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References

1. Bernstein N. *The Coordination and regulation of Movements*. Oxford New York: Pergamon Press; 1967.
2. Latash ML. Movements that are both variable and optimal. *J Hum Kinet*. 2012;34: 5–13.
3. Turvey MT. Action and perception at the level of synergies. *Hum Mov Sci*. 2007;26: 657–697.
4. Latash ML, Scholz JP, Schönner G. Toward a new theory of motor synergies. *Motor Control*. 2007;11: 276–308.
5. Sternad D. It's not (only) the mean that matters: variability, noise and exploration in skill learning. *Curr Opin Behav Sci*. Elsevier Ltd; 2018;20: 183–195.
6. Bongers RM, Zaai FTJM. The horizontal curvature of point-to-point movements does not depend on simply the planning space. *Neurosci Lett*. 2010;469: 189–193.
7. Desmurget M, Jordan M, Prablanc C, Jeannerod M. Constrained and unconstrained movements involve different control strategies. *J Neurophysiol*. 1997;77: 1644–1650.
8. Latash ML. *Synergy*. Oxford University Press; 2008.
9. Greene PH. Problems of organization of motor systems. *Progress in Theoretical Biology*. Academic press, inc.; 1972.
10. Kay BA. The dimensionality of movement trajectories and the degrees of freedom problem: A tutorial. *Hum Mov Sci*. 1988;7: 343–364.
11. Latash ML. Motor synergies and the equilibrium-point hypothesis. *Motor Control*. 2010;14: 294–322.
12. Bizzi E, Cheung VCK, d'Avella A, Saltiel P, Tresch M. Combining modules for movement. *Brain Res Rev*. 2008;57: 125–133.
13. Turvey MT. Coordination. *Am Psychol*. 1990;45: 938–953.
14. Bizzi E, Cheung VCK. The neural origin of muscle synergies. *Front Comput Neurosci*. 2013;7: 51.
15. Diedrichsen J, Shadmehr R, Ivry RB. The coordination of movement: optimal feedback control and beyond. *Trends Cogn Sci*. 2010;14: 31–39.
16. Todorov E, Jordan MI. Optimal feedback control as a theory of motor coordination. *Nat Neurosci*. 2002;5: 1226–35.
17. Scott SH. The computational and neural basis of voluntary motor control and planning. *Trends Cogn Sci*. Elsevier Ltd; 2012;16: 541–549.
18. Kelso JAS, Tuller B, Vatikiotis-Bateson E, Fowler CA. Functionally Specific Articulatory Cooperation Following Jaw Perturbations During Speech: Evidence for Coordinative Structures. *J Exp Psychol, Hum Percept Perform*. 1984;10: 812–832.
19. Beek, Peter J.; Peper, C.E.; Stegeman DF. Dynamical models of movement coordination. *Hum Mov Sci*. 1995;14: 573–608.
20. Kugler PN., Kelso JAS, Turvey MT. On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In: Stelmach GE, Requin J, editors. *Tutorials in Motor Behavior*. North-Holland Publishing Company; 1980.
21. Mottet D, Bootsma RJ. The dynamics of goal-directed rhythmical aiming. *Biol Cybern*. 1999;245: 235–245.
22. Bootsma RJ. Ecological movement principles and how much information matters. In: Post AA, Pijpers JR, Bosch P, Boschker MSJ, editors. *Models in human movement science: Proceedings of the second symposium of the institute for fundamental and clinical human movement sciences*. Print Partners Ipskamp; 1998. pp. 51–63.
23. Golenia L, Schoemaker MM, Otten E, Mouton LJ, Bongers RM. What the Dynamic Systems Approach Can Offer for Understanding Development: An Example of Mid-childhood Reaching. *Front Psychol*. 2017;8: 1–6.
24. Warren WH. The dynamics of perception and action. *Psychol Rev*. 2006;113: 358–389.
25. Newell K. Constraint on the development of coordination. *Mot Dev Child Asp Coord Control*. 1986; 341–360.
26. Riley MA., Richardson MJ, Shockley K, Ramenzoni VC. Interpersonal synergies. *Front Psychol*. 2011;2: 1–7.
27. Abbs JH, Gracco VL. Control of Complex Motor Gestures : Orofacial Muscle Responses to Load Perturbations of Lip During Speech. *J Neurophysiol*. 1984;5: 705–723.
