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Exploiting system fluctuations

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Differential training in physical prevention and rehabilitation programmes for health and exercise

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Summary

Background. Traditional causal modelling of health interventions tends to be linear in nature and lacks multi-disciplinarity. Consequently, strategies for exercise prescription in health maintenance are typically group based and focused on the role of a common optimal health status template towards which all individuals should aspire.

Materials and Methods. In this paper we discuss inherent weaknesses of traditional methods and introduce an approach exercise training based on neurobiological system variability. The significance of neurobiological system variability in Differential Learning and Training was highlighted.

Results. Our theoretical analysis revealed Differential Training as a method by which neurobiological system variability could be harnessed to facilitate health benefits of exercise training. It was observed that this approach emphasises the importance of using individualised programmes in rehabilitation and exercise, rather than group-based strategies to exercise prescription.

Conclusion. Research is needed on potential benefits of Differential Training as an approach to physical rehabilitation and exercise prescription that could counteract psychological and physical effects of disease and illness in sub-elite populations. For example, enhancing the complexity and variability of movement patterns in exercise prescription programmes might alleviate effects of depression in non-athletic populations and physical effects of repetitive strain injuries experienced by athletes in elite and developing sport programmes.

Keywords: Neurobiological variability; physical rehabilitation; exercise prescription; health; Differential Training; system fluctuations

1 Introduction

Returning to a healthy state after injury or disease or prevention of ill health and disability (in order regain or maintain lifestyle quality) seems be a major goal across the globe, especially for white and blue collar workers, athletes and for individuals who work at home fit with the job demands in the current tense economic context. Despite the development of increasingly sophisticated technology for occupational health and safety diagnostics, the scientific basis for subsequent physical rehabilitation therapy programmes appears to be not well understood. A major problem of the challenge in transferring emphasis in health initiatives away from diagnostics towards the development of preventive interventions seems to be created by adherence to the classical scientific experimental methodology implemented in clinical rehabilitation programmes, where usually one variable is modified while all others are kept constant (1).

For the treatment of movement disorders that are caused by spontaneous injuries or chronic postural problems, typically two approaches (models) are applied: clinical testing and biomechanical movement analysis. Both approaches are based on models of behavioural changes that have in common the subsequent interpretation of a single individual's test score or biomechanical data on the basis of averaged larger groups that are clinically defined as 'apparently healthy' or "normal". By relying on these normative, group-based methodologies clinical measures which deviate from a perceived normal value are averaged towards the clinical "normal" zone. On the basis of these methods, a strong causality for variations in health parameters is not constructed consider specific tolerance thresholds. In contrast a weak causality of health variables assumes identical effects based on identical causes (2). These implicit assumptions are in accordance with the classical scientific approach where a system is analyzed by means of experiments which only allow variation of single variables while keeping the values of other intervening variables constant. If the influence of several inter-related variables is assumed, then typically the values of these variables are modified successively by keeping all other variables fixed again. Complex interactions of several

variables, unfortunately, are rarely investigated and simulated in clinical biomechanics models of movement disorders on the basis of differential equations. The underlying model of cause and effect for such approaches is a nonlinear model. As a consequence of the classical linear models of cause and effect, strategies for exercise prescription and interventions has been adapted from sports training programmes leading to a great deal of similarity of interventions in exercise rehabilitation programmes and sports training. Mainly, four classical approaches in motor learning have been pursued in sports training interventions: a) the repetitive approach (3), b) teaching on the basis of methodical rows of exercises (4), c) variability of practice training in accordance with Schmidt (5) and d), the contextual interference approach adopted from language acquisition (6) to motor control (7). Major problems of these approaches are common implicit assumptions of an ideal movement template (model) that is constant over time, fairly narrow, and independent of the individual learner/performer. A major distinction within these classical approaches is the method of progressing towards this ideal template (model) or target from different initial states.

The main aim of this article is to discuss the implicit assumptions of these classical motor learning theories for exercise rehabilitation interventions and to suggest alternative consequences from other assumptions that are already well established in the literature, but in most cases only serve for the explanation of exceptions to assumed 'normal' behaviours. These alternative explanations are predicated on the notion that neurobiological system variability is an inherent feature which can be exploited by individuals to maintain health or enhance learning. In addition, a further related aim is to provide a theoretical basis for several alternative approaches that coincide with the explanation of linear models of diagnosis and interventions but rather have been named master theories. Nevertheless they have challenged the assumptions of classical models and generate a more general understanding of the design of therapeutic interventions.

