SPECIAL-PURPOSE DEVICE HYPOTHESIS IN MOTOR LEARNING:

SPECIFIC, INDIVIDUAL AND GENERALIZABLE

by

MATHEUS MAIA PACHECO

(Under the Direction of Karl M. Newell)

ABSTRACT

Motor learning is central to understand both the underlying processes of how behavior comes to be the way it is as well as to provide the best approaches to intervene on it. Despite its importance in human behavior, the area is far from a proper characterization of what it is that is learned with practice. In the present dissertation, I provide a review of the traditional and contemporary positions on what is learned in practice and, in failing to find convergence between theoretical and empirical results, derive a hypothesis from the view of the dynamical systems approach. The general hypothesis holds that individuals learn what is in effect a special-purpose device that is specific, individual, and generalizable. The special-purpose device is a coordination function that is specific (i.e., functional) to the task at hand and can be generalized to other conditions depending on its properties. Given the differences on initial states, search-strategies and the redundancy at the task level, individuals find different solutions that influence their performance when new situations are presented. Experiment 1 assessed the proposition that learning results in an individual learned solution. I tested whether individuals would diverge during practice showing equally functional responses with different coordination functions and whether the properties of these learned solutions predicted performance in two transfer tests.

Experiment 2 investigated the special-purpose device hypothesis against the traditional assumption of group homogeneity in learning. The experiment tested whether the individual properties of the coordination function would be more appropriate to explain differences on subsequent transfer tests of performance when compared to predictions considering groups and their respective practice conditions. The findings showed that individuals diverged in terms of the learned coordination function and these demonstrated a high relation to tests performed after practice. The present proposition of learning as the formation of a special purpose device provides an understanding of how learning emerges from the constraints present from the interaction of the organism, environment and task.

INDEX WORDS: motor learning, dynamical systems theory, coordination, control, transfer

SPECIAL-PURPOSE DEVICES HYPOTHESIS IN MOTOR LEARNING: SPECIFIC, INDIVIDUAL AND GENERALIZABLE

by

MATHEUS MAIA PACHECO

BS, University of São Paulo, Brazil, 2012

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2017

SPECIAL-PURPOSE DEVICES HYPOTHESIS IN MOTOR LEARNING: SPECIFIC, INDIVIDUAL AND GENERALIZABLE

by

MATHEUS MAIA PACHECO

Major Professor:	Karl M. Newell
Committee:	Kathy J. Simpson
	Zhenqiu Lu
	Caner Kazanci

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
December 2017

DEDICATION

I dedicate this dissertation, primarily, to my family: Josiane Cristina Maia (my mother), Pedro Severino Pacheco (my father), Mariana Maia Pacheco (my sister), Mirian Cazzarotti Pacheco (stepmom), and Silvio Renato Mourão Porto (stepfather). They always supported my goals and are the source of motivation and knowledge that no college or title can provide. Specially, I dedicate this dissertation to my beloved girlfriend Carolina Ernani da Silva. She is and will always be the example of what love can make. She sustained, motivated, loved, took care of, and supported me in all aspects of my life. I am sure that I would have never get to be the person that I am today, if it was not for her. This dissertation is for you.

ACKNOWLEDGEMENTS

First, I am thankful for the support, confrontation, or indifference that, at any point of my life so far, contributed to the present dissertation. It is quite complicated for me to remember all the persons and events that led me to this point in my career or made me write the present document the way it is. If anybody feel not appreciated because of the lack of direct citation, please consider that this paragraph was made thinking about you. Even if I am thankful to your presence in my life, my memory is completely independent of this.

From those who I remember as being worth of citation, I should start from those who started my path on the academic career. Thus, I would like to acknowledge the support of Fernando Garbeloto dos Santos, Ricardo Drews, Timóteo Daca, Fabian Romero, Natalia Fontes Alves Ambrósio, Andrea Freudenhein, Flávio Bastos, and Luciano Basso. These persons helped me to understand the beauty of research and helped me to build background to pursue my dreams in farther lands. Their friendship was clearly a backbone to my career. It is worth saying that, although the scientific and economic scenario does not favor a reunion, I will keep working to put together Ricardo, Fernando and myself under the guiding of Timóteo – a group that Daca called as “the next generation”.

I would also like to thank those who helped me survive during the long journey of the doctoral studies. These include my close friends Max Maguire, Charley Lafe, Thomas Novak, Martijn Verhoeven, Ju-Han Lin (Happy), Christine Samson (Pickles), Yen-Hsun Wu, Stan Solnik, Melissa Kilby, and my second family from Taiwan: Tsung-Yu Hsieh (Steven) and I-Chieh Lee (EJ). I would like to also include my friends from Groningen that became so close even with the small period of contact: Raoul Bonger, Paulo Cezar, Ana Paula Vicentin, Alfredo Higueras, Rucia November and Tom Buurke. It is because of you guys that I still believe in fun, compassion, supportiveness, friendship, and drinking inside of the inhuman world of academia.

Finally, but not less important, I would like to acknowledge all the support that my advisor Karl M. Newell gave during four long years of my life. His support is way beyond this present dissertation. Despite all the fame that his name has inside of academia, he answered the email of an undergrad from Brazil who could barely speak English and was interested in understanding a little bit of his well-cited studies in many different topics of our area. Not only he supported me in my confusing ideas, but also showed that it is possible to be kind and save all international students from a lonely thanksgiving week in a warm dinner at his place. I will always be thankful for everything you provided.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS v

LIST OF TABLES ix

LIST OF FIGURES x

CHAPTER

1 INTRODUCTION 1

2 LEARNING A SPECIAL-PURPOSE DEVICE: A SOLUTION FOR TRANSFER BASED ON THE DYNAMICAL SYSTEMS APPROACH TO MOTOR BEHAVIOR 3

The Relation Between Learning and Transfer 3

Transfer: A Brief Overview on Similarities 5

Dynamical Systems Approach to Motor Behavior: An Overview 22

Special-Purpose Device: Specific, Individual and Generalizable 35

The Topic of this Dissertation: Special-Purpose Devices and Transfer 42

3 TRANSFER AS A FUNCTION OF THE LEARNED COORDINATION FUNCTION: SPECIFIC, INDIVIDUAL AND GENERALIZABLE 45

Methods 50

Results 59

Discussion 68

4 LEARNING A SPECIFIC, INDIVIDUAL AND GENERALIZABLE COORDINATION FUNCTION: EVALUATING THE VARIABILITY OF PRACTICE HYPOTHESIS 76

Methods....80

Results....87

Discussion....96

5 GENERAL DISCUSSION 103

Unification of the Dynamical Systems Approach 104

Theoretical Advances From and For a Special-Purpose Device Hypothesis 107

REFERENCES 116

APPENDICES 139

A EIGENVECTORS FROM EXPERIMENT 1....139

B EIGENVECTORS FROM EXPERIMENT 2....140

LIST OF TABLES

Page

Table 1: LME for performance over days and blocks 60

Table 2: Parameters of the 1st and 2nd components..64

Table 3: Correlation between the first two components in velocity with the first two components in position..65

Table 4: Multiple regression for performance in HT and VT transfer tests 66

Table 5: LME for performance over days and blocks in practice and change between pre- to post-test 88

Table 6: LME for performance during transfer tests 89

Table 7: Coordination function characteristics (derived from the first and second components of the PCA analysis) 92

Table 8: LME for performance during transfer tests in terms of the measures of coordination function 94

LIST OF FIGURES

Page

Figure 1. Targets of original practice (a), and transfer tests (b), and one of the plastic golf balls (c) used with the four markers. 52

Figure 2. Performance as a function of practice days: (a) Average and confidence interval for group performance; (b) Average performance for each individual; (c) Average performance per day (different lines) and blocks (along abscissa). The confidence interval of (a) was corrected according to Loftus and Masson (1994). 59

Figure 3. Average performance for P1, P2, P8 and P10 on the last day, HT and VT. 61

Figure 4. (a) Kinematics of shoulder, elbow and wrist flexion/extension for P1, P2, P8 and P10 for 50 trials (30 ms of movement up to the release point). For shoulder, 0 degrees mean neither flexed or extended; for elbow, 180 degrees mean full extension; for wrist, 0 degrees mean neither flexed or extended. (b) Data of the release parameters for P1, P2, P8 and P10 for 10 trials. The start of the arrow is located at the position of release and the arrow itself represents the velocity of release. 61

Figure 5. Landing plane with the depiction of the target and projections of the first and second main axes of variation for (a) P1, (b) P2, (c) P8, and (d) P10 63

Figure 6. The relation between relative performance in VT and the results of the fitted regression with sensitive parameters and the variance accounted for of the first main axis of variation for: (a) low and (b) high angles. 67

Figure 7. The relation between relative performance in HT and the results of the fitted regression with sensitive parameters of the second main axis of variation and the variance accounted for by the first main axis of variation for: (a) low and (b) high angles. 68

Figure 8. One of the plastic golf balls (a) used with the markers, target of the pre- and post-test (b), and target of the original practice and after-tests (c). (b) and (c) had erasers attached to the target to guarantee that it would not move when hit by the ball. 80

Figure 9. Performance as a function of practice days: (a) Average and 95% confidence interval of group performance; (b) Average performance for each individual;.................................... 87

Figure 10. Group average (± 95% C.I.) performance per target combining DT and AT tests 89

Figure 11. Distribution of individuals in sensitivity, projected angle and tuning of PC1 (left) and 2 (middle) and the dendrogram based on the similarity of individuals on these measures. ... 90

Figure 12. The relation between performance in AT and DT with the results of the fitted regression with tuning and projected angle variables of the first and second PCs. 95

Figure 13. The general relation between performance in all targets with the results of the fitted regression with tuning and projected angle variables of the first and second PCs............. 96

CHAPTER 1

INTRODUCTION

It is indispensable for a science of behavior to consider the ways that one learns through life. A main consideration in studying learning is that it cannot be seen solely as the simple act of improving performance in a specific situation. Learning must be generalizable. One must be able to apply what was learned in one context to another; if not, provided all variability in our body and surroundings, every context would be new and no appropriate behavior would occur. Another consideration is that this generalization is limited. Learning a given act in one situation will not generalize to *all* other contexts. *Something* from the learned act must be in consonance to the new context for generalization to occur. Consequently, to deal with these two considerations, one must understand what is this *something* of the learning act. In other terms, one must understand what is learned.

The consideration on the movement properties of the learned act and how these predict performance in a new context is the topic of the present dissertation. Current theories have failed to provide a framework that could encompass all the empirical findings in motor learning. Here, I provide a view that what is learned is a special-purpose device (SPD) that is functionally specific to the task being performed, individual, and yet generalizable. That is, one individual learns a movement pattern that can fulfill the task goal, in a way that is specific to his individual way of approaching and practicing the task, and this movement pattern can be modulated to achieve a range of new goals. This view emerges from the propositions of the dynamical systems approach to motor behavior (DSA) and current research on motor learning and control. The ways that the

SPD generalizes to new contexts is dependent on the perception-action system acquired through practice. This view is proposed as a solution for the contradictory evidence on early and current literature on transfer.

The dissertation has its importance rooted in the two most prominent paths in motor learning research literature: theoretical explanation of the learning act and factors that influence learning. Both paths are intricately related. Understanding what is learned and the processes that lead to learning invites potential factors that might modulate the process. Understanding the relation between learning and factors of influence is insightful in the development of intervention and practical programs in several applied settings (e.g., rehabilitation, physical education, human-machine design, etc.). The present dissertation relates to both aspects in suggesting a construct that reflects the learned solution in practice and evaluates the variability of practice hypothesis under this new view.

The dissertation is organized in five chapters: Introduction, Literature Review, Experiment 1, Experiment 2, and General Discussion. In the next chapter, I start by explaining the intricate relation between learning and transfer – which leads to the proposition that transfer would be a better test for theories of learning (than retention tests). Then, an overview of past and current theories of transfer highlighting their limitations is presented. Finally, I briefly review some aspects of DSA and propose the SPD. In the Experiment 1, a test of whether individuality of the SPD can be observed and its predictive power on performance in transfer tests is presented. In Experiment 2, I extend the SPD to address the topic of variable practice and its assumptions. Finally, in the General Discussion I provide a summary of the findings, their relevance for the literature and necessary further steps.

CHAPTER 2

LEARNING A SPECIAL-PURPOSE DEVICE: A SOLUTION FOR TRANSFER BASED ON THE DYNAMICAL SYSTEMS APPROACH TO MOTOR BEHAVIOR

In this chapter I explain through the dynamical systems approach how the concept of a special-purpose device that is specific to the task, individual and generalizable emerges as consequence. The motivation to consider the integration of all the aspects of the theory and literature comes from the inconsistency of previous theories in explaining the phenomenon of what is learned and how this is further applied in new contexts. In the next section, I explain why the connection between these two processes (learning an action and further employing it/transfer) are tied together making one the best form to analyze the second. Then, I present an overview on the current problems in understanding transfer (and, consequently, learning), provide a brief historical context for the dynamical systems approach, and integrate theoretical and empirical studies into a coherent possibility: the special-purpose devices hypothesis.

The Relation Between Learning and Transfer

Learning is a construct that is not directly assessed. As defined by Schmidt and Lee (2005), "motor learning is a set of processes associated with practice or experience leading to relatively permanent changes in the capability for movement" (p. 302). Researchers must provide a theory about these "set of processes" to base the decision of how learning must be assessed. This is the case because the simple observance of change in performance might not be enough to characterize learning (see Schmidt & Lee, 2005 for a review).

Traditionally, learning is assessed through tests of retention and transfer. Retention tests measure the degree to which change in performance observed in the sessions of practice is maintained after some period without practice. This matches to the "relatively permanent changes" in the definition provided above. Transfer, in general, is the effect of practicing one given task condition on the performance of another task condition (Adams, 1987). This effect could be positive (an improvement in performance), negative (a decrease of performance) or neutral (no change in performance) depending on a number of factors. Thus, a transfer test is a condition different from the condition practiced in the practice sessions. Transfer tests relate to the "changes in capability for movement" part of the definition.

Note, however, that transfer is the test that requires more theoretical insights. most theories are consonant that learning involves relatively permanent changes. However, depending on the content of the theory of learning, the expectation on transfer changes – as well as the rationale for choosing the new condition in the transfer test. Without getting into the actual history of transfer and its theories (that will be overviewed in the next section), the role of the transfer tests has changed depending on the period of history and the theoretical background to learning theory of the time. Transfer can be seen in many ways. For instance, one can state that transfer tests provide how individuals generalize (adapt) to new contexts (e.g., Tani et al., 2014), test predictions of what was learned (as it will be used here, see also Moxley, 1979; Schmidt, 1975), or as a test of whether learning occurred or not (see Salmoni, Schmidt, & Walter, 1984).

Thus, transfer might be the best candidate to contrast theoretical insights. Given that this dissertation proposes a view on what is learned with practice, transfer tests are a requirement in our experimental paradigms. Obviously, the proposition has as one of its main points the consideration of how generalization occurs and, thus, transfer is relevant for this reason also.

Transfer: A Brief Overview on Similarities

The idea of practice in one context influencing others is not new. The main idea throughout the literature is that there must be *something* that is similar between the context of practice and the transfer test for transfer (positive or negative) to be observed. The actual property that must be similar is, so far, not known but many propositions have been offered. I briefly present some content and discussion of some of the most relevant theories of similarity and transfer below.

Stimulus-Response Period

From late 1890's to late 1940's, a large consideration on learning was derived from the ideas of stimulus-response provided by Thorndike (1931). In sum, the learning was seen as the process of becoming apt to respond correctly to determined stimulus. Thus, much of the theoretical development on transfer of this period came in terms of the strengthening or weakening of the connections between stimuli and responses.

Nevertheless, the first episode described here comes from a reaction of Thorndike to another theory of the period – the Formal Discipline. The Formal Discipline advocated that the mind was formed by mental faculties (logical reasoning, synthesis, memory, etc.). The idea was that if a given practice strengthened a given mental faculty, any other task that is based on this same faculty would have increased performance as a result. For instance, learning logic in mathematics was said to improve the logical reasoning in other situations of life (e.g., Metzler, 1910) or, in motor terms, learning about refraction theory would help shooting in objects under water (see Hendrickson & Schroeder, 1941).

Concerned with the extent by which this effect of faculties could occur, Thorndike and Woodworth (1901a, 1901b, 1901c) performed a series of experiments on length estimation, finding letters, memorization and others. The argument was that "the general consideration of the cases of retention or of loss of practice effect seems to make it likely that spread [transfer] of practice occurs only where identical elements are concerned in the influencing and influenced function" (Thorndike & Woodworth, 1901a, p. 250). An example is the experiment on learning to estimate the area of a range of rectangles (Thorndike & Woodworth, 1901b). Individuals practiced estimating a given range of areas of rectangles. After, individuals were asked to estimate different rectangles with areas within or outside the range practiced and also estimate different shapes (i.e., triangles). The data showed that the improvement in the estimation of rectangles of other sizes and other shapes was minimal with less and less effect as the object gets more different from the practiced range. Thus, transfer would occur only if identical elements were shared between the practiced task (original practice) and the transfer test.