28. Schettino LF, Adamovich S V., Tunik E. Coordination of pincer grasp and transport after mechanical perturbation of the index finger. *J Neurophysiol*. 2017;117: 2292–2297.
29. Riley MA, Turvey MT. Variability and Determinism in Motor Behavior. *J Mot Behav*. 2002;34: 37–41.
30. Greene PH. Why is it easy to control your arms? *J Mot Behav*. 1982;14: 260–286.



31. Romero V, Kallen R, Riley MA, Richardson MJ. Can Discrete Joint Action Be Synergistic? Studying the Stabilization of Interpersonal Hand Coordination. *J Exp Psychol Hum Percept Perform*. 2015;41: 1223–1235.
32. Scholz JP, Schöner G. The uncontrolled manifold concept: Identifying control variables for a functional task. *Exp Brain Res*. 1999;126: 289–306.
33. Schöner G. Recent Developments and Problems in Human Movement Science and Their Conceptual Implications. *Ecol Psychol*. 1995;7: 291–314.
34. Wu YH, Pazin N, Zatsiorsky VM, Latash ML. Practicing elements versus practicing coordination: changes in the structure of variance. *J Mot Behav*. 2012;44: 471–8.
35. Yang JF, Scholz JP, Latash ML. The role of kinematic redundancy in adaptation of reaching. *Exp Brain Res*. 2007;176: 54–69.
36. Black DP, Smith B a., Wu J, Ulrich BD. Uncontrolled manifold analysis of segmental angle variability during walking: Preadolescents with and without Down syndrome. *Exp Brain Res*. 2007;183: 511–521.
37. Domkin D, Laczko J, Djupsjöbacka M, Jaric S, Latash ML. Joint angle variability in 3D bimanual pointing: Uncontrolled manifold analysis. *Exp Brain Res*. 2005;163: 44–57. d
38. Greve C, Zijlstra W, Hortobágyi T, Bongers RM. Not All Is Lost: Old Adults Retain Flexibility in Motor Behaviour during Sit-to-Stand. *PLoS One*. 2013;8.
39. Klous M, Danna-dos-Santos A, Latash ML. Multi-muscle synergies in a dual postural task: evidence for the principle of superposition. *Exp Brain Res*. 2010;202: 457–471.
40. Krüger M, Borbély B, Eggert T, Straube a. Synergistic control of joint angle variability: Influence of target shape. *Hum Mov Sci*. 2012;31: 1071–1089.
41. Shim JK, Hsu J, Karol S, Hurley BF. Strength training increases training-specific multifinger coordination in humans. *Motor Control*. 2008;12: 311–329.
42. Togo S, Kagawa T, Uno Y. Uncontrolled Manifold Reference Feedback Control of Multi-Joint Robot Arms. *Front Comput Neurosci*. 2016;10: 1–18.
43. Van Der Steen MC, Bongers RM. Joint angle variability and co-variation in a reaching with a rod task. *Exp Brain Res*. 2011;208: 411–422.
44. de Freitas SMSF, Scholz JP, Stehman AJ. Effect of motor planning on use of motor abundance. *Neurosci Lett*. 2007;417: 66–71.
45. Gera G, Freitas SMSF, Latash ML, Monahan K, Schöner G, Scholz JP. Motor abundance contributes to resolving multiple kinematic task constraints. *Motor Control*. 2010;14: 83–115.
46. Zhang W, Scholz JP, Zatsiorsky VM, Latash ML. What Do Synergies Do? Effects of Secondary Constraints on Multidigit Synergies in Accurate Force-Production Tasks. *J Neurophysiol*. 2008;99: 200–513.
47. Park J, Wu Y-H, Lewis MM, Huang X, Latash ML. Changes in multifinger interaction and coordination in Parkinson's disease. *J Neurophysiol*. 2012;108: 915–924.
48. Park J, Lewis MM, Huang X, Latash ML. Effects of olivo-ponto-cerebellar atrophy (OPCA) on finger interaction and coordination. *Clin Neurophysiol. International Federation of Clinical Neurophysiology*; 2013;124: 991–998.
49. Vaz D V., Pinto VA, Junior RRS, Mattos DJS, Mitra S. Coordination in adults with neurological impairment – A systematic review of uncontrolled manifold studies. *Gait Posture*. Elsevier B.V.; 2019;69: 66–78.
