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Adaptations During the Acquisition of Expertise

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Abstract: For a long period, outstanding performance in complex domains was explained by innate abilities. Research on expertise questioned this assumption and showed that performance can tremendously be influenced by intensive deliberate practice. Evidence about the plasticity of the human mind and body suggests that the acquisition of expertise should rather be described as process of specific adaptations to typical tasks of the domain rather than as development of pre-existing innate abilities. Cognitive adaptations have been addressed in research on expertise for nearly half a century, whereas the investigation of physiological and neural adaptations as result of deliberate practice in specific domains is still at its beginning. Recent developments in sciences like neuroscience, training and exercise theory, physiology, or neurology, open new theoretical and technical possibilities to investigate such adaptations. Neuroimaging methods allow empirical analyses of functional and structural (anatomical) changes of the brain as result of intensive domain-specific practice. In this article, recent research concerning motor, physiological and neural plasticity is reviewed. Considerations are suggested how such research might influence educational issues of supporting the acquisition of expertise.

Keywords:

adaptations, deliberate practice, expertise, functional neural plasticity, physiological plasticity, structural neural plasticity

Expertise: Mental and Physical Excellence

Outstanding performers in music, sport and many other domains have fascinated both the public and researchers of different fields since centuries, but the rapidly growing availability of information technologies (television, internet, etc.) has even increased the interest in understanding what stars are made of. Their unbelievable excellence compared to average individuals or even "normal" professionals easily leads to the assumption that innate (or even god-given) abilities play a major role. Stars are considered to be humans of a different nature, and sometimes it is even assumed that they reached their level of performance effortlessly. Among the most famous examples are Usain Bolt and Wolfgang A. Mozart – obviously domains like music, arts, or sport are particularly prone to "innate ability explanations". In the 16th century humanists attributed the excellence of artists and scientists to innate divine gifts, and confirmation was delivered by 19th century biological and genetic theories, when for example Galton found close associations between the level of performance and heritable differences in the nervous system and in the size and structure of the brain (Ericsson, 2005).

The assumption of innate abilities was questioned in the very moment, when domain-specific and general abilities of subjects of different levels of excellence were investigated systematically. The seminal work of the Dutch psychologist DeGroot (1946) inspired a huge number of studies about the nature of expert performance. In particular after the "cognitive revolution" initiated by the development of the information-

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processing paradigm, many studies investigated problem-solving, search processes or memory recall of experts. Much empirical evidence was found that the experts' advantages were not based on a general superiority, but rather were restricted to the domain of expertise. This evidence shook the assumption of innate abilities to the core. Instead, theories about the acquisition of expertise emerged, as well as assumptions about the role of practice – usually extended practice over a period of several years – and its design ("deliberate practice"; Ericsson, Krampe, & Tesch-Römer, 1993), theories about experience-based restructuring of expert knowledge (Boshuizen & Schmidt, 1992), and about instructional support during the acquisition of expertise.

Deliberate training studies confirmed the enormous plasticity of human cognitive performance, so that limiting or enabling body, motor, physiological, neural or anatomical factors were not any more in the focus of research on expertise. The idea of (bodily) innate abilities lost its attraction, since the interest for modifiable cognitive measures and adaptations has become paramount.