From the same theoretical view, E. J. Gibson (1940) observed that in forming pairs between stimuli and responses, individuals tended to generalize the same response to many stimuli (and vice-versa). Concerned as to the degree that connections between stimuli and response learned affected practice with similar pairings, she proposed a comprehensive theory about transfer based on the concept of differentiation. The point was that, at the beginning of practice, a signal could serve as stimulus for more than one response (or "generalization"). Nevertheless, for some situations a specific response must be given when one stimulus is provided. Thus, through practice, a learner would decrease the generalization, *differentiating* specific responses to given stimulus (E. J. Gibson, 1940). The point for transfer was that a previous task that reinforces differentiation would allow better performance in a subsequent task in which similar differentiation is required. The degree in which generalization and differentiation interact would be dependent on the amount of reinforcement and the original link between stimuli and response.

Transfer would also depend on these asoects and the nature by which the two lists are similar to each other (see Gagné & Foster, 1949; E. J. Gibson, 1942).

Both Thorndike's and Gibson's interpretation on transfer were strongly based on the concept of similarity. Nevertheless, both had many problems in specifying what should be considered similar. Thorndike, for instance, described many "functions" (e.g., eye movements, adaptation of biases in estimation) but never provided an exhaustive list of all possible functions or how to find them (Schmidt & Lee, 2005). E. J. Gibson (1940) provided that similarity was based on the "original generalization tendency" (p. 208) – a measure of how one, before practice, would generalize. However, how to measure such a tendency was never described.

These are minor issues, nevertheless. A critical problem on the concept was pointed out by Osgood (1949) (following Robinson, 1927).

> "The classic statement of the relation between similarity and interference in human learning, as found in most textbooks in psychology, is that 'the greater the similarity, the greater the interference.' [similar to negative transfer] … When carried to its logical conclusions, however, this law leads to an impossible state of affairs. The highest degree of similarity of both stimulus and response in the materials successively practiced is that where any simple habit or S-R association is learned. The stimulus situation can never be precisely identical from trial to trial, nor can the response, but they are maximally similar—and here the greatest facilitation (ordinary learning) is obtained. *Ordinary learning, then, is at once the theoretical condition for maximal interference but obviously the practical condition for maximal facilitation* [his emphasis]." (p. 132).

Osgood (1949) tried to overcome this apparent paradox by identifying the relations between stimulus and response that would lead to either positive transfer or interference. He stated three empirical laws relating stimulus-response changes. 1) If stimuli are varied and responses are functionally identical, positive transfer and retroactive facilitation (the opposite of interference) occurs; the more similar the stimuli varied the highest the effect. 2) If the stimuli are functionally identical and responses are varied, negative transfer and retroactive interference is observed; the effect is decreased as similarity between responses increase. 3) If both stimuli and responses are varied, negative transfer and retroactive interference is observed; the effect increases as similarity increases. These laws were summarized in a transfer surface of stimulus-response similarity designed by Osgood (1949).

Osgood, however, is not exempt of definitional problems. How does one identify responses that are "functionally identical"? Osgood states that this would occur when the experimenter could score the response to be the same at any level of analysis. Nevertheless, the possibility of such "identity" might never be fully achieved. Variability is ubiquitous in motor behavior (see Newell & Corcos, 1993; Newell & Slifkin, 1998; Slifkin & Newell, 1998) and to identify what can be categorized as "the same" is a large problem.

Nevertheless, the core drawback of these early theories are not specific problems on their definitions but on their reliance on the S-R tradition. Adding to what will be said in the next section, the S-R idea of strengthening connections between stimuli and responses is overly simplistic for motor behavior. This causes the definitions to be inappropriate *a priori*. The environment that surround us is not made of stimuli but of patterns that must be detected by perception (J. J. Gibson, 1986). Also, responses are not simply outcomes that can be maintained or described by a single number. Outcomes are the result of coordination patterns emergent from a highly interactive and nonlinear system (Kugler, Kelso, & Turvey, 1980, 1982) and have as their main characteristics variability – at all levels of analysis (Newell & Corcos, 1993). Although some current theories are reviving concepts from Thorndike's writings[1], these also do not do justice to the richness of motor behavior.

Learning to Learn and Scoring

The hypothesized transfer surface of Osgood (1949) did not satisfy Holding (1976).

> "a large number of perceptual-motor variables known to affect transfer – such as control parameters, display-control relationships, augmented feedback, and part-whole relations – may be organized into at least 20 different variables. … It is clear, therefore, that any proposed surface will constitute an extremely loose predictive device …" (Holding, 1976, p. 2).

A main advance in Holding's consideration was a new interpretation on the negative transfer. Agreeing with Bilodeau and Bilodeau (1961) who proposed that negative transfer in motor learning rarely occurs and with little practice converts to positive transfer, Holding (1976) challenged the idea of negative transfer as it was. Holding argued that negative transfer depends on the scoring system not reflecting the underlying mechanism in which the negative transfer occurs. For him, "negative transfer does not exist in the sense of an opposing process, but it consists of positive transfer misapplied." (p. 4). Negative transfer would occur when the similarity between two tasks is high, but differ in an obscure but important way (scoring system or real-world

[1] It is not that Thorndike did not provide many important insights or that his writings cannot be revived. The problem is that these current theories in motor behavior (e.g., H. G. Wu, Miyamoto, Castro, Ölveczky, & Smith, 2014) (mainly based on computer science – Sutton & Barto, 1998) are using concepts of the early period, such as reinforcement, rewards, etc. to base their work without any justification as to why that can be done even after a long history of studies has strongly opposed such concepts.

consequences). However, this would occur against a background of great facilitation in performance.

An example on this view of Holding is the transfer that might occur when a tennis player practices badminton. Provided the previous experience in sports of racquet and striking, the tennis player will be performing in a higher level in badminton than individuals that never played any of these sports. Nevertheless, in some cases, the tennis player will employ strategies or movements that are specific to tennis and do not fit the context of badminton. For instance, a smash (an overarm strike) in tennis is intended to put the ball towards the ground while the same movement causes the bird to hit the net in badminton. Thus, if the smash performance is used as a score, then negative transfer will be described but this could be changed if the scoring system is different[2].

Harry Harlow went forward in dismissing the S-R approach. But in addiction, he was strongly against the idea of learning as a single experience that occurs within the laboratory. He criticized vehemently the research on theoretical psychology that employed as subjects the "sub-humans" (as he would call monkeys, rats, etc.). These researchers overemphasized the single experience (i.e., a single session of experiment) as a mean of studying learning under the conditioned response paradigm. Harlow's concern was that the results obtained on these fast experiments were tentatively generalized as general principles to human learning. As Harlow puts it, "The behavior of the human being is not to be understood in terms of the results of single learning situations but rather in terms of the changes which are affected through multiple, though comparable, learning problems." (Harlow, 1949, p. 51).

[2] Although accidentally, Whiting, Savelsbergh, and Pijpers (1995) put forward a similar example when arguing against the specificity hypothesis of Proteau, Marteniuk, and Levesque (1992 – see the Specificity of Practice section). Nevertheless, the example was in terms of squash and not badminton and the argument was in terms of decrement in performance because of the specificity of practice – an argument that *can be* twisted to say the same I am saying here.

Harlow (1949) argued that the formation of learning sets would be the main point for study. Learning sets are what he called learning to learn. This transforms a creature that responds in terms of trial-and-error to one that can adapt fast by insight (Harlow & Harlow, 1949). This became an intermediary position between the trial-and-error based psychologists that interpreted learning as associations linking given stimuli to responses (for instance, Thorndike) and psychologists that saw problem solving as innate insight abilities (the Gestalt psychologists such as Köhler).

As an example of this idea, we cite one of Harlow's (1949) works on monkeys. He provided three objects to the monkeys (two similar and one different in a given aspect) and "taught" monkeys to learn to pick up the dissimilar object by providing peanuts or raisins if they performed correctly. The monkeys would perform some trials under the same set of objects and then would have the objects changed maintaining the relation of two similar and one dissimilar (in some experiments using the same aspect of similarity, e.g., color, and sometimes changing it, e.g., shape – but always changing the objects). After several trials for different set of objects, the monkeys would be able to learn that the task was related to picking up the odd object and they would do it correctly for almost all trials. That is, after practice, when a new set of objects was presented, the monkeys would take maximally two trials to answer correctly while took them hundreds of trials at the beginning of practice. Thus, the monkeys have learned to distinguish objects, independent of which objects were presented and the parameter that the discrimination should be based on (Harlow, 1949; Harlow & Harlow, 1949).

Harlow emphasized that transfer of practice would not occur because of specific linkages (or bonds) between stimuli and response as advocated by previous theories on transfer, but rather because of learning "adaptable abilities" (Harlow, 1949). His view was much more general than the identical elements position advocated by Thorndike. Note that the position, however, is not the same as the formal discipline in which faculties were trained resulting in transfer in tasks of the same faculty. Harlow advocated for a learned set that would allow the learner to understand the "structure" of the problem more than the specifics of the problem itself.

The ideas of Harlow and Holding emphasized the point that the S-R tradition was limited in the richness of motor behavior considered. Holding added interesting insights in terms of negative transfer and even considered a new surface (adapting Osgood, 1949 surface with the scoring influence) but his insights were – as he acknowledged – approximate provided the complexity of possibilities in transfer. Harlow also provided a great advance in presenting that learning might involve higher-order variables which *speed* learning in new situations. Also, he was one of the first to consider previous experience in how one learns. Nevertheless, the idea of learning to learn is still abstract in that it is hard to identify exactly what kind of general structure the learner is "getting" from practice.

Harlow had an idea of higher and higher-order sets that one would learn.

> "… the individual learns to cope with more and more difficult problems. At the highest stage in this progression, the intelligent human adult selects from innumerable, previously acquired learning sets the raw material for thinking. His many years of education in school and outside have been devoted to building up these complex learning sets, and he comes to manipulate them with ease that he and his observers may easily lose sight of their origin and development." (Harlow, 1949, p. 38).

His ideas might be correct but their abstract nature prevented researchers to test or apply them in other contexts.

Programs and Structures

After a long period of S-R tradition, information processing theory took over the field of psychology (see Fitts, 1964; Kay, 1957; Miller, 1953) which led to investigations of the processes that are occurring inside of the box (the central nervous system) in between a stimulus and response. The human as a computer (the computer-metaphor) became a strong position (see, for instance, Fitts, 1964) and the notion of a program-like structure (or a software, see Connolly, 1977) in the central nervous system (CNS) as the controlling device of movements became common place. The motor program was hypothesized to be learned through practice and this would be, for our current concern, the construct to be considered when understanding transfer.

General Motor Program. It was because of the concept of motor program of Keele (1968) together with the debate of efficiency in storage and novelty that connected the ideas of programs with transfer (or generalizability)[3]. Keele's (1968) concept of motor program involved the assumption that for every single variation of a movement, there would be a motor program that would be responsible for it (a one-to-one relation between motor programs and movements). Schmidt (1975) pointed out that such an assumption results in an inefficient system. He discussed the problems of storage and novelty. Simplifying the point, let us accept the fact that the same movement is not performed in the same manner twice – variations appear in each attempt. So, if there is a one-to-one relation between programs and movements, this would result in the system having to store an immense number of programs (the storage problem). Also, provided the variations, some movements would have never been performed before which raises the question

[3] Lashley (1930) and Bernstein (1967) had already advocated on program-like structures in the CNS that would explain the fact that individuals could perform the same outcome with different parts of the body (i.e., motor equivalence). Nevertheless, this literature was developed in parallel to the experimental psychology literature (the one mainly considered here). Lashley and Bernstein readings were "integrated" to the core area of motor learning (and control) many years later (in different periods and for different reasons).

of how someone can perform new movements without having learned them before (the novelty problem).

To solve the issue, Schmidt (1975) proposed the Schema Theory that involved the General Motor Program (GMP) and Schema concepts. The GMP would be a program that applies for a class of movements. For instance, one could assume that overarm throwing is represented as a single GMP. If one wants to throw an object farther or closer, this would depend on the parameters added to the GMP, but the GMP is the same. This relaxes the storage problem by assuming a one-to-many relation between programs and movements. To specify the parameters and deal with the novelty, the schema is necessary. Assuming that the individual can store initial conditions, response specifications of the parameters, sensory consequences of the movement and movement outcome, the individual would develop a relationship (a schema) between these as practice occurs. As soon as a new situation for the same GMP is required, the individual would use the initial conditions and movement outcome to interpolate the required parameters (the specification). This would solve the novelty problem.

An experimental consequence of Schema theory became known as the variability of practice hypothesis (Moxley, 1979). If the schema provides stronger generalization to new situations as different initial conditions, response specifications, sensory consequences and movement outcome are fed to the schema, then, a practice that maintains the same GMP but varies situations will result in better generalization when compared to a practice that does not. The variability of practice hypothesis received support in several early studies (e.g. Kelso & Norman, 1978; McCracken & Stelmach, 1977; Moxley, 1979) and became a widely-accepted empirical finding in motor behavior (as will be observed in other propositions).

Nevertheless, both the theory and variability of practice hypothesis were not corroborated as advertised. The first signs of problems were noted by Schmidt himself in his discussion about transfer (cf., Schmidt & Young, 1987). The GMP was hypothesized to be characterized by invariant relative measures such as relative timing, sequencing and force. Schmidt and Young (1987) found problems on the identification of consistent relative measures to characterize the GMP (e.g., Gentner, 1987; Heuer, 1991; Zelaznik, Schmidt, & Gielen, 1986), and that, provided the observed small transfer between tasks, the span of single GMP would be limited (bringing the storage problem again into the point). Specific to the variability of practice hypothesis, they argued that the effect of varying conditions in practice for transfer was well established – especially for studies that involved young participants (i.e., children). Nevertheless, the somewhat surprising effects of contextual interference (see Shea & Morgan, 1979) – that also employs variations during practice – made the authors question whether the variability of practice would be related to increasing variation for the schema (as the Schema Theory holds) or to avoiding repetition of the same movement (as the contextual interference proposes)[4].

A more definite evaluation of the variability of practice hypothesis came three years later. Van Rossum (1990) addressed the issue reviewing the literature and considering potential confounding factors (e.g., age of the learner). Even disregarding studies that could not control for proximity effects (how "similar" the transfer condition was to the contrasted practice conditions) and those studies that did not show a learning effect during practice, many studies were not supportive of the hypothesis. For studies involving adults, from the 12 studies discussed, only two

[4] The contextual interference phenomenon is the observance of a decreased performance during acquisition because of high interference in the task to be performed (usually implemented by random variations in movement patterns or parameters of the movement) but an improved retention and transfer results when compared to a group with blocked variations. Although the phenomenon is said to be robust, the literature provided several factors that should be considered such as the level of the individual, task and many others for an effect to be observed – especially when the task is non-laboratorial (see Brady, 1998, 2008). What should be manipulated and when manipulation should be introduced is still an issue to discuss (Magill & Hall, 1990).

were clearly supportive while others were mixed between partial support and not supportive of the hypothesis. It was the case that other factors could be interfering (e.g., level of expertise of the subjects, the order of presentation in the variable group, sex of subjects, etc.) but, clearly, the hypothesis was not robust. For studies involving children, from the 11 studies discussed, three supported the hypothesis with no questions while the rest was divided into not supportive or partial support – two studies even provided evidence for the contrary! (i.e., the constant group was better).

A Perceptual-Motor Program (and Specificity of Practice). The idea of the GMP and Schema allowed the individual to practice for a long period and decrease the reliance on sensory consequences to perform a task. This assumption was held in numerous theories of the period (e.g., Fitts, 1964; Fleishman & Rich, 1963; Schmidt, 1975) and can be said to be a result of the view of how the system would perceive and control actions – through representations. If a built representation of an act is well-representative of its commands and sensory requirements (through long practice), then the real sensory consequences are no longer necessary to perform the act.

Some authors (Abbs, Gracco, & Cole, 1984; MacKenzie & Marteniuk, 1985), however, proposed that the act is not only a motoric representation that could be run without reliance on the sensory input but a sensory-motor integrated representation that results in the movement goal. In this vein, the sensory consequences or information source that was present in practice was necessary for the act to be performed successfully. Proteau and colleagues performed several studies that corroborated this view (e.g., Proteau, 1995; Proteau, Marteniuk, Girouard, & Dugas, 1987; Proteau et al., 1992; L. Tremblay & Proteau, 1998, 2001). The idea of these studies was to show that, even after long periods of practice, individuals would still rely on external information ("extrinsic feedback") if this was the "most appropriate" source of information. This became known as the "Specificity of Practice Hypothesis".

