Motor Learning Principles and the Superiority of Whole Training in Volleyball

Steven Bain, Ph.D.[1], and Carl McGown, Ph.D.[2]

[1]Associate Professor, Department of Orthopaedics & Sports Medicine, University of Washington

[2]Professor Emeritus, College of Health & Human Performance, Brigham Young University

Address for Correspondence:

Steven Bain, Ph.D.

Associate Professor

Dept. Orthopaedics and Sports Medicine

University of Washington

Seattle, Washington

sdbain@u.washington.edu

206-390-9259

In London, on the South Bank of the Thames River, stands a museum doorway that displays the inscription “Facts not Opinions” (Figure 1). This particular museum was created in 1981 on the ground floor and basement of the building that once housed *Kirkaldy’s Testing and Experimenting Works*, commemorating the Scottish engineer David Kirkaldy, the father of modern materials science. This is the site where in 1874 Kirkaldy established the engineering principles and methods underlying the testing and evaluation of structural materials in order to optimize the fabrication of all things structural, from railways to rocket ships [1].

The broad application of material testing in structural engineering at the beginning of the 20th century was simply one example of a much wider revolution in evidence-based research across an array of scientific disciplines from chemistry and physics, to biology and medicine. Indeed, even sport and athletics participated in this evidence-based revolution with the advent of motor learning science. Grounded in a rich body of scientific literature that continues to evolve in breadth and neurological sophistication, the discipline of motor learning is the study of the acquisition and development of permanent changes in motor behaviors (i.e. functional skills) appropriate for different tasks and environments [2]. This research has led to the identification of a number of evidence-based motor learning principles, which, when properly understood and applied, can have a significant impact on athletic development and achievement: as significant as the principles of material science have had on architectural triumphs.

From this perspective, it is therefore surprising that despite its rich heritage and an overwhelming body of scientific literature, motor learning principles remain poorly understood and/or incorrectly applied by a large number of individuals in the coaching profession. An example of this incomplete understanding is exemplified by a recently published article in “Coaching Volleyball”, the official technical journal of the American Volleyball Coaches Association[1]. This article, “Whole vs. Part Training”, [4] seeks to encourage the reader, “*to consider using part-to-whole training progressions in your gym and to make fundamental skills training a high priority for your program.*” While we acknowledge that the author is entitled to share his opinion on the use of part teaching methods, we are compelled to observe that the material presented in this article, which advocates part-to-whole training progressions for volleyball, reflects neither the current knowledge in the field of motor learning research nor an informed application of the motor learning principles to development of skilled motor behaviors. Consequently, the novice coach or uninformed instructor might agree with the author’s statement that, *“A teaching progression that starts with a narrowly-focused action without a lot of distractions (part), which is then progressed by adding more and more complexity to be almost game-like (whole), makes too much sense to be ignored.”*

Regrettably, concluding and/or seeking to demonstrate that “*part-to-whole training progressions*” are a preferred instructional paradigm simply because such progressions appear to “*make sense*”,

[1] In the same issue of “Coaching Volleyball”, Dr. Vickie Grooms-Denny presented the first of two articles on the application of motor learning principles to coaching [3]. The aim of this article is not to reproduce Dr. Groom-Denny’s effort but to frame a response to the Weitl article by applying motor learning principles to address three questions posed in the original AVCA article by Weitl.

ignores nearly a century of scientific evidence and volumes of published research that have conclusively demonstrated that part progressions have minimal transfer to the whole skill [2] and in a number of scientific studies part training methods have actually demonstrated negative transfer [5, 6]. Consequently, given the educational and technical nature of “Coaching Volleyball”, we believe that a comprehensive, evidence-based rebuttal of the thesis that, *“part to whole progressions represents a viable teaching model”* is required. In this context, the original article published in the AVCA Journal posed three questions as a framework for validating the use of part to whole progressions for players of different age, ability, and experience. The three questions were as follows:

1. *Is it always better to teach skills to players of all levels strictly by repetition of the whole skill?*
2. *Is it appropriate for younger players or players that have not yet imprinted proper motor patterns to learn skills by performing only part of the skill?*
3. *Should a distinction be made for what training methods are appropriate for more advanced players as compared to players in their early years of training?*

As these questions reflect many of the key considerations that coaches must address prior to designing a practice and training their athletes, the primary objective of this article (i.e. conveying the motor learning principles that guide the acquisition of skilled behaviors), can be achieved by answering each of these questions in turn. Before turning to these questions however, it is important to establish a contextual framework by first reviewing the nomenclature and briefly summarizing the following key, motor learning principles:

- *Specificity vs. Generality*: Franklin Henry is considered the father of motor learning science and first proposed the specificity hypothesis of motor learning in 1958 [7], which predicted that abilities are specific to the task or goal of the activity and not transferable. Henry’s motor learning thesis emerged from the academic tradition established by Thorndike and Woodworth [8], who challenged the doctrine of formal discipline in education, which assumed that intellectual practice would yield general effects; for example, students were assumed to increase their “general skills of learning and attention” by learning Latin or other difficult subject matters. However, in a study involving over 8,000 high school students, Thorndike and colleagues were unable to demonstrate any significant correlation between differing intellectual capabilities. As Thorndike and Woodworth state: *"The mind is ...a machine for making particular reactions to particular situations. It works in great detail, adapting itself to the special data of which it has had experience.... Improvements in any single mental function rarely brings about equal improvement in any other function, no matter how similar, for the working of every mental function group is conditioned by the nature of the data of each particular case" (pp. 249-250).* Henry’s work extended Thorndike’s specificity of mental function thesis to the field of motor learning, providing experimental data to demonstrate that sensory stimuli and movement are tightly coupled and that training specificity is required to achieve meaningful results [9-12]. Indeed, a convincing body of scientific research now indicates that the most important practice variable in terms of motor skill acquisition is practicing the criterion skill itself [13, 14]. Rushall and Pyke [15] have expressed it this way, "*Training is specific. The maximum benefits of a training stimulus* (i.e. acquiring functional skills as permanent behavioral changes), *can only be obtained when the stimulus replicates the movements and energy systems involved in the activities of a sport. This principle may suggest that there is no better training than actually performing in the sport*". Taken together, the weight of scientific evidence indicates that the specificity hypothesis may be as close to a law as any principle in motor learning science.

- *Transfer*: Transfer (of learning) in motor research can be loosely framed as the dependency of current performance on prior experience. Stated this way, transfer is a measure of practice effectiveness as it relates to relatively permanent improvements in the execution of skilled motor behaviors. Significantly, the optimization of transfer from practice settings to competitive performance is highly dependent upon the principle of specificity. Consequently, instructional paradigms that simulate actual performance settings, which engender movement patterns and functional skills required in competition, are predictably superior. Transfer is enhanced by environments that utilize contextual interference; i.e. random practice [16, 17], drill variations that increase contact opportunities [18, 19], and by the nature, scheduling, and rates of feedback [20-22]. An important feature of the transfer principle is that while practice conditions that optimize transfer lead to permanent improvements of functional skills, there could be some decrease in initial performance [2]. Moreover, measurable gains in the ability to perform one skill can have a positive, negative, or neutral effect on the transfer of learning to closely related skills (i.e. motor skills are specific to the task and there is very little transfer from one skill to another). However, any initial decrements are temporary and understanding their transient nature can be achieved by examining the next two principles; whole vs. part training and random vs. blocked practices.

- *Whole vs. Part Training*: One of the first questions asked when training a new skill is, “Should the athlete practice the skill in its entirety (whole training) or break down the skill and practice the component parts independently (part training)?” In spiking, the “whole” would be the approach footwork and arm work, the jump, ball contact, and recovery. In contrast “part” would focus on a single element of the whole skill, for example, the ball contact. This query, “whole or part training?” has in fact been asked and answered hundreds of times in the scientific literature. Most notably, Nixon and Locke [6] examined the research comparing effects of whole training vs. part on motor learning and were unable to identify a single study that favored part or progressive-part methods of instruction. During the intervening decades, the analysis of Nixon and Locke has been confirmed [23], substantiating the evidence that athletic, musical, or ergonomic skills that require a high degree of interlimb coordination are best served by whole-skill practice [24-28]. Given the overwhelming body of scientific evidence demonstrating the superiority of whole versus part training it is puzzling that part progression methodologies remain such a popular instructional paradigm.

- *Random vs. Blocked Practice*: The random versus blocked practice methods represent a fundamental paradox regarding athletic performance during training and subsequent performance during competition [29, 30]. Based on performance measurements during practice, blocked activities, in which athletes repeatedly rehearse the same task, result in superior performance during the training session [2, 31]. In comparison, performing tasks and skills in random order decreases skill acquisition during training. Consequently, based on measurement of performance effects during practice, many coaches and players believe that blocked practice is superior to random practice [25]. Such a conclusion however, mistakenly assumes a positive correlation between performance in practice and long-term skill retention [32]. The paradox arises from the fact that blocked practice is in fact very ineffective for transfer of learning to competition as performance improvements measured during practice degrade rapidly, and inefficient because retraining on the same skills will be necessary [29, 31, 33]. Conversely, random practice is both effective, transfer to competition is high, and efficient, skill acquisition is relatively permanent. Indeed, the superiority of random practice has been substantiated for a large number of sports skills including volleyball [34, 35], badminton [36, 37], baseball [38, 39], basketball [40], tennis [41], and soccer [42], and its utility and training applications thoroughly reviewed by Schmidt and Lee [2]. Finally, scientific research into the neurological reasons for this superiority have revealed that variable activities increase and strengthen the brain connections that are responsible for learning motor skills whereas simply repeating the same activities exerts no measurable effect on these brain connections [43-45][2]. Therefore, if motor learning (transfer and retention) is the goal, random practice is a fundamental principle to follow.