One of the basic strategies in research on expertise is the contrastive approach. Subjects of different levels of performance in a given domain are identified and then compared according to variables which constitute the respective theoretical explanation of the nature of expertise. In most cases, two levels of expertise are identified, "experts" and "novices". The identification of experts is one of the most challenging difficulties in research on expertise. Ericsson, Roring, and Nandagopal (2007) argue that this problem can be avoided in domains in which the quality of performance can be measured rather easily and without controversial opinion, for example in running and swimming (time needed for a particular distance). The expert-performance approach is based on the definition of reproducible superior performance in real domain activities, in particular in representative tasks. Examples are the move-choice task in chess or the task to play the same piece of music twice in the same manner. In their handbook of research on expertise, Ericsson, Charness, Feltovich, and Hoffman (2006) collected a large number of theoretical foundations of the nature of expertise in different domains as well as empirical attempts to test these foundations. Much evidence is collected showing that superior reproducible performance generally emerges only after extended periods of deliberate practice that result in subsequent cognitive, motor, physiological and neural adaptations (Ericsson et al., 1993). It is important to note that deliberate practice is a particular kind of activity which aims solely at improving this activity. Deliberate practice thus is not inherently enjoyable, but requires a large amount of time. Unlike executing already acquired skills (like in competitions, concerts, etc.), such practice is not immediately rewarded with prizes or by social approval. The motivation inherent in the engagement in deliberate practice is often extrinsic in nature. The direction of the practice in order to reach beyond one's current level usually is based on the activities of "persons in the shadow of experts" (Gruber, Lehtinen, Palonen, & Degner, 2008) like trainers, teachers or coaches who contribute through the design of practice activities and through successive refinement of the activity by providing feedback. It is still under discussion, whether the nature of deliberate practice is similar in different domains. For example, Baker, Côté, and Deakin (2005) argued that some assumptions of the theory of deliberate practice, e.g. the notion of a monotonic relationship between practice and performance, might be specific to some domains, but not to others.

There is general agreement, however, that deliberate practice contributes to the acquisition of expertise, if a successful interaction of biological, psychological, and sociological constraints is achieved (Baker, Horton, Robertson-Wilson, & Wall, 2003). Expert performance thus primarily results from specific training and practice rather than innate talent. Ericsson and Ward (2007) argue that reproducible superior performance is mediated by substantial adaptations. Interestingly, body, motor, physiological, neural and anatomical factors thus re-emerge in research on expertise. Rather than constituting limiting or enabling factors for the development of expertise, they now are conceived as being influenced and formed through practice.

Acquisition of Expertise as Adaptation to the Requirements of the Professional World

The acquisition of expertise results from substantial adaptations to the typical task constraints of the domain (Ericsson & Lehmann, 1996), involving changes in cognitive, physiological, and perceptual-motor parameters that facilitate superior performance. Expert performance is mediated by cognitive and perceptual-motor skills, by domain-specific physiological and anatomical adaptations, and in particular by the complex interplay of these components. Laboratory analyses of expert performance in many domains provided evidence of cognitive adaptations of experts to domain-specific constraints. Recent developments in many sciences (e.g. neuroscience, training and exercise theory, physiology, neurology) opened new theoretical and technical possibilities to investigate the nature of expertise from different perspectives.

For example, the detailed recording of eye movements can be used to relate experts' visual processing and their reasoning. Assumptions about cognitive clustering of domain-specific information like those made in the pattern recognition theory can be verified by measuring fixations and thus regions of interest in experts' visual scanning of typical stimuli. Research on visual pattern recognition in medicine has been used to explain processes of the acquisition of expertise through data from recording of eye-movements (Krupinski et al., 2006). Medical imaging has since developed due to high rates of technological innovation, making it a priority in research and practice to explore competence development in new technological settings (Manning, Ethell, Donovan, & Crawford, 2005; Nodine, Kundel, Lauver, & Toto, 1996). Goulet, Bard, and Fleury (1989) showed that levels of expertise were systematically related with eye movements preceding domain-specific decisions. In tennis, experts mainly observe the shoulders and the body trunk of their opponent to anticipate the next ball to be played. In contrast, novices rather focus on the opponent's head. Accordingly, Paillard, Costes-Salon, Lafont, and Dupui (2002) found in a study in the domain of judo, that visual information was more substantial for judo experts than for others. Helsen and Starkes (1999) confirmed these results in a study conducted with experts from soccer. Superior visual information-processing is confined to the own domain of expertise (Abernethy, 1999; Abernethy, Neal, & Koning, 1994), although some selective transfer of pattern recall skills may be possible between related domains (e.g. netball and basketball; Abernethy, Baker, & Côté, 2005).

