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Bewegungswissenschaft

Jürgen Birklbauer

Optimal Variability for Effective Motor Learning

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Dedicated to my father, Wilhelm Birklbauer,
who left us suddenly and far too early.

Spektrum Bewegungswissenschaft
Band 9

Jürgen Birklbauer

Optimal Variability for Effective Motor Learning

A Theoretical Review and Empirical Work on Movement Variability

Meyer & Meyer Verlag

Herausgeber der Reihe Spektrum Bewegungswissenschaft:
Prof. Dr. Erich Müller, Universität Salzburg

Unterstützung durch die Stiftungs- und Förderungsgesellschaft
der Paris-London-Universität Salzburg

Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der
Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet
über http://dnb.d-nb.de abrufbar.

Auckland, Beirut, Dubai, Hägendorf, Hongkong, Indianapolis, Kairo, Kapstadt,
Manila, Maidenhead, Neu-Delhi, Singapur, Sydney, Teheran, Wien

Member of the World
Sport Publishers’ Association (WSPA)

Lektorat: Amnet Services
ISBN 756162.1/07/3
E-Mail: verlag@m-m-sports.com
www.wissenschaftundsport.de
www.dersportverlag.de

Table of Contents

From Theoretical Background to Practical Implications 11

1 Introduction 12

2 The Contextual Interference Effect 17

2.1 Potential moderating variables 19

2.1.1 Task (dis)similarity 20

2.1.2 Task complexity 21

2.1.3 Interaction of task similarity and task complexity 24

2.2 A couple of attempted explanations 28

2.3 Analyzing the neural basis by means of fMRI and TMS 32

3 The Differential Teaching and Learning Approach 38

3.1 Synergetics and coordination dynamics 39

3.1.1 Synergetic principles derived from inanimate nature 41

3.1.2 Non-linear dynamics of rhythmic uni- and bimanual coordination 44

3.1.2.1 Modeling coordination dynamics: the classic HKB model and its progression 47

3.1.2.2 Central neural correlates of relative phase dynamics 53

3.1.3 Phase transitions on short time scale: beyond standard finger coordination 61

3.1.3.1 Further control parameters and coordination constraints 61

3.1.3.2 From rhythmic interlimb through to discrete gross-motor coordination 63

3.1.3.3 Interpersonal coordination 66

3.1.3.4 On some further coordination domains of human nature 70

3.1.4 Phase transitions on medium time scale: motor and perceptual learning 73

3.1.4.1 Motor learning in the framework of coordination dynamics 74

3.1.4.2 The influence of initial coordination dynamics on learning and memory 75

3.1.4.3 Findings on gross-motor learning of continuous and discrete sport-related skills 81

3.1.4.4 Neural indices of learning-induced changes in coordination dynamics 83

3.1.4.5 Individual routes of learning-induced changes in perceptual dynamics 85

3.1.5 Phase transitions on long time scale: developmental psychology and psychotherapy 85

3.1.5.1 Anomalous variability as a harbinger of abrupt changes in child development ... 85

3.1.5.2 Detecting and using periods of anomalous variability in psychotherapy 90

3.2 Stochastic resonance 94

3.2.1 Generic theoretical models and characterization quantities 101

3.2.2 Noise and its degree of (non-)determinism 105
  3.2.2.1 Variability amplitude versus randomness using the example of postural control 108
  3.2.2.2 The different colors of noise 109
  3.2.2.3 1/f noise 116
3.2.3 Stochastic resonance and its origins in physics 125
3.2.4 The benefits of noise in biological functioning: simulations and experiments from ion channels to behavior 126
  3.2.4.1 Optimal noise can improve neural processing 127
  3.2.4.2 Optimal noise can improve sensory and perceptual processing 130
  3.2.4.3 Optimal noise can improve behavioral processing in animals and humans 140
3.2.5 Stochastic resonance and the link to (differential) motor learning 148
3.3 Biological and computational neuroscience 152
3.3.1 Extracting rules out of experiences: the ability to generalize 152
3.3.2 Neural plasticity as the natural base for the generalization ability 156
  3.3.2.1 The synaptic plasticity hypothesis 158
  3.3.2.2 Synaptic changes: different mechanism on different time scales 162
  3.3.2.3 Principles of plasticity or biological learning rules 169
3.3.3 Artificial neural networks: mathematical models of nature 174
  3.3.3.1 Fundamental components and principles 175
  3.3.3.2 Basis network architectures 177
  3.3.3.3 Basic learning rules 180
  3.3.3.4 Topographic mapping of common features 186
3.3.4 Associative memory, self-organization and generalization quality 205
  3.3.4.1 Distributed memory storage 205
  3.3.4.2 Self-organization: learning by examples 208
  3.3.4.3 Validating generalization and some general factors of influence 211
3.3.5 Motor learning as the extraction of appropriate sensorimotor rules 213
  3.3.5.1 The need for rule extraction even in closed conditions 213
  3.3.5.2 Learning to utilize non-muscular forces 215
  3.3.5.3 The whole may be different from the sum of its parts 218
  3.3.5.4 The change of structuredness of execution variability during learning 219
3.3.6 Implicit generalization: an essential ability and ubiquitous phenomenon 224
  3.3.6.1 Physical world comprehension 225
  3.3.6.2 First language acquisition 227
  3.3.6.3 Finite-state artificial grammars 232
  3.3.6.4 Perceptual illusions 238
  3.3.6.5 Superstition: extracting rules even if there are none 242
  3.3.6.6 Logical reasoning even by relatively simple animals 243
  3.3.6.7 Detecting abstract-rule-encoding neurons in monkeys 245