2 Classical motor learning approaches and their implicit assumptions

The most common and oldest theoretical approach to learn specific movements is the repetitive approach (3) in which a target movement is repeated frequently for the purposes of imitation. This approach proposes that learners improve a skill just by repeating it. In psychological learning theories this approach is most similar to learning by imitation in connection with reinforcement learning (8). In practice the imitations by individuals tend to display decreasing deviations from a to-be-learned movement that can be described by an exponential function (9). Here we should note that the improvement of a movement implies a deviation from a previous movement execution and, although the learning effect is assigned to the repetition of the execution, it can be questioned whether the learning effect was due to the deviation as well. From this theoretical perspective, therapeutic rehabilitation programmes are based on the production of numerous repetitions of a perceived 'optimal' exercise pattern by a patient, accompanied by corrective instructions and feedback from therapists.

Almost the same degree of recognition has been given to the approach of methodical rows of exercises (4). In this training or teaching strategy, in addition to the presence of a target movement template, the initial athlete's conditions are taken into account in order to successively approach the target movement by means of increasingly similar exercises. The type of exercises used in interventions is mainly chosen on the basis of principles of kinematic and dynamic congruence of training and target exercises (10). According to these pedagogical teaching principles, exercises are selected along continua from easy to hard and from simple to complex. Once the exercises have been chosen for an intervention programme, every exercise is repeated several times according to the repetitive approach until observed movement deviations drop below a specified tolerance threshold. In this way, the training exercises are considered as preparatory training for production of the specified target movement. Once the target movement can be imitated within certain variation limits, the target movement is typically trained with numerous repetitions. The methodical rows of exercise approach can be considered as an extension of the initial preparatory phase of the

repetitive approach where bigger deviations in the beginning can be observed. It is important to note that both approaches end up with an ideal target movement template that has to be repeated until the level of perceived deviations are reduced over time. Typically, this approach is supported by means of frequent corrective instructions and feedback from the therapist or trainer.

Distinct from the previous two approaches, which display a rather normative background with a close connection to historically dominant ideas in teaching philosophy, the variability of practice approach suggested by Schmidt (5,11) is derived from a more psychologically oriented concept of motor control. The model distinguishes between invariant and variable components of movements, whereby the invariant parts are inherent to a range of similar movements that are grouped together in specific movement classes by means of a generalized motor program (GMP). For a specific movement execution the GMP is connected with discrete variable parameters by means of schemata. Despite the fact that the schema theory developed by Schmidt (5) was originally intended to model only highly automated ballistic movements, specific consequences for the acquisition of motor skills were derived. A major consequence is the claim that a GMP, mainly measured in relative force- and relative timing-variables, achieves increasing stability when it is trained with a high number of variable parameters (11,12). Originally, the training recommendations were directed towards a blocked training sequence signifying that an invariant is repeated several times with a specific variable parameter before the next specific variable parameter is connected with the GMP. In comparison to the previous approaches the variability of practice approach widens the inclusion of variability into the acquisition or learning process in so far as the stability of a generalized motor program is brought into direct connection with the movement variability present during a skill acquisition programme. Despite the provision of supportive data with respect to the existence of some movement invariants (13) and the variability of practice hypothesis in laboratory tasks (14), in health care (15) and multi segment motor tasks (16) a detailed methodological analysis of the empirical basis of

schema theory (17) led to the ramification that “[the] variability prediction cannot, therefore, rest upon consistent supportive evidence, neither with adult nor with child subjects” (17, p.387). Beside the methodological shortcomings of the analyzed designs in order to test the variability of practice hypothesis with respect to learning effects the biomechanical basis for detailed movement analysis has been widely neglected. In short, the invariants described by the schema theory are exclusively based on muscular forces by neglecting gravitational and inertial forces as they typically occur in every days or sports movement. Furthermore, a discussion of the findings on the background of an alternative, mainly biomechanically and neuro-physiologically based motor control approach like the equilibrium point hypothesis (18-20) where movement mainly is controlled by the relative length and relative tension of two antagonistic muscles never took place. However, despite the lack of research evidence, the generalized motor program is assumed as an invariant that has to be repeated as often as possible in connection with the variable parameters and therefore, relies on blocked repetitive training as well.

The influence of the time sequence of exercises on the learning, of a single and a set, of movement patterns (as evaluated in a retention test) shifted the focus of research to the contextual interference (CI) approach (7). CI research has provided evidence that practicing several skills in an interleaved or random fashion produces some short term interference (degradation of performance) occur but results in better long-term retention compared to blocked practice. Reviews of the contextual interference literature regarding the influence of practice schedules in retention and transfer have reported mixed results (21-23). Positive effects of random practice schedules in a number of sport skills have been observed (e.g., badminton - 24; baseball – 25; kayaking – 26; Volleyball – 27). From a psychological point of view two hypotheses for the explanation of the phenomena are discussed. The elaborative-processing hypothesis is related to the elaboration of the memory representation of the skill variations that a learner is practising (7). The forgetting –reconstruction hypothesis argues that by switching between at least two movements the learner is forced to ‘dump’ a given

pattern from working memory in order to learn to plan and execute the to-be-learned movements (28,29). Because a given pattern is superceded by planning and execution of trials of another program, it must be drawn from long term memory, or constructed from scratch (30). Recent transcranial magnet stimulation (TMS) experiments provide support for the elaboration hypotheses by showing that perturbing information processing, evoked by random practice, deteriorates the original benefit of random practice. On the other side, unlike the prediction of the forgetting-reconstruction hypothesis, TMS perturbations during blocked practice did not significantly improve motor learning (31).