- *Appropriate Regulatory Stimuli*: Motor learning represents a permanent change in skilled behavior and involves information processing and voluntary movement in response to sensory stimuli. For optimal learning to occur, the sensory stimuli that trigger voluntary movements during training must replicate environmental cues to which the athlete will respond in competition. To place this idea into a volleyball context, Dr. Marv Dunphy, the Men's Volleyball Coach at Pepperdine University (and the head coach of USA's 1988 Men's Olympic Gold Medal team) continues to say that the best passing drills are pass, set, hit (P-S-H), the best setting drills are P-S-H, the best hitting drills are P-S-H, and the best digging drills are P-S-H and dig. Marteniuk [46] assists with the idea when he explains: "*Anything less than a game situation, unless very well planned, has the possibility of introducing artificial situations, and*

[2] Interestingly, the relation between variable practice and the neuronal acquisition of motor skills was predicted in the Schema Theory of Motor Learning first proposed by Schmidt [14]. According to Schmidt, 'Schema Formation' is a consequence of repeated practice whereby, *"The strength of the relationship among the four stored elements…"* (i.e. initial conditions, response specifications, sensory consequences, and response outcome), *"increases with each successive movement of the same general type and increases with increased accuracy of feedback information from the response outcome*" (p. 235).

complete transfer to the game situation will not occur. When practice activities are developed, the instructor should carefully consider the way the skills are performed in a game to structure drills that are as close to the game as possible (p. 219)." Applying this principle to volleyball leads to a number of factors that must be considered when planning drills and instructional activities, including[3]:

- The players' positions and movements on the court;
- The players' orientation to the net;
- The sequence of events in an activity and the rate and timing of the sequence;
- The stimulus to which the players react (a coach standing on a table and hitting balls at back row diggers is not a stimulus that a player reacts to in a game);
- The way in which the activities are scored and performance rewarded (winners and non-winners);
- The natural termination of the ball in play; and
- The timing, type, frequency, and amount of verbal and/or visual feedback

It should be clear from the preceding summaries that the underlying principles of motor learning are firmly grounded in evidence-based, scientific research. Therefore, a basic understanding of these principles will enable coaches to design learning environments and apply training methods that will markedly improve both individual player skills and competitive team performance. With this background in place we can now systematically answer the questions posed by the AVCA "Whole vs. Part" article.

1. *Is it always better to teach skills to players of all levels strictly by repetition of the whole skill?*

   Essentially all of the available scientific evidence comparing whole vs. part teaching methods indicates that teaching the whole skill is superior to part teaching methods, regardless of initial skill level. In recent years, the neuronal basis for the superiority of whole training has become increasingly clear. As described by Gentile [47], the neurological basis of skill acquisition appears to rely on two distinct but interdependent brain processes: an *explicit* domain, which is directed towards attaining the action goal and an *implicit* domain that is concerned with the dynamics of force generation. Importantly, explicit processes are cognitive, allowing the athlete to consciously guide changes in the shape and structure of the motor skill, while implicit processes associated with limb trajectories and force generation are subconscious and can only be developed via experience and practice variability. Further, explicit control predominates during the early stages of motor learning, while fully implicit control characterizes the nearly automated movements of the expert performer [48-50]. From a coaching perspective, it is important to know that the movement shape structures (explicit learning) stabilize rapidly while the assembly of limb trajectories and force generation (implicit learning) is gradual and erratic. When we apply this knowledge to

[3] Adapted from Gold Medal Squared Coaching Clinic Notebook ~ Level 1. Version 01.2010. pp. 11

coaching volleyball players of any skill level we can conclude that optimal training environments require: 1) biomechanically correct examples when demonstrating skills; 2) clear functional goals for practice activities; 3) a wide range of force production variables within context of goal-directed functional activities; and 4) early implementation of variable practice and whole skill training. Thus, an understanding of the neuronal mechanisms that underlie motor learning indicates that teaching whole skills in a random practice setting is the most effective method to teach skills to players of all levels.