A classical study of this approach was Proteau et al. (1992). They asked participants to perform aiming movements as accurately as possible. The participants were divided in three groups (vision of the limb available, vision only of the target and a control group) in a design that involved a pre-test and two transfer tests (one after 200 and one after 1200 trials). The tests were all in a condition in which the limb could be seen. In this experiment, the idea was that if the representation is an integration of specific information and movements and different information is added to the context (specially an influencing one as it is vision), this would cause a decrease in performance level. Indeed, this effect was observed. That is, individuals that practiced without vision of the limb and performed a transfer test in which they could see the limb showed a deterioration of performance (both from practice to transfer, as well from pre-test to transfer).

Although some empirical support was observed, some studies failed to support the idea (e.g., Bennett & Davids, 1995, 1997; Whiting et al., 1995). The problem on specificity of practice hypothesis was two-fold. First, it was too restrictive for the fact that individuals *can* learn to use different sources of information when performing the same movement (Whiting et al., 1995). In some tasks, this seems to be a natural progression. For instance, dribbling in basketball might require visual tracking of the ball at first but not later in practice. Second, the issue of specificity seemed to depend on the degree by which visual information is naturally involved in the task. Most tests were performed by taking the possibility to visually guide movements. The interesting effect of Proteau et al. (1992) was not observed in other studies (e.g., Whiting et al., 1995) and might be a consequence of the task used.

Structural Learning. Long time after the proposition of the Schema theory, Braun, Mehring, and Wolpert (2010) proposed a similar theoretical formulation relating Harlow's (1949) idea of learning to learn to the new computational approach to generalization: structural learning.

Although this approach has a new label, the essence of the idea relates to early Schema theory propositions. To explain the idea – and relate it to early literature – let us consider that in describing a task, one can specify the variables (at some level of analysis) and describe in terms of these how to achieve the task. The number of variables for many tasks is quite large and it would be hard to control or monitor all these. The idea of structural learning is that the task allows one to find and learn a single function that relates all these variables – facilitating the performance. These variables can be defined in terms of forces, joint motions, etc.

If one decides to choose a task that can be described in terms of joint motions and the structure that is observed during task is that the relative time between the joint motions is maintained, then the structure acquired is the same as the idea of GMP. This would occur for forces and sequences of events in a task as well. The difference between GMP and the current structure is that the authors did not assume *a priori* which measures would characterize the structure. Nevertheless, the result, for transfer, is the same: variability of practice would be good for generalizations in the same dimension varied during practice. They also add that a *preferential* exploration on the dimension of the learned structure would occur even when the new task requires something different (see Braun, Aertsen, Wolpert, & Mehring, 2009; Braun et al., 2010).

Although this approach advances aspects of Schema Theory, it still over emphasizes the effectiveness of variable practice and computational metaphors to explain its results. As observed for Schema Theory, they also presented some contrary evidence to their expectation (Braun et al., 2009). This highlights that it is probably not the case that variability of practice is sufficient for better transfer.

Other perspectives (Adolph, 2005; Latash, 2010) have also proposed the task space (the space formed by the variables that influence performance) as the basis for learning either emphasizing specific structures (a task synergy, Latash, 2010; Latash, Scholz, & Schöner, 2002) or the whole space (Adolph, Berger, & Leo, 2011). While the former already confronted results that challenge their view (Y.-H. Wu, Truglio, Zatsiorsky, & Latash, 2015) the latter presents a view that should be further tested (see Adolph, 2005).

General Limitation of Programs and Structures View. The propositions advocated in this section all observed contrasting empirical studies challenging their views. This outcome is sufficient to support the search for a new theoretical formulation in transfer. Nevertheless, I can add one more caveat to the issue that relates to all these theoretical formulations.

The question that should be answered is why do individuals performing the same task condition differ between them in the same transfer test? The question refers to the fact that, although not explicitly stated in the preceding theories, there is an expectation that individuals performing different task conditions will be different. Specifically, that individuals performing variable practice will learn something different than individuals performing a constant practice condition. Even more hidden in this assumption is the idea that individuals performing the same task will be similar – or at least more similar than when compared to individuals in other groups.

As we will argue from our SPD proposition, there is no reason to believe that individuals should learn similar *structures* even when performing the same task. Recent papers on perceptual learning (Michaels, Gomes, & Benda, 2017; Withagen & Michaels, 2005; Withagen & van Wermeskerken, 2009) and search strategies (Pacheco, Hsieh, & Newell, 2017; Pacheco & Newell, 2017a) provide evidence to highlight that individuals can be more different than similar and this might result in different learning outcomes (Pacheco & Newell, 2015). Before presenting the DSA approach to motor behavior and the consequent SPD proposition, we highlight another caveat that is resultant from the whole literature in transfer.

A Summary and View on Transfer

As might have become clear from this review, there was not a single view on transfer and the extent of how transfer should occur varied highly from one to other theoretical perspective. While Harlow (1949) held that individuals would be *learning to learn* in understanding the underlying structure of the task, being able to transfer to structurally similar tasks with highly different stimuli and responses, Thorndike and Woodworth (1901a) would imply that only highly similar tasks (same stimuli and responses) would realize transfer. This was nicely pointed out by Barnett and Ceci (2002) when describing transfer on the field of cognitive learning that showed disagreements from the beginning to the end of the century on the principles of transfer.

This incoherent picture results from a problem of point of view. Without being precise in terms of the variables being discussed, the argument is that there would *always* be transfer. First, transfer can be observed at many different levels of analyses that were not directly discussed here, such as tactical strategies in games (e.g., Mitchell & Oslin, 1999), general aspects of the movement (e.g., Nelson, 1957; O'Keefe, Harrison, & Smyth, 2007), pattern recognition (e.g., Smeeton, Ward, & Williams, 2004), etc. This highlights that *general* aspects of many activities can promote better performance in other activities if these general aspects are maintained – or are at least similar. The example on tennis and badminton presented earlier when discussing Holding's position is valid here as well (see also Wagner et al., 2014)

Second, as highlighted by Holding (1976), if specificities within general aspects of the task differ, then *negative* transfer is observed. Following the author, the scoring system is highly relevant. Not only that, but how the comparison is formulated. Comparing the tennis player with a novice in striking sports in practicing badminton will clearly favor the result of positive transfer for the tennis player – even if his/her smash promotes some errors during practice. Nevertheless, comparing the tennis player with an expert of a sport that is more similar to badminton than tennis promotes the opposite result. One could argue that to control for such a problem, one must have pre- and post-tests, control groups and so on. Note, however, that good performance in tennis requires years of practice. It can clearly be that a week of practice might highlight *some* aspects of transfer that are general but this might, as well, not be the case. Studies have highlighted the idea that transfer is affected by the amount of practice (as hypothesized by E. J. Gibson, 1940; and shown by Gagné & Foster, 1949; Park & Shea, 2003). In any case, if the scoring and comparison is controlled appropriately, transfer will be always observed.

Although transfer is said to always occur, I am arguing that this might not be observed in performance. How can that be so? First, depending on the scoring system, variations between individuals cannot be captured – a point that supports the position of Holding (1976). Second, the point to be advocated is that there is always some kind of influence of previous experiences on how one performs a new task. It could occur in terms of how the individual starts the task, searches for solutions of the task, and the way the solution is explored when he/she finds it. Thus, in this view transfer cannot be assumed to be *just* a performance change provided previous practice in another context, but a behavioral change provided previous practice in another context. This seems to be in line to what Holding and Harlow proposed in their views. Additionally, this is supported by the recent evidences on structural learning (Braun et al., 2009) that showed that individuals demonstrate preference in the trial-to-trial variations in terms of the structure practiced in previous tasks.

Although I advanced a different position on how to think about transfer in the present section, the view still requires understanding of how the previous experience influences new contexts. This is the goal of the proposition developed in this dissertation. The next section reviews the DSA to provide a robust background on motor behavior and learning, and then we propose the SPD proposition that aims to solve some of the concerns in learning and, consequently, transfer.

Dynamical Systems Approach to Motor Behavior: An Overview

History Summary and Main Guidelines

The DSA started as a counter-movement to the then current ideas on movement control (end of 70s and beginning of 80s). The initial framework (known either as the ecological psychology or the action perspective) were based in aspects highlighted many years before by Nikolai Bernstein (Bernstein, 1967) and James Gibson (J. J. Gibson, 1966, 1986) and on the expanding usage of ideas of thermodynamics and nonlinear dynamics to other fields of study.

Central vs. peripheral control. In the end of 70s and beginning of 80s, there was a debate on the role of peripheral and central mechanisms as well the efferent and afferent pathways of signals. The prevailing view at the time was that movements could emerge due to peripheral and central sources but the quality of them would be highly different. The central pathway would be responsible for intentional and adaptive movements while the periphery would "control" reflexes (pre-established and rigid motion of the limbs) and would be responsible to send commands to the central system to update the central commands (when necessary). Several studies on animals that had the afferent pathways (information from periphery to CNS) surgically interrupted (studies on "deafferented" animals, see Taub, Ellman, & Berman, 1966; Taub, Goldberg, & Taub, 1975) showed that these animals could still perform movements – reaffirming the idea of a central prescriptive mechanism. These experiments were highly influential for theories on motor behavior; they supported, for instance, the work of Keele (1968) on central motor programs previously discussed.

Turvey (1977) and Reed (1982) debated the central/peripheral issue in providing a different position. They did not argue against a "role" for the brain in the organization of movements. Nevertheless, the centralist view of control was untenable in their view. Bernstein (1967) had demonstrated that if the CNS would send a command without "knowledge" of the muscle and join status, the interactive forces between joints and interaction between muscle length, innervation and velocity would result in uncontrollable movements that could not be foreseen by the brain. Thus, the activity of the muscle would require high interaction between CNS and periphery. This would result in an equivocal relation between muscle impulses and its movements. As Bernstein puts it

> "a determinate effect is possible for a movement only in a case where the central impulse *E* is very different under different conditions, being a function of the positions and the velocities of the limbs and operating very differently in the differential equation with various initial conditions" (Bernstein, 1967, p. 81).

Thus, a central command would be equivocal in terms of the movement that would be performed. Two different central commands could perform the same movement while the same command would generate different ones.

Two sets of experiments supported the argument. First, studies on deafferented frogs showed that the periphery could perform a number of well-adapted movements. For instance, Fukson, Berkinblit, and Feldman (1980) deafferented frogs and put their bodies in different positions (suspended or laying on a table). They stimulated chemically the frogs on the skin in different regions of the trunk and forelimb to observe how the wiping reflex (a motion of the limbs elicited to remove hurtful stimuli from the skin) would adjust. Although this reflex is peripherally triggered (thus, thought to lack adaptability), the movement of the hindlimb was quite adaptable with different parts of the movement (preparation and wiping) being specific to the area affected.

That is, differences of 1 to 2 cm in the region of stimulus provoked responses that were different and specific to the given region stimulated.

Second, studies showed that the central control of deafferented monkeys was quite limited. In investigating which parameters of the movement were centrally controlled, Polit and Bizzi (1979) performed pointing experiments with intact and deafferented monkeys perturbing the movements of head and limb by applying a constant or dynamic load after the initiation of movement or changing the initial position of the limb. The monkey could not see its own arm. The monkeys rested their forearm on a moving apparatus that allowed pointing by motion around the elbow joint. In most cases the movement was successful in both intact and deafferented monkeys – supporting the central command idea. Nevertheless, when the initial position was slightly changed by putting the elbow forward (by one or two inches), the deafferented monkeys showed a large decrease in performance. Even in trials that vision of the limb was allowed, the monkeys successfully pointed to the right location in only one third of the trials. The authors (see also Bizzi, 1980) agreed that although some movements can occur without the afferent pathway, there is the necessity of such a mechanism for dealing with slight changes in initial positions.

The conclusion that emerged was that there is a clear integration between central and peripheral levels in a way that one cannot distinguish them. It is not possible for a central mechanism to order all requirements without knowledge of the periphery situation – and the command comes regulated by the periphery information – and in the same way the periphery can work in an adaptive way. As stated by Reed (1982), “output would sometimes have a sensory function and input a motor function” (p. 100).

Coordinative Structures. To replace the current dichotomy between central and peripheral control, Turvey (1977) proposed a comprehensive view of how the system might organize actions. For him, the action plan – the highest level of "representation" – would be a projection of the environment (characterized by a topological class on the CNS). Perception would be an equivalent class of the action plan by a topological transformation. The relatively autonomy of lower levels of the system would promote a heterarchy – instead of hierarchy (i.e., central perspective on control) – that would translate such projection into joint-muscle schemata. That is, Turvey held that by no means would the executive ("central") oversee all details that are observed in action. It would be the case that, although the executive would constrain an equivalent class of states, it would be ignorant to the details that are carried on by lower levels of control.

Considering the reflexes as evolved systems of interaction within the motor system, Turvey characterized the reflexes as a basis in which actions can be formed (similar to Easton, 1972). The organization of these reflexes into functional units was called coordinative structures. A way that such organization could occur would be in terms of the executive modulating interactions among neural mechanisms at the spinal level. The control at the spinal cord is held to be based on the feedback loop of the α-γ servomechanisms that regulates the muscle contraction. This servomechanism can be biased to act and maintain a given action occurring by its internal loops that cancel out differences in signals that might specify forces, length and velocity. In such sense, the organization of actions would be related by organizing and tuning coordinative structures to act in a way specific to the goal at hand (Gel'fand, Gurfinkel, Tsetlin, & Shik, 1971).

Kugler et al. (1980, 1982) went further on the issue of building theoretical background for the new approach to be maintained. They, first, provided strong arguments against the philosophical basis of, at the time, current centralist-information processing models of motor behavior[5]. These authors brought concepts from synergetics (cf. Haken, 1996, 2004), thermodynamics (Prigogine, 1955) and Homeokinetics (Iberall, 1977) to postulate that the coordinative structures (discussed by Turvey, 1977) could be a dissipative system. The idea is that nonlinear interacting subsystems bounded by some constraints – in a constant exchange of information, energy and matter with the environment – would show stable forms of organization that could be maintained in a range of parameters. The system is, then, self-organized in the sense that no superior ghost in the machine (or homunculus-like) controller was necessary. The coordinative structure – as a subset of muscles and joints that work together as a unit – would be a "thermodynamic engine that draws energy from a high-potential source, rejects some to a lower potential energy sink and does work in a periodic, limit-cycle fashion" (Kugler et al., 1980, p. 17). Also, the coordinative structures

> "constitute a set of organizational constraints which emerge as a function of various energy transactions, and scale changes at multiple levels of organization (ranging from motor units to muscles). Emerging constraints form a dynamic manifold of gradients and equilibrium points. The 'layout' of the manifold *uniquely* and *specifically* indexes biomechanical configurations in terms of *stability* and *energy dissipation* [their emphases]." (Kugler et al., 1982, p. 61).

[5] It is not our purpose here to provide a full consideration on the issue. Nevertheless, we can cite three arguments, for illustrative purposes. One is the infinite regression when a representation or homunculus-like being is assumed to "control" all the order at the periphery (well organized movement patterns): If a thing can be assumed to control all the order observed in movements, what is the superordinate-thing that controls the thing in the first place? The second is the computational requirement for an executive to "control" all the degrees of freedom at periphery (Kugler et al., 1980). Consider the number of muscles that must be controlled, consider all the redundant muscle "activations" that one can perform to achieve a given goal and now require a computer to calculate the best one for a given situation. Clearly, a good computer would take long time to do it – if it can. And finally, the limitations of the motor program and information (as hypothesis testing procedures) concepts to increase complexity (Kugler et al., 1982). A motor program was believed to work in terms of feedback and to control forces. If the body is growing (as it is expected during the development), the same diagram of forces cannot be expected to maintain the same movement from time t to time $t+1$. A new diagram is required to perform qualitatively similar movements. How can a system that works in terms of negative feedback (and a reference) can accommodate new requirements?

In this way, the system would be categorized as a non-linear open system far from equilibrium maintained by the continuous flux of information and matter. The observed order in movement would be an *a posteriori* fact instead of a top-level-defined attribute.

Dynamic Patterns. With the introduction of nonlinear dynamics into the discussion of the human movement system, the concepts of attractors, vector-spaces and others were introduced (Kugler et al., 1980, 1980; Kugler & Turvey, 1987). These concepts refer to the long-term behavior of a system that evolves over time. Attractors are states that the system gravitates to and vector-spaces are ways to show how these system's tendencies would appear if the initial condition would be different. As observed in Kugler et al. (1980) citation, stability was another concept to be considered. Although these concepts might not be hard to grasp, a specific (and simple) empirical demonstration was necessary.