50. Singh P, Jana S, Ghosal A, Murthy A. Exploration of joint redundancy but not task space variability facilitates supervised motor learning. *PNAS*. 2016;113: 14414–14419.
51. Morasso P. Spatial control of arm movements. *Exp Brain Res*. 1981;42: 223–7.
52. Flash T, Hogan N. The coordination of arm movements: an experimentally confirmed mathematical model. *J Neurosci*. 1985;5: 1688–1703.
53. Ledouit S, Casanova R, Zaai FTJM, Bootsma RJ. Prospective control in catching: The persistent angle-of-approach effect in lateral interception. *PLoS One*. 2013;8: 1–11.
54. Peper L, Bootsma RJ, Mestre DR, Bakker FC. Catching Balls: How to Get the Hand to the Right Place at the Right Time. *J Exp Psychol Hum Percept Perform*. 1994;20: 591–612.
55. Michaels CF, Jacobs DM, Bongers RM. Lateral interception II: predicting hand movements. *J Exp Psychol Hum Percept Perform*. 2006;32: 459–472.
56. Montagne G, Laurent M, Durey A, Bootsma RJ. Movement reversals in ball catching. *Exp Brain Res*. 1999;129: 87–92.
57. Desmurget M, Plablanc C, Jordan M, Jeannerod M. Are Reaching Movements Planned to be Straight and Invariant in the Extrinsic Space? Kinematic Comparison Between Compliant and Unconstrained Motions. *Q J Exp Psychol Sect A*. 1999;52: 981–1020.



58. Osu R, Uno Y, Koike Y, Kawato M. Possible explanations for trajectory curvature in multi-joint arm movements. *J Exp Psychol Hum Percept Perform.* 1997;23: 890–913.
59. Palleu-Germain R, Boy F, Orliaguet JP, Coello Y. Visual and motor constraints on trajectory planning in pointing movements. *Neurosci Lett.* 2004;372: 235–239.
60. Togo S, Kagawa T, Uno Y. Changes in motor synergies for tracking movement and responses to perturbations depend on task-irrelevant dimension constraints. *Hum Mov Sci. Elsevier B.V.;* 2016;46: 104–116.
61. de Freitas SMSF, Scholz JP, Latash ML. Analyses of joint variance related to voluntary whole-body movements performed in standing. *J Neurosci Methods. Elsevier B.V.;* 2010;188: 89–96.
62. de Freitas S, Scholz JP. A comparison of methods for identifying the Jacobian for uncontrolled manifold variance analysis. *J Biomech. Elsevier;* 2010;43: 775–777.
63. Krishnamoorthy V., Scholz JP., Latash ML. The use of flexible arm muscle synergies to perform an isometric stabilization task. *Clin Neurophysiol.* 2007;118: 525–537.
64. Zaiontz C. Real Statistics Using Excel. www.real-statistics.com [Internet]. 2018.
65. Maxwell SE, Delaney HD. Designing experiments and analyzing data. Brooks/Cole Publishing Company; 1990.
66. Valk TA, Mouton LJ, Bongers RM. Joint-Angle Coordination Patterns Ensure Stabilization of a Body-Plus-Tool System in Point-to-Point Movements with a Rod. *Front Psychol.* 2016;7: 826.
67. van Andel CJ, Wolterbeek N, Doorenbosch CAM, Veeger D (H EJ), Harlaar J. Complete 3D kinematics of upper extremity functional tasks. *Gait Posture.* 2008;27: 120–127.
68. Wu G, Van Der Helm FCT, Veeger HEJ, Makhssous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. *J Biomech.* 2005;38: 981–992.
69. Cohen J. Statistical Power Analysis for the Behavioral Sciences. Erlbaum, Hillsdale; 1988.
70. Tseng Y, Scholz JP, Schöner G. Goal-equivalent joint coordination in pointing: affect of vision and arm dominance. *Motor Control.* 2002;6: 183–207.
71. Verrel J. Distributional properties and variance-stabilizing transformations for measures of uncontrolled manifold effects. *J Neurosci Methods.* 2010;191: 166–170.
72. Golub GH, Loan CF V. Matrix Computations. The John Hopkins University Press; 1996.
73. Muceli S, Falla D, Farina D. Reorganization of muscle synergies during multidirectional reaching in the horizontal plane with experimental muscle pain. *J Neurophysiol.* 2014;111: 1615–1630.
