

**Processing speed and motor planning: the scientific background to the skills trained by Interactive Metronome® technology.**

**Susan J. Diamond, Ph.D. Dec. 2003**

Dr. Susan Diamond is a licensed psychologist in private practice in British Columbia. She specializes in remediation of learning difficulties and attention deficit disorder. She is a member of CPA & APA. She has spent thirteen years studying the psychophysiology of learning, including brain electrical activity and educational kinesiology, and is a new user of Interactive Metronome. Email to [diamonds@intergate.bc.ca](mailto:diamonds@intergate.bc.ca)

This paper will summarize scientific findings that explain why a movement based repetition program, made with feedback in millisecond precision, might be influential in improving brain efficiency, and hence, cognition. This paper was volunteered independently, by its author, to answer queries about the brain interactions behind this technique. Interactive Metronome® (IM) likely increases speed of brain processing, and reduces “noise” or variability, making it more efficient as a signal processor. Efficient signal processing has been demonstrated to be associated with higher IQ scores (e.g. Jausovec, 2000, 2001), and better task performance (e.g. Siffit & Khalsa, 1991). These points will be developed below.

This author has reviewed the literature for brain plasticity, hemispheric interaction, motor planning, attention, memory and language, the role of the evoked potential electrical signal, and the role of soft signs. The psychophysiology of learning is not well understood in psychology and education, and rarely taught in graduate schools. This is a brief overview of key studies that help explain the role of a movement re-education program in learning (for an in-depth review, see Diamond 2003 a, b). Objectives of this paper include that: clinicians understand specific processing difficulties faced by ADHD subjects in daily activity (most instructions include a movement component); review the specific brain structures and networks activated by a systematic movement menu; and, identify sources in the scientific literature for further study. A review of motor difficulties in ADHD is included.

The ability of the brain to reorganize, through plasticity, has been established (see Clifford, 1999), as is the idea that a well exercised brain retains cognitive function and myelinates through the lifespan (see McDowell et al, 2003). These factors are important to the rationale of movement, efficiency and integration technologies, such as Interactive Metronome® or Educational Kinesiology techniques. Computer based functional brain imaging techniques such as MRI, PET scans and regional cerebral blood flow studies have demonstrated very specific networks of brain activation associated with contralateral and homolateral body movements. Motor maps elaborate in very specific ways, as tasks are learned, and look quite different in people who have achieved mastery than they do in novices. An example is the brain of an expert musician. Hundreds of studies, using many neuroimaging techniques, examine brain activation upon specific movements, its effects on within-and-inter-hemispheric function, and differences for successful versus unsuccessful task completion. A few are described here.

*What brain regions are activated by a precise menu of movements?*

Sanes and Donoghue (2000) have written a review article on plasticity and the motor cortex. They make the points that primary motor cortex (MI) controls voluntary movements, through distributed networks not discrete representations, and that they are capable of modification in adult mammals. MI representations and cell properties show considerable plastic changes, with everyday experiences “including motor skill learning and cognitive experience.” The substrate for this map reorganization is probably intrinsic horizontal connections in MI, which show activity dependent plasticity (Sanes & Donoghue, 2000). Sadato and colleagues (1996) studied regional cerebral blood flow (rCBF), an important index of brain metabolism, in simple and complex sequential finger movement tasks. They found these tasks to equally, and consistently, activate the following regions: bilateral primary sensorimotor area, left ventral premotor cortex, posterior supplementary motor area, right superior part of the cerebellum, and left putamen. Brodman’s area 6- right dorsal premotor cortex, and right precuneus, Brodman area 7, which show increased activation as complexity increased. Possibly these areas help with storage of motor sequences in spatial working memory and in producing ongoing sequential movement with reference to that of buffered memory. Cerebellar vermis and left thalamus activity also increased with complexity, and left inferior parietal lobule decreased at that time (an area associated with short term phonological storage).

Numerous studies of brain activation in bimanual coordination (finger movement) tasks have been done. Stephan et al (1999) used functional magnetic resonance imaging (fMRI) to study finger to thumb movements, noticing a strong contralateral activation of primary sensorimotor cortex, with midline activity lateralized to the left in right-hand movements and to both sides in left-hand movements. Frontal midline activity was not specific only to bimanual movements but even operates in unimanual movements and increases in complex movement control tasks. When studying the cyclical coordination of ipsilateral (same side) wrist and foot movements using fMRI, (Debaere et al., 2001) found that for flexion-extension movements of foot, and wrist to an auditory paced rhythm, a distributed network was responsible for inter-limb coordination activities. Activations involved the supplementary motor area (SMA), cingulate motor cortex, primary sensorimotor cortex, premotor cortex, and cerebellum. These activations exceeded the sum of each action independently. Coordination of limbs in different directions activated the SMA more than movement in similar directions. The SMA is suggested to be more important for less stable, parallel, instead of mirror movements, and its role may be for higher-order on-line planning of movement sequences as well as their execution (Debaere et al, 2003). These are similar tasks to the IM program, and the activation has been shown to be greater than the sum of parts (see also Karni et al, 1995).