Adaptations in the movement are frequently found in sports. In dancing, the relation of movement and arts led researchers to investigate embodied cognition effects, imagery, and proprioception. Research on training and exercise effects in sports has analysed adaptations of the physiological systems in detail, e.g. an increase of the maximum oxygen consumption rate in endurance athletes (e.g. marathon runners), or an increase of muscular blood flow and thus muscle performance. The observed physiological and anatomical adaptations are closely related to practice and training schedules.

The advent of modern neuroimaging methods allowed empirical studies of the neuroplasticity assumption. Both functional and structural (anatomical) changes of the brain could be related to ongoing experience and, in particular, intensive practice periods of experts within their domain of excellence. In their review, Münte, Altenmüller, and Jäncke (2002) presented much evidence that the size and temporal organization of cortical representations of stimuli are continually shaped by experience. Many studies have been conducted since then, using traditional as well as novel brain-imaging tools. Functional Magnetic Resonance Imaging (fMRI) as a specific form of Magnetic Resonance Imaging (MRI) is still the most commonly used technique. Whereas MRI is based on the magnetic properties of the *hydrogen atoms* in the human brain, fMRI measures the differences in the magnetic properties of oxygenated and deoxygenated *haemoglobin* of the brain. When neural activity increases during motor or cognitive processing, more oxygen is consumed in the active nervous tissue. Dependent on the oxygen, haemoglobin has different magnetic properties, it is diamagnetic when oxygenated, but paramagnetic when deoxygenated. The difference in these two magnetic properties leads to differences in the magnetic resonance signal of the blood flow, called BOLD ("Blood Oxygenation Level Dependent"). It is measured when participants or patients lie in a magnetic resonance tomograph and were exposed to an intense and homogeneous magnetic field. If the focus of interest lies more on metabolic processes, e.g. the turnover-rate of neurotransmitters, Positron-Emission-Tomography (PET) is commonly used: In PET, a tracer is injected and circulates with blood flow to the brain. Here, the tracer emits pairs of gamma rays which are measured by a scanner. This allows calculating the local distribution of the emitting tracer and as a consequence the locus of highest tracer activity, be it due to metabolic processes or to mere blood flow. Beside these imaging-techniques, which only indirectly measure neural activity, magneto- and electroencephalography are two non-invasive techniques to directly measure the activity of the neurons in the brain. They both are related, MEG measures magnetic fields which are generated by electrical currents in neurons; EEG measures the electrical potentials.

Not only motor areas however are subject to structural adaptation. By means of magnetoencephalography (MEG), the number of nerve cells involved in the processing of auditory or somato-sensory stimuli can be estimated.

Non-invasive electrophysiological and imaging techniques are increasingly used to investigate function and structure of the body and the brain. Whereas electrophysiological techniques have a high temporal resolution, brain imaging techniques have a superior spatial resolution. Using these techniques it was shown that adaptive changes of these features are clearly related to training and practice (Landau, Schumacher, Garavan, Druzgal, & d'Esposito, 2004; Nielsen & Cohen, 2008). This sheds new light on the discussion of "innate or acquired" capabilities. There is much evidence that practice contributes to physiological and neural adaptations, in particular from the musical domain.

Physiological and Neural Plasticity: How Practice Leads to Adaptations

Physiological adaptations are an everyday phenomenon and happen in response to habitual usage of our bodies, e.g. the growth of muscles after running training. Lehmann and Gruber (2006) showed in their review that musicians undergo a number of adaptations, for example in forearm rotation of violinists, in vital and total lung capacities of singers, or in inhalation and expiration pressures of trumpet players.

In the central nervous system, a series of studies showed that pre-attentive processing of musical stimuli is improved through practice and experience. Measures of event-related potentials (ERPs) indicated that auditory grouping and segmentation of sounds depend on musical skill (Koelsch, Schröger, & Tervaniemi, 1999; van Zuijen, Sussman, Winkler, Nätäänen, & Tervaniemi, 2004). Musicians differ from non-musicians in event-related brain potentials (ERPs) and event-related magnetic fields (ERFs) while listening to melodies (James, Britz, Vuilleumier, Hauert, & Michel, 2008; Neuhaus, Knösche, & Friederici, 2006). Musicians processed the phrases in a highly structured way which reflects complex cognitive processes of phrasing, while non-musicians rather detect discontinuations in the melody. Münte and colleagues (2003) conclude from a number of ERP studies that qualitative differences of the neural correlates of auditory processing between musicians and non-musicians exist.