2. *Is it appropriate for younger players or players that have not yet imprinted proper motor patterns to learn skills by performing only part of the skill?*

   As presented earlier in this article, the evidence has unequivocally demonstrated that skills requiring a high degree of interlimb coordination are most effectively learned by whole-skill practice [9-12]. Inferring from the question posed above, the execution of a volleyball skill is therefore a goal-oriented movement that arises from an "imprinted… motor pattern". The question then becomes, what is the relation between imprinted motor patterns and the execution of volleyball skills? If we consider the question from a computational perspective, then the brain is a processing system that converts inputs (sensory stimuli) to outputs (functional skills) [51]. Thus, the superiority of whole practice as a teaching method lies in understanding how the brain learns, assembles, and reproduces skilled behaviors. In this context, a common fallacy associated with part training is the assumption that the brain is a serial processing device, allowing skills to be taught in component parts, which can then be rearranged and assembled by the brain as needed for subsequent execution. Functional neuroscience has displaced this false notion by revealing that the brain structures responsible for controlling voluntary movements are massively interconnected (trillions upon trillions of synapses) and operate in parallel. The brain is therefore a parallel processor [52, 53], far more complex and sophisticated than the most advanced computers[4]. The brain's computational power notwithstanding, modern neuroscience also indicates that the acquisition of motor programs for complex skills is based upon repetitive and variable stimulation of the neuronal connections responsible for achieving specific functional goals [55]. This repeated and variable stimulation leads to the formation of motor maps that contain the neuronal solutions for rapid execution of voluntary movements. Significantly, as movement patterns stabilize rapidly even in young players (conscious, explicit domain), motor map formation and skill development will be driven by practice methods that elicit limb trajectories and force applications (subconscious, implicit domain) that reflect the same movement patterns and functional goals as those required in actual competition. Consequently, it is not surprising that the

[4] The sophistication and computing power possessed by the brain can be appreciated by illustrating the computational problems that must be solved to perform even the simplest movements. Consider that the human body has 600 voluntary muscles and for simplicity sake they can either be contracted or relaxed. This simplification still yields 2^{600} possible combination states for muscles of the human body, a number so enormous that it exceeds the known quantity of atoms in the visible universe [54]! Given this computational challenge, it is remarkable that the human brain can compute the limb mechanics, trajectories and forces required to time and execute a spike approach in milliseconds, a truly astounding computational feat.

development of expert performance will take thousands of hours of deliberate practice [56]. Therefore, as expert performance in sport is exemplified by the consistent execution of whole skills in game-like settings, the sooner we have the whole-skill practice algorithm in place, the faster our athletes will imprint the proper motor patterns that characterize expert performance.

3. *Should a distinction be made for what training methods are appropriate for more advanced players as compared to players in their early years of training?*

   By now, the reader should have begun to grasp the importance of motor learning principles as a guide in the selection of training methods. If so, than it will be apparent that training methods are essentially independent of age. However, while the training methods themselves are invariant, the learning environment must be structured to match the information processing ability and skill levels of the learners. The basic algorithm for structuring the learning environment is the more experienced the players, the more complex the regulatory stimuli and vice versa. This algorithm is also grounded in neuroscience as novice players will have limited ability to process new information [57-59]. Thus, when using whole-teaching methods with players of any age, the instructor must select the regulatory stimuli that are most appropriate for a particular athlete's ability level [60-63]. Too much novel information and the player's processing abilities will be overwhelmed. Conversely, too little novelty and motor learning will not occur [64]. Here we can refer to the illustration of a Part to Whole Teaching progression that was offered in the original "Whole vs. Part" article[4][5]. It should be noted, however, that the illustration in question (a puppy fetching a ball), is in fact an example of block training for a whole skill, not a "part to whole teaching progression". Regardless, the illustration serves to demonstrate that as a new learner the puppy has a limited ability to process information. Appropriately, the trainer prepares a controlled environment in the form of a long hallway in which the puppy can execute the whole skill, which is retrieving the ball. The hallway serves to reduce the information content in the training environment, much the same as a shorter net, a smaller court, fewer players, or a lighter ball would limit information content when training 3rd grade volleyball players. As the puppy becomes more proficient at retrieving the ball, (or, analogously, as players become more skilled), novel regulatory stimuli can be introduced and the motor behaviors will become increasingly complex.

   The foregoing description of block training is useful as well because it serves to illustrate that, at least in very early stages of training, blocked practice of whole skills can be effective [31, 39]. The reason for this is that regulatory stimuli are easier to control in a block-training environment [64]. It is important to emphasize however that studies by Wulf [62] and Yan et al [63] have demonstrated that random training has even more profound learning effects in younger subjects than old.

[5] "Illustration of a Part-to-Whole Teaching Progression: 1.Select a long hallway with all of the doors closed. Toss the ball to the end of the hallway and say, "fetch". 2. Praise the puppy when he retrieves the ball and repeat many times to reinforce. 3. After many successful repetitions start to open a few doors in order to provide distractions to the puppy while continuing the feedback. 4. In time with repetition and good feedback the puppy successfully retrieves the ball without regard to the many 'game-like' distractions happening through the open doors."