3.3.7 Interpolation is better than extrapolation 247
3.3.7.1 Concerning artificial neural networks........ 247
3.3.7.2 Concerning humans and animals 250
3.3.8 Meta-plasticity: changing the learning rate over time 259
3.3.8.1 The change of plasticity in natural learning........ 262
3.3.8.2 Meta-plasticity as a function of the learning process itself........ 263
3.3.9 A "perfect" memory: is it really desirable?........ 265
3.3.9.1 The problem of over- and underfitting in computational networks........ 266
3.3.9.2 When memorizing idiosyncratic details becomes patho-logical........ 271
3.3.9.3 Implications for (motor) learning 278
3.3.10 Random noise and its beneficial effects on neural network performance 279
3.3.10.1 Adding random noise to computational networks 279
3.3.10.2 From computational to biological networks........ 300
3.3.10.3 Simulated annealing 307
3.3.11 Simulating contextual interference by computational networks........ 348
3.3.11.1 Evaluating acquisition and retention........ 349
3.3.11.2 Evaluating generalization and relearning 351
3.3.11.3 Beyond the simple multi-layer perceptron........ 355
3.3.11.4 A brief résumé 359

4 Summary and Discussion 361
4.1 The seeming paradox of reducing noise by noise 363
4.2 The time-dependent structure of movement time series and the coupling between effectors........ 369
4.3 The predictive brain notion: forming a (causal) model of the world 377
4.4 The improvement of neural networks by random perturbations 397
4.5 The improvement of neural networks by structured variability 412
4.6 The contextual interference effect 430
4.7 The differential learning approach 447

Empirical Study 468

5 Statement of the Problem 469
6 Methods 475
6.1 Overall study design 475
6.2 Subjects 475
6.3 Intervention program........ 477

6.4 Test design and data collection 492
6.5 Statistical analysis... 493
7 Results 495
7.1 Target shooting.. 495
7.2 Slalom dribbling.. 497
7.3 Target shooting – slalom dribbling relationship 499
8 Discussion and Conclusion 501
Bibliography.. 511
Appendix A: questionnaire 598

Abstract

This thesis addresses different manifestations and practical implementations of movement variability in respect to their beneficial effects on movement coordination and learning. The focal point of this topic, which has been a long-standing, and still ongoing, issue of debate in academic research and among practitioners, is formed by the comparison between the contextual interference paradigm and the differential learning approach, representing two variable practice strategies found to improve motor learning performance under certain conditions. The theoretical backgrounds and empirical findings of each approach are thoroughly reviewed in the first part of this work. From contextual interference research, it is advised to frequently switch between different task variations during the acquisition phase in order to facilitate delayed retention and transfer. Established theoretical accounts are largely based on the cognitive-psychological perspective with the focus on the additional information-processing demands imposed by the changing context of practice. The literature review in this respect outlines evidence from actual neuroscientific findings and elaborates on major factors of influence, while arguing from the viewpoint of movement variability that the spatial variance and temporal structure of the task variations have to be tuned to the individual's inherent variability at the given task to advance learning. The differential training approach is conceived as a practical application of the fundamental ideas in synergetic and coordination dynamics, movement complexity analysis, stochastic resonance, and (artificial) neural network research. These basic concepts, which are introduced and discussed in the context of movement variability, led to a sustainable paradigm shift in motor science by highlighting variability as an essential functional entity of flexible and adaptive systems within different theoretical frameworks. Drawing on synergetic principles of self-organization, dynamical pattern theory identifies variability as a central feature for creating instabilities via which the movement system spontaneously shifts into qualitatively different organizational states on different time scales. The stochastic resonance framework elucidates the counterintuitive phenomenon of how random noisy perturbations can enhance the quality of information signals from positively impacting neuronal function to improving movement performance. Simulations by artificial neural networks, whose power rests upon their built-in generalization ability, provide valuable predictions for the selection of variable and representative training stimuli, as well as for the addition of noise, in order to reasonably respond to unseen situations. These theoretical concepts, and their resultant practical training approaches, arrive at the notion of an optimal magnitude and structure of movement variability that should be encouraged during practice. The second part of this work presents a parallel-group study designed to contrast the effects of a high contextual interference and schema-based practice regime with two variants of differential training on the adoption of two indoor hockey skills in beginners. In relation to the contextual interference strategy that involved random practice of a discrete number of incrementally complex exercises, differential learners were confronted with an even larger amount of practice variability by increasing the differences between consecutive exercises that included erroneous movement executions and were performed only once in either a systematic or a random arrangement across multiple training sessions. Study results demonstrated positive acquisition and learning effects on target shooting and slalom dribbling for all three highly variable practice programs, with the improved criterion and transfer performance persisting over the 6-month retention interval except for random differential training. However, neither of the two differential training designs resulted in better acquisition, retention or transfer outcomes than the contextual interference approach. This supports the proposition that the amount of optimal practice variability is limited if the acquisition period is confined to several training sessions at the early stage of learning complex sport skills.

Part I

From Theoretical Background to Practical Implications

1 Introduction

Effective technique training and the resulting questions about optimized motor learning are of interest not only for competitive and recreational sports, but also for therapy and a vast number of occupational categories. This interest attracts particular attention in movement science; consequently, it is a great challenge of such research to develop a practicable learning strategy to achieve a certain skill at best.

At least since Schmidt's schema theory and the resulting development of the variability-of-practice hypothesis (postulated in 1975), variable practice has become well accepted learning strategy, even for closed skills.

N. A. Bernstein already mentioned in 1947, that the uncontrollable dynamics of the environment is in contrast to any possibility of a standardized motor formula being imprinted in the brain. According to Bernstein, one should take into account that forces producing a certain movement output are not predefined only by the muscles' innervation state and their length and velocity at a given time. Apart from those active muscle forces, passive external and internal dynamics such as position-dependent gravitational forces and mechanically reactive or motion-dependent forces (i.e. inertial, centrifugal and Coriolis forces), as well as passive forces arising from muscle deformation and other soft tissues are (inter)acting as well, resulting in an equivocal relationship between the innervational impulses and the movement outcome. Expressed another way, more than one motor signal can lead to the same movement trajectory and vice versa: identical motor signals can cause different movements under non-identical initial conditions and/or in the presence of variations in the external force field.

