled conditions, by directing participants to switch between different mental representations of bimanual movement, and examining the resulting motor performance.

**CONCLUSION**

In this short paper, two highly complex human actions, typical of music performance, were discussed. We suggest each of these theories and its advantages and shortcomings. The experience of piano playing may suggest that multiple coding exist for the same bimanual movements. Hence, pianists may choose the optimal coding for bimanual movement using mental control during practice. This proposition is relatively simple to check in controlled conditions, by directing participants to switch between different mental representations of bimanual movement, and examining the resulting motor performance.

**REFERENCES**

Cohen, J. R. C., and Poldrack, R. A. (2008). Automaticity in motor sequence learning does not impair response inhibition. *Psychon. Bull. Rev.* 15, 108–115. doi: 10.3758/PBR.15.1.108

Donchin, O., Gribova, A., Steinberg, O., Bergman, H., and Vaadia, E. (1998). Primary motor cortex is involved in bimanual coordination. *Nature* 395, 274–278.

Franz, E. A. (1997). Spatial coupling in the coordination of complex actions. *Q. J. Exp. Psychol. A* 50, 684–704.

Gabrielson, A., and Justlin, P. N. (1996). Emotional expression in music performance: between the performer’s intention and the listener’s experience. *Psychol. Music* 24, 68–91. doi: 10.1177/03057356960240107

Goebel, W., and Palmer, C. (2009). Synchronization of timing and motion among performing musicians. *Music Percept.* 26, 427–438. doi: 10.1525/mp.2009.26.5.427

Harris, S. R. (1987). Brief cognitive-behavioral group counselling for musical performance anxiety. *J. Int. Soc. Study Tension Perform.* 4, 3–10.

Haslinger, B., Erhard, P., Altenmüller, E., Hennenlotter, A., Schweiger, M., Graf, von Einsiedel, H., et al. (2004). Reduced recruitment of motor association areas during bimanual coordination in concert pianists. *Hum. Brain Mapp.* 22, 206–215. doi: 10.1002/hbm.20028

Johansen-Berg, H., Della-Maggiore, V., Behrens, T. E., Smith, S. M., and Paus, T. (2007). Integrity of white matter in the corpus callosum correlates with bimanual co-ordination skills. *Neuroimage* 36(Suppl. 2), T16–T21.

Juslin, P. N. (1997). Emotional communication in music performance: a functionalist perspective and some data. *Music Percept.* 14, 383–418. doi: 10.2307/40285731

Juslin, P. N., and Laukka, P. (2003). Communication of emotions in vocal expression and music performance: different channels, same code? *Psychol. Bull.* 129, 770–814.

Kelso, J. A. (1984). Phase transitions and critical behavior in human bimanual coordination. *Am. J. Physiol.* 246(6 Pt 2), R1000–R1004.

Kelso, J. A., Southard, D. L., and Goodman, D. (1979). On the coordination of two-handed movements. *J. Exp. Psychol. Hum. Percept. Perform.* 5, 229–238. doi: 10.1037/0096-1523.5.2.229

Kendrick, M. J., Craig, K. D., Lawson, D. M., and Davidson, P. O. (1982). Cognitive and behavioral therapy for musical-performance anxiety. *J. Consult. Clin. Psychol.* 50, 353–362. doi: 10.1037/0022-006X.50.3.353

Kenny, D. T. (2005). A systematic review of treatments for music performance anxiety. *Anxiety Stress Coping* 18, 183–208. doi: 10.1080/10689360500167258

Lashley, K. S. (1951). “The problem of serial order in behavior,” in *Cerebral Mechanisms in Behavior*, ed L. A. Jeffress (New York, NY: Wiley), 112–131.

Logan, G. D. (1979). On the use of a concurrent memory load to measure attention and automaticity. *J. Exp. Psychol. Hum. Percept. Perform.* 5, 189–207. doi: 10.1037/0096-1523.5.2.189

Marteniuk, R. G., MacKenzie, C. L., and Baba, D. M. (1984). Bimanual movement control: Information processing and interaction effects. *Q. J. Exp. Psychol. A* 36, 335–365.

Miller, G. A. (1956). The numerical magic seven plus or minus two: some limits on our capacity for processing information. *Psychol. Rev.* 63, 81–97. doi: 10.1037/h0043158

Muetzel, R. L., Collins, P. F., Mueller, B. A., Schissel, M. A., Lim, K. O., and Luciana, M. (2008). The development of corpus callosum microstructure and associations with bimanual task performance in healthy adolescents. *Neuroimage* 39, 1918–1925. doi: 10.1016/j.neuroimage.2007.10.018

Münte, T. F., Altenmüller, E., and Jäncke, L. (2002). The musician’s brain as a model of neurolasticity. *Nat. Rev. Neurosci.* 3, 473–478.