Moreover, limiting the use of block training to the earliest stages of practice is strongly supported by Schmidt [2], who advocates that optimal learning of a single movement class requires random variations from trial to trial.

The neuronal explanation for these effects are perhaps best exemplified by our own observations (Bain and McGown), of inexperienced coaches training novice players where the instructor(s) become frustrated by the performance variability and lack of successful repetitions of new learners. As a consequence, these inexperienced coaches limit or abandon whole teaching methods for part, and random practice for blocked. Unfortunately, this course of action deprives the learner of the environmental variability and sensory inputs that are essential for the formation of motor maps and implicit behaviors, which are ultimately reflected in the acquisition of functional skills and expert performance [13, 18, 19, 29, 65]. In total, the evidence on this topic is clear; drawing distinctions between training methods based on age or ability is a coaching practice that has no foundation in either motor learning science or in the application of motor learning principles.

In summary, we hope that we have effectively conveyed the motor learning principles that guide the acquisition of skilled behaviors, thereby substantiating the evidence-based superiority of whole training strategies. While some coaches may continue to ignore or minimize the significance of this evidence, in our view, there is no right way to do a wrong thing. Selecting methods based on, “it seems to make sense”, “that’s how I was taught”, or “it gets results in my gym”, is not a substitute for understanding the principles of motor learning and choosing methods that maximize acquisition and learning of skilled motor behaviors. We are therefore confident that coaches who study and use these principles in their training environments will become more effective teachers, and as a result, their players will experience significant increases in individual performance, and their teams’ successes will be measurably enhanced. We are equally as certain that motor learning research will continue to increase our understanding of how the brain learns and executes complex motor behaviors, unlocking great potential to expand our skills as coaches, optimize our training methods, and maximize competitive achievements.

Acknowledgements

The authors would like to thank John Kessel of USA Volleyball for his review and insightful comments during the drafting of this manuscript.

References

1. Miodownik, M., *Facts not opinions?* Nat Mater, 2005. **4**(7): p. 506-8.
2. Schmidt, R.A., Lee, T.D., *Motor Control and Learning: A Behavioral Emphasis*. Human Kinetics. 2005, Champaign, IL: Human Kinetics. 555.
3. Grooms-Denny, V., *Applying motor learning principles in coaching volleyball.* Coaching Volleyball, 2010. **27**(3): p. 24-25.
4. Weitl, D., *Whole vs. part training.* Coaching Volleyball, 2010. **27**(3): p. 8-11.
5. Doane, S., Alderton, D., Sohn, Y., Pelligrino, J., *Acquisition and transfer of skilled performance: Are visual discrimination skills stimulus specific?* J Exp Psychol: Human Perception and Performance, 1996. **22**: p. 1218-1248.
6. Nixon, J., Locke, L, *Research on Teaching Physical Education*. Second Handbook of Research on Teaching, ed. R. Travers. 1973, Chicago: Rand McNally.
7. Henry, F. *Specificity vs. generality in learning motor skills*. in *61st Annual Proceedings of the College of the Physical Education Association*. 1958. Santa Monica, CA.
8. Thorndike, E.L., Woodworth, R. S., *The influence of improvement in one mental function upon the efficiency of other functions.* Psychological Review, 1901. **8**: p. 247-261.
9. Henry, F., Rogers, DE, *Increased response latency for complicated movements and a "memory-drum" theory of neuromotor reaction.* Res Q, 1960. **1960**: p. 448-458.
10. Savelsbergh, G.J., Van Der Kamp, J., *Information in learning to coordinate and control movements: Is there a need for specificity of practice?* International Journal of Sports Psychology, 2000. **31**: p. 467-484.
11. Savelsbergh, G.J., Van Der Kamp, J., *Adaptation in the timing of catching under changing environmental constraints.* Res Q Exerc Sport, 2000. **71**(2): p. 195-200.
12. Yoshida, M., Cauraugh, J. H., Chow, J. W., *Specificity of practice, visual information, and intersegmental dynamics in rapid-aiming limb movements.* J Mot Behav, 2004. **36**(3): p. 281-90.
13. Hall, K.G., Magill, R. A., *Variability of Practice and Contextual Interference in Motor Skill Learning.* J Mot Behav, 1995. **27**(4): p. 299-309.
14. Schmidt, R.A., *A schema theory of discrete motor skill learning.* Psychological Review, 1975. **82**(4): p. 225-260.
15. Rushall, B., Pyke, FS, *Training for sports and fitness*. 1990, South Melbourne: Macmillan Education. 350.
16. Magill, R.A., Hall, K.G., *A review of the contextual interference effect in motor skill acquisition.* Human Movement Science, 1990. **9**: p. 241-289.
17. Shea, J.B., Morgan, R.L., *Contextual interference effects on the acquisition, retention, and transfer of a motor skill.* J Exp Psychol, 1979. **5**: p. 179-187.
18. Davids, K., Glazier, P., Araujo, D., Bartlett, R., *Movement systems as dynamical systems: the functional role of variability and its implications for sports medicine.* Sports Med, 2003. **33**(4): p. 245-60.