*motor planning is intimately connected to sensory processes*

Rossini and Pauri (2000) says that the use of sensory perception to assess motor plans involves large brain areas. These include the primary somatosensory, visual, motor, cortices as well as secondary sensory and motor areas. “Basal ganglia and thalamic relays significantly contribute to motor planning, sensory performance and sensorimotor integration. Supplementary motor and premotor cortices have a pivotal role in motor preparation and execution which, on their own, are carried out via corticospinal fibres

from primary motor cortex. Cerebellar relays constantly monitor the motor output and motor execution.” Movement is controlled by a network of neurons distributed throughout the MI (motor) cortex. There are both spatial and temporal overlaps of multiple representations underlying the motor functions (reference in Rossini and Pauri, 2000). Sensory flows modulate both excitatory and inhibitory mechanisms of motor cortical circuits. Neural re-organization, in event of accident, is assisted or inhibited by this fact. Plastic reorganization during sensorimotor learning is accomplished by: changes in neuronal membrane excitability, removal of local inhibition, or by changes in synaptic efficacy (excitatory, based on Sodium/Potassium channels, for short term changes, and, on Long Term Potentiation as well as NMDA receptor activation for longer changes. Potentiation and inhibition significantly affect the “amplitude of cortico-cortical EPSP’s, IPSP’s, and reflect the changes of synaptic efficiency” (Rossini and Pauri, 2000).

*Learning acquisition and retrieval stages differ, and are influenced by which side of body is engaged.*

Sakai’s results suggest that the acquisition of visuomotor sequences requires frontal activation and the retrieval of visuomotor sequences requires parietal activation, which might reflect the transition from the declarative stage to the procedural stage (Sakai et al, 1998). Jancke et al (2000) studied bimanual and unimanual hand activations in tapping tasks at variations in speed, and is an excellent resource. SMA and SMC activations were studied. SMA should strongly activate to tasks which involve both sequencing and bimanual integration. Results indicated a marked activation, not asymmetrical, for the bimanual task, with a rate effect (SMC contralateral to the faster hand is activated most). SMA is more responsive to bimanual than unimanual activity. SMA activations appear to favor the left hemisphere consistent with theory that there is a functional asymmetry in right-handers and that the left hemisphere is therefore more prominently involved in motor planning than the right hemisphere. (Jancke et al., 2000, cites Ajersch & Milner, 1983; Peters, 1985; Liepman, 1905).

*Widespread task activations occur with even simple movements, and affect brain activities including memory and sequencing as well as sensory input areas.*

A study by deGuise et al (1999) indicated the importance of the corpus callosum and the frontal cortical areas for the procedural learning of a visuomotor skill. Bimanual and unimanual key pressing to a visual stimuli prompt with recall tasks, to assess knowledge of the sequence was established. Visuomotor learning is “a subdivision of procedural memory which refers to the ability to acquire a motor skill or cognitive routine through practice (Cohen & Squire, 1980). This acquisition is expressed by significantly reduced reaction time or errors over trials. This type of memory can be dissociated from declarative or explicit memory, which is the ability to store and consciously recall or recognize data in the form of words, visual pictures or events (Tulving, 1983; Squire, 1986).”

The two types of memory are anatomically independent. The declarative memory system, is mediated by a corticorhinothalamocortical circuit (see Mishkin and Appenzeller, 1987); and the procedural memory system, about which, less is known. Frontal lobes are implicated in skill acquisition especially for ordered sequences (Moscovitch et al, 1993), programming of spatial learning (Vilkki and Holst, 1989), and

bimanual coordination of parallel movements (Pascual-Leone et al, 1994, all cited by de Guise et al, 1999). “The frontal cortex is known to have strong projections to the striatum. The striatum, on its part, projects to the internal portion of the globus pallidus, which in turn projects to thalamic nuclei. The latter projects back to the frontal area of origin (Heilman and Watson, 1991). Unilateral visuomotor learning requires the integrity of these structures as well as that of the cerebellum” (see de Guise). Transfer of unilateral procedural learning seems to require the integrity of the corpus callosum, which would connect the two separate neural loops. By studying which types of learning were possible in subjects with various callosal damage, authors have concluded that the frontal lobes were important for unilateral procedural learning and that the anterior part of the corpus callosum, which connects these lobes, is crucial for integration and transfer of a procedural visuomotor skill. Declarative and procedural systems, as Squire reported in 1992, are in fact independent (de Guise, 1999).

*Motor routines alter hemispheric interactions in specific ways*

Inter-hemispheric coupling was studied in a task involving learning bimanual coordination (Gerloff, 2002). Establishment of a motor routine, as the task is mastered, is associated with dynamic changes in the hemispheric interaction. In learning a novel task, the hemispheric interaction is especially important in the early phase of command integration. In the repetition of mastered sequences and in the learning of a uni-manual task, it is not so important. It is the novel task that is affected in this way since mastery does not depend on the inter-hemispheric coupling. Probably, once learned they become part of a motor routing. A modulation of inter-hemispheric communication is inferred that may regulate the reduction (inhibition) of mirror movements and suppresses (through GABAergic neurons transcallosal projections), the previously learned but not applicable, coordination tendencies (Gerloff, 2002).

*The role of the corpus callosum:*

Knyazeva et al., (1994) studied children using EEG measures, to understand the hemispheric interaction in speeded finger tapping with one and both hands. They found that inter-hemispheric alpha coherence levels can be regarded as an index of the inter-hemispheric activity in bimanual tapping. Geffen et al (1994) studied the control between the hemispheres in manual motor activity, reviewing findings in callosal patients. The corpus callosum does not seem to transfer explicit motor commands. Instead, it seems to transfer *premotor* commands, transferring lateralized information like verbal or visuospatial activity. Once movement begins, it also sends motor signal and feedback sensory signals to control bimanual movements that are not synchronized, and to inhibit the opposite hemisphere from interfering when a simple unimanual movement is required. This is a process of transfer of motor commands from one hemisphere to the other. There is a separate programming in each hemisphere of motor-act planning, and an asymmetrical transfer of information between the hemispheres. Transfer from the right to the left hemisphere is faster than the reverse (Geffen et al.1994, cites Marzi et al, 1991; Balfour et al, 1992).