A transfer of these ideas to non-sport related tasks like automatic bank machine learning (32) and physical rehabilitation following stroke (33) supported the theoretically predicted advantages of random practice. Discussion of contextual interference effects have been engaged in areas as speech rehabilitation (34,35) as well as in physical therapy (36), and occupational therapy (37). Nevertheless, a transfer from motor learning theories to physical therapy training especially for rehabilitation of low back pain is considered critical because of too many discrepancies between exercise and motor skill learning (38).

However, although the CI approach in comparison to the other three approaches suggests the biggest amount of variation, it still relies on the assumption of a narrow fixed target movement template that has to be programmed by an adequate number of repetitions. Thereby the assumed program seems to become more stability when the to-be-learned movement can be compared with a second to-be-learned movement already during the acquisition process. A problem with the transfer of this idea to physical therapy rehabilitation programmes is the selection of the optimal additional type of movements because typically a single movement like walking after hip or knee -replacement is required in a rehabilitation programme.

3 Two implicit assumptions revised

The two major assumptions which the classical motor learning theories rely on can be considered as a) the to-be-learned movement is considered to be independent of an individual and independent of time; and b), the performance with respect to a to-be learned movement can be improved by repetitions of at least invariant parts of the movement. In both cases mostly detailed biomechanical diagnosis is undertaken for the purposes of constructing an ideal movement technique. Most intriguingly, both assumptions are accompanied by two observations that directly limit their influence: The phenomenon of individuality and the low probability of the production of identical movement repetitions. Unfortunately, both phenomena are most often interpreted as the exceptions to a specified rule, rather than studied as phenomena in their own right. Individuality is used for explanation as a form of exception, when the data do not fit into the scientific group oriented approach and the low probability of identical movement repetitions is interpreted as measurement error or as destructive negligible motor system noise.

Evidence against the production of identical movement patterns

With respect to the low probability of the production of an identical movement pattern, a rather long history exists in the literature. Heraklit once provided the philosophical adage that “You will never step into the same river twice” and Bernstein transferred it to the study of human movements with his famous definition of practice as “repeating without repetition”. In biomechanics, Hatze (39) has extensively discussed chemical, biological and biomechanical aspects of the extremely low probability of identical movement repetitions. Sensory noise and feedback delay are also considered as potential sources of instability and variability for the online control of movement (40). Biomechanical analysis of athletic movement production with several thousand repetitions, such as high performance athletes in Karate (41), national team discus (42), or javelin throwers (43) or even the kinematic analysis of reaching movements in normal healthy individuals, (44,45) reveal even after thousands of repetitions

that there is still significant levels of variability in movement outcomes. Overall this observation leads to questioning of the assumption of how movement repetitions can be achieved. If movement repetitions are never identical and even after several thousand repetitions we can diagnose deviations, then it is really plausible to consider an approach that prepares the individual for the novel aspects of a movement repetition and that will occur anyway. Furthermore, the time independence of the chosen ideal movement template is not valid as well.

In addition to the problem of time independence, recent research supports the problem of person independence in motor learning as well. Although medical treatment and physical rehabilitation therapy as well as high performance sports is normally targeted towards and realized for the individual patient and athlete, most research effort is put into group-oriented research with very small effects on the specificity of the individuals. In sports training the father of training principles (46) dedicated the first training principle to this phenomenon. Despite this dedication, exercise training science primarily is oriented towards analysis and development of group performance outcomes and averages. Predicated on evidence that identification of individuals by means of different biometric data such as face recognition (47), fingerprint (48) or ear recognition (49), there is a clear possibility of recognizing individuals on the basis of kinematic or dynamic movement data as well. By analyzing the kinematic and biomechanical data of the lower extremities of 14 female participants only during a single ground contact in gait, Schöllhorn, Nigg, Stefanyshyn and Liu (50) were able to recognize each individual subject by 96%. Most intriguingly the recognition was stable when participants walked in different heel heights up to 5,4 cm. Once the participants switched to 8.1cm in heel height, the recognition rate increased to 100%, a finding which was interpreted as displaying the real individual characteristics even better in extreme performance situations. Furthermore, by switching to a different heel height individual patterns of adaptation could be identified as well. On the basis of perceiving only silhouettes of individuals, Nixon, Carter, Shutler and Grant (51) were able to identify single participants with