19. Manoel, E.J., Connolly, K.J., *Variability and the development of skilled actions.* Int J of Psychophysiology, 1995. **19**: p. 129-147.
20. Wulf, G., Shea, C.H., *Understanding the role of augmented feedback: the good, the bad, and the ugly*. Skill Acquisition in Sport: Research, Theory, and Practice, ed. A.M. Williams, Hodges, NJ. 2004, London: Rutledge. 121-144.
21. Wulf, G., Schmidt, R. A., Deubel, H., *Reduced feedback frequency enhances generalized motor program learning but not parameterization learning.* J Exp Psychol Learn Mem Cogn, 1993. **19**(5): p. 1134-50.
22. Wulf, G., Shea, C. H., Matschiner, S., *Frequent feedback enhances complex motor skill learning.* J Mot Behav, 1998. **30**(2): p. 180-92.
23. Fontana, F.E., Mazzardo, O., Furtado, O., Jr., Gallagher, J. D., *Whole and part practice: a meta-analysis.* Percept Mot Skills, 2009. **109**(2): p. 517-30.
24. Palmer, C., Meyer, R. K., *Conceptual and motor learning in music performance.* Psychol Sci, 2000. **11**(1): p. 63-8.
25. Simon, D.A., Bjork, R. A., *Models of performance in learning multisegment movement tasks: consequences for acquisition, retention, and judgments of learning.* J Exp Psychol Appl, 2002. **8**(4): p. 222-32.
26. Swinnen, S.P., Lee, T.D., Verschueren, S. Serrien, D.J., Bogaerds, H., *Interlimb coordination: Learning and transfer under different feedback conditions.* Human Movement Science, 1997: p. 749-785.
27. Swinnen, S.P., Carson, R. G., *The control and learning of patterns of interlimb coordination: past and present issues in normal and disordered control.* Acta Psychol (Amst), 2002. **110**(2-3): p. 129-37.
28. Wenderoth, N., Puttemans, V., Vangheluwe, S., Swinnen, S. P., *Bimanual training reduces spatial interference.* J Mot Behav, 2003. **35**(3): p. 296-308.
29. Lee, T.D., Schmidt, R.A., Young, D.E., *Skill learning: Conditions of training*. International Encyclopedia of Ergonomics and Human Factors, ed. W. Karwowski. Vol. 1. 2002, Boca Raton, FL: CRC Press. 1951.
30. Oliveira, F.T., Goodman, D., *Conscious and effortful or effortless and automatic: a practice/performance paradox in motor learning.* Percept Mot Skills, 2004. **99**(1): p. 315-24.
31. Shea, C.H., Kohl, R., Indermill, C., *Contextual interference: Contributions of practice.* Acta Psychol (Amst), 1990. **73**: p. 145-157.
32. Schmidt, R.A., Bjork, R.A., *New conceptualizations of practice: common principles in three paradigms suggest new concepts for training.* Psychological Science, 1992. **3**(4): p. 207-217.
33. Lee, T., Magill, RA, *The locus of contextual interference in motor skill acquisition.* J Experimental Psychology Learning, 1983. **9**: p. 730-746.
34. Bortoli, L., Robazza, C., Durigon, V., Carra, C., *Effects of contextual interference on learning technical sports skills.* Percept Mot Skills, 1992. **75**(2): p. 555-62.