Physical exercise facilitates reaction times and decision-making in sports (Davranche, Audiffren, & Denjean, 2006). Subjects increased their performance in a choice reaction time task during moderate sub-maximal exercise compared to a rest condition. It was argued that the effect of exercise on cognitive performance was due to a major generalized improvement of the whole distribution of response time. In a study on motor learning, Doyon et al. (2002) found evidence of an experience-dependent shift of activation from a cerebellar–cortical to a striatal–cortical network with extended practice. Experts in rifle shooting showed a refinement and increased efficiency of cerebral cortical activity which facilitated visuomotor performance (Hung, Haufler, Lo, Mayer-Kress, & Hatfield, 2007).

Evidence of experience-based adaptations in motor and physiological components of complex activity exists in many areas in which motor skills are involved, e.g. in sports. In a review of adaptations of the muscular and nervous system after prolongued activity (e.g. strength training), Enoka (1997) reported many effects concerning maximal recruitment, specificity, and temporo-spatial pattern of the neural efferences to muscles.

Most suggestions derived from training and exercise sciences in sports are based on assumptions about substantial adaptations of the cardiorespiratory and neuromuscular systems that enhance the delivery of oxygen from the atmosphere to the mitochondria and enable a tighter regulation of muscle metabolism. Particularly in endurance sports (like marathon running), many effects have been reliably investigated and transferred into training programs (Jones & Carter, 2000). There is a growing body of evidence, that deliberate practice has substantial impact not only on body processes and physiological systems, but also on the brain. In research, it is plausible to differentiate between functional and structural (anatomical) neural plasticity.

The Brain: Functions and Structures – A Brief Overview

As mentioned, the acquisition of expertise is accompanied by functional and structural (anatomical) changes of the brain. The described brain imaging techniques such as high-resolution magnetic resonance imaging (MRI) allow the study of structural neural plasticity. With respect to research in expertise, the most important brain structures and functional systems are the cerebral cortex, the cerebellum, the limbic system, the basal ganglia and the brain stem. The cerebral cortex is the largest part of the brain and divided into four so-called lobes, the frontal, temporal, occipital and parietal lobe. The four lobes are associated with different functions. The frontal lobe plays a prominent role in motor control, reasoning and problem solving. One part of the frontal lobe is the motor cortex (primary and secondary motor cortex). The secondary motor cortex can be divided into the premotor cortex, the motor parts of the cingulate gyrus and the supplementary motor area. The temporal lobe is associated with auditory perception, speech and memory, the occipital lobe with visual processing and the parietal lobe with somatosensory processing and orientation among others. The cerebrum is divided into two halves - the two specialized hemispheres. Even though the cerebellum is at first glance similar to the cerebrum with its two hemispheres and the folded surface, it is much smaller and mainly associated with maintenance of body equilibrium, and fine motor coordination. The main parts of the limbic systems are the thalamus, the hypothalamus, the amygdala and the hippocampus. All of them have different functions, for example the amygdala is involved in emotional behaviour and the hippocampus in learning, memory and spatial cognition. The basal ganglia play an important role in movement automation and action selection. Among the areas that were found to be affected in structure during the acquisition of expertise are the primary motor cortex (at the posterior part of the frontal lobe), the planum temporale (posterior to the auditory cortex), and anterior part of the corpus callosum (the band between the two hemispheres) (Bangert & Schlaug, 2006; Schlaug, 2006).