By modeling performance optimization, Hatze (1986) pointed out that it is impossible to determine, solely from motion observation, which actions and neural activity generated the observed motion, and emphasized that "exact repetitions of motions are not possible". In a couple of empirical studies, Schöllhorn and colleagues took a holistic approach for non-linear analysis of different complex movement patterns that convincingly indicated a low probability of executing two identical movements. Even in top athletes, time series and artificial neural network analyses of relatively short movement phases affirmed the individuality of movement patterns over a period of up to 1 year, including pole vault (Jaitner & Schöllhorn 1997); contact phase in long jump (Jaitner et al. 2001); the final throwing phase of discus (Bauer & Schöllhorn 1997; Schöllhorn 1998) and javelin (Schöllhorn & Bauer 1998); a double step in running (Schöllhorn 1999a); free throw in basketball (Schmidt et al. 2009); as well as sprint (Simon & Schöllhorn 1997) and gait patterns during ground contact (Janssen et al. 2008; Janssen et al. 2011; Schöllhorn et al. 2002); finger and whole-body kinematics in flute playing (Albrecht et al. 2014); and tactical patterns in team sports (Jäger & Schöllhorn 2012).

Regarding altered initial conditions or reactive forces, the task requirements are permanently changing, even though the environment is kept constant. Such changes occur to a greater extent in more complex movements than in laboratory motor tasks because the relationship between central impulses and the movement outcome is "further removed from unequivocality" (Bernstein 1967, p. 21) in an exponential progression by each new degree of freedom of the kinematic chain. Against this background, it is not surprising that motor program concepts, and from there constant practice, are predominantly established in typical psychological test settings with simple motor tasks (cf. Wulf & Shea 2002; Birklbauer 2006). It is further obvious that even in closed skills, the number of executable solutions to a given motor task always far exceeds the small number of learned examples (motor redundancy). Hence, it is the objective and the challenge, not only in open skills, but also in more standardized motor tasks, to necessarily develop a task-specific interpolation ability to adequately and rapidly react to new situations in terms of changing external and internal forces acting on the body. The development of such, of course, neuronally based rules is a central element in Schmidt's schema theory, and consequently, in the variability-of-practice hypothesis, as well as in a more recent approach of so-called differential learning by Schöllhorn (1998, 2000), although both concepts approach from different research fields and differ in some key aspects, and hence lead to different consequences.

First of all, in contrast to the schema theory, in differential learning the nature of the rules that have to be acquired for a successful adaptation to changing constraints is not a priori determined, but emerges by itself only by interaction of the subsystems in a self-organized manner (cf. Frank et al. 2008). Furthermore, the schema theory does not explain the variability-of-practice effect in tasks where the environment is kept constant. Neglecting persistently varying position-dependent and motion-dependent forces restrains the application of prior predefined invariants to a limited number of movements that are almost exclusively generated by muscular forces. On the contrary, when moving in complex and dynamic performance contexts, the variations of Schmidt's predefined invariants are unavoidable (cf. Schöllhorn et al. 2007c).

Schöllhorn's differential learning and teaching is based on the system dynamic approach; it intends to apply the principles of self-organization, introduced in the 1960s by H. Haken (1983) and transferred to motor science in the 1980s by J. A. S. Kelso (1995), into practice of motor learning and technique training. Quite similar to Bernstein, who concluded that practice is a particular type of repetition without repetition by means of repetitively solving the same problem in different manner, the central postulation of differential learning concerns the intention of "never repeating an exercise twice" (Trockel & Schöllhorn 2003), which is not possible anyway, as was previously stated. However, with an increase in execution variability, differential learning seeks to more extensively scan the hypothetical solution space of a given task, encouraging the learner to gain appropriate neuronally coded rules that enable a context-dependent optimized use of external and reactive forces, and therefore, reliable and successful solutions of complex skills. Consequently, the construct of differential learning is mainly characterized by Schöllhorn et al. (2009b) as randomly adding variable elements to target movements.

While the variability-of-practice hypothesis corresponds to the comparison between variable and constant practice and offers no provision of how the order-of-practice trials should be conducted, the context interference effect refers to the effectiveness of different variable practice schedules. It originates in observations that practicing different exercises or tasks in a randomized order, compared to a blocked practice schedule, impedes acquisition, but favors retention and transfer performance. Different amounts of interference emerging from performing variations within the context of practice are seen as a continuum between two extremes: high contextual interference, wherein the sequence of exercises would be randomly assessed, and low contextual interference resulting from the practice of each task variation within its own block, or unit, of time (cf. Magill 2007). Various forms of serial practice (e.g. a serial order of task or block variations) organize variable practice between both extremes. Whereas the contextual interference effect is related to the order of exercises, their selection and other parameters act as moderator variables. The effect of different contextual interference on learning and memory roots in experimental cognitive psychology. It was first described by Battig (1966, 1972) in verbal learning, and brought forward to motor learning by Shea and Morgan (1979) in a serial reaction and movement time task.

In terms of differential learning, contextual interference is considered as a noise generating practice schedule in which randomized order, defined as high contextual interference, induces a higher level of noise than blocked order does. Whereas traditional models view noise as inherent changes of a given target movement, in differential learning noise also includes the instructed movement variations, traditionally referred to as variability (Schöllhorn et al. 2006a). In two case studies, Gebkenjans et al. (2007) and Janssen et al. (2010) demonstrated that executions of first and second tennis services in a serial order led to higher variance of each technique than a blocked arrangement; therefore, they cover a greater area of potential solutions. In a bifurcation model of differential learning on a dynamic system perspective by Frank et al. (2008), or in an evolving landscape approach including simulated annealing processes by Schöllhorn et al. (2009b), the amount of noise must exceed a particular threshold to enable further learning progress. Therein, training noise represents the variety of between-exercise difference.