35. Travlos, A.K., *Specificity and variability of practice, and contextual interference in acquisition and transfer of an underhand volleyball serve.* Percept Mot Skills, 2010. **110**(1): p. 298-312.
36. Wrisberg, C.A., Liu, Z., *The effect of contextual variety on the practice, retention, and transfer of an applied motor skill.* Res Q Exerc Sport, 1991. **62**(4): p. 406-12.
37. Goode, S., Magill, R., *Contextual interference effects in learning three badminton serves.* Research Quarterly for Exercise and Sport, 1986. **53**: p. 308-314.
38. Hall, K.G., Domingues, D. A., Cavazos, R., *Contextual interference effects with skilled baseball players.* Percept Mot Skills, 1994. **78**(3 Pt 1): p. 835-41.
39. Vickers, J.N., Livingston, L. F., Umeris-Bohnert, S., Holden, D., *Decision training: the effects of complex instruction, variable practice and reduced delayed feedback on the acquisition and transfer of a motor skill.* J Sports Sci, 1999. **17**(5): p. 357-67.
40. Landin, D.K., Hebert, E. P., Fairweather, M., *The effects of variable practice on the performance of a basketball skill.* Res Q Exerc Sport, 1993. **64**(2): p. 232-7.
41. Reid, M., Crespo, M., Lay, B., Berry, J., *Skill acquisition in tennis: research and current practice.* J Sci Med Sport, 2007. **10**(1): p. 1-10.
42. Williams, A.M., Hodges, N. J., *Practice, instruction and skill acquisition in soccer: challenging tradition.* J Sports Sci, 2005. **23**(6): p. 637-50.
43. Black, J.E., Isaacs, K. R., Anderson, B. J., Alcantara, A. A., Greenough, W. T., *Learning causes synaptogenesis, whereas motor activity causes angiogenesis, in cerebellar cortex of adult rats.* Proc Natl Acad Sci U S A, 1990. **87**(14): p. 5568-72.
44. Federmeier, K.D., Kleim, J. A., Greenough, W. T., *Learning-induced multiple synapse formation in rat cerebellar cortex.* Neurosci Lett, 2002. **332**(3): p. 180-4.
45. Kleim, J.A., Hogg, T. M., VandenBerg, P. M., Cooper, N. R., Bruneau, R., Remple, M., *Cortical synaptogenesis and motor map reorganization occur during late, but not early, phase of motor skill learning.* J Neurosci, 2004. **24**(3): p. 628-33.
46. Marteniuk, R.G., *Information Processing in Motor Skills*. 1976, New York: Holt, Rinehart & Winston. 244.
47. Gentile, A.M., *Implicit and explicit processes during acquistion of functional skills.* Scandavian Journal of Occupational Medicine, 1998. **5**: p. 7-16.
48. Eversheim, U. and O. Bock, *Evidence for processing stages in skill acquisition: a dual-task study.* Learn Mem, 2001. **8**(4): p. 183-9.
49. Mazzoni, P., Wexler, N. S., *Parallel explicit and implicit control of reaching.* PLoS One, 2009. **4**(10): p. e7557.
50. Willingham, D.B., *A neuropsychological theory of motor skill learning.* Psychol Rev, 1998. **105**(3): p. 558-84.
51. Wolpert, D.M., Z. Ghahramani, and J.R. Flanagan, *Perspectives and problems in motor learning.* Trends Cogn Sci, 2001. **5**(11): p. 487-494.
52. Alexander, G.E., DeLong, M.R., Crutcher, M.D., *Do cortical and basal ganglionic motor areas use "motor programs" to control movement?* Behavioral and Brain Sciences, 1992. **15**(4).

53. Houk, J.C., *Agents of the mind.* Biol Cybern, 2005. **92**(6): p. 427-37.
54. Wolpert, D.M., Ghahramani, Z., Flanagan, J. R., *Perspectives and problems in motor learning.* Trends Cogn Sci, 2001. **5**(11): p. 487-494.
55. Adkins, D.L., Boychuk, J., Remple, M. S., Kleim, J. A., *Motor training induces experience-specific patterns of plasticity across motor cortex and spinal cord.* J Appl Physiol, 2006. **101**(6): p. 1776-82.
56. Ericsson, A.K., Krampe, RT, Tesch-Romer, C, *The role of deliberate practice in the acquisition of expert performance.* Psychological Review, 1993. **100**(3): p. 363-406.
57. Leithwood, K.A., Fowler, W., *Complex motor learning in four-year-olds.* Child Dev, 1971. **42**(3): p. 781-92.
58. McPherson, S.L., *Expert-novice differences in performance skills and problem representations of youth and adults during tennis competition.* Res Q Exerc Sport, 1999. **70**(3): p. 233-51.
59. Ward, P., Williams A.M., *Perceptual and cognitive skill development in soccer: the multidimensional nature of expert performance.* J Sport Exerc Psychol, 2003. **25**: p. 93-111.
60. Farrow, D., Reid, M., *The effect of equipment scaling on the skill acquisition of beginning tennis players.* J Sports Sci, 2010. **28**(7): p. 723-32.
61. Sullivan, K.J., Kantak, S.S., Burtner, P.A., *Motor learning in children: feedback effects on skill acquisition.* Phys Ther, 2008. **88**(6): p. 720-32.
62. Wulf, G., *The effect of type of practice on motor learning in children.* Applied Cognitive Psychology, 1991. **5**: p. 123-134.
63. Yan, J.H., Thomas, K. T., Stelmach, G. E., Thomas, J. R., *Developmental differences in children's ballistic aiming movements of the arm.* Percept Mot Skills, 2003. **96**(2): p. 589-98.
64. Guadagnoli, M.A., Lee, T. D., *Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning.* J Mot Behav, 2004. **36**(2): p. 212-24.
65. Magill, R.A., *1997 C. H. McCloy Research Lecture: Knowledge is more than we can talk about: implicit learning in motor skill acquisition.* Res Q Exerc Sport, 1998. **69**(2): p. 104-10.