In looking for an experimental paradigm that could support the emerging view of dynamical systems, J. A. Scott Kelso observed that coordinated motion of fingers of the same or different hands could reproduce the qualitative phase changes observed in earlier studies of gait (e.g., Hoyt & Taylor, 1981; see Kelso, 1995). He first observed that the when flexing/extending two fingers (one of each hand) simultaneously, two main patterns of oscillation could be maintained reliably: in-phase (when both fingers flex and extend at the same time) and anti-phase (when one finger flex the other extends). Any other relation was not typically maintained or required long practice. This was an example of the system being stable and gravitating around two states only. Second, he observed that when the frequency of oscillation of the two fingers increased when the individual was performing the anti-phase mode, the relation between the two fingers would reliably change at a critical frequency from anti-phase to in-phase. This was an example of an attractor losing stability and the state of system moving to another, more stable, attractor (i.e., a bifurcation occurred).

With the help of Hermann Haken (the proponent of synergetics; see Haken, 1996), Kelso formalized the experimental results found in accordance with synergetics (Haken, Kelso, & Bunz, 1985), providing a testable characterization of nonlinearity and behavioral emergence in the field of motor behavior. The work of Kelso also resulted in the introduction and clarification of many other concepts such as intrinsic dynamics, bifurcations, phase-transitions, meta-stability. These were fundamental to the development of the approach – that resulted in many other researchers following it in several studies (e.g., Buchanan, Kelso, DeGuzman, & Ding, 1997; Kelso & Jeka, 1992; Scholz & Kelso, 1990). The view became later known as *coordination dynamics* (Jirsa & Kelso, 2004).

Currently. After more than thirty years of the initial proposition, the approach struggle to take from the computational/representational perspective the lead in neurosciences (together with the inferential perception in psychology). For instance, Turvey and Fonseca (2009) differentiate four approaches to behavior: neuroanatomical, computational, self-organized and ecological views (each of them, to some degree, overlap with some other). It is observed that problems such as context-dependent variability (Turvey, Fitch, & Tuller, 1982) – as the adaptability of the wiping reflex, intelligence loan, and others are still being neglected by neuroanatomical and computational approaches.

However, although the DST is not the predominant approach in the area of motor behavior[6], the approach has shown to be fruitful in that influenced highly the subfields of motor development

[6] The field of motor behavior is described to be in an infinite crisis from a Kuhnian perspective (Kuhn, 1970) in philosophy of science (Aune, Pedersen, & Ingvaldsen, 2008, see also, Abernethy & Sparrow, 1992). That is, it is expected that, within a given field (e.g., physics, biology, etc.), when a leading theory cannot hold the current empirical

(e.g., Adolph, Eppler, Marin, Weise, & Clearfield, 2000; Thelen & Smith, 1994), motor learning (e.g., Newell, 1985; Newell & Vaillancourt, 2001; Zanone & Kelso, 1994), motor control (e.g., Kelso, 1984; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984), perception (e.g., Jacobs & Michaels, 2007; Turvey, 1996), and cognition (e.g., Van Orden, Holden, & Turvey, 2003). It provided grounds for rejection of overly prescriptive approaches and development of new hypotheses which are now open for expansion and tests (e.g., meta-stability, tensegrity, dynamic touch, etc.). Now, I move to the specific of the theory in terms of skill acquisition.

DSA on Learning

In the following section, I briefly describe two DSA approaches to motor learning pointing out specific insights that they provide and are important for our current purposes.

Synergetic Approach to Learning. Kelso developments on synergetics on motor behavior also led to theoretical and empirical studies in motor learning. Learning, under the synergetic view, is a qualitative change in the intrinsic dynamics. Intrinsic dynamics refers to the layout of attractors that individual presents being the result of the interaction of many subsystems of the human movement system. This reflects the tendencies of the system that are carried phylogenetically and previous experiences. The qualitative change discussed was the appearance of a new attractor in this layout. Provided that the intrinsic dynamics could be described as a system of differential equations, when a new attractor emerged out of practice, this was called as a nonequilibrium phase transition (Zanone & Kelso, 1992, 1994, 1997).

The usual experimental procedure was to learn a new relative phase (a new movement pattern) when oscillating two limbs. Usually, the studies followed the same experimental design

results ("anomalies" to the theory as Kuhn named it), the field enters a period of crisis when many theories are proposed in an attempt to become the standard view in the area. In motor behavior, provided the criticisms onto the traditional information-processing approach, many theories have been proposed but none has taken the lead after a long period. Thus, the term "infinite crisis".

comprised of a *probing*, practice, and a new *probing*. In the probing, individuals would be asked to perform all possible relative-phases from 0 to 360 degrees in incrementing steps of 15 degrees. Each relative-phase would be performed for a period providing the variability and bias in each possible movement pattern. Then, the individual would practice the to-be-learned pattern (the 90 degrees' relative phase) and a new probing would occur. Depending on the question addressed in each specific study, a transfer, retention or other tests could be performed.

The idea of *probing* in this paradigm was a requirement to understand the intrinsic dynamics of the individual at beginning of practice. In this approach, an emphasis was given to the fact that individuals do not start the learning process as a *tabula rasa*, but rather have action tendencies on which the system gravitates around. Thus, to understand learning, a first consideration was to know how the individual approached the task – what is the movement repertoire before practice starts? The importance of this information relies on the fact that it is against the intrinsic dynamics at the start of practice that learning occurs. Depending on the initial state, the intrinsic dynamics might compete/cooperate with the to-be-learned movement pattern. Thus, a main predictor of learning would be the initial state of the learner and the relation of this to the to-be-learned movement pattern (see Zanone & Kelso, 1994 for several predictions based on the relation).

The relevance of understanding the intrinsic dynamics was shown by Thelen et al. (1993) study on the emergence of reaching in early infancy. Infants were observed (before they could reach) to be either over or under active in terms of arm motions when a toy was presented in front of them. These two categories of infants showed totally distinct patterns of movement modulation to achieve reaching. The ones who were over active would move their arms in a rhythmical way – showing "flapping" movements with their arms – when observing the toy. The change in this group occurred as a decrease in arm motion to reach the toy. The one who were under active took longer to reach the toy, but they made by increasing activity of their arms – which never became "flapping" – and looked more mature since the first successful reaching. Thus, totally distinct patterns of change emerged because of different intrinsic dynamics.

Search-strategies and Direct Learning. Learning can be seen as a search for the best solution for a given problem. As Bernstein (1967) put it,

> "The process of practice towards the achievement of new motor habits essentially consists in the gradual success of a search for optimal motor solutions to the appropriate problems. Because of this, practice, when properly undertaken, does not consist in repeating the *means of solution* of a motor problem time after time, but in the *process of solving* this problem again and again by techniques which we changed and perfected from repetition to repetition. It is already apparent here that, in many cases, 'practice is a particular type of repetition without repetition [his emphases]'" (p. 362)

This view was developed further by Gel'fand and Tsetlin (1962, 1971). They postulated that the interaction between an animal and its environment could be considered of the class of complex systems that requires problem solving different than simpler systems. That is, one could not use an algorithm that can find the optimal of a given function because the system at hand involves too many variables and interactions that would result in the algorithm requiring long time to find the optimum. In this case, an approximate solution could be found by methods of search. They proposed that local and non-local types of search would occur to make possible for the learner to find an approximate solution without getting trapped in local minima of the space. These strategies of search would be guided by different informational variables (see also Fowler & Turvey, 1978).

The view was systematically studied, however, only when Newell and colleagues (Newell, Kugler, Van Emmerik, & McDonald, 1989; Newell & McDonald, 1992; Newell, Mcdonald, & Kugler, 1991) considered the idea. They proposed the notion of a perceptual-motor workspace, that was the space characterized in terms of perceptual and motor variables that influence the task at hand. This would highlight the attractive regions (stable movements to be performed) that channels the search in this n-dimensional space. The local and non-local strategies hypothesized by Gelfand and Tsetlin (1962, 1971) would be apparent in observing the motion of an individual through this space.

In their studies, they observed how the individuals would find the solution for a given task when biomechanical and task constraints were modified (McDonald, Oliver, & Newell, 1995). They employed the Krinskii and Shik (1964) paradigm: the individuals had to flex/extend two joints to find the correct relation between them. The individual was guided by a score that was a function of the two joint positions. In this way, the authors manipulated the joints used in each experiment (biomechanical constraints) or the function that related the two joints (task constraints). The results of their studies demonstrated some interesting principles in search such as the reliance on low-dimensional spaces to search and the usage of informational variables (Newell et al., 1991).

Although many authors have since considered the concept of search during learning (e.g., Brady, 1998; Handford, Davids, Bennett, & Button, 1997; Morice, Siegler, Bardy, & Warren, 2007), the approach did not expand the pre-existing literature in providing new insights of how individuals search in the perceptual-motor workspace. In addition, the perceptual-motor workspace itself was never characterized provided the complexity of the definition – how to encompass perceptual-motor variables within a single space? (cf. Beek & van Santvoord, 1992) The solution found was usually to present the task space (the function of the variables that related to performance) and observe the behaviour through it to infer about informational variables and tendencies in action.

Recently, two developments occurred. First, Newell's group took on the approach again trying to unravel specifics of the motion through the workspace and characterize the intrinsic tendencies of individuals in search (e.g., Pacheco et al, 2017; Pacheco & Newell, 2015, 2017a). These studies have shown that the search itself was emergent, dependent on task constraints. More importantly, it revealed that the search was highly individual in terms of perceiving specific variables or how they use the information available.

A second development – that is not directly linked to the initial developments on search strategies – was the proposition of the Direct Learning theory (Jacobs & Michaels, 2007). This theory evolved from the established literature on perceptual learning following works of E. J. Gibson (2000); J. J. Gibson and Gibson (1955) and the ecological group (Withagen & Michaels, 2005; Withagen & van Wermeskerken, 2009). The idea was that individuals would search through the possibilities of informational variables converging to the informational variable most relevant to the situation at hand (process called education of attention). The information would not be a discrete category to be perceived but could be a function of these categories (see Michaels et al., 2017). Also, the response would be modified to scale to the information perceived (process called calibration). The ideas were quite similar to the search-strategies literature: there is an information space on which individuals search (Jacobs, Ibañez-Gijón, Díaz, & Travieso, 2011); the authors are trying to reveal the process by which search is directed (Michaels, Arzamarski, Isenhower, &

Jacobs, 2008; Michaels et al., 2017); individualities appear (Withagen & Michaels, 2005; Withagen & van Wermeskerken, 2009), etc.

Studies have provided some support to the idea (e.g., Huet et al., 2011; Michaels et al., 2008) and recently the approach was partially supported when extended to the motor domain (Michaels et al., 2017). Furthermore, in line with the process of search in the information space, some studies provided interesting evidence on individual differences that corroborate to the recent literature on search strategies (e.g., Withagen & Michaels, 2005; Withagen & van Wermeskerken, 2009). That is, individuals show distinct patterns of search and they might not converge to the same solution.

Summary on learning. Beek and van Santvoord (1992) proposed that, to understand learning in terms of DSA, a number of requirements existed: description of the initial state, process of change, and the to-be-learned pattern. These synergetic and search-strategies approaches (and others not considered[7]), do not encompass fully this list of requirements. Although one could try to integrate all approaches into a single and coherent theory of learning, there is much required to be done in terms of each one of them. As instances of the concerns, the synergistic approach was hardly expanded to more than few degrees of freedom and is required to encompass other kinds of tasks (discrete, sequential, etc.) (although see Saltzman & Kelso, 1987; Schöner, 1990). The

[7] I avoided touching on two other approaches beyond the described ones. A third approach was described by Beek and van Santvoord (1992) as a result of their criticisms on the synergetic and search-strategies approaches. I avoided touching on this approach because, although they provide some insights on the process of learning, I cannot agree either with their arguments against synergetic and search-strategies approaches and their new postulation. The postulation follows an idea of understanding the expert behavior in a given activity and then understand how novices approach that behavior. Experts (or very skillful individuals) in a large range of activities are different from each other and, thus, cannot be used as standards (the novice might become similar to one of them – we do not know who; or the novice might show a "new expert" behavior).

Also, I did not touch on a fourth approach, the Intentional Dynamics of Shaw and colleagues (Shaw & Alley, 1985; Shaw, Kadar, Sim, & Repperger, 1992). It provides a formalization of the process by which external dynamics (instructions and goals) are internalized. Although it seems to be highly necessary for the approaches presented here – none of them touch directly the process of *stabilizing* a new movement pattern or, in other words, learning – its concepts are beyond my current comprehension involving *integral-differential equations* and functionals (functions of functions).

synergistic predictions on some aspects of learning were not followed (see Fontaine, Lee, & Swinnen, 1997; Wenderoth, Bock, & Krohn, 2002). The search-strategies (and direct learning) must provide grounded hypotheses on what are the principles that guide search in a way that individual differences observed become different instantiation of these principles. Other approaches must be developed to encompass findings of these two approaches as well.

Nevertheless, the findings observed in each of these approaches provide insights on the question of what is learned in practice. We highlight the fact that both provide evidence in terms of individual differences in the process of learning. The synergistic approach highlighted the fact that the individuals come to practice with a background that influences how learning occurs. Evidence shows that individuals come to practice with different intrinsic dynamics (Thelen et al., 1993, see also Kelso, 1995) and this influences the pattern of change (see Kostrubiec, Tallet, & Zanone, 2006; Kostrubiec, Zanone, Fuchs, & Kelso, 2012). The search-strategies approach (and direct learning) showed that search was highly individual (Pacheco et al., 2017).

Thus, it seems that what is learned has large dependence on the individual. This contrasts with theories presented earlier that considered the task as the source of differences in the performance of transfer tests. If we still hold on the relation between what is learned and transfer, we need to reconsider these theories to accommodate the dependence on the individual. Provided the goal of this dissertation (understand the properties of the learned act, in motor behavior, and how these predict performance in a new context), we provide a way that encompasses the influences of task and individual in a coherent way.

Special-Purpose Device: Specific, Individual and Generalizable

To understand the special-purpose device hypothesis, I provide the considerations on DSA that lead to our proposition.

Learning as a Search Process

As a first point, I agree with the position that learning involves (at least) a process of search. That is, individuals when trying to acquire a new goal must explore the space of possibilities to achieve the task goal. This space of possibilities is in line to the perceptual-motor workspace proposed by Newell et al. (1989). Notice, however, that we do not need to provide a specific description of either how search occurs on the perceptual-motor workspace or the perceptual-motor workspace itself. What matters for the current point is that if learning involves a process of search, then, the known aspects of the motion through perceptual-motor workspace is of main importance.

Different initial states. The research on the synergistic approach for motor learning emphasized the point that the way individuals behave during practice (in terms of rate of learning and *form/shape* of learning[8], see Zanone & Kelso, 1994) depends heavily on the intrinsic dynamics of the individual and its relation to the to-be-learned pattern. Assuming that the change in performance over time is dependent on the individuals' position and motion on the perceptual-motor workspace, it is necessary for us to consider such individuality.

Different search patterns. Current research on search-strategies has shown differences in how individuals use information to change movement behavior (Pacheco & Newell, 2017a) and how individuals perceive information for change (Pacheco et al., 2017) – basically completing the loop between perception and action proposed by Shaw, Turvey, and Mace (1982). Note that this adds to the differences in initial conditions provided that the same initial conditions do not predict

[8] The learning rate and form are not exactly about learning but about performance – as it is argued in a number of studies (see Schmidt & Lee, 2005, for an instance of this discussion). Thus, it is just expected that change in performance will be different depending on the relation between intrinsic dynamics and the to-be-learned pattern.

the same pathway of change (Michaels et al., 2017; Pacheco et al., 2017) and that initial conditions invariably result in different pathways of change.

Searching for a specific way of acting. Shaw and Alley (1985) proposed that learning can be seen as an increase in coordination between perception and action. During practice, the individual is gradually acting in a more coordinated way in terms of the environment and task being perceived resulting in improved performance. Specifically, the individual in the context of learning is searching through a parameter space in terms of its movements in a way to solve a task. During the process, better information to guide the search might be found and the individual thus changes in both motor and perceptual space to perform in a higher performance in the given task.

This is in line with the ideas of Fowler and Turvey (1978) and Bingham (1988). Fowler and Turvey (1978) outlined that, contrary to the view that the perceptual-motor system acts as a general automaton (or any other kind of general algorithm or machine), the system would be able to become any of many special-purpose devices that is compatible to the task that the system must perform. In their approach, the authors made the analogy of the actor (individual) as a finite-state transducer in that can demonstrate context-sensitivity in comparison to the finite-state automaton (the analogy for the associationism). Clearly, this is a consequence when one indicates that the order (movement pattern observed) is an *a posteriori* aspect of the organization (Kugler et al., 1980, 1982) being emergent from the organism, environment and task constraints (Newell, 1986).