a 85% rate. Whether specific insole treatment of Parkinson patients was effective could be diagnosed for each individual subject by means of foot pressure data as well. Once the data of the pre test could be clearly (disjunctively) separated from the data of the post test, the intervention was diagnosed as successful (52). The analysis of demonstrated emotions and emotions elucidated by music during gait on 22 and 16 participants was the objective of Janssen, Schöllhorn, Lubienetzki, Fölling, Kokenge and Davids (53). Again, the individuality dominated the recognition process with respect to dynamic, kinematic, or both data sets. Once the individuals were identified, the recognition of the demonstrated and music induced emotions was possible for up to 100%, in average 84% over all participants and trials. In another study the participants fatigued them self by means of exhaustive leg extension exercises. The ground reaction force patterns during a single gait ground contact immediately before and after the intervention were dominated by the recognition of the individuals first and afterwards the influence of fatigue differentiated the individual gait patterns in more detail (54,55). Despite all the diagnosed individual dominance and all the automaticity of the gait movement no identical gait pattern provided further evidence for the presence of continuous fluctuations in our movements.

4 System Fluctuations: A necessary phenomenon for adaptation

Despite the recognition of variability in all kind of movement repetitions, the inherent noise in movement control was considered a destructive influence until the last few decades of the last century (56,57). Almost in parallel researchers from different fields of research such as system dynamics, neurophysiology, or robotic research became aware of the constructive influence of noise or fluctuations on system performance with increasing interest. In the field of motor control the outstanding works of Haken, Kelso and Schöner (58-60) suggested a revised view of system fluctuations as functional and made several predictions that were validated subsequently. By means of simple rhythmic finger, arm and leg movements the fundamental influence of fluctuations, especially during the transition between two stable system states could be shown. However, although fluctuations were diagnosed as

fundamental in human movements, learning was still recommended in the form of movement repetitions (61). The constructive influence of noise was also shown in the physiology of heart rhythms (62). In robotic research the addition of noise during the training process of robots revealed better results in the subsequent practical or application phase than training without noise (63). The most familiar applications of constructive noise (although termed differently) in the area of physical training concern the suggestion of using variable exercises for increasing postural stability (64) or perturbations training for regeneration or for preventing falls (65). Immediate effects on postural stability by applying sub-threshold signals with a stochastic resonance characteristic to sensors on the soles of the feet were demonstrated by Collins and coworkers (66,67). Detailed biomechanical analysis of high performance discus throwers provided further evidence for rethinking the influence of variations (68) on complex whole body movements. Time discrete and time continuous parameter of selected joint angles and angular velocities were observed during training and competition over a period of one year and showed constant fluctuations with changing variation in different variables.

Indirect support for the advantageous influence of system variability was derived from research in the behavioural neurosciences. When a kitten's visual system immediately after birth received only vertical oriented stimuli during the first sensitive weeks of the development of their visual cortex, they were observed to stumble down surfaces and were not able to recognize horizontal lines (69). The cat's visual cortex was never be able to develop neurons that are orientation sensitive. Such a normal development of the visual cortex is only possible, when the visual cortex is stimulated during a critical sensitive period in early development with a big variety of orientation sensitive signals. Because the whole cortex cerebri is structured similarly: a) with 6 layers of neurons that are connected to each other in varying distances and b) in a neighbourhood preserving structure (70-72) we can assume similar stimulus sensitivity in the somato sensory and motor areas of the cortex. Later, Müller, Metha, Krauskopf, and Lennie (73) found again in the visual cortex a high

sensitivity of adaptation to the similarity of the stimulus:” If successive fixations expose neurons’ receptive fields to images with similar but not identical structure, adaptation will remove correlations and improve discriminability” (73, p.1405). Learning in general seems to be improved with the amount of dopamine that is produced in the striatum during the acquisition process. Dopamine is considered to work as a reward system and its concentration increases with events that surprise with respect to expectations (74). Consequently, training programmes that create most surprising events will most probably support learning the most and will lead to most discriminable cortex areas with greater levels of excitation.

In summary, overwhelming evidence for the individuality of movements as well as for the low probability of two identical movement repetitions in connection with neurophysiological principles and dynamic systems characteristics for adaptive systems training or therapy that is based on numerous repetitions is to be questioned.