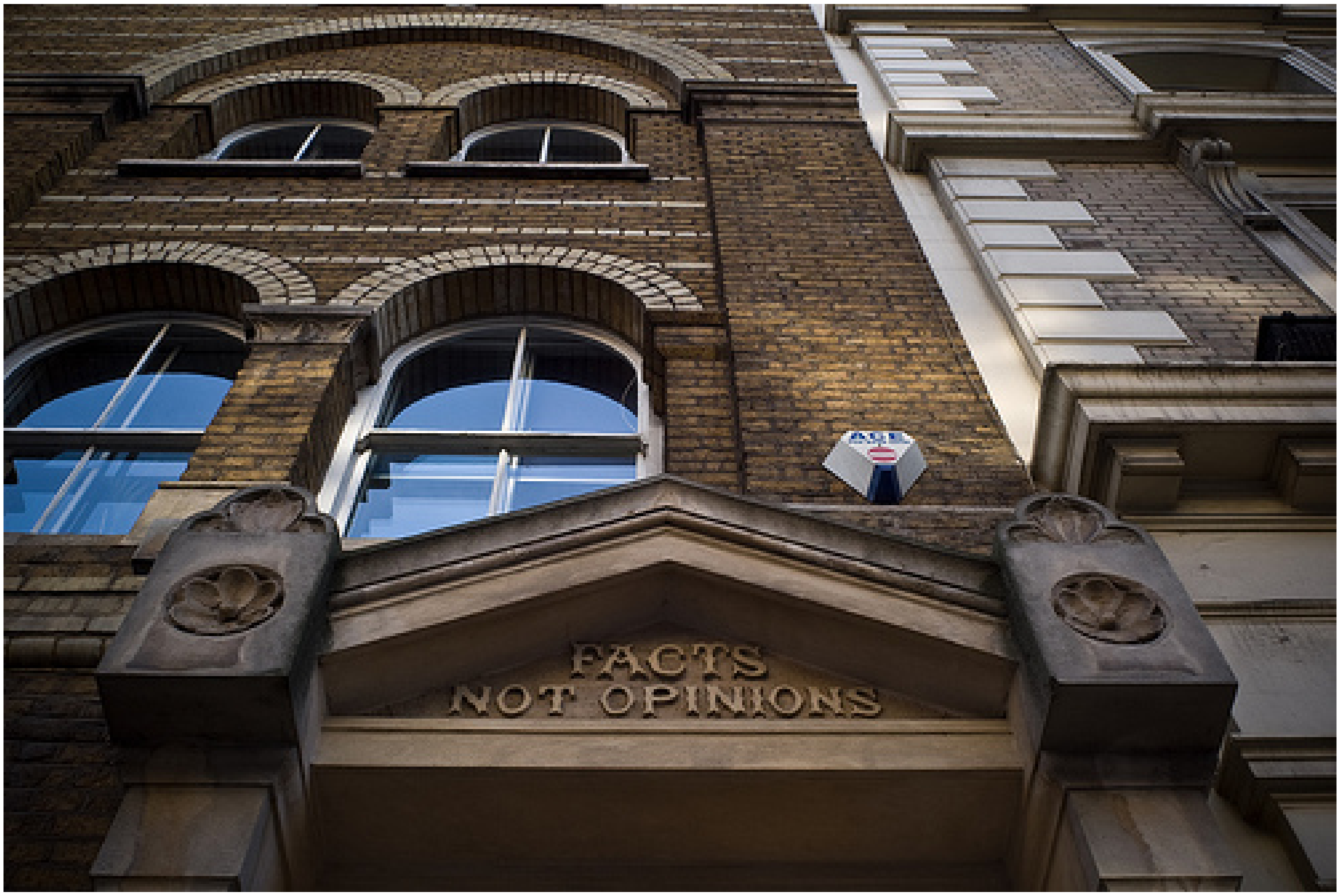

Figure 1. A photograph of the inscription, "Facts Not Opinions" over the main entrance to Kirkaldy's Testing and Experimenting Works in London. Original photo by Lars Plougmann reproduced here under license by Creative Commons (http://creativecommons.org/licenses/by-sa/2.0/deed.en)