74. Kang N, Shinohara M, Zatsiorsky VM, Latash ML. Learning multi-finger synergies: an uncontrolled manifold analysis. *Exp Brain Res.* 2004;157: 336–50.
75. Shinohara M, Scholz JP, Zatsiorsky VM, Latash ML. Finger interaction during accurate multi-finger force production tasks in young and elderly persons. *Exp Brain Res.* 2004;156: 282–292.
76. Schöner G, Scholz JP. Analyzing variance in multi-degree-of-freedom movements: uncovering structure versus extracting correlations. *Motor Control.* 2007;11: 259–275.
77. Jacquier-Bret J, Rezzoug N, Gorce P. Adaptation of joint flexibility during a reach-to-grasp movement. *Motor Control.* 2009;13: 342–61.
78. Ambike S, Mattos D, Zatsiorsky VM, Latash ML. Synergies in the space of control variables within the equilibrium-point hypothesis. *Neuroscience. IBRO;* 2016;315: 150–161.
79. Scholz JP, Schöner G, Latash ML. Identifying the control structure of multijoint coordination during pistol shooting. *Exp Brain Res.* 2000;135: 382–404.
80. Müller H, Sternad D. A randomization method for the calculation of covariation in multiple nonlinear relations: illustrated with the example of goal-directed movements. *Biol Cybern.* 2003;89: 22–33.
81. Reschektko S, Latash ML. Stability of Hand Force Production: I. Hand Level Control Variables and Multi-Finger Synergies. *J Neurophysiol.* 2017;118: 3152–3164.
82. Sternad D, Park S-W, Muller H, Neville Hogan. Coordinate Dependence of Variability Analysis. *PLoS Comput Biol.* 2010;6: e1000751.
83. Latash ML. The bliss (not the problem) of motor abundance (not redundancy). *Exp Brain Res.* 2012;217: 1–5.
84. van Beers RJ. Motor Learning Is Optimally Tuned to the Properties of Motor Noise. *Neuron. Elsevier Ltd;* 2009;63: 406–417.
85. Gelfand IM, Latash ML. On the Problem of Adequate Language in Motor Control. *Motor Control.* 1998;2: 306–313.
86. Latash ML. There is No Motor Redundancy in Human Movements. There is Motor Abundance. *Motor Control.* 2000;4: 257–259.



87. Mattos DJS, Latash ML, Park E, Kuhl J, Scholz JP. Unpredictable elbow joint perturbation during reaching results in multijoint motor equivalence. *J Neurophysiol.* 2011;106: 1424–1436.
88. Zhang W, Olafsdottir HB, Zatsiorsky VM, Latash ML. Mechanical analysis and hierarchies of multidigit synergies during accurate object rotation. *Motor Control.* 2009;13: 251–279.
89. Latash ML, Kang N, Patterson D. Finger coordination in persons with Down syndrome: Atypical patterns of coordination and the effects of practice. *Exp Brain Res.* 2002;146: 345–355.
90. Wu YH, Pazin N, Zatsiorsky VM, Latash ML. Improving finger coordination in young and elderly persons. *Exp Brain Res.* 2013;226: 273–283.
91. Wu YH, Truglio TS, Zatsiorsky VM, Latash ML. Learning to Combine High Variability With High Precision: Lack of Transfer to a Different Task. *J Mot Behav.* 2014; 1–13.
92. Alberts JL, Saling M, Stelmach GE. Alterations in transport path differentially affect temporal and spatial movement parameters. *Exp Brain Res.* 2002;143: 417–425.
93. Saling M, Alberts J, Stelmach GE, Bloedel JR. Reach to grasp movements during obstacle avoidance. *Exp Brain Res.* 1998;118: 251–258.
94. Greve C, Hortobágyi T, Bongers RM. Physical demand but not dexterity is associated with motor flexibility during rapid reaching in healthy young adults. *PLoS One.* 2015;10: 1–21.
95. Bakeman R. Recommended effect size statistics for repeated measures designs. *Behav Res Methods.* 2005;37: 379–84.
96. Olejnik S, Algina J. Generalized eta and omega squared statistics: measures of effect size for some common research designs. *Psychol Methods.* 2003;8: 434–447.