Motor commands are transferred smoothly through excitatory or inhibitory processes. Bimanual movements require sensory feedback about the movement (vision,

proprioception). This sensory information is transferred by the corpus callosum, and each hemisphere is informed of the output of the other through the corpus callosum, too. This process is verified by transcranial magnetic stimulation study of interhemispheric transfers between motor cortex areas (Meyer et al 1995). If one motor cortex is stimulated it reliably leads to transcallosal inhibition of the other motor cortex in normal subjects.

The corpus callosum continues to develop through at least the first decade of life, so inter-hemispheric communication is limited by the functional capacities of the immature brain. This restriction has been demonstrated in many studies (see Knyazeva et al, 1994). Relatively independent functioning of the two hemispheres can be assumed prior to age 6-8. Late maturing brain structures include the frontal cortical areas and the rostral callosum (Knyazeva, 1994). The posterior part of the corpus callosum has been understood as the sensory window through which each hemisphere shares its own visual, sensory and motor information (cites Volpe, et al, 1982). Two pathways of motor information transfer are known, one through the left prefrontal cortex and anterior middle corpus callosum; the second crosses corpus callosum through parietal level and travels to the right hemisphere, this pathway in children can be assumed to be more reliably functioning, earlier.

#### *Attention Deficit Hyperactivity Disorder (ADHD)*

Central nervous system inefficiency is implicated in many learning and behavior disorders. Sources that show movement difficulties and processing speed concerns have also been found for other learning disorders, including dyslexia. Other sources document the relationship of movement skill and neurological soft signs to academic success, but space does not permit including them here. For ADHD, we review below research findings where motor difficult and corresponding performance weaknesses have been studied.

- weak performance in frontal lobe tests; slow gross motor output in ADHD (Carte et al., 1996 reviews).
- weakness in organizing a response, rather than the actual motor output activity itself, that may be the problem (Van Der Meere, 1992).
- Fine motor skills such as handwriting are a common deficit in ADHD (see: McMahan & Greenburg, 1977; Shaywitz & Shaywitz, 1984; Barkley, 1990; Doyle et al, 1995; Whitmont & Clarke, 1996).
- longer Response times (RT), longer ITI (intertap interval), greater PF (peak force) output, and greater variation in both ITI and PF for ADHD subjects. Distinct timing and force dysfunctions of both output and variability (Pereira et al., 2000; Steger et al, 2001; Pitcher et al., 2002).
- Pereira (et al. 2000) also found impairments to sensory motor control. In agreement with this finding, a study by van der Meere et al (1992) showed undue reaction time delays in hyperactive children when incompatible instructions are given.
- greater variability in grip force; greater variability of motor performance than controls. ADHD problems in adapting the grip force to various weights (a task of anticipatory control based on a memory image of the requirement) (Pereira et al., 2000).

- ADHD boys became increasingly slower than the control group with the finger portion of the task, having speed and quality differences (longer intervals, multiple force peaks, increased variability of force onset, and more errors). Force onset variability significantly differentiated the groups (Steger et al., 2001),
- kinaesthetic acuity and fine motor performance issues (Whitmont & Clarke, 1996)
- significant difficulties with timing, force output, and greater variability in motor outcomes (Pitcher, Piek and Barrett, 2002). In boys aged 8-13 they used two tests specifically related to movement: (Movement Assessment Battery for Children, 1992, and the finger tapping task) which targets motor processing, preparation and execution. Boys with any type of inattention had significant difficulty with timing, force output and greater variability in motor outcome. Authors call for increased awareness of the relationship of ADHD and motor dysfunction.
- motor output deficit hypothesis proposed by Sergeant and van der Meere, 1998; Van der Meere, 1996; Van der Meere and Sergeant, 1988.
- slow and inaccurate, in studies by Jennings et al, (1997) Oosterlaan & Sergeant, 1996; Scheres, Oosterlaan & Sergeant, 2001, especially where delayed motor processing is a core deficit (see also Sergeant & van der Meere, 1988; van der Meere, Vreeling and Sergeant, 1992).
- Reaction time variability is often greater in ADHD (see studies by Douglas, 1972; Jennings et al, 1997; Van der Meere & Sergeant, 1988).
- In primed and delayed Response Time tasks, ADD children have output difficulties (e.g. study by Leung & Connolly, 1997); though these are quite specific and did not extend to motor organization or execution stages.
- Timed finger tapping tests (speed) are sometimes included in neuropsychological batteries. Literature is mixed in this area. Some studies have found slower speeds in inattentive or hyperactives (Seidman et al, 1997), but others have not (Gordon & Kantor, 1979; Seidman et al, 1995).
- More complex motor sequences more frequently show problems in learning disabled and ADHD children, whereas fine motor skill/simple tapping speed tests do not (see Breen, 1989; Grodzinsky & Diamond, 1992; Mariani & Barkley, 1997).
- differences from controls in fast instructional set (Carte et al, 1996)
- epileptiform discharges in 30% of ADHD children (Hughes, 2000)
- early indicators of ADD-ADHD include speech delay, inattention, and soft neurological signs (Ornoy et al, 1993). 80% of children with these markers in age period 2-4, were later identified as with ADD-ADHD, when reexamined 7 years later.
- Kroes and colleagues (2002) published an excellent study in *Developmental Medicine and Child Neurology*. In reviewing the results of previous studies Kroes and colleagues noted that Denckla (1985), and Carte (1996) found that speed of movements is associated with ADHD, although a large group of studies do not find this association. (Kroes et al, 2002; Grodzinsky & Diamond, 1992; Barkley, 1997; Leung & Connolly, 1998) and Steger et al, 2001). While ADHD children are in general slightly slower, this is not always a significant difference.
- fMRI was used to study motor control tasks in ADHD boys in comparison to non ADHD subjects. Findings indicated that, a stop task and a motor timing task led to lower power of response in right mesial prefrontal cortex in both tasks and also in right inferior prefrontal cortex and left caudate in stop task. Authors conclude that there is subnormal

activation of the prefrontal systems required for higher-order motor control (Rubia et al., 1999).