5 Differential training – never train in the ‘right way’ in order to become the best

The differential training (DL) approach (68,75) has been developed according to the principles of individuality, movement system variability and the non-repeatability of movements on the basis of findings in neurophysiology and systems dynamics. Instead of just describing the fluctuations in the DL, they are considered as intrinsic to the movement system and indispensable for adaptation. Fluctuations are understood as evidence for unstable regions of the system and instead of trying to eliminate them, it is more functional to enhance them in order to discover the space of possible performance solutions to prepare the athlete or patient for future events. Several predictions were validated in a couple of experiments in sports with subjects of different ages and different levels of performance. At a phenomenological level one prediction was the facilitation of individuality and the other was, to be able to adapt in each situation more individually, more rapidly and more precisely (75). Three soccer experiments with juvenile and adult skilled players within a pre post test design

and 8 interventions over 4 weeks resulted in significant higher acquisition rates than classical training methods (76). During the intervention period perturbations were added to the main technique by means of instruction. Instead of keeping the standing leg stiff, for example, the task was adapted for participants to kick with an extremely bent standing leg, The intervention period was characterized by no precise repetitions and no corrective instructions, but rather one new set of instructions after another. From a classical point of view the movement executions looked like the training of erroneous movements. In a similar design with two additional retention tests after two and four weeks students were taught the action of shot putting (77,78). The results not only revealed significantly higher skill acquisition rates but also a further gain in performance during the following 4 weeks, while the classically trained group were able improve their performance during the acquisition phase, but relaxed to the starting performance level within the first two subsequent weeks. Furthermore the individual results displayed some improvements and some decrements in the classical group, whereas in the DL group only one athlete showed no change at all, while all others improved their performance at least to the same level as the best learners in the classical method group. In addition the average of three shots in the test situations resulted in the DL group displaying an enormous reduction in variance, while the classical group increased their performance variance during the acquisition phase and dropped back to the initial level at the end of the retention tests. Obviously, the DL approach initiated the development of most effective individual shot put performance solutions that could be applied in each situation in a most adequate way. In the search for further improvement of the effects during the retention phase, mental training was added in another experiment. After having three weeks of differential training of the service in tennis, the group was divided into three experimental groups (79,80). One group did nothing for 3 more weeks according to previous DL experiments, the second group had to read training and biomechanical literature about the service technique in tennis and the third group practiced 3 times a week for 1 hour mental training in accordance with the programmes of (81). The results showed an expected increase in precision for the classical DL group (as expected). The literature group had a

lightly smaller increase in performance, whereas the mental training group had a significant decrease in performance. At first glance these results seem perplexing. But a second more detailed review of the data reveals an interpretation that provides a rethinking of the assumption of a constant time independent system. By means of mental training on the basis of recorded videos during the acquisition phase we can see an attempt to keep the mind constant. Meanwhile the body conditions seem to change and are no longer compatible with a time independent mind which relies on a body that has changed from 4 weeks ago. On the other hand, when athletes are trained by repetitive movement then mental training can be assumed to increase the variation and consequently increases future performance. In contrast mental training as a supplement to differential training is a clear reduction in variation and therefore detrimental for performance. If we change the classical assumption of a constant body and variable mind into a continuously changing body and mind (in a most simple case we assume this change as linear), then the system has to increase the noise from the beginning in order to keep up with the physical and mental changes (cf. fig 1). A transfer of the DL approach to the area of writing skill acquisition in school first grades has revealed similar advantages for the DL group with respect to the pressure on the pencil and with respect to the writing fluency (82).

About here figure 1.

6 Transfer to physical training/therapy

The clear advantages with respect to skill acquisition in addition to the overwhelming results in the learning phase independent of gender, age or performance level suggests a general learning principle. In accordance with neuro-scientific evidence, the self similarity of the brain, findings in computer science and system dynamics that support the importance of noise in living systems in general, makes it plausible to apply the same approach to physical

rehabilitation therapies and exercise prescription for counteracting effects of disease and illness. In addition to an immediate application in physical rehabilitation programmes, adding noise in to the performer's system during performance of a single movement in training before surgery is of some interest. Once the patient is trained differentially in advance, the time span during surgery and post surgery can be considered as the learning phase like in previous experiments where a further increase in performance could be diagnosed. Furthermore the theoretical background of DL provides a fruitful basis for the analysis of existing physical training recommendations. Over all the data as well as the perspective of an improved therapy or training process should be worth considering in applications of the DL approach in Physical training and therapy. Another application of DL that might have some clinical benefits concerns the occupational health and safety hazard of repetitive strain injury (RSI) that might exist in work settings where employees repeat a similar movement pattern on many thousands of occasions such as computer operators and process manufacturing workers. Encouraging a rehabilitation programme which includes the introduction of varied movement exercises may alleviate RSI symptoms by the introduction of variable joint movements and muscle function in a distinct manner. In a similar manner, use of DL methodologies in psychotherapeutic programmes to alleviate illnesses such as depression may benefit from varied mental exercises to bring patients out an emotional and psychological environment which may have become too stable. Finally, in many exercise interventions to alleviate effects of the onset of ageing to the musculoskeletal system, using a DL approach is likely to benefit individuals by enhancing the complexity of movement patterns. It has been observed that movement complexity reduces as a result of the ageing process (57) and it is possible that a carefully controlled DL intervention may be able to counteract these effects.