Functional Neural Plasticity

Brain plasticity is best observed in complex tasks with high behavioural relevance for the individual such that they cause strong emotional and motivational activation. Plastic changes are more pronounced in situations where the task or activity is intense and the earlier in life it has been developed. Some evidence was provided from sport domains. For example, Kim et al. (2008) demonstrated that expert and novice archers differed in levels of brain activation during the pre-performance routine period of a simulated archery task. When the experts were aiming, the occipital gyrus and temporal gyrus were activated; in novices' simulations, mainly the frontal area was activated. (In both groups, the anterior cingulate and posterior cingulate gyrus of the limbic lobe were activated.) Obviously, the continued activities of professional musicians provide the prerequisites of brain plasticity in an ideal manner. It is therefore not astonishing that the most dramatic brain plasticity effects have been demonstrated in professional musicians.

The first study that received widespread attention was one that found that the cortical representation of the fingers of the left hand in string players was enlarged compared to that of the thumb and compared to non-musicians controls (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995). Further contrastive studies showed that cortical reorganization was not restricted to playing music but also occurred when listening. Pantev, Roberts, Schulz, Engelien, and Ross (2001) showed that larger areas of the cortex were activated involuntarily when musicians listened to tones of instruments they played (see also Pantev, Engelien, Candia, & Elbert, 2006; Pantev, Ross et al., 2006). Sensorimotor-auditory training in playing an instrument caused more pronounced plastic reorganization in the auditory cortex auditory than auditory training alone (Lappe, Herholz, Trainor, & Pantev, 2008). Expert conductors develop enhanced auditory localization mechanisms, as Münte, Kohlmetz, Nager, and Altenmüller (2001) found.

Evidence exists about a functional connection between auditory and motor cortices during the learning of a novel music piece. For example D'Ausilio, Altenmüller, Belardinelli, and Lotze (2006) observed an increase of motor excitability over time related to intracortical facilitation. Transcranial magnetic stimulation of the cortical motor representation involved in musical performance of piano players was compared in two conditions: (a) during auditory presentation of a rehearsed piece, (b) during the auditory presentation of a non-rehearsed piece. The increased motor excitability was found only for the rehearsed piec

Schwenkreis et al. (2007) found a close relation between motor performance and hand representation in the primary motor and somatosensory cortex of professional violin players. The enlargement of the left hand representation in the sensorimotor cortex was clearly use-dependent. As these cortical asymmetries were not related to analogous asymmetries at a behavioural level, Schwenkreis et al. (2007) conclude that the functional reorganization is task-specific rather than general in terms of improved motor abilities.

Bangert et al. (2006) studied the interplay of cortical auditory and motor coupling in professional pianists using a passive task paradigm. Subjects had to either passively listen to short piano melodies or press keys on a mute MRI-compliant piano keyboard. Experts showed larger auditory-sensorimotor integration, measured by activity in a distributed cortical network during both, the acoustic and the mute motion-related task. This network is comprised of dorsolateral and inferior frontal cortex (including Broca's area), the superior temporal gyrus (Wernicke's area), the supramarginal gyrus, and supplementary motor and premotor areas. The link between auditory and motor networks seems to be relevant even when the subjects' task involves only auditory or only motor processing. In the same sense Haueisen and Knösche (2001) argued that pianists listening to well-trained piano music exhibit covert (unconscious) contra-lateral primary motor cortical activity. Lotze, Scheler, Tan, Braun, and Birbaumer (2003) found related co-activation patterns in expert violinists (compared to novices) while tapping out a well-trained concerto. Analogous patterns were found in a quite different domain, dancing. Calvo-Merino, Glaser, Grèzes, Passingham, and Haggard (2005) presented a study in which they showed that the simulation or observation of movements can elicit complex brain activities; the size of activation was larger when the dancing style was observed which corresponded to one's own field of expertise compared to a different dancing style (classical ballet vs. capoeira dancing). Cross, Hamilton, and Grafton (2006) found even evidence that not only the viewing of a complex well known movement led to an increased neural activity but also the viewing of a newly learned movement pattern compared to the viewing of an unlearned movement. This effect could also be found for the imagination of newly learned movement patterns, which seems to be an early indicator of expertise development.