Bingham (1988) went further on the idea of specificity. He argued that the human action system (HAS) has intricate and nonlinear relations within its subsystems in ways that understanding a single subsystem in isolation would not be enough to understand the body at work. A strategy to deal with such complexity would be to analyze the HAS “backwards”. The reason is that when acting, the system can decrease the number of degrees of freedom that the HAS naturally has in ways to couple with the incidental dynamics of the current task. The result is a task-specific device (TSD).

Two Levels of Organization

Two levels of organization in the system are assumed under the DSA. A macro level would relate to a nonmetrical invariant (a topologically invariant) characteristic of the action: the coordinative structure. This level was named in many ways (e.g., assembly – Goldfield, Kay, & Warren, 1993, coordination function – Newell, 1985, synergy – Latash et al., 2002; collective variable – Mitra, Amazeen, & Turvey, 1998, etc.). This level was always believed to be the result of the self-organization of the system and, thus, emergent. The question of how the assembly would occur varied from coordinating relatively autonomic spinal processes (e.g., reflexes, Easton, 1972; Turvey, 1977) to more elaborated ideas (e.g., Kelso et al., 1984; Turvey, 2007) but the nature of the system (its complexity) and divergent positions in the area never allowed for a single position to be settled (see Santello et al., 2016 and comments on it for current discussions).

The second level, the parameter level (or control level, tuning, etc.), relates to a level that would be more related to absolute changes in the movement without affecting the topological property of the action. The control of this level would occur by tuning the system in terms of the current context (Turvey, 1977) but, as in the case of the first level, much is required to understand how such process occur. The direct relation between the two levels is nonlinear in which a given topological property (e.g., throwing pattern) can be maintained for a large range of values for a given parameter (e.g., distance of throwing) but might lose stability if the parameter crosses a given value; allowing other patterns to be observed (as reviewed in the Dynamic Pattern section). Usually, the first level of organization is observed as the outcome of a nonlinear differential equation with the second level being the parameters of such equation (e.g., Haken et al., 1985; Turvey, 2007).

In the context of learning change would occur in terms of these two levels. That is, the individual would assemble a function to perform an action and then, he/she will optimize this function searching in the parameter space for a set of parameters that allow better performance (cf. Berthouze & Goldfield, 2008; Goldfield, 1995; Goldfield et al., 1993). How such process of assembly and the exact process of "optimization" occur (if one can say that we ever achieve an optimal solution) is still not known but it follows mainly from the ideas that the assembly occurs in a self-organized fashion while the parameter space is explored. Provided the relation between these two levels, the search through the parameter space would occur as a function of the continuous interaction between parameter and coordination. That is, the coordination function restricts and releases the space that the parameter can be searched as a result of stability maintenance or breaking at the coordination level. Learning occurs as new regions of the whole range of possibilities become more stable and can be performed again in the future (Kostrubiec et al., 2006; Kostrubiec et al., 2012; Zanone & Kelso, 1992, 1994, 1997).

Redundancy

In previous sections, I discussed the concept of task spaces. A task space is a function that relates as independent variables those that can alter the performance at a given task, and as dependent variable the performance of the task. The potential independent variables are several and it is usually arbitrarily defined in terms of the task and apparatus used to measure it. Latash, Scholz, and Schöner (2007) just put the constraint that these (elemental) variables should be theoretically independent of each other. The characterization of the task space reveals properties of the task that are of main relevance in understanding how individuals might search[9].

Of main importance here is the fact that understanding formally how the task can be performed, one can provide whether the task is redundant or not. For a task to be redundant, the function that describes it must have more variables than equations describing it. Thus, the task must be described by a system of unconstrained equations. This allows a whole set of variables to lead to the goal. In other words, this allows a many-to-one relation between independent variables and the performance goal. Note that a description of a non-redundant task at one level might be superficial in the sense that it might be said that the task is not-redundant only if considering this given level of analysis. As an extreme argument, if we accept Bernstein (1967) position of the equivocality between motor commands (from CNS) and movements, there would always be many-to-one relations in movements. It is not a problem for the current position whether there are non-redundant tasks or not. The fact that a great majority can be considered redundant is the necessary point.

The Consequence

As advocated by Fowler and Turvey (1978) and Bingham (1988), individuals, in learning, form task-specific or special-purpose devices that are specific to the task at hand. Thus, what is acquired is **specific** to the task. For completeness, an individual starts practice in a given starting conditions, searches for new coordination patterns or parameters that can make him/her achieve the task goal. Note that in the process, the learner increased the coordination between perception

[9] For instance, from direct learning, it is expected that individuals searching during practice might be moving *in terms* of the task space (see Jacobs et al., 2011). Nevertheless, this might not be the case. There are described patterns of motion that do not follow the task space (see Pacheco et al., 2017) and, thus, such an assumption is contrary to the evidence. Newell et al. (1989) provided a description of what might occur in describing that individuals perceive the topology of the perceptual-motor workspace by moving through it. Note that the task space must be part of the perceptual-motor workspace.

and action (Shaw & Alley, 1985) – which led him/her to use a more relevant information and a more appropriate action.

Now, provided that that tasks are, in their majority, *redundant*, by definition, the same goal can be achieved in many ways. There is, thus, the *possibility* for a large range of specific solutions to occur. It could be, however, that individuals are so similar that they start and finish using the same solution. As stated, and contrary to this possibility, individuals start the practice in different initial conditions (provided different intrinsic dynamics and preferences of the task) and search differently through the perceptual-motor workspace. This provides that individuals, when finding solutions (i.e., movement patterns) that are specific to the task, find solutions that are **individual**. For completeness, the learners start the task in different positions and search differently with the same goal of finding a specific solution for the task. Then, given different initial conditions and pathways of search, and no constraint from the task guiding them to the same region, they achieve the task in different regions of the redundant space of the goal (the goal space).

In this view, the motor behavior is assumed to be organized in two levels: the coordination and its parameters. The coordination level has an intricate relation to the invariant topological relations afforded by the environment while its parameters are *tuned* (scaled) to the variant specific information of the environment (Turvey, 1977). If the individual found a stable coordination pattern to perform the task in the process of learning, note that it can always be scaled to deal with small differences in scaling. As Bingham (1988) stated, the SPD has many properties: specificity, smartness, soft-assembly, controllability, and scalability. The specificity, smartness and scalability comes from the fact that the HAS is tightly linked to its perceptual system in ways that allow a specific device to be assembled from inherent and incidental dynamics, be locally optimal (smart) and scaled to the requirements of the task to allow precision. Thus, in learning a special-purpose device, the individual is learning something that is **generalizable** – can be adapted to new contexts.

In conclusion, what is learned is a coordination function that can be generalized in terms of its dynamics (depending on critical values and parameters that are free to vary in this organization) but is also specific to the task. Additionally, it is individual due to initial differences, distinct search and redundancy at the task: individual can find different coordination functions that can solve the task. The learned thing is then called, in reference to the background, a special-purpose device that is specific, individual and generalizable.

The Topic of this Dissertation: Special-Purpose Devices and Transfer

In the previous sections, I outlined issues with theories that address transfer and, consequently, highlighted issues on theories of what is learned. Subsequently, I provided a view on what is learned stating that it is a special-purpose device (a coordination function) that is specific to the task at hand, is individual in the sense that one cannot *assume* its properties provided redundancy of the task, and is generalizable provided it has possibilities to scale it to different contexts. The question that I must answer now is what are the consequences of this view on learning for transfer?

In the transfer section, I argued that transfer should not be considered in terms of performance but in terms of behavioral influences. This argument comes from the idea that sometimes – provided the redundancy in terms of means (ways of acting) and ends (performance) – the performance might suppress some information of transfer. Clearly, however, in some cases the behavioral influence that a previous practice has can be directly translated to differences in performance. Notice that these cases are special cases of the same argument and, thus, the argument is maintained.

In light of the SPD proposition, transfer should be understood in terms of the coordination function learned. Here, it is important to remember that the coordination function spans many levels of analysis; provided its intricate relation the variant/invariant properties of the environment, the coordination function can encompass more than just simply a movement but also the tactics/strategies in games and coupling between movement-perception given the situation. The appropriate level of analysis to investigate transfer would be dependent on the differences that the original task – that is thought to influence the new condition – has with the transfer test.

For instance, in Experiment 1, the transfer test differed slightly from that of the original practice, in terms of the main axis of variation that the task allowed individuals to vary. Thus, in this situation, transfer influences should be assessed in terms of the parameters of the coordination function that describe the axis of variation. Nevertheless, if, for instance, one is discussing about transfer between soccer and field-hockey (e.g., Smeeton et al., 2004), this cannot be assessed in terms of axis of variation of kicking or any other movement pattern because the transfer might occur at the level of positioning and moving on the field – provided similarities in being both invasion sports.

Specific Questions, Experiments, and Expectations

In this dissertation, I performed two experiments. Experiment 1 tested two consequences of the SPD proposition. It tested the hypotheses that individuals learn individual coordination functions and that these would predict different performances in two different transfer tests. The experiment required individuals to practice the same task (throwing a golf ball into a target) for five days in a row and, at the end of practice, perform two different transfer tests. The hypotheses were assessed by observing whether individuals showed similar or dissimilar patterns in the end of practice and analyzing whether these differences could predict the transfer test performance.

Experiment 2 tested the consequence of within condition individual variability to between condition individual variability. Participants were divided in three groups of different practice conditions: two random groups (varying distance of the target or the angle of the target) and one constant group (similar to Experiment 1). They performed common pre- and post-tests and had a after-tests varying target distances and angles. The questions were whether practicing different conditions would lead to bigger similarity within group rather than between groups in the learned coordination function and whether this would reflect in different results in the after-tests. The hypotheses were that first, the individual coordination function properties would represent better the transfer performance and, second, that between groups differences would not overshadow within groups individual differences. The hypotheses were assessed by performing cluster analyses on the coordination function learned in the end of practice, observing the differences between pre- and post-tests in coordination functions, and observing the influence of the learned coordination functions on transfer performance.

CHAPTER 3

TRANSFER AS A FUNCTION OF THE LEARNED COORDINATION FUNCTION: SPECIFIC, INDIVIDUAL AND GENERALIZABLE[10]

Traditionally, the investigation of the transfer of practice is seen to allow an understanding of the related constructs of learning and retention (Adams, 1987; Hilgard & Bower, 1975). There is a long-held position in motor learning that transfer through learning occurs as a function of the similarity between the original task practiced and the transfer test task (e.g., Holding, 1976; Osgood, 1949; Thorndike & Woodworth, 1901a, 1901b, 1901c). Nevertheless, there has been much debate as to the grounds on which transfer occurs (cf., Proteau, Marteniuk, & Levesque, 1992; S. Tremblay, Houle, & Ostry, 2008) and, in occurring, what the aspects are that must be similar (Schmidt & Young, 1987).

A current position holds that transfer occurs in terms of the similarity of features of the task space practiced during acquisition and those of the new task context (e.g., Adolph, 2005; Braun et al., 2010; Ranganathan, Wieser, Mosier, Mussa-Ivaldi, & Scheidt, 2014). The task space can be characterized by the function that relates performance in a task and the elemental variables of the

[10] This study is in preparation to be submitted to the journal *Human Movement Science*. **Abstract:** Current studies hold that transfer of practice is a function of the similarity between the original learned task and the subsequent transfer task. It is questionable, however, whether individuals would not be different between them provided different initial conditions, search-strategies and task redundancy. In the present paper, we examine the proposition that individuals learn a coordination function that is specific to the task, individual and yet generalizable, depending on the characteristics of the learned coordination function. Seventeen individuals performed a task of learning to throw for accuracy to a target for 5 days and then performed two transfer tests that differed in terms of the axis of variation that individuals could vary in outcome. The results showed that individuals differed in terms of the acquired movement pattern even when a similar performance was achieved. Additionally, the coordination function characterized by principal component analysis and its projection into the landing plane predicted the performances in the transfer tests. These results support the claim that individuals learn a coordination function that is specific, individual and generalizable.

movement that affect performance. In accepting the task space as the source of differences between individuals, this position cannot address, however, why individuals performing the same task differ in their transfer test performances (e.g., Pacheco & Newell, 2015). In the present paper, we first discuss the issues pertaining to the principles of the similarity of task space and then offer a contrasting hypothesis that addresses the question of individual differences within the same condition.

Individual Search and Redundancy in Task Spaces

A prevailing assumption is that during practice, individuals learn a *relation* that can be generalized to other contexts if these other contexts induce such a relation, or features of it. This relation is hypothesized to be one that coordinates elemental variables of the action in a specific way that can accomplish the task. One current example is the concept of structural learning (Braun et al., 2010; Wolpert & Flanagan, 2010). The idea is that learners when practicing a task that involves many variables find and learn a low-dimensional structure that suffices to achieve the goal of the task (a coordination function). This low-dimensional structure reflects a function that unites all elemental variables into functional units that can be tuned with few parameters. If a new task can be performed using the same lower-dimensional space, then transfer is observed. This idea is similar to many other propositions such as the earlier schema (Schmidt, 1975) and current task synergy (Latash, 2010) frameworks. A common ground in these positions is the assumption that under the same task conditions individuals will learn similar relations during practice. In this vein, knowing the task being performed, we know how the transfer would occur.

Here, we adopt the position that through practice individuals are searching through the space of movement possibilities (i.e., task-space) to find a solution for the task (the goal-space)[11] (Newell et al., 1989; Newell & McDonald, 1992; Newell et al., 1991). This search is demonstrated by the change in aspects of the action performed in each moment of practice (e.g., trial-to-trial, within-trial, etc.). From this position, one of two properties must occur for the position of similarity between task-spaces for transfer to hold. Either the goal-space is over-constraining in that learning the task would result in the availability of only a single possible relation to be learned or individuals are highly similar in that they start and perform the search similarly between them – resulting in a single relation. In both ways, in knowing the task, one knows what is learned and, then, one knows how transfer would occur.

We propose, however, that these two possibilities cannot hold. First, individuals bring different tendencies of action to the task (i.e., their initial state differs). These tendencies are the individual's intrinsic dynamics (Kelso, 1995) or preferences in approaching the task (e.g., King, Ranganathan, & Newell, 2012) that can change the interaction with the task in presenting tendencies that cooperate or compete with the to-be-learned pattern (see, Kostrubiec et al., 2012; Zanone & Kelso, 1992, 1994). The nature of the intrinsic dynamics can alter the type of change that the individual must go through to reach the task goal (Thelen et al., 1993). Second, studies that have investigated the search strategy on a trial-to-trial basis have revealed that individuals do not search similarly: individuals differ in their exploration patterns (Pacheco & Newell, 2015) and

[11] The task-space is defined here as the function that relates the performance (in our case, error) to the variables that influence performance. For example, in a throwing for precision task, considering only two dimensions, the target to be at the same height of the release point and error evaluated as the distance to the target at that height, the function has the following format $E = ((v_x * v_y)/g) - d$, where E is error, v_x and v_y are the release velocity in the x and y axes, g is gravity, and d is the distance of the target from the release point. The goal-space is defined as the relation between variables that that result in the goal being achieved: in our example, $d = (v_x * v_y)/g$. The goal-space is contained in the task-space.

in their use of information in the search (Pacheco, Hsieh, & Newell, 2017; Pacheco & Newell, 2017a). These findings point to the position that the search needs to be considered on the level of the individual learner.

Are tasks over-constraining in the sense that they cannot be performed differently by individuals? Although this might hold for situations in which a common movement pattern is predetermined (e.g., some tasks of gymnastics), we note that most tasks are defined in terms of a goal that does not directly constrain movement patterns. This means that these tasks afford several means of solution for the same outcome (i.e., redundant tasks). Although there is agreement on the idea of task redundancy (cf. Sternad, Huber, & Kuznetsov, 2014), it is usually considered that individuals will converge to similar patterns by assuming that knowing the task conditions would be enough to predict transfer. Nevertheless, in many studies, the results have not conformed to this expectation (Ranganathan & Newell, 2010; Schmidt & Young, 1987; van Rossum, 1990, Y-.H. Wu et al., 2015).

Special-Purpose Devices: Specific, Individual and Generalizable

The coordinative structure approach (Kugler et al., 1980, 1982) holds that, in learning, individuals increase the coordination between perception and action (Shaw & Alley, 1985). From this, emerges what Newell (1985) called a "coordination function" – a function that relates all elemental variables of the system into a functional unit assembled for the task at hand (also referred as a "special-purpose device", Bingham, 1988; Fowler & Turvey, 1978). The increase in coordination between perception and action occurs as a function of the search through the perceptual-motor workspace (Newell et al., 1989; Newell & McDonald, 1992; Newell et al., 1991). That is, individuals, in trying to improve performance in a given task, alter the aspects of action or variables being picked up by perception to act. This affords new ways of acting and highlight other informational variables to guide action. The process leads to a coordination function that is functional to the task at hand and is tuned to a reliable informational variable (a specifying variable, cf. Jacobs & Michaels, 2007).