The amount of contextual interference, as well as noisiness, not only depends on exercise schedule, but also depends strongly on the types of exercise. In most studies on the contextual interference effect, exercises are selected with regard to Schmidt's schema theory intending to develop and to automatize a generalized motor program, or to differentiate between different programs. A contrasting juxtaposition of task variations between different motor programs (program variable practice) and variations within the same motor program (parameter variable practice) has been a key issue in past research since Magill and Hall (1990) proposed this hypothesis in relation to task difficulty.

Against the contextual interference approach, where exercises are picked due to program parameters, differential learning does not focus only on the variation of movement parameters or movement invariants; nor do exercises belong to a particular movement class. From a system dynamics' point-of-view, predefined movement classes or schemata do not exist. In contrast, in differential learning, subjects experience as many different invariant and variable parameters as possible, which leads to the knowledge of a larger pool of potential solutions. Therefore, Schmidt's variable practice is only a small subset of differential training, which, as defined by Schöllhorn (2000) and Schöllhorn et al. (2007c), involves all forms of variable and constant learning approaches. Schöllhorn et al. (2009b) consider traditional learning approaches, including constant practice and methodical rows of exercises, as well as different schedules of variable practice as different levels of stochastic perturbations, whereby the highest level is achieved with the differential learning strategy.

As mentioned above, the contextual interference approach concerns the organization of a certain selection of exercises, but is essentially influenced by the character of the exercises themselves. The contextual interference hypothesis does not imply a predefined number of variations; rather, it compares different practice schedules that contain the same exercises and the same total number of executions per variation. Previous studies used a limited number of three to four variations. If their number is increased and the character of variations is not taken into consideration, contextual interference approach advances toward differential learning.

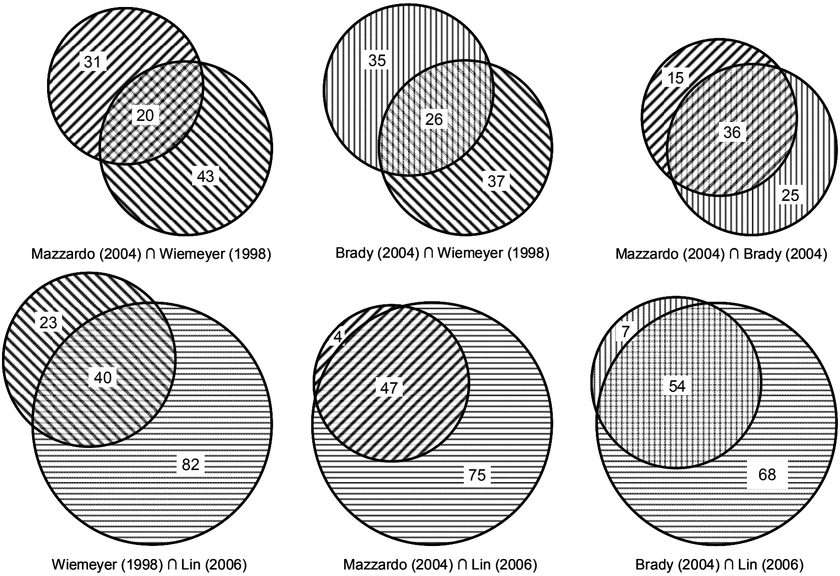
In contrast to the observed contextual interference effect where randomized practice showed worse performance in the acquisition phase, the differential learning approach postulates not only superior retention and transfer, but also acquisition performance. This may occur if the learning environment is noisy enough to extensively scan the hypothetical solution space of the task (cf. Schöllhorn et al. 2006a; Frank et al. 2008; Schöllhorn et al. 2009b). As indicated by Gebkenjans et al. (2007) in tennis and Beckmann et al. (2010) in hockey, contextual interference or noise must be optimized, not maximized, for maximal learning success; that is, an inverted U-shaped relationship between the amount of noise and learning performance. Contextual interference supports that notion by showing worse results when interference exceeds a certain level, depending on the task to be learned and the performance level (see Chap. 2.1). This raises the question of whether and how to structure the training progress.

2 The Contextual Interference Effect

After the early findings of Battig (1972) and Shea and Morgan (1979), a considerable number of studies on the contextual interference effect were conducted in different conditions leading to several extensive reviews and meta-analyses. However, at issue results caused by a multitude of moderator variables pose more questions than answers.

Contextual interference effect meta-analyses were conducted by Wiemeyer (1998) with 112 effect sizes out of 63 studies; by Brady (2004) with 139 effect sizes out of 61 studies; by Mazzardo (2004) with 115 effect sizes out of 51 studies; and by Lin (2006) with 336 estimates of effect sizes out of 122 studies. All studies included in those analyses were published from 1979 to 2005, but they differed considerably across meta-analyses. The fewest identical studies were found between Wiemeyer and Mazzardo with 36%, whereas the Mazzardo had 64% in common with Brady representing the highest concordance (cf. Fig. 1). Only 18% of the studies were analyzed in all four meta-analyses. The results of those analyses should be compared with caution despite the fact that the same effect size was used calculating Cohen’s d corrected for bias and sample size by Hedges and Olkin (1985). Mazzardo set effect sizes being not significant as zero yielding in a possible underestimation of the contextual interference effect. Brady put scores for retention and transfer tests in a single analysis, and thus violated the independence assumption of standard meta-analysis.

The overall contextual interference effect is supported and warranted by significant overall mean effect sizes over acquisition, retention and transfer. In accordance with the contextual interference hypothesis, the blocked group outperformed the random group in acquisition with small to medium effects stated by Mazzardo (−.31) and Lin (−.42), whereas Wiemeyer found a large mean effect (−.84). For retention and transfer, the mean treatment effect was similar and of small to moderate size in Brady’s (.40/.31), Mazzardo’s (.31/.23) and Lin’s (.31/.28) analyses, but once again larger in Wiemeyer’s study (.56/.43), which may be explained by the least study concordance with the other three meta-analyses.