References

1. Mitchell SD. Dimensions of scientific law. *Philos Sci* 2000;67:242-65.

2. Argyris J, Faust G, Haase, M. Die Erforschung des Chaos (Researching chaos) Wiesbaden: Vieweg; 1994.
3. Gentile AM. A working model of skill acquisition with application to teaching. *Quest* 1972;17:3-23.
4. Gaulhofer K., Streicher M. Grundzuege des oesterreichischen Schulturnens (Fundamentals of austrian school gymnastics.) Wien: Deutscher Verlag für Jugend und Volk; 1924.
5. Schmidt RA. A schema theory of discrete motor skill-learning. *Psychol Rev* 1975;82:225-60.
6. Battig WF. Facilitation and interference. In: Bilodeau E, editor. *Acquisition of skill*. New York: Academic Press; 1966. p.215-44.
7. Shea J, Morgan R. Contextual interference effects of the acquisition, retention and transfer of a motor skill. *J Exp Psychol* 1979;5:179-87.
8. Miller NE, Dollard J. *Social learning and imitation*. New Haven: Yale University Press; 1941.
9. Newell KM, Liu YT, Mayer-Kress G. Time scales in motor learning and development. *Psychol Rev* 2001;108:57-82.
10. Djatschkow VM. Die Vervollkommnung der Technik der Sportler (Perfection of athletes technique.) Berlin: Sportverlag; 1973.
11. Schmidt RA. The search for invariance in skilled movement behaviour. *Res Q Exerc Sport* 1985;56:122-40.
12. Meijer OG, Roth K, editors. *Complex movement behaviour: The motor-action controversy*. New York: Elsevier; 1988.
13. Shapiro DC, Zernicke RF, Gregor RJ, Diestel JD. Evidence for generalized motor programs using gait-pattern analysis. *J Mot Behav* 1981;13:33-47.
14. Wulf G, Schmidt RA. Variability of practice and implicit motor learning. *J Exp Psychol Learn Mem Cogn* 1997;23:987-1006.

15. Andel R. Application of variability of practice Hypothesis in Alzheimer Patients. *Journal of Clinical Geropsychology* 2000;6:111-20.
16. Proteau L, Blandin Y, Alain C, Dorion A. The effects of the amount and variability of practice on the learning of a multi-segmented motor task. *Acta Psychol* 1994;85:61-74.
17. Van Rossum JH. Schmidt's schema theory: The empirical base of the variability of practice hypothesis: A critical analysis. *Hum Mov Sci* 1990;9:387-435.
18. Feldmann AG. Functional tuning of the nervous system with the control of movement of maintenance of a steady posture. II: Controllable parameters of the muscles. *Biophysics* 1966;11:565-78.
19. Feldmann, AG. Functional tuning of the nervous system with the control of movement of maintenance of a steady posture. III: Mechanographic analysis of the execution by man of the simplest motor task. *Biophysics* 1966,11:766-75.
20. Bizzi E, Polit A, Morasso P. Mechanisms underlying achievement of final head position. *J Neurophysiol* 1976;39:435-44.
21. Brady F. A theoretical and empirical review of the contextual interference effect and the learning of motor skills. *Quest* 1998;50:266–93.
22. Brady F. The contextual interference effect and sport skills. *Percept Mot Skills* 2008;106:461-72.
23. Magill RA, Hall KG. A review of the contextual interference effect in motor skill acquisition. *Hum Mov Sci* 1990;9:241-89.
24. Goode S, Magill, RA. Contextual interference effects in learning three badminton serves. *Res Q Exerc Sport* 1986;57:308-14.
25. Hall KG, Dominques DA, Cavasos R. Contextual interference effect with skilled basketball players. *Percept Mot Skills* 1994;78:835-41.
26. Smith PJK, Davies M. Applying contextual interference to the pawlata roll. *J Sports Sci* 1995;15:455-62.

27. Bortoli L, Robazza C, Durigon V, Carra C. Effects on contextual interference on learning technical sports skills. *Percept Mot Skills* 1992;75:555-62.
28. Lee TD, Magill RA. The locus of contextual interference in motor-skill acquisition. *J Exp Psychol Learn Mem Cogn* 1983;9:730–46.
29. Lee TD, Magill RA. Can forgetting facilitate skill acquisition? In: Goodman D, Wilberg RB, Franks IM, editors. *Differing perspectives in motor learning, memory, and control*. Amsterdam: Elsevier; 1985. p.3–22.
30. Lee TD, Simon D. Contextual interference. In: Williams AM, Hodges NJ, editors. *Skill Acquisition in sport: Research, theory and practice*. London: Routledge; 2004. p.29-44.
31. Lin CH, Fisher BE, Winstein CJ, Wu AD, Gordon J. Contextual interference effect: elaborative processing or forgetting-reconstruction: A post hoc analysis of transcranial magnetic stimulation induced effects on motor learning. *J Mot Behav* 2008;40:578-86.
32. Jamieson BA, Rogers WA. Age-related effects of blocked and random practice schedules on learning a new technology. *The Journals of Gerontology. Series B: Psychological Sciences and Social Sciences* 2000;55:343-53.
33. Hanlon RE. Motor learning following unilateral stroke. *Arch Phys Med Rehabil* 1996;77:811-5.
34. Knock TT, Ballard KJ, Robin DA, Schmidt RA. Influence of order of stimulus presentation on speech motor learning: a principled approach to treatment for apraxia of speech. *Aphasiology* 2000;14:653–68.
35. Verdolini K, Lee TD. Motor learning principles of intervention. In: Sapienza C, Casper J, editors. *Vocal rehabilitation in medical speech–language pathology*. Austin (TX): Pro-Ed; 2003. p.403-46.
36. Winstein CJ. Designing practice for motor learning: clinical implications. In: Lister MJ, editor. *Contemporary management of motor control problems: proceedings of the II. step conference*. Alexandria: Foundation for Physical Therapy; 1991. p.65-76.