Extensive practice contributes to an increased efficiency of cortical and sub-cortical systems for bimanual movement control in musicians (Haslinger et al., 2004). This may be fundamental to achieve high-level motor skills allowing the musician to focus on artistic aspects of musical performance. Bimanual motor coordination is essential for piano playing. When expert pianists carried out in-phase (*mirror*) and anti-phase (*parallel*) bimanual sequential finger movements – an activity that corresponds to bimanually playing scales practiced daily by pianists – they showed significantly different functional activation patterns than non-musicians. Comparisons of bimanual parallel to mirror movements suggested stronger signal increases in non-musician than in experts in a number of brain areas (mesial premotor cortex (SMA), bilateral cerebellar hemispheres and vermis, bilateral prefrontal cortex, left ventral premotor cortex, right anterior insula, right basal ganglia).

Debaere, Wenderoth, Sunaert, van Hecke, and Swinnen (2004) argued that bimanual skill learning is associated with a shift in activation among cortico-subcortical regions. There seems to be a transition during the acquisition of skills from highly attention-demanding task performance, involving processing of sensory information and corrective action planning, to automatic performance based on memory representations and forward control.

Structural Neural Plasticity

A comparison of the brain anatomy of expert musicians with that of non-musicians shows that prolonged instrumental practice leads to an enlargement of the hand area in the motor cortex (Amunts et al., 1997) and to an increase in grey matter density corresponding to more and/or larger neurons in the respective area (Gaser & Schlaug, 2001, 2003). These adaptations appear to be particularly prominent in all instrumentalists who have started to play prior to the age of ten and correlate positively with cumulative practice time.

Furthermore, in professional musicians, the normal anatomical difference between the larger, dominant (mostly right) hand area and the smaller, non-dominant (left) hand area is less pronounced when compared to non-musicians. These results suggest that functional adaptation of the gross structure of the brain occurs during training at an early age.

Similar effects of specialization have been found with respect to the size of the corpus callosum. Professional pianists and violinists tend to have a larger anterior (front) portion of this structure, especially those who have started prior to the age of seven (Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995). Since this part of the corpus callosum contains fibres from the motor and supplementary motor areas, it seems plausible to assume that the high demands on coordination between the two hands and the rapid exchange of information may either stimulate the nerve fibre growth – the myelination of nerve fibres that determines the velocity of nerve conduction – or prevent the physiological loss of nerve tissue during aging.

Using MEG techniques, professional violinists were shown to possess enlarged sensory areas corresponding to the index through to the small (second to fifth) fingers of the left hand (Elbert et al., 1995) even though their left thumb representation is no different from that of non-musicians. Again, these effects were most pronounced in violinists who started their instrumental training prior to the age of ten.

A further example of functional specialization reflected by changes in gross cortical anatomy can be found in musicians possessing absolute pitch. In these musicians the upper back portion of the left temporal lobe (Wernicke region) is larger in comparison to those musicians without absolute pitch (Schlaug, Jäncke, Huang, & Steinmetz, 1995). Using

MEG, the functional specialization of the auditory cortex was demonstrated by Pantev et al. (1998). When compared to subjects who had never played an instrument, the number of auditory nerve cells involved in the processing of piano tones, but not of pure sinusoidal tones, was about 25% greater in pianists. Bengtsson et al. (2005) found an increase in the size of the posterior part of the corpus callosum in professional pianists. This finding seems to correspond to a more effective connectivity between the left and right auditory regions in the respective temporal lobes.

Asymmetry of the planum temporale was suggested as a marker of cerebral dominance, because its direction and size correlate with handedness (Jäncke, Schlaug, Huang, & Steinmetz, 1994). Musicians with absolute pitch (AP) had a more pronounced leftward planum temporale asymmetry than other subjects (Keenan, Thangaraj, Halpern, & Schlaug, 2001; see also Aydin et al., 2005; Ohnishi et al., 2001).