Mazzardo (2004) ∩ Wiemeyer (1998)
Brady (2004) ∩ Wiemeyer (1998)
Mazzardo (2004) ∩ Brady (2004)
Wiemeyer (1998) ∩ Lin (2006)
Mazzardo (2004) ∩ Lin (2006)
Brady (2004) ∩ Lin (2006)

Fig. 1: Intersections of the analyzed literature in the contextual-interference meta-analyses by Brady (2004), Lin (2006), Mazzardo (2004) and Wiemeyer (1998)

Tests for homogeneity done by Wiemeyer, Brady and Lin to assess whether all the effect sizes were similar revealed that the overall effects were inhomogeneous in acquisition, retention and transfer, indicating that some other factors (i.e. moderator variables) influence the contextual interference effect. To estimate the publication bias, Wiemeyer and Brady calculated the fail-safe N in order to answer the so-called file drawer problem that represents the number of unpublished studies with null effect that would be necessary to reduce the cumulated effect size to a non-significant level. Brady found a fail-safe N of 204 for the overall effect including retention and transfer, so it is unlikely that there are that many studies sitting in file drawers. This is in accordance with Wiemeyer's results in acquisition and retention; however, for transfer, the validity of the effect sizes is not supported. Additionally, Brady calculated the overall mean power of the studies reviewed based on an estimated effect size of .40. An overall beta error of .57 indicates a lack of adequate sample size, especially in those studies where the effect size is small.

2.1 Potential moderating variables

Due to the inhomogeneous results of contextual interference studies, multiple moderator variables were theoretically debated and their influence was calculated if the number of studies was sufficient. Such variables are ecological and internal validity; amount of practice and contextual interference; type of skill, test and task; skill level; age; gender; knowledge of result; personality; and theoretical explanations.

The only moderator variable that was analyzed in all four cited meta-analyses belongs to the nature of research or ecological validity. Whereas in acquisition, significant larger contextual interference effects were consistently revealed in laboratory oriented research than applied, the meta-analytic studies disagreed in retention. Wiemeyer and Brady found again bigger advantages for random practice for settings lacking real-world features (2.4 to 3 times as many mean effects), while Mazzardo and Lin demonstrated similar magnitude of effect sizes. A possible explanation for this disagreement could be provided by the different inclusion of applied studies. Contrary to Mazzardo and Lin, in Wiemeyer's and Brady's analyses applied studies contained only real sport settings and tasks. As typical sport skills are more often of complex nature with a higher degree of freedom, random practice more likely leads to a mental overload through movement variability.

Furthermore, Brady established an interaction of age and nature of research; that is, young learners showed relatively small effect sizes in applied sport settings; however, when the comparison is limited to adults, the effect size differences between laboratory and applied studies are of less magnitude. Besides Brady's revealed age difference in contextual interference effect, Lin could confirm larger effects for adults even though in acquisition, but neither in retention nor in transfer. The observation that the movement variability induced through random practice schedule overwhelms the learner's capability as seen in age could be further expanded to novices and female. As Lin pointed out, male or experienced had two to three times larger effects sizes in retention being moderate to large.

Brady detected in a comparison between different amounts of contextual interference that high amounts were more effective than mixed, but not when sport skills were taught. Mean effect sizes differed also across different types of tests and different amounts of practice. Against precision tasks, Wiemeyer calculated about two times larger effects for tasks with focus on movement speed in retention and three times larger effects in transfer. Although Mazzardo and Lin classified the amount of practice equally, their results diverged favoring, on the one hand, medium amount studies with 51 to 90 trials; and on the other hand, studies with larger amounts.

Neither during acquisition nor retention or transfer did the presence or absence of augmented feedback significantly influence effect sizes, as Mazzardo unveiled; however, different types of knowledge of result were not distinguished. The analysis of the internal validity demonstrated higher effect sizes in studies where participants, tasks and the methodological procedures were more tightly controlled, which could have been expected.

2.1.1 Task (dis)similarity

Based on the extended review of different types of tasks, Magill and Hall (1990) recognized that the contextual interference effect is not a global effect and may be manipulated by the type of task variations to be practiced. Their "between- vs. within-motor program hypothesis" is related to the diverse similarity or dissimilarity of task variations and the thereof derived task difficulty, which generates different amounts of contextual interference. When the variations to be practiced in random order are quite different (i.e. requiring different generalized motor programs) a higher level of contextual interference is created leading to enhanced retention and transfer performances. However, if the task variations are similar involving parameter modifications, which are within the same motor program, the contextual interference effect due to reduced task difficulty will not be found. Based on the assumption that varying between different motor programs requires the reconstruction of the program inclusive parameter adjustments each time, learners engage in more effortful processing than when the task variations are similar.

Wiemeyer and Mazzardo confirmed in their meta-analytic studies for both parameter variable and program variable practice contextual interference effects. While parameter alterations during practice yielded in small results, varying between different movement patterns produced more than two times larger effects in retention and transfer, although negative effect sizes did not differ in acquisition phase. In an early laboratory experiment, Wood and Ging (1991) directly compared different levels of similarity of the task variations to be learned. Results of the retention and novel transfer tests supported contextual interference effects for low, but not high, similarity tasks. In place of defining task similarity as a function of the spatial characteristics (i.e. size versus shape) of the movement patterns, Boutin and Blandin (2010a) more recently compared parameter variable practice of more or less similar absolute movement times in a three-segment timing task. While no blocked-random difference was found for the similar parameter condition, varying more dissimilar target times produced higher intertrial variabilities during acquisition with the highest by random practice, and again, a typical contextual interference effect. In both studies, however, task variations were restricted to simple skills with few degrees of freedom, or even to the same motor program which thus may induce lower movement variability by itself.