97. Woodworth RS. The Accuracy of Voluntary Movement. *Psychol Rev Monogr.* 1899;3: 27–54.
98. Fitts PM. Information Capacity of Human Motor System Controlling Amplitude of Movement. 1954;47: 381–391.
99. Yang JF, Scholz JP. Learning a throwing task is associated with differential changes in the use of motor abundance. *Exp Brain Res.* 2005;163: 137–158.
100. Domkin D, Laczko J, Jaric S, Johansson H, Latash ML. Structure of joint variability in bimanual pointing tasks. *Exp Brain Res.* 2002;143: 11–23.
101. Borbély BJ, Straube a., Eggert T. Motor synergies during manual tracking differ between familiar and unfamiliar trajectories. *Exp Brain Res.* 2013; 1–13.
102. Scholz JP, Kang N, Patterson D, Latash ML. Uncontrolled manifold analysis of single trials during multi-finger force production by persons with and without Down syndrome. *Exp Brain Res.* 2003;153: 45–58.
103. Wolpert DM, Ghahramani Z, Jordan MI. Perceptual distortion contributes to the curvature of human reaching movements. *Exp Brain Res.* 1994;98: 153–156.
104. van der Graaff MC, Brenner E, Smeets JB. Misjudgment of direction contributes to curvature in movements toward haptically defined targets. *J Exp Psychol Hum Percept Perform.* 2014;40: 802–812.
105. van Thiel E, Meulenbroek R, Hulstijn W. Path curvature in workspace and in joint space: evidence for coexisting coordinative rules in aiming. *Motor Control.* 1998;2: 331–351.
106. Ambike S, Schmiedeler JP. The leading joint hypothesis for spatial reaching arm motions. *Exp Brain Res.* 2013;224: 591–603.
107. Haggard P, Richardson J. Spatial patterns in the control of human arm movement. *J Exp Psychol, Hum Percept Perform.* 1996;22: 42–62.
108. Gordon J, Ghilardi MF, Ghez C. Accuracy of planar reaching movements - I. Independence of direction and extent variability. *Exp Brain Res.* 1994;99: 97–111.
109. Turvey MT., Shaw RE., Reed ES., Mace WM. Ecological laws of perceiving and acting: In reply to Fodor and Pylyshyn (1981). *Cognition.* 1981;9: 237–304.
110. Newell KM, Vaillancourt DE. Dimensional change in motor learning. *Hum Mov Sci.* 2001;20: 695–715.
111. Bruton M, O'Dwyer N. Synergies in coordination: a comprehensive overview of neural, computational and behavioral approaches. *J Neurophysiol.* 2018;120: 2761–2774.
112. Profeta VLS, Turvey MT. Bernstein's levels of movement construction: A contemporary perspective. *Hum Mov Sci. Elsevier;* 2018;57: 111–133.
113. Kelso JAS. Progress in motor control: a multidisciplinary perspective. Springer. 2009.
114. Schöner G. Motor equivalence and the uncontrolled manifold. 8th Int Semin Speech Prod 23. 2008; 23–28.
115. Golenia L, Schoemaker MM, Otten E, Tuitert I, Bongers RM. The development of consistency and flexibility in manual pointing during middle childhood. *Dev Psychobiol.* 2018;60.



116. Krüger M, Eggert T, Straube a. Age-related differences in the stabilization of important task variables in reaching movements. *Motor Control*. 2013;17: 313–9.
117. Hansen E, Grimme B, Reimann H, Schöner G. Carry-over coarticulation in joint angles. *Exp Brain Res*. Springer Berlin Heidelberg; 2015;233: 2555–2569.
118. Tseng Y-W, Scholz JP, Schöner G, Hotchkiss L. Effect of accuracy constraint on joint coordination during pointing movements. *Exp Brain Res*. 2003;149: 276–288.
119. Golenia L, Schoemaker MM, Otten E, Mouton LJ, Bongers RM. Development of reaching during mid-childhood from a Developmental Systems perspective. *PLoS One*. 2018;13: 1–17.
120. Bockemühl T, Troje NF, Dürr V. Inter-joint coupling and joint angle synergies of human catching movements. *Hum Mov Sci*. Elsevier B.V.; 2010;29: 73–93.
121. Mazyn LIN, Montagne G, Savelsbergh GJP, Lenoir M. Reorganization of catching coordination under varying temporal constraints. *Motor Control*. 2006;10: 143–159.
122. Faul F, Erdfelder E, Buchner A, Lang AG. Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behav Res Methods*. 2009;41: 1149–1160.