37. Jarus T. Motor learning and occupational therapy: the organization of practice. *Am J Occup Ther* 1994;48:810–6.
38. Stevans J, Hall KG. Motor skill acquisition strategies for rehabilitation of low back pain. *J Orthop Sports Phys Ther* 1988;28:165-7.
39. Hatze H. Motion Variability – its Definition, Quantification, and Origin. *J Mot Behav* 1986;18:5-16.
40. Crevecoeur F, McIntyre J, Thonnard J, Lefevre P. Movement stability under uncertain internal models of dynamics. *J Neurophysiol* [Internet]. 2010 Juni 16 [cited 2010 Aug 31]. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/20554851>.
41. Sforza C, Turci M, Grassi GP, Shirai YF, Pizzini G, Ferrario VF. Repeatability of mae-geri-keage in traditional karate: a three-dimensional analysis with black-belt karateka. *Percept Mot Skills* 2002;95:433-44.
42. Bauer HU, Schöllhorn WI. Self-organizing maps for the analysis of complex movement patterns. *Neural Process Lett* 1997;5:193-9.
43. Schöllhorn WI, Bauer HU. Identifying individual movement styles in high performance sports by means of self organizing Kohonen maps. In: Riehle H, Vieten M, editors. *Proceedings of the XVI. International Symposium on Biomechanics in Sports*. Konstanz: Universitätsverlag; 1998.
44. Gordon J, Ghilardi MF, Ghez DJ. Accuracy of planar reaching movements. I. Independence of direction and extent variability. *Exp Brain Res* 1994;99:97-111.
45. Lametti DR, Ostry DJ. Postural constraints on movement variability. *J. Neurophysiol* 2010;104:1061-7.
46. Matwejew LP. *Das Problem der Periodisierung des sportlichen Trainings* [The problem of sports training over periods of time]. Berlin: Sportverlag; 1956.
47. Zhao W, Chellappa R, Phillips PJ, Rosenfeld A. Face Recognition: A literature survey. *ACM Comput Surv* 2003;35:399-458.
48. Maltoni D, Maio D, Jain AK, Prabhakar S. *Handbook of fingerprint recognition*. Berlin Springer; 2009.

49. David JH, Nixon M. Physical analogies for ear recognition. In: Li SZ, editor. Encyclopedia of Biometrics; 2009. p.1082-89.
50. Schöllhorn WI, Nigg BM, Stefanyshyn D, Liu W. Identification of individual walking patterns using time discrete and time continuous data sets. Gait Posture 2002;15:180-6.
51. Nixon MS, Carter JN, Shutler JD, Grant MG. New advances in automatic gait recognition. Information Security Technical Report 2002;7:23-35.
52. Schöllhorn WI, Schaper H, Kimmeskamp S, Milani T. Inter- and intra-individual differentiation of dynamic foot pressure patterns by means of artificial neural nets. Gait Posture 2002;16:S172.
53. Janssen D, Schöllhorn WI, Lubienetzki J, Fölling K, Kokenge H, Davids K. Recognition of emotions in gait patterns by means of artificial neural nets. J Nonverbal Behav 2008;32:79-92.
54. Janssen D, Schöllhorn WI, Newell KM, Jäger JM, Rost F, Vehof K. (submitted for publication). Diagnosing fatigue in gait patterns by support vector machines and self-organizing maps.
55. Jäger JM, Alichmann M, Schöllhorn WI. Erkennung von Ermüdungszuständen anhand von Bodenreaktionskräften mittels neuronaler Netze (Recognition of fatigue in ground reaction forces by means of neural networks). In: Brüggemann GP, Morey-Klapsing G, editors. Biologische Systeme. Hamburg: Czwalina; 2003. p.179-83.
56. Riley MA, Turvey MT. Variability of determinism in motor behavior. J Mot Behav 2002;34:99-125.
57. Slifkin AB, Newell KM. Noise, information transmission and force variability. J Exp Psychol Hum Percept Perform 1999;25:837-51.
58. Haken H., Kelso JAS, Bunz H. A theoretical model of phase transitions in human hand movements. Biol Cybern 1985;51:347-56.
59. Schöner G, Haken H, Kelso JAS. A stochastic theory of phase transitions in human hand movement. Biol Cybern 1986;53:247-57.