In contextual interference literature, parameter learning is sometimes equated with parameter variable practice and program learning with program variable practice, respectively. In order to avoid confusion, this should be separated. Whereas the parameter or program variable practice refers to the properties of the variation, program or parameter learning refers to what is learned through practice, that is, the construction of particular motor programs or the improvement of parameter modification within motor programs.

Magill and Hall's view concerning the superiority of program variable practice predicts that both program learning and parameter learning would be enhanced in contrast to parameter variable practice. When programs are reconstructed, parameters added to them have to be modified as well. Opposing this prediction, contextual interference effects were mostly detected in parameter learning, but not in program learning, regardless of whether skill variations are controlled by the same or different programs (cf. Mazzardo 2004). However, those studies, which drew the comparison between both kinds of learning practicing within or between motor programs, used serial practice schedules as high contextual interference and very simple laboratory tasks.

2.1.2 Task complexity

Besides the subjects' skill levels and ages, the difficulty or amount of interference created during practice depends on the complexity of a given task. This probably caused, as Hebert et al. (1996) stated, different results between laboratory and applied research settings.

The topic was taken up by Wulf and Shea (2002) in their extended review about the different properties of simple and complex skill learning. As opposed to laboratory experiments of the contextual interference effect that involve typically multi-segment tasks, simple aiming and anticipation-timing tasks or movement patterning and tracking tasks, complex skills feature several degrees of freedom, cannot be mastered in a single session and tend to be ecologically valid as categorized by Wulf and Shea (2002). According to their view, practicing more complex movement patterns calls for higher attention, motor control and memory demands, which make those tasks themselves more difficult, especially when learners are relatively inexperienced. More demanding practice schedules like random practice may, therefore, overload learners' capacities and thus diminish the advantages of high contextual interference schedules.

Albaret and Thon (1998) corroborated the hypothesis that the complexity of the task to be learned modulates the contextual interference effect. Comparing random and blocked practice in different levels of complexity of a laboratory drawing task, retention and transfer tests revealed a clear advantageous effect for random practice, but only in the simplest condition. When the task complexity was increased, the random practice benefits were reduced and in the most complex condition almost reversed. Similar results were reported more recently by Boutin and Blandin (2010b) for a timing task whose target times had to be performed either in one single or three different movement directions with the latter being more complex due to its higher degrees of freedom. While practicing the simple task variants yielded a typical contextual interference effect, no blocked-random difference was found for the more complex movement pattern regardless of the amount of practice. Furthermore, advantages of random relative to blocked practice are all the more lost, when the complexity and difficulty of the task is increased by producing both a goal movement outcome and a specific relative force or timing pattern (Wulf & Shea 2002).

From a cognitive-psychological perspective, Wulf and Shea (2002) interpreted those findings to the effect that with an excessive degree of complexity in movement task and practice schedule, the development of memory representations or motor programs would be degraded. This is because, on the one hand, short-term memory may be overloaded, limiting motor processing or elaboration or on the other hand, make a full reconstruction from trial to trial difficult. In the "challenge-point" framework postulated by Guadagnoli and Lee (2004) from an information-theoretical point of view, task complexity relates to the constant, nominal task difficulty while the functional difficulty of a given task additionally depends on the skill level of the performer and the conditions under which the task is being practiced. For optimal learning, practice conditions, such as the trial order, need to be adjusted to one's information-processing capabilities, which in turn is a function of the skill level, and the nominal task difficulty such that an optimal amount of interpretable information is available (i.e. the optimal challenge point). For instance, a complex task or a random trial order will increase the functional task difficulty, and thus, will provide for more information generated in the performance of the task because more uncertainty can be reduced. Still, beyond an individual's optimal challenge point, further increase of potential information would be increasingly noninterpretable as it overflows the information-processing capacity of the learner resulting in less learning benefit. As such, random practice of a complex task may offer an appropriate functional difficulty for an expert performer, whereas it would presumably overshoot the amount of information efficiently processed by a beginning performer. Practicing a simple task in a constant or blocked manner without changing environmental conditions, on the other hand, might be functionally too easy for novices and even more so for advanced performers; again, precluding the individual from his/her optimum challenge point for learning. But this time because, rather than too much, too little potential information is available as there is high certainty about the potential success of performance. From a dynamical system point of view (see Chap. 3.1), the combination of inherent variability and introduced variability – the first caused among others by the task complexity and the second by the practice schedule – might exceed an optimal level of movement variability or noise. Such an excessive amount of noise would then rather impede than enhance the development of the task-specific interpolation ability necessary to successfully adapt to changing constraints.

2.1.3 Interaction of task similarity and task complexity

Introduced variability is not only determined by the practice schedule (i.e. constant, blocked, serial or random practice), but also by the similarity or dissimilarity of the task variations. Given a complex task setting, variations to be practiced with small similarity and in random order would predict a tremendous amount of movement variability. That might exceed the optimal level of noise; therefore, it impedes learning, whereas the same amount of introduced variability in laboratory tasks might be optimal noise, and thus, enhance learning.

According to already mentioned Magill-and-Hall-hypothesis (1990), in laboratory-based research high contextual interference is more effective than low when tasks using different motor responses are performed. Contrarily, in research using complex sport skills the contextual interference effect could be demonstrated, in particular, when variations were within the same motor program; hence, it is relatively similar. This fact is supported by a meta-analysis by Gelber (2005) including 27 applied studies published between 1986 and 2004, where it was differentiated between the type of exercises (i.e. within the same or between different generalized motor programs).