Different intrinsic dynamics, search-strategies and redundant solutions might lead individuals to different regions of the perceptual-motor workspace resulting in the learning of individual specific solutions that fit to the same task. This individual task-specific solution consists of a coordination function that can be parameterized for other contexts (Newell, 1985) by tuning the action in terms of the variants of the environment (Turvey, 1977). Thus, what is learned is a special-purpose device that is specific to the task, individual (in terms of the region of the goal space used to achieve the goal) and yet generalizable to other contexts (depending on how the coordination function can be parameterized). In this way, transfer is not a matter of the similarity of the task space of original practice with the task space of the transfer test, as currently held (e.g., Ranganathan et al., 2014). Rather, transfer is about the similarity of the coordination function acquired through practice and the requirements of the transfer test. If the coordination function can be parameterized to accommodate the transfer test, then, we would observe positive transfer. The experimental challenge is to find a way to characterize the coordination function and how it is parameterized in learning and transfer.

Here, we have chosen to describe the coordination function in terms of the covariance patterns demonstrated by the individuals in the n-dimensional space of the task using principal component analysis (PCA). The main axes of variation determined by PCA would reveal how an individual coordinated the variables of the task allowing some dimension(s) to vary while constraining others. Thus, using this tool we can refer to the low-dimensional space described as the coordination function (cf. Turvey et al., 1982). In understanding the relation of the coordinated variables and performance we can relate this to the task space. This coordination function is expected to be specific to the task and, thus, should be tuned to the outcome of the task (cf., Warren, 2006). This would be observed as a strict relation between the variation in the low dimensional space and outcome. Having this information at hand, we understand the coordination function at work and how it is parameterized in terms of the task. We expect that these aspects will predict the differences between individuals in a new task given that these characterize the possible ways that the coordination function can be adapted.

In the present experiment, individuals practiced throwing plastic golf balls into a triangular-shaped target. The practice occurred for 5 days and, on the last day, two transfer tests were applied that changed the tolerance for variation in one or another axis of the landing plane (see the Methods section). We expected, in line with the theorizing presented above, that even after a long period of practice, individuals will not converge to a single solution – even when the performances are similar. Furthermore, we investigated the hypothesis that the differences in terms of the coordination function acquired through practice will predict differences between individuals in the two transfer tests.

Methods

Participants

Seventeen college-level students (age: 24.71 ± 3.17 years, nine females) voluntarily participated in the present study. All of them were right handed. Informed consent was provided prior to participation with approval from the University of Georgia Institutional Review Board.

Task and Apparatus

The participant's task was to throw a plastic golf ball into a target. In different stages of the task (practice and transfer tests), the shape of the target was modified. The target used for practice was a triangle-shaped target of 15 cm height and 22.8 cm for each side. The target used for both transfer tests was a hexagon-shaped target of 15 cm height, 11.4 cm each side, with four equal obtuse angles (≈ 154 deg) and two equal acute angles (≈ 52 deg). The short aperture had 10 cm. These targets were made of cardboard (if the target got worn, it was replaced by a new one). Figure 1 shows the targets and the ball. For each stage, these targets were placed above a table of 73 cm height with their center point at 2.05 m of the center position of which individuals would throw.

The shapes of the targets were selected for several reasons. All targets allowed variation in, at least, one dimension on the landing plane. This allowed the possibility of different coordination functions. The triangle-shaped target was selected because it resembled the pub game beer pong (which had an additional benefit in attracting participants), it was of easy building and allowed variations in both horizontal and vertical axes of the landing plane. The hexagon-shaped target was selected because it restricted the dimension of variation to either vertical or horizontal axes of the landing plane.

Although individuals could see the distance of their throw, the target was placed above a white cardboard marked with red tape indicating increasing distances of 5 cm from the target. Also, to avoid the balls to lose their markers due to hitting the surface of the table, this white cardboard was placed above a small foam sheet of 4 cm that covered the table. The foam was rigid enough to maintain a horizontal and plane support for the cardboard and target.

All trials were recorded using the VICON system (sampling rate: 100 Hz). For this, the individuals wore a dark tight shirt and had markers placed on their right arm and trunk. Following the Plug-in Gait marker localization, the markers were placed at the spinous process of the seventh cervical vertebra, spinous process of the 10th thoracic vertebra, jugular notch where the clavicula meet the sternum, xiphoid process of the sternum, right scapula, acromion-clavicular joint, lower lateral one-third surface of the right arm, lateral epicondyle, lower lateral one-third surface of the right forearm, thumb-side of the wrist, little-finger side of the wrist, and middle knuckle on the right hand. To measure the release parameters, the balls were also marked. The balls were first covered with black tape and four markers were glued to the ball (see Figure 1).

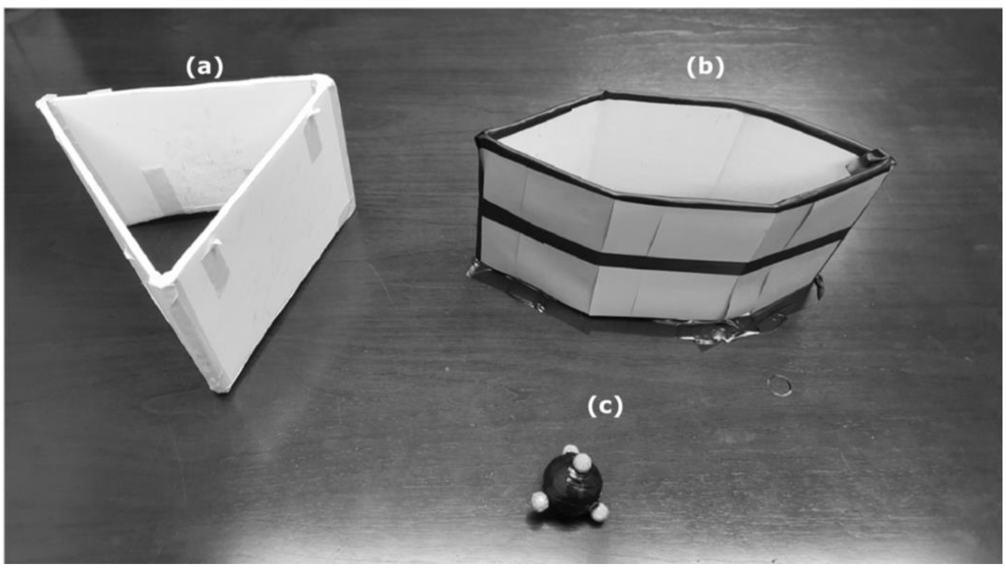

Figure 1. Targets of original practice (a), and transfer tests (b), and one of the plastic golf balls (c) used with the four markers.

Instructions and Procedures

On getting to the laboratory on the first day, individuals read and signed the informed consent form and had the markers placed on their body. The experimenter explained that the goal of the task was to throw the balls inside of the target. The instructions emphasized that the participants were not restricted to throw using a specified movement pattern but could explore different movement patterns as long as this exploration had the goal to improve performance.

The individuals practiced with the triangle-shaped target for 210 trials on each day. The experiment took five days (a total of 1050 trials)[12]. The triangle-shaped target was placed in a way that one of the vertices was pointing at the participant's direction. On the last day, individuals performed also two transfer tests (counter-balanced) in which the hexagon target was differently placed. In the Horizontal transfer test (HT), individuals performed with the main axis of the hexagon-shaped target parallel to the coronal plane of the individual while in the Vertical transfer test (VT) the target was perpendicular to it. The participants performed 20 trials in each transfer test.

To have both a short- and long-term control of performance for individuals, we managed the practice in the following way. We gave them a set of 6 balls at a time. After each set, the experimenter counted the number of balls in the target and informed the individual. Also, after 30 trials, the experimenter summed up the performance of the last 5 sets of 6 balls and provided the score to the individual. If any individual required rest, a break was provided.

Data Analysis

The data of the digitized positions of the markers first passed two filling gaps procedures: Woltring spline for maximum of 10 frames of gaps; and filling based on the trajectories of the other markers of the rigid body for maximum of 25 frames gaps. Then, the trajectories were filtered using the fourth order Butterworth filter at 10 Hz. If any resultant missing trajectory were still present, the trajectories were interpolated by using a spline method (interp1 function in

[12] One participant only performed four days of practice (first, second, fourth and fifth day of the regular schedule) because of technical issues. Provided four days could still be considered as a good amount of practice (840 trials), we maintained her for our analyses.

MATLAB). The small occurrence of missing data was due to markers being covered – mainly at the ball when individuals were preparing to start the throwing movement (a period of usually ten frames). Provided the ball markers were mainly utilized to know the release parameters and the missing period occurred way before the release, we had no problems with missing data. The choice for the cut-off frequency was done after inspection of the spectral distribution of data.

A few trials were discarded because of technical issues (i.e., markers not being recorded, markers falling, etc.). This represented 11 trials out of 4250 analyzed here (0.0023%).

Performance. The performance was analyzed in terms of blocks of 30 trials. For each block, the performance measure was the sum of hits (i.e., successfully throwing the ball inside of target) divided by the number of trials (30). We performed a linear mixed-effect model (LME) (with a backward method) with performance as the dependent variable and days and blocks (also their interaction) as the independent variables. The advantage of the LME is that it allows nested data to be modeled (in our case, variables within a given individual) and the independent variables within a given level to vary (in our case, variability between individuals) (see Raudenbush & Bryk, 2002). The initial random variables (i.e., the variables allowed to vary between individuals) were days and blocks with their variances allowed to be full (e.g., the variance of blocks could be related to the variance of days between individuals). By using a backward method, we tested all (fixed and random) effects comparing models with different variables.

We based the maintenance of variables in the equation comparing the Bayesian Information Criterion (BIC, Schwarz, 1978). The models were examined by estimating the parameters using the maximum likelihood estimation and restricted maximum likelihood estimation for fixed and random effects, respectively. The LME was performed using the fitlme code in MATLAB and the backward regression was performed by an algorithm developed for this purpose.

Release parameters. To identify the release parameters, we determined the moment at which the distance between ball and hand crossed a threshold. For each trial, we averaged the three markers that relate to the hand (thumb-side of the wrist, little-finger side of the wrist, and middle knuckle on the right hand) to have a single 3D location of the hand in space. We did the same for the ball using its four markers. Then, the Euclidean distance between hand and ball was calculated. To identify the ball-hand distance before the release, we ran a moving window through the ball-hand distance time-series and identified a moment in which the average (the 'cut') could describe a window of 10 frames with a squared error smaller than 2 cm^2. Then, to identify the release point, we identified the point in which the ball-hand distance was above the cut value by 2 cm. The cut and the threshold criteria were tested iteratively up to the moment that it could better predict the observed ball trajectory.

Describing the coordination function. Provided that the release parameters describe the sensitive moment of the movement of the performer for the task and the direct relation with the ball landing position (and, thus, performance), we used the release parameters to describe the coordination function. The coordination function is said to occupy a lower-dimensional space than the whole space of possibilities (Turvey et al., 1982). We expect then, that the release parameters could be described by a lower dimension space; a function that relates the 6 dimension variables of the release parameters into a lower-dimensional space. It is not necessary that individuals use a single dimension (a line), but we expect the number to not be high. Also, we expect that the lower space reflects how the individual adapted to the requirements of the task. That is, the coordination function will be tuned to the performance of the task.

To describe the coordination function, a PCA was run on the release parameter data of each individual on the last day of practice. To do this, we had to consider how to deal with two different units (position is in m and velocity is in m/s). The solution we found (see Footnote 14) was to first verify whether individual's results were mainly dictated by velocities or positions. To do this, we observed how much variance in position and velocity altered the landing parameters. We estimated the standard deviation for each individual in each position component (*x*, *y*, and *z*) and velocity component (*x*, *y*, and *z*). Then, using equations of oblique movements varied uniformly[13] we could estimate how much the variations in position or velocity influenced the landing parameters. Using this approach, we found that velocities had 2 to 3 times more influence on the result than position. Accordingly, the PCA was run on the velocity release parameters.[14]

To characterize the tuning of the coordination function, we correlated the change within each component (from PCA) with distance of throw. Distance of throw was calculated from the release parameters of each trial and was chosen as the outcome variable of importance for tuning because most of variance in landing occurred along the anterior-posterior direction (see the Results section). The change was calculated as the difference between the trial t+1 and trial t. Also, the correlation between change within each component and performance was made in terms of the trials in which the individual missed the target – when a change was necessary. The absolute values of the correlations were used for analyses.

[13] $x_f = x_0 + v_x * t$, $y_f = y_0 + v_y * t$, $z_f = z_0 + v_z * t + (g * t^2)/2$ where x_f, y_f, and z_f are the final points in *x*, *y* and *z* axes, respectively; x_0, y_0, and z_0 are the release positions in *x*, *y*, and *z* axes, respectively; and v_x, v_y, and v_z are the release velocities in *x*, *y*, and *z* axes, respectively; and g and t are gravity and time at landing, respectively. g was set as -9.8 m/s^2. z_f was defined at the top of the target (≈ 0.82 m) and t was calculated.

[14] We could have used the PCA with the correlation matrix that considers the correlation rather the covariance to identify the main components, but this could turn small dimensions in large components provided large correlation. Also, we could have normalized position and velocity in terms of their maximum variation. That is, we could have divided all position vectors by the standard deviation of the position axis (*x*, *y*, or *z*) with highest variability and do the same for velocity. This, nevertheless, assumes positions and velocities with equal *importance* in their variation. It could be that individuals only used velocities to perform the task and performing this procedure would cause position to have a large portion of variance. If both had similar influence on the landing parameters, this last procedure would be possible.

Another two properties of the coordination function were angle of variation on the landing plane and sensitivity of each PC. To find these, we used the eigenvectors found in the PCA analysis. By using the equations of motion that relate the release velocities to the position that the ball will be after thrown in relation to the target (landing plane, see Footnote 13), we projected the eigenvector into the landing plane. The magnitude of the eigenvector was defined as a change from -0.25 to 0.25 of the eigenvalue. From this, we had a line of given length in the landing plane. The first measure was estimated as the angle between the projected line and the medial-lateral axis of the landing plane (*x* axis). This was used provided that the angle projected onto the landing plane related directly to how much the individual would need to modify its throwing for one of the transfer tests (HT or VT). The sensitivity was calculated as the length of the projected line onto the landing plane. Note that sensitivity relates to how much changes in eigenvalue along the eigenvector defined on the release parameters would generate changes in the landing position. This was used because it is possible that individuals use the main variance of release parameters to not vary in the landing plane, but to compensate maintaining the same landing point – similar to what has been shown elsewhere (Arutyunyan, Gurfinkel, & Mirskii, 1969; Müller & Sternad, 2004; Scholz & Schöner, 1999).

Even though the release position influence was not as high as the release velocities, to understand whether individuals also included the position in the coordination function, we correlated the first two PCs in velocity with the first two PCs in position. This extra analysis was performed to understand, first, the degree by which the release position was integrated in the coordination function and, second, to observe whether all individuals would have similar coordination functions relating position and velocity.

Coordination Function and Transfer. To test whether the coordination function properties explain the transfer results, we performed linear regressions (using the backward method) including the parameters of the coordination function as independent variables and the transfer performance as dependent variable. The parameters of the coordination function were the following: a) the angle of the projected PC; b) the sensitivity; c) tuning; and d) the explained variance of the PC. The angle was mirrored and confined between the 0 and 90 degrees for our analyses (being a measure of closeness to the dimension of variation allowed in the transfer tests).

Note that these parameters could interact resulting in many independent variables for only 17 points at the dependent variable. As will be shown in the results, only two PCs were necessary (position could be disregarded, as discussed above, and only the two first PCs in velocity were necessary). The full model contained the variables and interaction between each PC measures (no interaction between PCs) and their interaction with explained variance of the first PC. Nevertheless, the resultant number of independent variables was still large for the number of observations. Thus, we used the backward method to avoid over fitting. Here, nevertheless, the most conservative measure (the measure that would take more independent variables from the initial model) for the backward method was not the BIC but the sum of squared errors – being the one used in the current analyses.

As dependent variables, we used the two transfer test performances. The intention was to characterize using relative measures how well an individual could perform in a new context taking into account his past practice experience. Thus, we used the relative change from practice to transfer in HT and VT. That is, we divided the HT and VT performance by the performance at the last day of practice. This allowed us to avoid using performance during practice as an independent variable.

Results

Performance Analysis

Figures 2a, 2b and 2c show the averaged and individual performances per day and on the transfer tests ((a) and (b)) and per block (c). The individuals showed an increment in performance through days and a poorer performance on the transfer to HT. Nevertheless, between individuals, there was considerable variability. Table 1 shows the resultant LME functions. The results show an increase in performance in terms of days (p = .032) and blocks (p < .001) with significant variance for each individual in terms of improvement per day.