60. Kelso JAS. Dynamic patterns. Cambridge (MA): MIT Press; 1995.
61. Zanone PG, Kelso JAS. Evolution of behavioral attractors with learning: nonequilibrium phase transitions. *J Exp Psychol Hum Percept Perform* 1992;18:403-21.
62. Goldberger AL. Is the normal heartbeat chaotic or homeostatic? *News Physiol Sci* 1991;6:87-91.
63. Miglino O, Lund HH, Nolfi S. Evolving mobile robots in simulated and real environments. *Artif Life* 1995;2:417-34.
64. Gardner MM, Buchner DM, Robertson MC, Campbell AJ. Practical implementations on exercise-based prevention programme. *Age Ageing* 2001;20:77-83.
65. Gruber M, Gollhofer A. Impact of sensorimotor training on the rate of force development and neural activation. *Eur J Appl Physiol* 2004;92:98-105.
66. Collins JJ, Priplata AA, Gravelle DC, Niemi J, Harry J, Lipsitz LA. Noise-enhanced human sensorimotor function. *IEEE Eng Med Biol Mag* 2003;22:76-83.
67. Priplata A, Niemi J, Salen M, Harry J, Lipsitz LA, Collins JJ. Noise-enhanced human balance control. *Phys Rev Lett* 2002;89:238101.
68. Schöllhorn WI. Systemdynamische Betrachtung komplexer Bewegungsmuster im Lernprozeß (A systemdynamic perspective on complex movement patterns during a learning processes). Frankfurt: Peter Lang; 1998.
69. Hubel DH, Wiesel TN. Receptive fields of single neurons in the cat's striate cortex. *J Physiol* 1959;148:574-91.
70. Nieuwenhuys R, Voogd J, van Huijzen C. Das Zentralnervensystem des Menschen (The human central nervous system). Berlin: Springer; 1991.
71. Creutzfeld OD. *Cortex Cerebri*. Berlin: Springer; 1983.
72. Kandel ER, Schwartz JH, Jessell TM. *Principles of Neural Science*. 3rd ed. East Norwalk (CN): Appleton & Lange; 1991.
73. Müller JR, Metha AB, Krauskopf J, Lennie P. Rapid adaptation in visual cortex to the structure of images. *Science* 1999;285:1405-8.

74. Schultz W, Dayan P, Montague RR. A neural substrate of prediction and reward. *Science* 1997;275:1593-9.
75. Schöllhorn WI. Individualität - ein vernachlässigter Parameter? (Individuality – a neglected parameter?) *Leistungssport* 1999;29:5-12.
76. Schöllhorn WI, Michelbrink M, Beckmann H, Trockel M, Sechelmann M, Davids K. Does noise provide a basis for the unification of motor learning theories? *Int J Sport Psychol* 2006;37:34-42.
77. Beckmann H, Schöllhorn WI. Differential learning in shot put. In: Schöllhorn WI, Bohn C, Jäger JM, Schaper H, Alichmann M, editors. 1st European Workshop on Movement Science. Köln: Sport & Buch Strauß; 2003. p.68.
78. Beckmann H, Schöllhorn WI. Differenzielles Lernen im Kugelstoßen (Differential learning in shot put). *Leistungssport* 2006;36:44-50.
79. Schöllhorn WI, Oelenberg M, Michelbrink M. Can mental training enhance the learning effect after differential training? A Tennis Serve Task In: Theodorakis Y, Goudas M, Papaioannou A, editors. Proceedings of the 12th European Congress of Sport Psychology. Halkidiki: FEPSAC; 2007. p.241.
80. Schöllhorn WI, Humpert V, Oelenberg M, Michelbrink M, Beckmann H. Differenzielles und Mentales Training im Tennis (Differential learning and mental practice in tennis). *Leistungssport* 2008;38:10-14.
81. Draksal M, Nittinger N. Mentales Tennis-Training [Mental Training in Tennis]. Leipzig: Draksal-Fachverlag; 2002.
82. Vehof K, Janssen D, Schöllhorn WI. Handwriting acquisition in primary school by means of the differential learning approach. In: Araújo D, Cabri J, Barreiros J, editors. 3rd European Workshop on Movement Science. Lisbon; 2009. p. 45.

Figure caption:

Figure 1: Two training approaches dependent on the assumption of time independent (circles) and time dependent (black circles) target movement.