- Di Scala and colleagues (1999) did a retrospective analysis of files of tens of thousands of hospital patients as part of a major study. They found that ADHD children were more likely to have severe injuries, more rehabilitation care, more multiple regions injured, and differing injuries- bike, pedestrian accidents, when compared to non-ADHD children, whose injuries were typically falls or sport related. This is another reason why treatments for ADHD are warranted.

*Frontal problems are found in ADHD and motor difficulties would therefore be expected.*

Frontal-striatal brain regions are implicated in poor executive processing and organization (Heilman, Voeller, Nadeau, 1991). As these authors have pointed out, motor abnormalities would be expected if these regions malfunction. It is not always assumed that the motor deficit is primary, but possibly areas of executive function and information processing may be faulty. If, however, activating these regions more effectively can be shown to improve most motor functions, it is presumed these pathways may be used for other functions and the general activation of frontal regions will be improved. Processing speed is a known difficulty in ADHD for complex tasks. Rubia et al. (1998) have suggested that *the* main deficit in childhood hyperactivity is of frontal-lobe mediated self-regulative functions such as inhibitory control.

Lazar and Frank (1998) investigated frontal system dysfunction in tests of inhibition, working memory, motor learning and problem solving, and finding that there were significant differences in the ADHD, ADHD +LD, and LD only groups, with the ADHD group performing the best on these measures, but with differing profiles among the groups. This study indicates that frontal dysfunction is not only found for ADHD subjects but is implicated in other learning problems of children.

*Deficits in response inhibition are associated with ADHD, Tourette's, OCD and other disinhibition syndromes (sources, see Garavan et al., 1999).*

When a person is asked to inhibit, or withhold a motor response (as for go-no go tasks), fMRI studies show that a distributed cortical network is responsible, including strongly lateralized right hemisphere activation. This is called "response inhibition", and it is often tested in ADHD. Regions involved include the middle and inferior frontal gyri, frontal limbic area, anterior insula, and inferior parietal lobe (Garavan, et al., 1999). A distributed network is implicated. Dorso-lateral prefrontal regions respond to target probability (Casey et al.); Anterior cingulate regions respond to accuracy in false-alarm situations (e.g. hold, its not the correct target on a go/no-go test); and the distributed area responsible for response inhibition is thought to include: Supplementary motor area, dorsal and ventral frontal regions, anterior cingulate and occipital and parietal lobes (references cited in Garavan). Heart rate measures were used in a study by Jennings et al. (1997), in a standard inhibition task. They found longer latencies in ADHD, the normal psychophysiological changes; however, careful attention to a task was more effortful and less successful for ADHD boys. In IM, one acts on the cowbell, but waits, or inhibits, the rest of the time. Commission errors on the TOVA continuous performance task are an index of response inhibition, which can be improved with training by various techniques, including neurofeedback.

*Response speed, and the ability to inhibit responding appropriately, are both associated with learning, with ADHD, and with developmental difficulties.*

Inefficient central nervous system activity can be described by many neurodevelopmental indices, including neuropsychological tests, and neurological “soft signs” (Spreen et al, 1996). Delays in the normal developmental sequence are associated with poorer performance on academic measures, weaker motor skills performance and increased risk for psychiatric disorder. In one study, five-year old children were followed-up at ages 7 and 10, for the study published by Whitmore and Bax (1990). They found that children with abnormal neurodevelopmental scores at age five were many times more likely to have learning disability or behavior disorders at follow-up. Prevalence was 4% and 8% respectively in the typical children, and was 25% and 46% in the subject children (cited in Kadesjo & Gillberg, 1999). Clumsiness is associated with a range of other issues including social problems in children, self confidence, behavior issues and affective disorders. This area is not treated in detail here, but is reviewed in Kadesjo & Gillberg, (1999). A range and variety of systematic and repeated movement activities can improve the circumstances of many children. Such interventions should be part of an integrated remediation program for children at risk.

*Response times in discrimination tests can be improved by a movement program*

Khalsa et al (1988), in their study of static balance in LD children, and Sifft et al (1991) in their study of simple response times and visual choice response times, have found that Brain Gym movements, and re-patterning, are effective for improving physical traits related to focus and attention. The Visual Choice response times task (how quickly and accurately can you decide about a target and respond?) such as that tested by Sifft, are a feature of Continuous performance tests (e.g. IVA, TOVA, CONNERS). Test performance on these tests has been shown to be related to cognitive abilities (for example, a timed multiple choice exam) and is one diagnostic measure for ADHD. Karni et al (1995) say that daily practice of a motor skill can improve both speed and accuracy in complex motor tasks. They found, using fMRI, that cortex areas enlarged for practiced sequences by week four of training, and suggest an experience-dependent reorganization of adult primary motor cortex, with changes that lasted several months. These changes were specific to the practiced task.

*What are the brain activation processes in the steps of learning a motor skill?*

Complex human movements have also been studied with fMRI (Rao et al, 1993). Functional changes have been seen in the primary cortex for simple activation tasks, and here, were also seen in the non-primary cortex in response to complex mental activities. Simple and complex finger movements using each hand separately were studied. Areas of activation support the idea that voluntary motor control is hierarchical in organization. Supplementary motor area (SMA) selectively activates in complex motor tasks, and, in imagined movements the premotor cortex also activates (planning and execution steps) (Rao, 1993).