123. Black DP, Riley MA, McCord CK. Synergies in intra- and interpersonal interlimb rhythmic coordination. *Motor Control*. 2007;11: 348–73.
124. Kelso JAS. *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, MA, US: The MIT Press.; 1995.
125. Kugler, P., Turvey M. *Information, Natural Law, and the Self-Assembly of Rhythmic Movement*. Hillsdale, NJ: Erlbaum.; 1987.
126. Saltzman E, Scott Kelso JA. *Skilled Actions: A Task-Dynamic Approach*. *Psychol Rev*. 1987;94: 84–106.
127. Ranganathan R, Newell KM. Goal and Execution Redundancy Levels Execution Redundancy Levels. 2010; 37–41.
128. Schmidt RC, Carello C, Turvey MT. Phase Transitions and Critical Fluctuations in the Visual Coordination of Rhythmic Movements Between People. *J Exp Psychol Hum Percept Perform*. 1990;16: 227–247.
129. Haken H, Kelso JAS, Bunz H. A theoretical model of phase transitions in human hand movements. *Biol Cybern*. 1985;51: 347–356.
130. Beek PJ, Rikkert WEI, van Wieringen PCW. Limit cycle properties of rhythmic forearm movements. *J Exp Psychol Hum Percept Perform*. 1996;22: 1077–1093.
131. Buchanan JJ, Kelso JAS, De Guzman GC. Self-organization of trajectory formation I. Experimental evidence. *Biol Cybern*. 1997;76: 257–273.
132. Zaal FTJM, Bongers RM. Movements of Individual Digits in Bimanual Prehension Are Coupled into a Grasping Component. 2014;9: 1–6.
133. Van De Kamp C, Zaal FTJM. Prehension is really reaching and grasping. *Exp Brain Res*. 2007;182: 27–34.
134. Cole KJ, Abbs JH. Kinematic and electromyographic responses to perturbation of a rapid grasp. *J Neurophysiol*. 1987;57: 1498–1510.
135. d'Avella A, Saltiel P, Bizzi E. Combinations of muscle synergies in the construction of a natural motor behavior. *Nat Neurosci*. 2003;6: 300–308.
136. Tresch M, Jarc J. The case for and against muscle synergies. *Curr Opin Neurobiol*. 2010;19: 1–11.
137. Faisal AA, Selen LPJ, Wolpert DM. Noise in the nervous system. *Nat Rev Neurosci*. 2008;9: 292–303.
138. D'Andola M, Cesqui B, Portone A, Fernandez L, Lacquaniti F, d'Avella A. Spatiotemporal characteristics of muscle patterns for ball catching. *Front Comput Neurosci*. 2013;7: 1–11.
139. Haken H, Wunderlin A. Synergetics and its paradigm of self-organization in biological systems. In: Whiting HTA, Meijer OG, van Wieringen PCW, editors. *The Natural-Physical Approach to Movement Control*. 1990.
140. Cuijpers LS, Zaal FTJM, De Poel HJ. Rowing crew coordination dynamics at increasing stroke rates. *PLoS One*. 2015;10.
141. Latash ML. Stages in learning motor synergies: A view based on the equilibrium-point hypothesis. *Hum Mov Sci*. Elsevier B.V.; 2010;29: 642–654.
142. Feldman AG, Levin MF. The Equilibrium-Point Hypothesis -- Past, Present and Future. In: Sternad D, editor. *Progress in Motor Control: A Multidisciplinary Perspective*. Boston, MA: Springer US; 2009. pp. 699–726.
143. Sülzenbrück S, Heuer H. The trajectory of adaptation to the visuo-motor transformation of virtual and real sliding levers. *Exp Brain Res*. 2010;201: 549–560.
144. Edelman GM, Gally JA. Degeneracy and com-



plexity in biological systems. *Proc Natl Acad Sci U S A*. 2001;98: 13763–13768.

145. Daffertshofer A, Lamoth CJC, Meijer OG, Beek PJ. PCA in studying coordination and variability: A tutorial. *Clin Biomech*. 2004;19: 415–428.
146. Wijnands ML, Bosman AMT, Hasselman F, Cox RFA, van Orden CG. 1/f scaling in movement time changes with practice in precision aiming. *Nonlinear Dyn Psychol Life Sci*. 2009;13: 75–94.