Nagel, J. I., Himle, D. P., and Papsdorf, J. D. (1989). Cognitive-behavioral treatment of musical performance anxiety. *Psychol. Music* 17, 12–21. doi: 10.1177/03057356891702

Nefel, K. A., Adler, R. H., Kappeli, L., Rossi, M., Dolder, M., Kaser, H. E., et al. (1982). Stage fright in musicians: a model illustrating the effect of beta blockers. *Psychosom. Med.* 44, 461–469.

Niemann, B. K., Pratt, R. R., and Maughan, M. L. (1993). Biofeedback training, selected coping strategies, and music relaxation treatments for musical-performance anxiety. *Int. J. Arts Med.* 2, 7–15.

Nube, J., and Musicobgy, M. A. (1991). Betablockers: effects on performing musicians. *Med. Probl. Perform. Art.* 6, 61–68.

Rammayer, T., and Altenmüller, E. (2006). Temporal information processing in musicians and
nonmusicians. *Music Percept.* 24, 37–48. doi: 10.1525/mp.2006.24.1.37

Repp, B. H., and Doggett, R. (2007). Tapping to a very slow beat: a comparison of musicians and nonmusicians. *Music Percept.* 24, 367–376. doi: 10.1525/mp.2007.24.4.367

Ridding, M. C., Brouwer, B., and Nordstrom, M. A. (2000). Reduced interhemispheric inhibition in musicians. *Exp. Brain Res.* 133, 249–253. doi: 10.1007/s002210000428

Rokni, U., Steinberg, O., Vaadia, E., and Sompolinsky, H. (2003). Cortical representation of bimanual movements. *J. Neurosci.* 23, 11577–11586.

Rumelhart, D. E., and Norman, D. A. (1982). Simulating a skilled typist: a study of skilled cognitive-motor performance. *Cogn. Sci.* 6, 1–36. doi: 10.1207/s15516709cog0601_1

Sadato, N., Yonekura, Y., Waki, A., Yamada, H., and Ishii, Y. (1997). Role of the supplementary motor area and the right premotor cortex in the coordination of bimanual finger movements. *J. Neurosci.* 17, 9667–9674.

Schlaug, G. (2001). The brain of musicians. A model for functional and structural adaptation. *Ann. N.Y. Acad. Sci.* 930, 281–299. doi: 10.1111/j.1749-6632.2001.tb05739.x

Schlaug, G., Jancek, L., Huang, Y., Staiger, J. F., and Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia* 33, 1047–1055. doi: 10.1016/0028-3932(95)00045-5

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychol. Rev.* 82, 225–260. doi: 10.1037/0003-066X.82.2.225

Schneider, P., Sluming, V., Roberts, N., Scherg, M., Goebel, R., Specht, H. J., et al. (2005). Structural and functional asymmetry of lateral Heschl’s gyrus reflects pitch perception preference. *Nat. Neurosci.* 8, 1241–1247. doi: 10.1038/nn1530

Serrien, D. J., Nirkko, A. C., and Wiesendanger, M. (2001). Role of the corpus callosum in bimanual coordination: a comparison of patients with congenital and acquired callosal damage. *Eur. J. Neurosci.* 14, 1897–1905. doi: 10.1046/j.1460-955x.2001.01798.x

Slobounov, S., Chianga, H., Johnstona, J., and Ray, W. (2002). Modulated cortical control of individual fingers in experienced musicians: an EEG study. *Clin. Neurophysiol.* 113, 2003–2024. doi: 10.1016/S1388-2457(02)00298-5

Stanton, H. E. (1994). Reduction of performance anxiety in music students. *Aust. Psychol.* 29, 124–127. doi: 10.1080/00050069408257335

Stephan, K. M., Birnboim, F., Posse, S., Seitz, R. J., and Freund, H. J. (1999). Cerebral midline structures in bimanual coordination. *Exp. Brain Res.* 128, 243–249. doi: 10.1007/s002210050844

Sweeney, G. A., and Horan, J. J. (1982). Separate and combined effects of cue-controlled relaxation and cognitive restructuring in the treatment of musical performance anxiety. *J. Couns. Psychol.* 29, 486–497. doi: 10.1037/0022-0167.29.5.486

Watson, A. H. D. (2006). What can studying musicians tell us about motor control of the hand? *J. Anat.* 208, 527–542.

Zatorre, R. J., Chen, J. L., and Penhune, V. B. (2007). When the brain plays music: auditory-motor interactions in music perception and production. *Nat. Rev. Neurosci.* 8, 547–558. doi: 10.1038/nrn2152

Received: 01 June 2013; accepted: 11 July 2013; published online: 31 July 2013.

Citation: Globerson E and Nelken I (2013) The neuro-pianist. *Front. Syst. Neurosci.* 7:35. doi: 10.3389/fnsys.2013.00035

Copyright © 2013 Globerson and Nelken. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) or licensor are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.