Motor skill learning was studied using rCBF and PET scanning (Grafton et al., 1992). Motor execution was associated with activation of a distributed network involving cortical, cerebellar and striatonigral sites. Early motor learning of pursuit rotor activity

resulted in speeded improvements with longitudinal increases in relative CBF in left primary motor cortex, left supplementary motor area and left pulvinar thalamus.

*Early learning of skilled movements thus involves a subset of the same regions used for motor execution, and this is a widely distributed network*

Tasks studied by Grafton (1992) were not learned to full automaticity, and in the early phase of skill acquisition, visual feedback would be important to acquisition of the motor set. These studies demonstrate that the regional activation for motor tasks is widely distributed and involves functions including motor planning, imagery, sensory integration, and inter-hemispheric communication. These abilities are inseparable from the brain's chemical excitatory and inhibitory processes. Learning these movement procedures involves known explicit and implicit memory activation, frontal and striatal structures, and others. The information cited here clearly indicates that a structured motor program involving procedural learning, repetition, rhythm, and precise, consistent feedback, which at the millisecond level is consistent with brain synaptic signal processing, can indeed create new learning, and richer network elaboration. The important role of precise, very fast feedback has not been evaluated here. This feedback probably enables the latency delays (these are electrical, evoked potential, stimuli-processing signals) noted in many learning-disabled populations to be improved to more typical speeds. This is akin to increasing the processing speed of one's computer. Interactive Metronome and similar programs likely also increase accuracy, by narrowing the variability range of the response speed also. The brain's signal processing becomes more efficient and more consistent, able to exclude irrelevant information. Future studies of this technique must demonstrate that the gains seen are transferable to cognitive processing (early studies and theory suggest this), and whether they sustain at long term follow-up.

*Brain efficiency involves chemical and electrical brain signaling, and is associated with the general factor in IQ.*

Hatfield and Hillman (2001) expanded the concept that the central nervous system will use less resources to perform the same work when it is more efficient, an extension of similar findings in the motor system. Consistent with the theories of Haier, and of Bates, increasing task demands and focused attention involves the group of more intelligent students actively excluding irrelevant neural networks. More selective and efficient mobilization of resources in higher intelligent individuals would also show higher P300 amplitudes (cognitive resources to stimulus processing) and shorter P300 latencies, reflecting the duration of the stimulus evaluation process (see Michie, 1995). Individuals in the study were all right handed. More highly intelligent individuals have a more spatially and temporally coordinated electrocortical activity when engaged with cognitive tasks.

Better IQ scores, according to the Jausovec & Jausovec (2000) study, relate to fewer but more specifically and simultaneously activated neural networks. Full scale IQ, verbal IQ, and Performance IQ correlated negatively with response times (RT) in visual and auditory oddball paradigms, as well as with P300 and N400 peak latencies (especially in auditory tasks). This is consistent with Jensen's (1992) theory that speed of information

processing is an essential component of intelligence, and that a possible neurological basis for it is the speed of transmission through the nerve pathways.

Mortiani and deVries (1979) explained the relative efficiency of the motor unit recruitment in trained skeletal muscle such that the integrated EMG activity recorded from stronger muscle is reduced relative to that observed in the untrained state during similar work, termed “the efficiency of electrical activity of muscle” (EFA) (cited by McDowell, 2003). This is a primary characteristic of the nervous system after training and is also “expressed in the biomechanical quality of movement” (cites Sparrow, 2000).

“Movement results from a synergistic action of motor outputs, which are interconnected (Keller, 1993) by inhibitory and excitatory pathways. The balance of these connections is likely to govern the kinematics of voluntary movements and also of movements governed by cortical stimulation. This pattern of connectional weights is regulated by mechanisms that alter the efficacy of synapses (Donoghue et al, 1996; Markram & Tsodyks, 1996), and the neocortex is richly equipped with mechanisms for changing synaptic efficacies (Donoghue, 1995). Of these, short term potentiation or short term depression are mechanisms possibly related to the present results” (see Classen et al, 1998).

*movement plays a role in establishing patterns that go into long term memory*

“The plasticity identified in this study may underlie the initial stages of skill acquisition for motor skills, a type of procedural memory, as well as in the recovery of function that follows rehabilitation from cortical injury.” The primary motor cortex has been found to be involved in the acquisition of procedural knowledge (Karni et al, 1995; Pascual-Leone et al, 1994). Authors hypothesize that the storage and rehearsal of procedural information in short term memory promotes the formation and consolidation of information in the longer term. It appears likely that the motor cortex undergoes continuous plastic modifications. Frequently repeated movements reinforce particular network connectional patterns, but those patterns weaken if the movements have not been recently executed (Classen et al, 1998).

*Brain electrical activity is another way to describe these changes. Chemical and electrical synapse activity is connected to cell polarization and is the language of network communication.*

The role of the motor cortex in implicit and explicit learning was studied by measuring ERD (event related desynchronization of cortical potentials) by Zhuang et al., (1997). Right handed individuals performed a serial reaction-time task. A decline in alpha band power maximal over the contralateral central region was seen when initial learning took place. ERD reached a transient peak amplitude as subjects gained full explicit knowledge, peak at C3, and declined subsequently. Transient changes in cortical architecture may occur in conjunction with learning, some are expressed at the level of the synapse, others at the level of neural circuits (cites Lopes da Silva, 1979; Steriade, 1990). Authors found that repetitive trials with the same sequence produced both greater procedural learning and more explicit knowledge of the sequence.