Fifty-seven mean effect sizes weighted by sample size were calculated for acquisition, retention and transfer. Taking both types of tasks together, a similar, but slightly lower mean effect size of .14 was discovered in retention than Brady (2004) found for field-based research. Mean effects in acquisition (.02), as well as transfer (.10) were below .20 – representing small and trivial differences as defined by Cohen (1988), where results in acquisition were quite similar to Wiemeyer (1998), Mazzardo (2004) and Lin (2006). However, by differentiating between task types and taking only complex sport settings into account as a higher inherent variability is assumed, the contextual interference effects were apparent only in parameter variable practice (see Fig. 2). In comparison to the ten studies varying between different skills, the 13 parameter altering studies showed notably higher contextual interference effects for acquisition (−.17), retention (.38) and transfer (.19), whereas program variable practice fails to achieve mean effects for acquisition (−.03), for retention (.04) or for transfer (.01).

The assumption that varying different motor responses combined with high task complexity leads to a noise overload (i.e. exceeding the optimal level of movement variability) is brought forward by a self-performed research review. Twenty-six applied studies related to complex sport skills, published between 1984 and 2007, were analyzed in the style of a traditional voting method. Fourteen of those 26 studies involved similar variations within one skill (Pigott & Shapiro 1984; Goode & Magill 1986; Porretta 1988; Boyce & Del Rey 1990; Wrisberg 1991; Wrisberg & Liu 1991; Hall et al. 1994; Smith & Davies 1995; Goodwin & Meeuwsen 1996; Farrow & Maschette 1997; Landin & Hebert 1997; Granda & Montilla 2003; Hwang 2003; Jackson 2006); whereas 11 studies included program variable practice (French et al. 1990; Bortoli et al. 1992; Hebert et al. 1996; Nair & Bunker 2000, 2002a, 2002b; Koufou et al. 2003; Ata 2005; Ata et al. 2005; Jones & French 2007; Zetou et al. 2007). An early study by Wulf (1988) contained both variations within and between generalized motor programs.

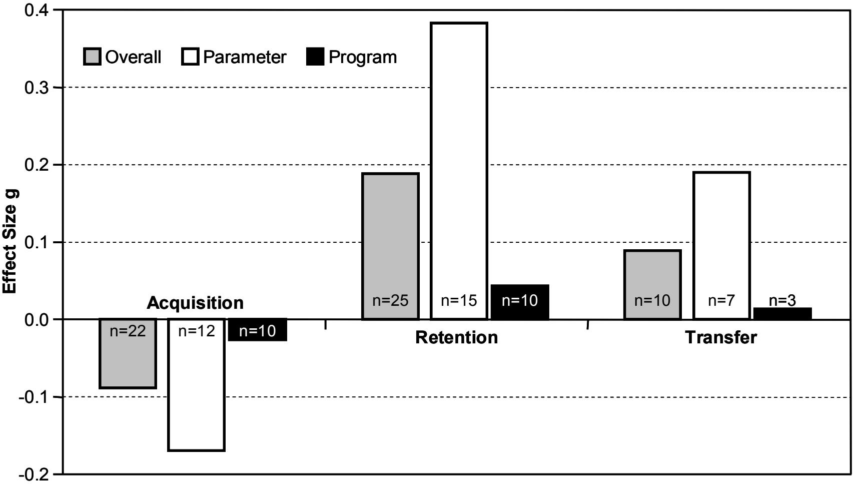


Fig. 2: Mean effect sizes for contextual interference effect in acquisition, retention and transfer of the 27 applied studies in the meta-analysis by Gelber (2005) separated in the overall effects as well as parameter and program variable practice effects

Nine out of the 12 studies related to dissimilar task variations found no significant advantages for random practice schedules either in retention or in transfer. Only the study by Ata et al. (2005) revealed a trend toward high contextual interference, in which two of the three skills to be learned showed significance in short-term retention; however, only one skill for long-term and none of the three for transfer differed to lower contextual interference schedules. Two studies by Nair and Bunker (2000, 2002b) backed the idea of an optimal variability level, because schedules between blocked and random demonstrated significantly better contextual interference effects. Conversely, none of the 12 studies varying between motor programs verified significantly better results for variable practice in a blocked manner. Demonstrating no significant effect is not tantamount to there being no difference between the practice schedules; it could also be caused by too low test power or a too high beta error, respectively. This argument is invalidated by the low effect sizes throughout, indicating that in more complex tasks varying between quite different motor responses blocked practice was found to be as beneficial as random.

In contrast to studies involving various skills, most parameter variable studies contradict the Magill-and-Hall-hypothesis. Thirteen out of the 15 reviewed studies show at least partial, if not clear superiority, for high contextual interference. Moderate variability schedules outperformed blocked or random practice in two studies by Landin and Hebert (1997) and Pigott and Shapiro (1984), indicating again an inverted U-shaped contextual interference effect. Greater effect sizes for high amounts of contextual interference than mixed amounts could only be detected in lab-oriented research according to Brady's meta-analysis (2004).

Contrary to the negative contextual interference effect for acquisition performance in laboratory tasks, in applied complex settings 5 of the 26 studies showed even in the acquisition phase at least partially better results for high than for low contextual interference, as postulated in the differential learning approach. This was regardless of task variation type since three studies varied within the same motor program (Pigott & Shapiro 1984; Farrow & Maschette 1997; Smith & Davies 1995), whereas two were related to between program variations (Nair & Bunker 2000, 2002b).

Taking account of both inherent variability and introduced variability

The different contextual interference results between parameter and program variable practice in isolated laboratory and complex sport settings indicate the necessity for an optimal amount of movement variability, which is composed of the task inherent variability and the variability introduced through the exercises and their schedules.

If the level of noise or movement variability induced by the differential practice strategy in fact exceeds both that of parameter and program variable practice, as predefined by Schöllhorn et al. (2009b), such a level exceeds the optimal amount of noise even more. That is the case if inherent variability is not considered as well, because movement variability is furthermore affected by the subject's age, skill level and other moderator variables. Young and unskilled subjects innately or by definition have a high level of movement variability. Alike complex sport-related and open tasks are more variable than laboratory ones caused by the high number of degrees of freedom and the less predictable environmental conditions. In combination with a high amount of introduced variability by varying between different motor responses and in random order, the movement variability supposedly exceeds the optimal noise level and leads to an inferior learning performance (see Fig. 3).