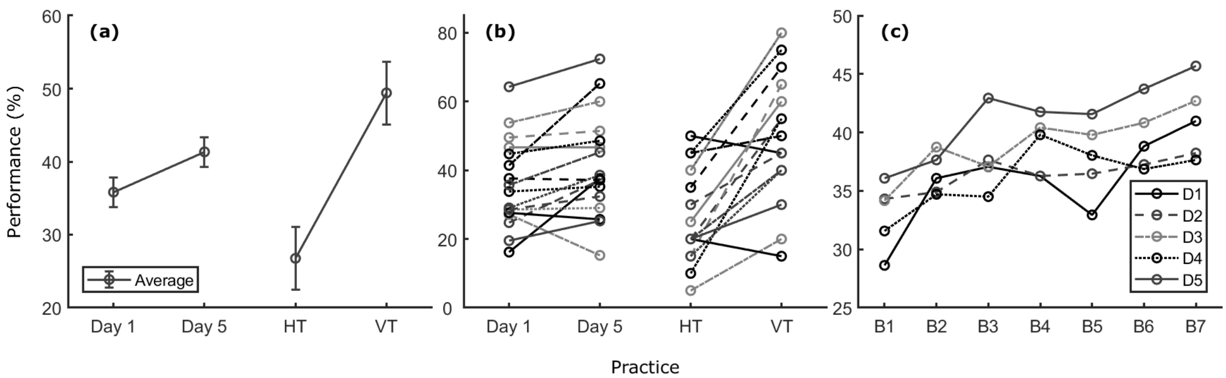

Figure 2. Performance as a function of practice days: (a) Average and confidence interval for group performance; (b) Average performance for each individual; (c) Average performance per day (different lines) and blocks (along abscissa). The confidence interval of (a) was corrected according to Loftus and Masson (1994).

Table 1. LME for performance over days and blocks (R^2 = 0.64).

p (full)[a] = .212		p (intercept)[b] < .001	
Fixed Effects			
	Estimate (± S.E.)	t-stat	p-value
(Intercept)[c]	0.32 (± 0.028)	11.39	< .001
Day	0.01 (± 0.005)	2.14	.032
Block	0.01 (± 0.001)	5.52	< .001
Random Effects			
	Estimate	Lower Boundary	Upper Boundary
(Intercept)	0.11	0.077	0.157
Day	0.02	0.010	0.027
Residual	0.09	0.089	0.101

[a] Comparison with the full model. A non-significant p-value indicates that the final model (with fewer variables) explains similarly the data as the full model; [b] Comparison with the model including only the intercept. A significant p-value indicates that the final model explains better the data than when compared to the simplest possible model; [c] The intercept relates to the first day/first block performance S.E.: Standard Error.

Coordination Function

One hypothesis to be examined was that even when performing the same task, individuals would not converge to the same movement pattern and/or movement parameters. To illustrate this point Figure 3 shows four individuals who showed similar performance on the last day of practice (P1: 37.6%, P2: 37.1%, P8: 38.5%, and P10: 37.1%). Their performances differed quantitatively and qualitatively in the transfer tests. Figure 4a shows data of these four individuals in terms of their movement patterns derived from motions of the wrist, elbow and shoulder. Figure 4b shows the release parameters (average) for the same individuals; again, the difference between individuals is considerable. While P2, P8 and P10 showed a throwing pattern based on elbow and wrist extension and flexion, respectively (a dart-throwing like pattern), P1 used mainly flexion of the shoulder (an underhand throw). Differences can also be observed in the release parameters in that P8 and P10 used a similar release position but differed in terms of the release velocities while both P1 and P2 differed from all in both release position and velocity. This supports the hypothesis that individuals could diverge in terms of their coordination functions even performing the same task.

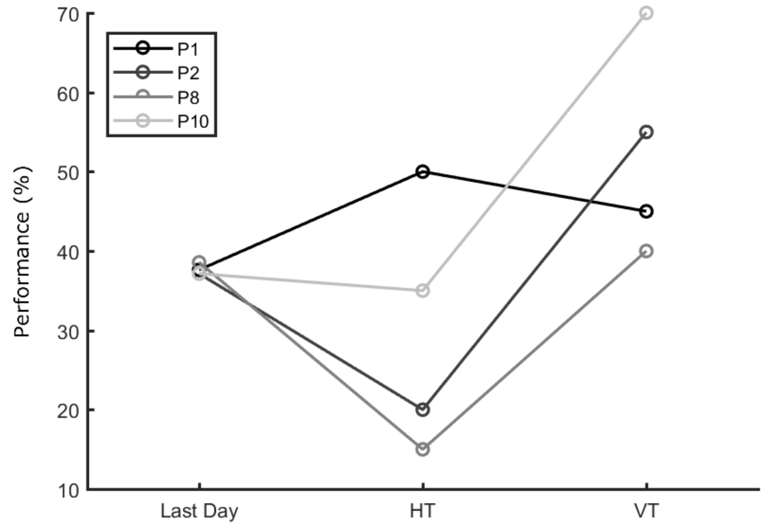

Figure 3. Average performance for P1, P2, P8 and P10 on the last day, HT and VT.

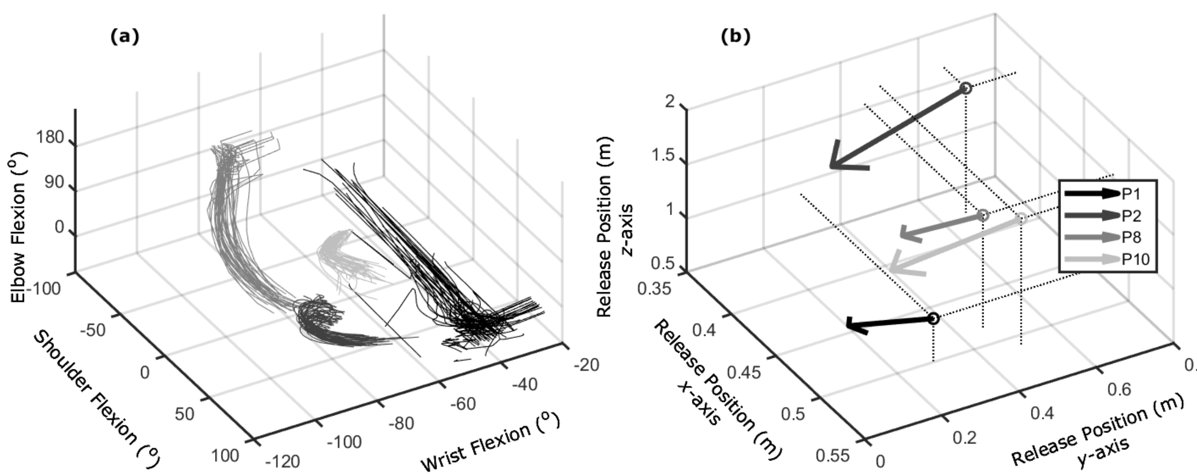

Figure 4. (a) Kinematics of shoulder, elbow and wrist flexion/extension for P1, P2, P8 and P10 for 50 trials (30 ms of movement up to the release point). For shoulder, 0 degrees mean neither flexed or extended; for elbow, 180 degrees mean full extension; for wrist, 0 degrees mean neither flexed or extended. (b) Data of the release parameters for P1, P2, P8 and P10 for 10 trials. The start of the arrow is located at the position of release and the arrow itself represents the velocity of release.

The PCA analysis on the velocity parameters revealed a variable sharing between first and second components (see Table 2). The variance accounted for in the first components was around

62% and in the first two components around 90% of the variance (mean: 92.18%). We, thus, decided to consider the first two components as representative of the coordination function (Appendix A provides the resultant eigenvectors for each individual).

Figure 5 shows the target in terms of the landing plane with the eigenvectors of the two PCs projected in the landing plane for the four participants mentioned before. The first eigenvector, when plotted in terms of the landing plane, varied more in angle (96.45 ± 29.99) when compared to the second eigenvector (89.67 ± 7.54) but, for most individuals, both eigenvectors showed a close-to-90-degrees angle (F (1, 32) = 0.71, p = .406 – Watson-Williams two-sample test for circular data; see Table 2). In general, individuals performed in a way that the first component organization did not result in large variation on the landing plane. That is, it seems that the variables in the first PC were compensating to maintain (almost) the same landing position, being less sensitive to variation. Also, the second PC showed much more sensitivity than the first one (t (16) = 5.25, p < .001) – variations on it would create more variability in position in the landing plane, as illustrated by the long length of the plotted line. The results highlighted that the second PC was the one mainly correlated to the distance of throw (t (16) = 3.02, p = .008; using z-scores). Thus, it seems that although the individuals showed large divergence in terms of the movement patterns acquired during practice, the majority placed the first component (large variance) along the task space and used a second component to correct for errors.

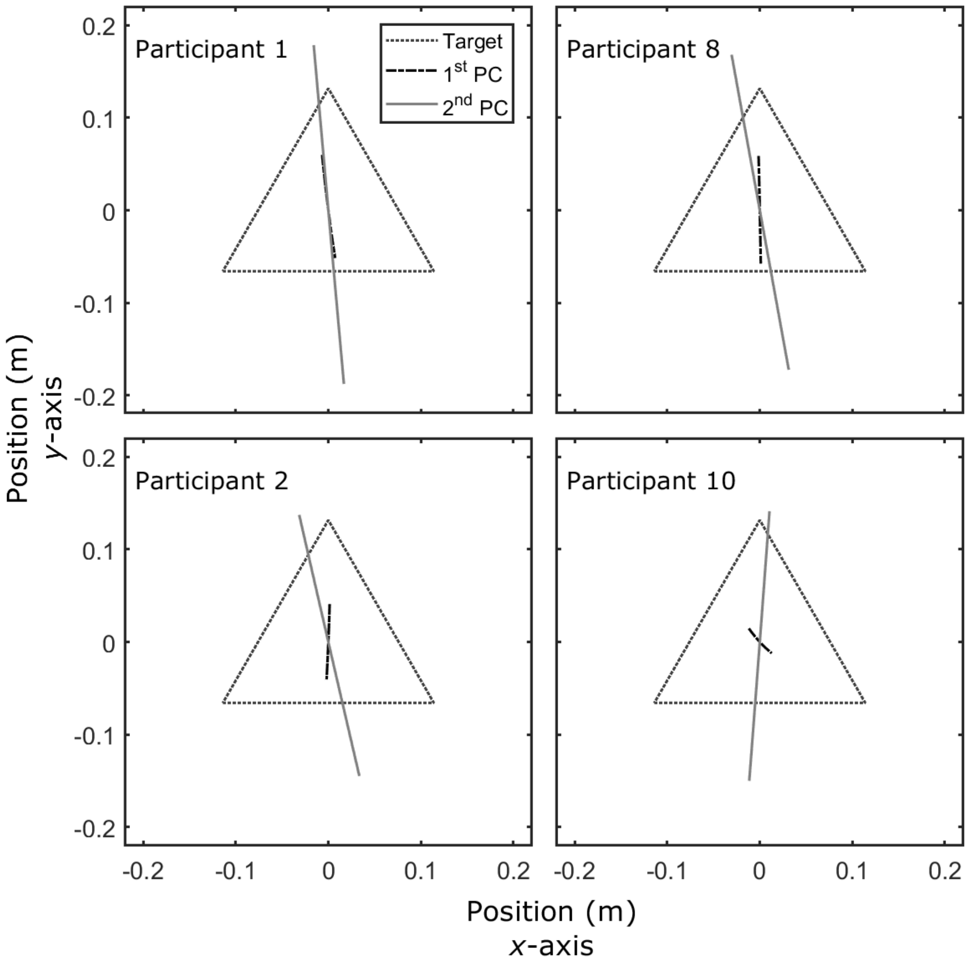

Figure 5. Landing plane with the depiction of the target and projections of the first and second main axes of variation for (a) P1, (b) P2, (c) P8, and (d) P10

Table 2. Parameters of the 1st and 2nd components.

Part.	Explained Variance (%)		Angles (º)		Sensitivity (m)		Tuning (r)[a]	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
1	54.68	38.71	82.99	84.90	0.07	0.22	0.22	0.69
2	64.38	30.32	87.80	77.01	0.05	0.17	0.32	0.76
3	72.61	18.43	86.88	89.70	0.10	0.14	0.43	0.54
4	74.22	14.78	65.21	75.77	0.04	0.20	0.10	0.72
5	76.21	19.91	83.82	89.73	0.10	0.15	0.23	0.54
6	59.35	35.52	87.20	87.11	0.09	0.14	0.02	0.67
7	84.35	13.39	87.20	77.95	0.21	0.09	0.69	0.08
8	54.12	36.45	88.79	79.71	0.07	0.21	0.25	0.76
9	63.91	29.68	31.63	83.76	0.01	0.17	0.15	0.61
10	69.33	23.84	48.27	85.69	0.02	0.18	0.12	0.53
11	66.52	28.34	88.21	83.03	0.05	0.15	0.28	0.51
12	57.85	33.03	13.52	81.91	0.00	0.17	0.05	0.63
13	55.07	39.39	82.40	85.81	0.04	0.19	0.00	0.68
14	46.95	38.16	81.61	85.86	0.07	0.18	0.42	0.67
15	98.86	1.05	89.43	88.99	0.11	0.09	0.92	0.09
16	64.67	31.75	88.81	84.53	0.06	0.17	0.12	0.69
17	60.19	28.96	33.08	85.82	0.00	0.19	0.37	0.72

[a] These are the absolute values.

Finally, to investigate whether position – even with its small contribution – was included in the coordination function, we performed correlations between the first two PCs in velocity with the first two PCs in position. Table 3 shows the results and, as for the other measures, individuals showed large differences between them. For instance, P5 showed a correlation of 0.83 between the first PC in position and the first PC in velocity, indicating a single dimension taking the largest part of variance. P3 showed low correlations between all PCs indicating that position and velocity were not working as one. Although one could relate this to performance (provided P5 has the best score and P3 the worse), in comparing individuals with similar performances (e.g., P1, P2, P8 and P10), we see large variability between them as well.

Table 3. Correlation between the first two components in velocity with the first two components in position.

Part.	PC1 Vel./ PC1 Pos.	PC1 Vel./ PC2 Pos.	PC2 Vel./ PC1 Pos.	PC2 Vel./ PC2 Pos.
1	-0.29	0.56	0.59	0.31
2	0.58	0.17	-0.27	0.13
3	-0.09	-0.42	0.46	0.18
4	-0.12	0.73	0.57	0.20
5	0.83	-0.11	-0.22	0.02
6	0.82	-0.12	-0.30	-0.07
7	0.48	-0.55	0.42	0.20
8	0.65	-0.27	0.13	0.38
9	0.46	0.39	-0.65	0.23
10	0.71	0.09	-0.38	-0.08
11	0.59	0.14	-0.44	0.24
12	0.16	-0.18	0.52	-0.27
13	0.62	0.06	-0.39	0.24
14	0.34	0.17	0.60	-0.13
15	0.39	-0.30	0.49	-0.27
16	0.54	-0.38	0.60	0.52
17	0.66	0.06	-0.38	-0.28

Coordination Function and Transfer Performance

The main hypothesis tested in the present paper was that the properties of the coordination function that influence transfer. Before running the analyses, we observed that some variables were highly correlated with others: the sensitivity and tuning of the second PC (r = .88) and tuning of the first PC with three variables ($r \approx 0.75$). To avoid multicollinearity, we decided to maintain the sensitivity of the second PC (selected by chance) and take out from the model tunings of the first and second PCs. Table 4 shows the results for the two dependent variables.

Table 4. Multiple regression for performance in HT and VT transfer tests.

Horizontal Transfer Test			
(R^2 = 0.68)	p (intercept)[a] = .014		
	Estimate (± S.E.)	t-stat	p-value
(Intercept)[b]	0.60 (± 0.05)	10.55	< .001
A_2	0.03 (± 0.01)	2.45	.031
E_1	0.006 (± 0.007)	0.81	.434
L_2	8.14 (± 2.57)	3.15	.009
A_2*L_2	1.10 (± 0.33)	3.35	.006
E_1*L_2	-0.25 (± 0.09)	2.72	.019

Vertical Transfer Test			
(R^2 = 0.77)	p (intercept)[a] = .071		
	Estimate (± S.E.)	t-stat	p-value
(Intercept)[b]	1.25 (± 0.28)	4.46	.002
A_1	-0.0002 (± 0.02)	0.01	.992
E_1	-0.003 (± 0.02)	0.16	.874
L_1	-0.24 (± 6.67)	0.04	.972
A_2*R_2	0.001 (± 0.001)	0.68	.515
A_2*L_2	0.25 (± 0.43)	0.59	.569
R_2*L_2	-1.27 (± 0.53)	2.40	.040
A_2*R_2*L_2	0.05 (± 0.02)	1.98	.078

[a] Comparison with the model including only the intercept. A significant p-value indicates that the final model explains better the data than when compared to the simplest possible model; [b] Provided all the variables had the mean taken to run the analyses, the intercept reflects the mean value of the dependent variable; S.E.: Standard Error.