*Response speed is clearly connected to the stage of learning, and can be indexed in*

### *electrical activity measurements*

Maximum improvement in response time is found when subjects were able to generate the entire learned sequence (consistent with Pascual-Leone, 1994). Progressive improvements in response time (RT) during task learning is accompanied by a change in the 10 Hz. ERD (Zhuang et al, 1999). Activity in the primary Motor Cortex increases in association with learning a new motor task and decreases after the task is learned. Cortical changes have been associated with motor skill learning in the studies of several authors (Merzenich et al, 1990; Sanes and Donoghue, 1992; Recanzone et al, 1992; Milliken, 1992, cited by Zhuang et al, 1999). People who have declarative knowledge of the task may hasten the acquisition of procedural knowledge, seen in a rapidly reducing response time. When a cortical area is preparing or processing information, alpha activity desynchronizes. This may be interpreted as a small neuronal assembly working in a relatively independent manner. According to Thatcher (1983), desynchronization may represent a state of both maximal readiness and information processing capacity, or active functioning. Coherent or synchronized alpha activity is found in a resting or idling brain over wide cortical areas. Information processing is reduced and little motor behavior occurs (Pfurtscheller, 1992).

Zuang et al (1997) summarizes some theories as to why learning related changes in cell properties and motor representation patterns may occur. Studies are cited to support each of these. The possibilities include: MI (motor cortex) maintaining a flexible relationship with muscles, excitatory horizontal connections between functionally different representations, a change in coupling thus creating new motor output architectures, activity dependent modifications in synaptic efficiency (e.g. long term potentiation and depression). Plasticity may occur by an LTP like mechanism and the literature on this is reviewed by Donoghue et al, (1996). Motor maps have been able to be altered by all of: electrical stimulation of MI, shifts in limb position, repeated limb movements and by morphological restructuring (see Zhuang, 1999, p.379). Blocking of NMDA receptors in the brain inhibited movement related reorganization of the primary motor cortex (Qui et al, 1990). Activity in primary motor cortex possibly increases with learning, as seen in studies with monkeys and humans (Suner et al, 1993 cited in Zhuang, 1999; Donoghue & Sanes, 1994; see also Sanes & Donoghue, 2000).

How these cell changes take place in learning ...might represent a type of "short-term, activity dependent cortical plasticity," possibly related to improvement of skilled motor performances (Bonato et al, 1996; cites also Zanette et al, 1995). Post exercise MEP amplitude decreases may be triggered by proprioceptive afferent inputs to MI induced by muscle stretch during the execution of the motor tasks or by primary intracortical modulation of pyramidal cell excitability (Bonato et al, 1996; Zanette et al, 1995). The potential anatomical substrate of this post-exercise inhibitory modulation may be feedback or feedforward mechanisms involving the long-horizontal excitatory axon collaterals of cortical pyramidal cells activated during exercise (Bonato et al, 1996).

*The same cortical circuits that are involved in motor execution are activated for imagery.* In a related piece of work, Fadiga and colleagues (1999) used TMS to find out whether the excitability of the corticospinal system is selectively affected by motor imagery.

Mental simulation of motions of hand and arm flexion and extension was practiced. Motor evoked potentials were recorded. The same cortical circuits that are involved in motor execution are activated for imagery. Right motor cortex activated for contralateral hand only, whereas left motor cortex revealed increased corticospinal excitability for imagery of ipsi-and-contralateral hands. Certain neurons activate for visual presentation of an object such as one that might be grasped, and another group activates for observing another individual (monkey) actually performing a task similar to those this monkey can motorically perform (sources in Fadiga, 1999). An action vocabulary is stored in the ventral premotor cortex, which may strongly facilitate the execution of motor commands and also creates brain storage of action schemes related to action goals (Fadiga et al., 1999) The same pool of motor schemes can be reached visually, by an object or by seeing an action. These groups of F5 neurons are called canonical and mirror neurons.

*Motor imagery and actual execution share many neural activation schemes*

The literature supports the idea that motor imagery has substantial similarity to movement execution. Eight studies cited show that regional cerebral blood flow (rCBF) increases in cerebellum and cortical motor areas during motor imagery tasks, and these have been verified by MEG and evoked potential studies. These may relate to movement intention or to simulation. The left hemisphere is known to play a dominant role in motor imagery (see also Beisteiner et al 1995). Two Fadiga papers (1999; 1995) indicate that mental simulation of movements involve the same neural substrate that is addressed in action execution and during observation of actions performed by others. Neural encoding of apparent human movement was studied by Stevens (2000). See also Decety (1996).

Motor performance and motor imagery has been studied by others. Porro et al., (1996) using fMRI, found that motor imagery and motor performance involve overlapping neural networks in the peri-rolandic cortical areas. They say that debate continues over the extent to which there is overlap between the areas used in motor imagery and those in actual motor action. They conclude that local changes in hemodynamics in brain activation is thought to represent alterations in synaptic activity attributable to increased firing of interneurons (excitatory or inhibitory) and/or afferent fibers (cites Raichle, 1987; Roland, 1993). EMG has been found to increase in muscles that are involved in the imagined motor act, in many but not all relevant studies (see Porro, 1996). Shibata and colleagues (1997) investigated EEG coherence in a go-no go task paradigm and concluded that coherence between sites F3 and F4 became significantly higher in the No-Go condition, suggesting that a synchronization between bilateral, dorsolateral frontal areas may play an important role in the motor inhibition process. Dynamic functional coupling occurs in these areas.

Mental simulation of sport activity has been shown to be beneficial (see Fadiga et al., 1999), and motor imagery is also used in microsurgery training. The motor system is helpful, according to PET activation studies, in tasks having no motor content, e.g. a judgment task of object rotation (see Parsons et al, 1995). Mental motor representations rely on the same neural circuits used for action generation. "Mental representations, traditionally ascribed to the cognitive domain, appear to be strictly linked, and possibly intrinsic to the "acting" and "perceiving" brain." (Fadiga et al., 1999).