In contrast, skilled adult subjects in closed laboratory tasks, varying between very similar motor responses in a low contextual interference schedule, may fall below the necessary amount of noise for best learning performance. Such a point-of-view is further supported by the consistent findings that in field-based research, adults gain more contextual interference effect than younger or less experienced learners (see Brady 2004, 2008). That is because for children or novices, random practice may result in too excessive response variability, as Wulf and Schmidt (1994) suggested earlier. Applied complex tasks, regardless of practicing program or parameter variations, seem to be sufficient contextual interference for young learners without the need for random practice. Therefore, blocked practice schedules should be preferred in early stages of skill learning and/or young subjects, as postulated by Hebert et al. (1996) and Wulf and Shea (2002).

An alternative not to exceed the optimal amount of variability in a random condition could be practicing variations, which differ less widely, especially within one skill. Conversely to applied contextual interference research, studies supporting the variability-of-practice hypothesis found that variable practice is more effective for children than for adults (cf. Schmidt & Lee 2011). What is commonly interpreted as a result of some lack of movement experiences in children could also be a consequence of a too low movement noise for adults, because most of those laboratory studies were conducted in a blocked practice sequence.

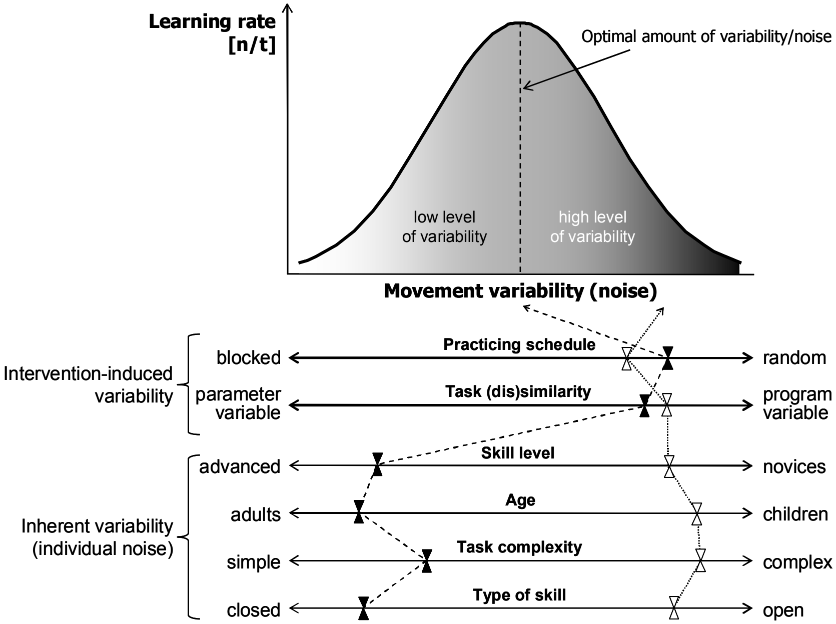


Fig. 3: Hypothesized optimal curve of motor learning as a function of movement variability (top); dependence of movement variability on different intervention-induced and inherent variability factors (bottom)

As Brady (2004, 2008) already urged, besides the moderating variables detected so far, upcoming meta-analytic studies should consider the number of skills and their magnitude of differences being taught. The emerged noise may not be easily considered as the sum of the magnitude of differences and their amount because highly diverging movements probably no longer interact with each other; therefore, they lead to reduced movement variability. Future meta-analyses might investigate moderating variables according to their inherent or introduced variability, and their interaction in order to find the right boundary or mediating conditions for the optimum of noise, if it indeed exists.

2.2 A couple of attempted explanations

A variety of theoretical explanations have been provided to elucidate the contextual interference effect including the impact of moderator variables being detected. Most of them are based on the cognitive-psychological perspective of motor learning, and although they appear as rivaling theories, they are not mutually exclusive (cf. Lee & Simon 2004). Brady brought the different theories in his extensive 1998 review to a common denominator, which may be the enhanced cognitive activity, or the more effortful processing engendered by high interference schedules, and the deficient or decreased processing load as a consequence of low interference practice.

The predominant theoretical accounts involve the elaboration, reconstruction, pro- and retroactive interference, feedback usefulness, appropriate transfer, self-efficacy and motivational hypothesis.

Based on the theoretical explanation of the contextual interference effect in cognitive learning by William Battig (1966, 1972), and primarily supported by research concerning explicit memory tests, the elaboration-and-distinctiveness hypothesis by Shea and Morgan (1979) proposes that random practice in opposition to blocked practice necessitates comparative and contrastive analyses of the variations to be performed. Through higher variability within practice schedule, different task variations remain together in working memory and thereby enable an enhanced comparison and increased distinctiveness between tasks. Due to alterations between different encoding strategies, the demand on memory processing leads to worse acquisition, but improved retention performance and enables the learners to adapt more accurately to novel situations during transfer test being able to identify the relevant task features.

The action-plan or forgetting-and-reconstruction hypothesis provided by Lee and Magill (1983, 1985) is linked to the forgetting-helps-remembering paradox early revealed on the spacing effect by Cuddy and Jacoby (1982). Because random practice promotes forgetting of the previous trial, for the subsequent trial the action plan traditionally referred to motor program or parameter modification needs to be reconstructed. As the previously executed movement is no longer available in working memory, random practice engages more actively in problem-solving activity, weakening acquisition, but strengthening retention and transfer performance. The distinction between the elaboration and reconstruction views deals with working memory. While the first approach proposes the concurrent presence of more than one movement pattern in working memory facilitating comparison and contrast, the latter view empha-