Exceptional musical performance requires the high-speed control of complex movement patterns under continuous auditory feedback. As a prerequisite, audio-motor integration at cortical and probably sub-cortical levels has to be established. Such audio-motor coupling is related with a larger anterior midsagittal corpus callosum. Because the size of the midsagittal corpus callosum is a good indicator of the number of axons that cross the midline, this finding indicates that this subgroup of musicians has an enhanced interaction between the two hemispheres. This hypothesis was supported by a bilateral transcranial magnetic stimulation (TMS) study in pianists and guitarists (Ridding, Brouwer, & Nordstrom, 2000), which revealed decreased interhemispheric inhibition. This, in turn, might facilitate bimanual coordination in musicians by increasing signal transfer between the hemispheres.

The precise timing of movements also requires the participation of the cerebellum (Hutchinson, Lee, Gaab, & Schlaug, 2003). Koeneke, Lutz, Wüstenberg, and Jäncke (2004) studied cerebellar hemodynamic responses in expert keyboard players and non-musicians during complex tasks requiring unimanual and bimanual finger movements. Both groups showed strong hemodynamic responses in the cerebellum during the task conditions, but the non-musicians' hemodynamic responses in the cerebellum were generally stronger than keyboard players'. Due to long-term motor practice a different cortical activation pattern can be visualized in keyboard players. For the same movements fewer neurons need to be recruited. The different volume of the activated cortical areas might therefore reflect the different effort necessary for motor performance in both groups.

Adkins, Boychuk, Remple, and Kleim (2006) studied structural changes in the motor cortex and spinal cord. Evidence is reported that the corticospinal system is not only plastic but that its nature and locus are consequences of the motor experiences and of specific behavioural demands of the tasks worked out through practice. The acquisition of expertise obviously induces a reorganization of neural circuitry within motor cortex that supports the production and refinement of skilled movement sequences. This process might be mediated by an increased capacity for activation and/or recruitment of spinal motoneurons.

Although most evidence of structural adaptations as result of experience and learning exists in musical domains, there are widely differing domains under investigation as well: Juggling (Draganski et al., 2004), mathematics (Aydin et al., 2007), or taxi-driving (Maguire et al., 2000). It seems that research is still at its very first attempts to discover how training affects cognition, body, physiology, and anatomy. An extremely interesting new aspect is that these plastic adaptations seem not to be restricted to younger age, but take also place in elderly probands although to a lesser degree. Using the same training in juggling as in the 2004 Draganski publication, Boyke et al. (2008) found in 60 years old seniors after three months an increase in size of various brain structures involved in visuo-motor control, memory and motivation.

Conclusion: Fostering the Acquisition of Expertise

Although much evidence has been accumulated during the last ten or 15 years about physiological and neural adaptations during the acquisition of expertise, the understanding of the molecular and cellular mechanisms underlying these adaptations is still far from complete. Brain plasticity may occur on different time axes. For example, the efficiency and size of synapses may be modified in a time window of seconds to minutes, the growth of new synapses and dendrites may require hours to days. An increase in grey matter density, which mainly reflects an enlargement of neurons, needs at least several weeks. White matter density also increases as a consequence of musical training. This effect is primarily due to an enlargement of myelin cells: The myelin cells, wrapped around the nerve fibres (axons) are contributing essentially to the velocity of the electrical impulses travelling along the nerve fibre tracts. Under conditions requiring rapid information transfer and high temporal precision these myelin cells grow and as a consequence nerve conduction velocity increases. Finally, brain regions involved in specific tasks may also be enlarged after long-term training due to the growth of structures supporting the nervous function, for example, in the blood vessels that are necessary for the oxygen and glucose transportation to sustain nervous function.

It is thus premature to expect that research about experience-based adaptations can directly be applied in training programs which aim to support deliberate practice activities delineated by trainers, teachers, or coaches. There are a number of promising suggestions, however, how training and learning issues might be enriched through activities aiming at the harmonized adaptation of cognitive, physiological and neural processes. Most evidence comes from the domain of music.