### *Conclusion*

A widely distributed, well studied brain activation occurs through a specific movement program. This creates neural network elaborations, with practice, and exercises many brain structures including those implicated in sensory processing, memory and imagery, as well as frontal structures responsible for executive functions and inter-hemispheric communication. Response times are associated with cognitive performance. Faster response times are associated with greater network efficiency and exclusion of irrelevant data. Delayed responding is characteristic of many learning disabilities. A practice tool such as the Interactive Metronome can be expected to increase efficiency and organization of central nervous system circuitry. Response speeds in activities using visual and auditory inputs should become less variable, and faster. The use of guide sounds helps in “choice discrimination”, and that, along with feedback to modulate chronically early responses, would be expected to affect the response inhibition difficulties of hyperactive students. This remains to be established through specific study.

There are preliminary, though encouraging, findings for cognitive benefits in a few studies using IM. These include improved motor control and motor integration, and better attention in special education students (Stemmer et al., 1996); correlation between academic performance and IM scores in elementary school students (Schaffer et al., 2001); reading and math fluency increases in Title 1 students (Cason, 2003) and high school students. While promising, not all of these studies are independent, and the field can benefit from a variety of other new studies. Study designs should include well known continuous performance test measures (e.g. TOVA, IVA, Conners), and standardized motor movement measures such as the Bruininck’s-Oseretsky, and others. Studies should include academic achievement measures, (e.g. WIAT), perhaps just prior to IM training, with a post-test one year follow-up. Direct measures of evoked potential function would also be helpful. Replication of the inhibition tasks of the studies cited in the ADHD section above would also be useful. It remains to be verified that timing gains are maintained on follow-up. Theories of brain plasticity, along with the activation evidence from a variety of neural imaging methods, are available to validate our use of this and similar techniques, as important tools in learning remediation.

### **Selected References:**

Bonato C, Zannette G, Manganotti P, et al. (1996) ‘Direct’ and ‘Crossed’ modulation of human motor cortex excitability following exercise. *Neuroscience Letters* **216**:97-100.

Carte ET, Nigg JT, Hinshaw SP (1996) Neuropsychological functioning, motor speed, and language processing in boys with and without ADHD. *Journal of Abnormal Child Psychology* **24**(4): 481-498.

Cason C. "No Child Left Behind" and IM-A program that really works. *Conference Paper, Interactive Metronome*. Denver, Co. October 17-19, 2003.

Clifford E. (1999) Neural Plasticity: Merzenich, Taub and Greenough. *Harvard Brain* **16**: 16-20.

De Guise E, del Pesce M, Foschi N, et al., (1999) Callosal and cortical contributions to procedural learning *Brain* **122**:1049-1062.

Debaere F, Swinnen SP, Beatse E, Sunaert S, et al., (2001) Brain areas involved in interlimb coordination: a distributed network. *Neuroimage* **14**:947-958.

Decety J. (1996) Do imagined and executed actions share the same neural substrate? *Brain Research and Cognitive Brain Research* **3(2)**: 87-93.

Decety J. (1996) The neuropsychological basis of motor imagery. *Behavioural Brain Research* **77(1-2)**: 45-52.

Diamond SJ. Disorders of learning and development-relating scientific findings and clinical practice. *SNR Conference*. Houston, Texas. September 18, 2003.

Diamond SJ. The Scientific foundations of educational kinesiology. *Brain Gym International Gathering*. York, England. August 8, 2003.

DiScala C, Lescohier I, Barthel M, Guohua L (1999). *Pediatrics*, **102(6)** 1415-1421.

Fadiga L, Buccino G, Craighero L et al. (1999) Corticospinal excitability is specifically modulated by motor imagery: A magnetic stimulation study. *Neuropsychologia* **37**:147-158.

Garavan H, Ross TJ, Stein A. (1999) Right hemispheric dominance of inhibitory control: An event-related functional MRI study. *Proceedings of the National Academy of Sciences of the United States of America* **96(14)**: 8301-8306.

Gerloff C, Andres FG (2002). Bimanual coordination and interhemispheric interaction. *Acta Psychologica* 110,161-186.

Grafton ST, Mazziotta, JC, Presty S et al. (1992). Functional anatomy of human procedural learning determined with regional cerebral blood flow. *The journal of Neuroscience* **12(7)**: 2542-2548.

- Grodzinsky G, Diamond R. (1992) Frontal lobe functioning in boys with ADHD. *Developmental Neuropsychology* **8**: 427-445.
- Heilman KM, Voeller KKS, Nadeau SE. (1990) A possible pathophysiological substrate of attention deficit hyperactivity disorder. *Journal of Child Neurology* **6(supp)**: S76-S81.
- Hughes JR, DeLeo AJ, Melyn MA. (2000) The electroencephalogram in attention deficit-hyperactivity disorder: emphasis on epileptiform discharges. *Epilepsy and Behavior* **1**:271-277.
- Jancke L, Peters M, Himmelbach M, et al. (2000) fMRI study of bimanual coordination. *Neuropsychologia* **38**:164-174.
- Jausovec N, Jausovec K. (2000) Correlations between ERP parameters and intelligence: A reconsideration. *Biological Psychology* **50**:137-154.
- Kadesjo B, Gillberg C. (1999) Developmental coordination disorder in Swedish 7 year old children. *Journal of the American Academy of Child and Adolescent Psychiatry* **38(7)**, 820-828.
- Karni A, Meyer G, Jezard P, Adams MM, et al. (1995) Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature* **377(6545)**: 155-158.
- Khalsa GK, Sifft JM (1988) Effect of educational kinesiology on static balance of learning disabled students. *Perceptual and Motor skills* **67**: 51-54.
- Knyazeva MG, Kurganskaya ME, Kurgansky AV et al (1994) Interhemispheric interaction in children of 7-8: analysis of EEG coherence and finger tapping parameters. *Behavioural Brain Research* **61**:47-58.
- Kroes M, Kessels AGH, Kalff AC, et al (2002) Quality of Movement as a predictor of ADHD: results from a perspective study in 5 and 6 year old children. *Developmental Medicine and Child Neurology* **44**: 753-760.
- Lazar JW, Frank Y. (1998) Frontal systems dysfunction in children with attention-deficit/hyperactivity disorder and learning disabilities. *Journal of Neuropsychiatry and Clinical Neuroscience* **10(2)**:160-167.
- Leung PWL, Connolly KJ. (1998) Do hyperactive children have motor organization and or execution deficits? *Developmental Medicine and Child Neurology* **40**: 600-607.

- McDowell K, Kerick, C, Santa Maria, DL, Hatfield, BD. (2003) Aging, physical activity, and cognitive processing: an examination of P300. *Neurobiology of Aging* **24(4)**, 597-606.
- Ornoy A, Uriel L, Tennebaum A. (1993) Inattention, hyperactivity and speech delay at 2-4 years of age as a predictor for ADD-ADHD syndrome. *Isr Journal of Psychiatry and Relat Science* **30(3)**: 155-163.
- Pascual-Leone A, Brafman J, Hallett M. (1994) Modulation of cortical motor output maps during development of implicit and explicit knowledge. *Science-New series* **263-5151**: mar 4, 1994: 1287-1289.
- Pereira HS, Eliasson AC, Forssberg H. (2000) Detrimental neural control of precision grip lifts in children with ADHD. *Developmental Medicine and Child Neurology* **42(8)**:545-553.
- Pereira HS, Landgren M, Gillberg C, Forssberg H. (2001) Parametric control of fingertip forces during precision grip lifts in children with DCD (developmental coordination disorder) and DAMP (deficits in attention motor control and perception). *Neuropsychologia* **39(5)**:478-488.
- Pfurtscheller G, Neuper C. (1997) Motor imagery activates primary sensorimotor area in humans. *Neuroscience Letters* **293**: 65-68.
- Pitcher TM, Piek JP, Barrett NC (2002) Timing and force control in boys with attention deficit hyperactivity disorder: subtype differences and the effect of comorbid developmental coordination disorder. *Human Movement Science*, **21(5-6)** 919-945.
- Porro CA, Francescato MP, Cettolo V, et al. (1996) Primary motor and sensory cortex activation during motor performance and motor imagery: A functional magnetic resonance imaging study. *The Journal of Neuroscience* **16(23)**: 7688-7698.
- Rao SM, Binder JR, Bandettini PA, et al. (1993) Functional magnetic resonance imaging of complex human movements. *Neurology* **43**: 2311-3218.
- Rossini PM, Pauri F. (2000) Neuromagnetic integrated methods tracking human brain mechanisms of sensorimotor area 'plastic' reorganisation. *Brain Research Reviews* **33**: 131-154.
- Rubia K, Oosterlaan J, Sergeant JA, Brandeis D, v Leeuwen T. (1998) Inhibitory dysfunction in hyperactive boys. *Behaviour and Brain Research* **94(1)**: 25-32.
- Rubia K, Overmeyer S, Taylor E et al. (2000) Functional frontalization with age: mapping neurodevelopmental trajectories with age. *Neuroscience Biobehavioural Re* **24**: 13-19.

Sadato N, Campbell G, Ibanez V, et al. (1996) Complexity affects regional cerebral blood flow change during sequential finger movements. *Journal of Neuroscience* **16**: 2691-2700.

Sanes JN, Donoghue JP. (2000) Plasticity and primary motor cortex. *Annual Review of Neuroscience* **23**: 393-415.

Schaffer RJ, Jacokes LE, Cassily JF, et al. (2001) Effect of Interactive Metronome® Training on children with ADHD. *The American Journal of Occupational Therapy* **2**: 155-162.

Seidman LJ, Biederman J, Faraone SV, Weber W, Mennin D, Jones J. (1997) A pilot-study of neuropsychological function in girls with ADHD. *Journal of the American Academy of Child and Adolescent Psychiatry* **36(3)**: 366-373.

Sifft JM, Khalsa GCK (1991) Effect of educational kinesiology upon simple response times and choice response times. *Perceptual and Motor Skills* **73**: 1011-1015.

Steger J, Imhof K, Coutts E, Gundelfinger R, Steinhausen HC, Brandeis D. (2001) Attentional and neuromotor deficits in ADHD. *Developmental Medicine and Child Neurology* **43(3)**:172-179.

Stemmer PM (1996). Improving student motor integration by use of an Interactive Metronome. *Annual Meeting of the American Educational Association*. Chicago, IL.

Stephan KM, Binfoski F, Posse S, Seitz RJ, Freund HJ. (1999) Cerebral midline structures in bimanual coordination. *Experimental Brain Research* **128**:243-249. *Child and Adolescent Psychiatry* 36(3):395-403.

Van Der Meere J, Vreeling HJ, Sergeant J. (1992) A motor presetting study in hyperactive, learning disabled and control children. *Journal of Child Psychological Psychiatry* **33(8)**:1347-1354.

Whitmont S, Clark C. (1996) Kinaesthetic acuity and fine motor skills in children with attention deficit hyperactivity disorder: a preliminary report. *Developmental Medicine and Child Neurology* **38(12)**: 1091-1098.

Whitmore K, Bax MC. (1990) Checking the health of school entrants. *Arch Disabled Children* **65(3)**: 320-326.

Zhuang P, Toro C, Grafman J, Manganotti P, Leocani L, Hallett M. (1997) Event-related desynchronization (ERD) in the alpha frequency during development of implicit and explicit learning. *Electroencephalography and clinical Neurophysiology* **102**:374-381.