A special quality of musicianship is the strong coupling of sensorimotor and auditory processing required for performing music. Practicing an instrument involves assembling, storing, and constantly improving complex sensory-motor programs through prolonged and repeated execution of motor patterns under the controlled monitoring of the auditory system. In a cross-sectional experiment, strong linkages between auditory and sensory-motor cortical regions as a result of many years of practice have been reported (Bangert et. al., 2006). Furthermore, in a longitudinal study, it was possible to follow up the formation of such neuronal multisensory connections along with piano training in beginning pianists (Bangert & Altenmüller, 2003). Non-musicians, who had never played an instrument before, were trained on a computer piano twice a week over a period of five weeks. They listened to short piano melodies of a three-second duration played in a five-tone-range, and were then required, after a brief pause, to replay the melodies with their right hand as accurately as possible. After 20 minutes of training, first signs of increased neuronal coupling between auditory and motor brain regions were observable. After five weeks, listening to piano tunes produced additional activity in the central and left sensorimotor regions. In turn, playing on a mute (soundless) keyboard produced additional activity in the auditory regions of both temporal lobes. This experiment impressively demonstrates how dynamically brain adaptations accompany these multi-sensorimotor learning processes.

Activation of motor co-representations can occur in trained pianists not only by listening to piano tunes, but also by observing a pianist's finger movements while watching a video. Besides the motor hand area in the primary motor cortex, secondary auditory cortices in the temporal lobe and the cerebellum are activated. As a consequence for musical practice, it follows that careful demonstration at the instrument may enhance learning. Such a teaching method based on demonstration and imitation is widely used at all levels of musical training, and would appear to be particularly effective in cases where teachers demonstrate an action or series of actions that are carefully and methodically observed by the student. The use of neuroimaging methods is most prominent in music, but a number of related studies has been published in different domains as well (Jansen-Osmann, 2008). Cross et al. (2006) support the assumption that mental training plays an outstanding role in sport. This assumption already had been confirmed by an early meta-analysis of Feltz and Landers (1983). Analyzing 60 studies, the authors revealed a middle-sized effect of mental training. This effect is especially high if the task is well known and includes a cognitive component.

Practicing through listening and/or observation can be considered as special cases of mental training. Narrowly defined, mental training is understood as the vivid imagination of movement sequences without physically performing them. As with observation of actions, principally the same brain regions are active as if the imagined action is performed; that is, the primary motor cortex, the supplementary motor cortex and the cerebellum (Kuhtz-Buschbeck et al., 2003). In a study investigating mental training of finger movement sequences of different complexities, brain activation increased along with the degree of difficulty of the imagined motor task. Furthermore, when continuing mental practice over a period of several days, the involved brain regions showed plastic adaptations. Although these adaptations are less dramatic than if the motor tasks were practiced physically, mental training produced a clear improvement in task performance as assessed in finger tapping tests.

Taken together, the relation between mental and physical components of expert performance seems to return into researchers' and educationalists' attention. The question is not, however, to what extent innate or acquired abilities are paramount. Whereas at the end of the 19th century and during the 20th century anatomical correlates of excellence were analysed in order to find evidence for outstanding innate abilities through anatomical post-mortem brain analyses of gifted individuals, nowadays' neuroimaging techniques help to develop new approaches. They provide the chance to investigate functional and structural adaptations of the brain which result from, rather than cause, skill acquisition (Stewart, 2008). Experts provide an outstanding possibility to study the role of experience in sculpting brain processes.

In their review, Habib and Besson (2009) conclude, that musical expertise, often linked to early and intensive learning, is associated with neuroanatomical distinctive features in several brain regions, all more or less involved in gestural motor skill. Thus they probably are related to the use of a specific instrument which indicates that experience shapes the brain – rather than providing evidence for innate abilities or talents. Habib and Besson (2009) discuss the evidence that brain plasticity can be found more clearly if practice starts early. For many kinds of music expertise, a "sensitive period" might exist, at around 7 years of age, beyond which music-induced structural changes and learning effects are less pronounced. Unfortunately, such studies are missing in sport science. The consequences for (expert) training, for education in general or even for special education are still vague – which opens a broad avenue for future research.

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