For VT, the stepwise regression showed that only the first PC predicted the results on transfer. Note, however, that not all effects are significant and the model is borderline better than the constant (p = .071). This is expected provided that both PCs projections were along the VT transfer test and thus it could be that redundancy in terms of the learned coordination functions during practice could occur here. That is, coordination functions that were specific (functional) to the previous task space would not be differentiated here. Figure 6 shows the fitted model. The results can be summarized as follows. When the projection of the first PC had low angle values (Figure 6(a)), high values of sensitivity combined with large variance accounted for in the first PC was detrimental (relative to other performances) and this effect was cancelled (or even twisted) in small variance accounted for. When the projection of the first PC showed a high angle (close to the target) the effect of the other variables was attenuated. Note, that the latter is the most common case (most individuals had the projection of the first PC coinciding with the VT target). This explains why individuals could maintain (or even improve) performance in this task.

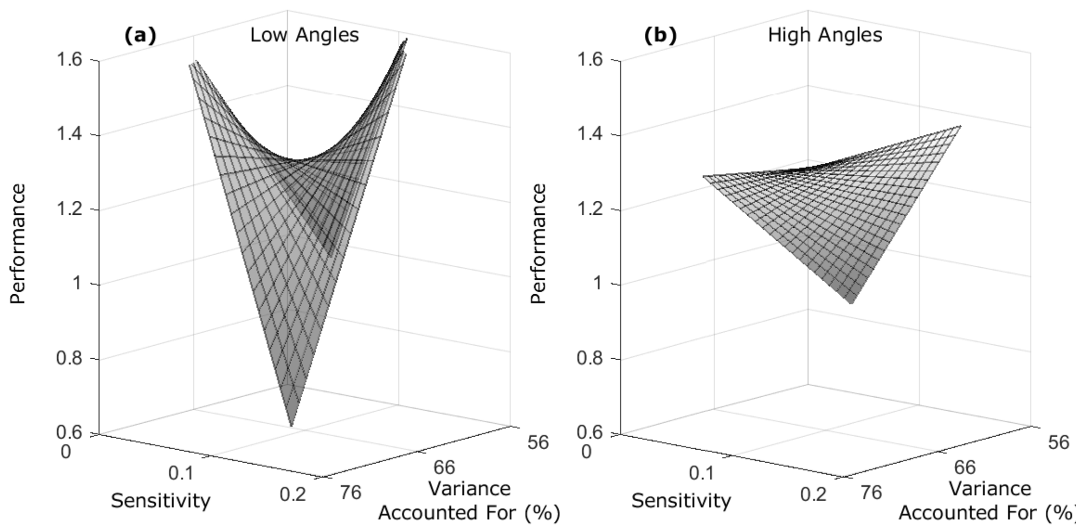

Figure 6. The relation between relative performance in VT and the results of the fitted regression with sensitive parameters and the variance accounted for of the first main axis of variation for: (a) low and (b) high angles.

For HT, the stepwise regression showed that characteristics of the whole coordination function had an influence on the results of transfer, namely, the amount of variance accounted for by the first PC and the sensitivity and projected angle of the second PC. This is expected provided that this was the condition that "challenged" our participants more – as evidenced by the low performances. Figure 7 show the effects in terms of the first and second component variables. The results can be summarized as follows. For high angles of the projected second PC (Figure 7(b)), high sensitivity accompanied by large variance accounted for by the first component resulted in lower scores while sensitivity resulted in better results for those with small variance accounted for by the first component. For low angles (Figure 7(a)), the results were worse (smaller than 1) but the effects were similar in that when the variance accounted for by the first PC was smaller, the sensitivity showed positive effects.

This result can be explained by the fact that sensitivity was highly correlated with tuning. Participants who had higher sensitivity were the ones that used the second PC to correct the outcomes that deviated from the target in the direction orthogonal to the HT target. This led to better performance for those who had this second component to correct the outcomes with a higher contributing percentage in the variance (low variance accounted for the first PC).

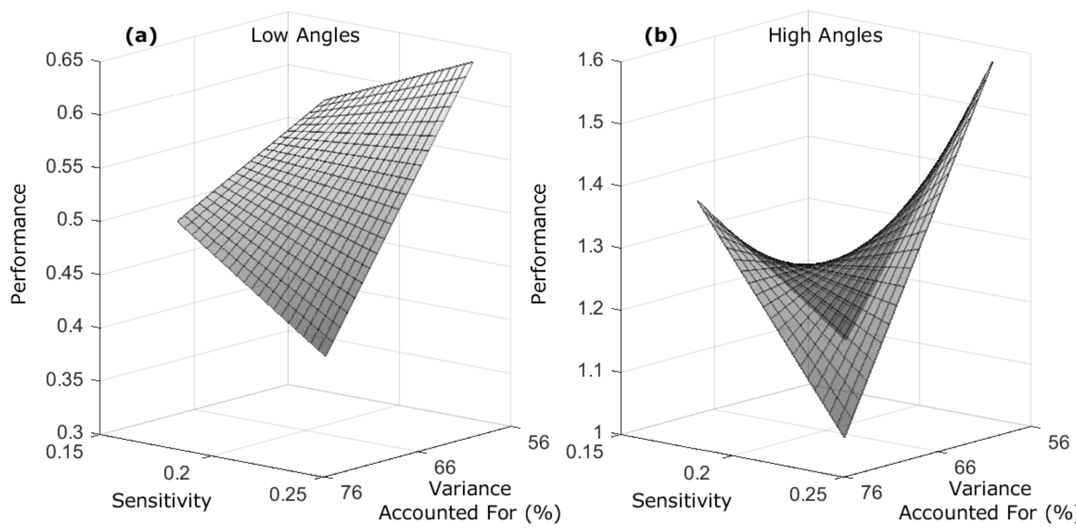

Figure 7. The relation between relative performance in HT and the results of the fitted regression with sensitive parameters of the second main axis of variation and the variance accounted for by the first main axis of variation for: (a) low and (b) high angles.

Discussion

The central hypothesis of the paper was that the similarity between original task-space and the transfer task (e.g., Braun et al., 2010) would not be sufficient to predict transfer provided individuals show different search pathways in the task-space (in terms of initial state and search) and that the goal space is not overly restrictive to make individuals converge to the same solution. On the contrary, individuals would learn specific, individual and generalizable special-purpose devices in practice and the properties of these individual solutions would predict transfer. The results are in line to our proposition that individuals do not learn the same solution for the task – even when considering similar performances and five days of practice. Furthermore, differences in the aspects of the coordination function predicted the transfer performance. This finding is a strong point for individual participant analyses and consideration of individual differences (see, Withagen & van Wermeskerken, 2009).

Although specificity, individuality and generalizability as properties of transfer can be thought of as contradictory to each other, they do not need to be so. Being specific to a task refers to being able to act and achieve the goal in a given task. This does not mean that the solution is functional to only the current task – rather, that it does work in the present task. Individuality of the solution refers to the fact that there are innumerous solutions afforded by a redundant task and individuals differ with respect to the ones they acquire through practice. Finally, generalizability reflects the fact that the system acquires coordination functions that are specific (functional) to a given situation but these can be parameterized to other contexts depending on its characteristics.

The Coordination Function

The findings showed that a low-dimensional space within the task space could describe the throwing actions. Note that although we only analyzed the release parameters, when we observe Figure 4a, the movement pattern in terms of shoulder, elbow and wrist extension/flexion is limited to a single although unique small space for all four individuals shown. This is consistent with the idea that the system works in terms of functional units that are specific to the task and low-dimensional coordination function facilitating control (Bernstein, 1967; Turvey, 1977; Turvey et al., 1982). The fact that the system self-organizes into low-dimensional spaces also facilitates the search through the task space in that not all dimensions are initially explored (Braun et al., 2009; Pacheco & Newell, 2017a).

In terms of the organization of the main axes of variation, for most individuals, they constrained the main axis of variation to be within the goal space. This means that the release parameters covaried to avoid the ball landing outside of the target (some individuals performed this covariation constraint better than others). This is in line with the proposition of TNC (Cohen & Sternad, 2009; Müller & Sternad, 2004) that during practice individuals learn to covary parameters of the action to maintain the performance intact. This was observed although different individuals performed using distinct movement patterns.

With respect to the coordination function, it is held that it should be tuned to performance in that the learner should be able to correct errors as they occur. We found that in most cases the second main axis of variation was strongly related to performance. The resultant values were high enough considering the inherent variability of the system and the fact that in some cases individuals would not show change proportional to performance (Pacheco & Newell, 2017a).

A forward step is to understand how the patterns in the coordination function emerge through practice. The available accounts (e.g., Bernstein, 1967; Latash, 2010) cannot provide how the trial-to-trial interaction between individual and task leads to the emergence of the organization observed in our results. Latash (2010), for instance, considers stages in which the learner demonstrated changes in the variability ratio within/outside the goal space that first increase and, depending on the task, might be modified again. This corroborates to our finding that most individuals are learning to act specific to the context: a special-purpose device, but cannot provide how would individuals would modify the intrinsic dynamics to make it occur.

Generalizable Special-Purpose Devices

Bingham (1988) proposed that special-purpose devices must be controllable in the sense that they can be parameterized to attend to task relevant changes in output. In addition, if tasks share dynamical properties, a device that emerged from one task might be adapted to another one. In the present paper, we modified the main axis of variation that a task would tolerate – along the vertical or horizontal axis of the landing plane. The fact that individuals performing the same task differed substantially on the transfer tests (see Figure 3) is evidence that they did not learn the same special-purpose device because they did not show similar capacity to adapt and control.

Furthermore, we assumed that the covariation patterns and their relation to performance and landing plane would provide the aspects necessary to characterize the coordination function (the special-purpose device) and, thus, predict the performance in both transfer tests. Our results corroborate this interpretation in showing that, for the transfer test that was *in line* to the projection of first and second PCs (i.e., VT), only the first PC sensitivity and variance accounted for influenced the results. This can be thought of as reflecting that participants who learned to maintain the first PC within the task space (small sensitivity) and, relied on this first PC only, showed better performance outcome. Note that, although the regression maintained the variables, the model was borderline significant. This can be said to have occurred due to the number of participants or because the effect of the learned coordination functions would be small in the more similar transfer task – it might allow the same space of redundant solutions.

When we consider the most challenging condition (i.e., HT) both PCs had an influence. Indeed, those individuals who relied mainly on the first PC (high variance accounted for) were the ones who showed detrimental effects of sensitivity. This is logical provided that sensitive "secondary" components will have large influences on the outcome for small variations in the pattern. Nevertheless, this was the opposite when the variance accounted for was smaller. If we interpret that those who showed higher sensitivity in these cases were the ones who could control their variations using the second PC, then the explanation is straightforward. Individuals that used the second component as the one to correct for deviations, could have lower variance accounted for in the first component without having decrement in transfer. A result that corroborates such a view comes from the fact that individuals that showed higher tuning in the second component were also the ones who had lower variance accounted for in the first component (r = -.81).

In general, we found that those individuals that could parameterize their actions to accomplish the task and could allocate the major variance of their movements within the goal space (or *along* the goal space) showed better transfer results. These findings extend those of the previous literature (e.g., Latash, 2010; Sternad et al., 2014) in that our findings do not only show that we have general aspects that the practice leads to (i.e., variation along the goal-space) but also that these general aspects are not enough to predict transfer. In short, the individual differences in the patterns are necessary to understand transfer performance.

These results are contrary to the expectation that in knowing the task requirements, we would know the transfer performance or even what is learned. Most studies that emphasize such a point consider the comparison between variable practice and constant practice (e.g., Braun et al., 2010, Schmidt, 1975). It is usually hypothesized that because variable practice requires variation in a given dimension of the task, the individual would learn how to vary the movement pattern in that dimension allowing for transfer to any situation that varies on this same dimension (cf. Moxley, 1979).

In the present study, we did not investigate variable practice but our findings lead to consider whether variable practice is better than constant practice. This is dependent on the special-purpose device acquired during constant practice. The fact that individuals could perform their task along the goal space and have a dimension related to varying distances might imply that even in constant practice individuals learn to vary a given dimension already. This is contrary to common expectation that learning in constant and variable practice would differ in terms of their main axis of variation (e.g., Ranganathan & Newell, 2013).

A limitation of our study is the limited sample size to perform the regression analyses. Nevertheless, we used the backward method to avoid over fitting and, provided the dependent variable (VT or HT) and its relation to the prediction measures, we did decrease the number of independent variables. Also, we found significant values for HT and the final model when compared to the constant model that considers the degrees of freedom (see Table 4). Additionally, we did not have a pre- and post-test design to know how much change in performance on the transfer tests occurred because of practice. Nevertheless, we can state that we identified potential variables that predict how the performance in the transfer tests are after practice – the main goal of the paper.

Convergence and Divergence in Skill Acquisition

One core point proposed here is that it is not necessary that individuals *converge* to the same movement pattern during practice. It is possible that our findings are influenced by the fact that we are implementing a multi-degrees-of-freedom task that allows a broader range of possibilities at the beginning and end of practice. Even if that is the case, theoretical discussions in motor behavior should not be limited to simplistic experimental paradigms.

The idea that lack of constraints lead to divergence is common in other literatures. For instance, the literature in evolution of morphology of species holds that provided the *selection pressure* occurs in terms of function, rather than structure, species can diverge structurally without much consequence through evolution (e.g., Alfaro, Bolnick, & Wainwright, 2004; Anderson & Patek, 2016; Young, Haselkorn, & Badyaev, 2007). This occurs because there is a many-to-one relation in terms of structure and function. This is similar to the context of practice of redundant tasks in that individuals can diverge in terms of movement patterns provided that evaluation of task is related to performance only. Although evolution dynamics might seem distant, there are several arguments on selectionism in behavior that would follow similar dynamics (e.g., Edelman, 1987; Rosengren, Savelsbergh, & van der Kamp, 2003).

Nevertheless, the pressure on performance can be enough for patterns to converge *even* if the pressure is not on movement patterns. The TNC approach characterizes such a point. Sternad and colleagues (Cohen & Sternad, 2009; Müller & Sternad, 2004; Sternad et al., 2014) proposed that individuals might improve performance by finding a region in goal space that is more tolerant to variation in the movement pattern, decreasing inherent variability (noise in their terms), and/or coordinating the movement pattern parameters to be within the goal space (or showing *covariation*). If we disregard for now the potential of decreasing noise, it is possible that for all possible solutions of the goal space, there is one that maximizes tolerance – making it a potential point for an *optimal* solution within all other solutions.

Additionally, individuals may converge because, despite the task space configuration, they have similar biomechanical, physiological and neural constraints that might provide a more common stable pattern. This pattern would be more reliable in terms of counteracting perturbations and when interacting with the task at hand. Potential examples of this would be the similar patterns between individuals observed in reaching, walking or maintaining posture. Although individuals might differ initially (see Thelen et al., 1993, for a reaching example), one can argue that provided the innumerous perturbations and experience provided through life-span, these patterns end up converging to similar coordination functions between individuals[15].

However, in considering the current results in the literature that provides that inherent variability is adaptable (e.g., Hasson, Zhang, Abe, & Sternad, 2016; Tumer & Brainard, 2007), we come back to the starting point in that convergence might not be necessary – even in the long term. That is, the fact that the human movement system can enhance or decrease variability – also argued in the TNC approach – seems to provide a strong argument against convergence in that individuals just need to find a single solution and then decrease variability to a given extent.

It is important that studies on trial-to-trial dynamics are performed to understand the influence of each aspect discussed here (i.e., initial state, search strategies, goal space tolerance, inherent variability, and task redundancy) to the learned coordination function. As it is, we emphasize that it is expected that the coordination functions learned are special-purpose devices that are specific, individual and generalizable. Analyzing data at the level of individual movement patterns and outcomes provides the general aspects that must be considered in transfer.

[15] Note that this convergence position might be limited to movements that adapt to stable environments and are practiced through whole life. Movement patterns of skilled athletes may never converge provided the necessity to adapt when different opponents are confronted. Anecdotal evidence can be given when comparing the quite distinct movement patterns (and even their strategies during the game) of Roger Federer and Rafael Nadal when they reached the highest position in ATP.

CHAPTER 4

LEARNING A SPECIFIC, INDIVIDUAL AND GENERALIZABLE COORDINATION FUNCTION: EVALUATING THE VARIABILITY OF PRACTICE HYPOTHESIS[16]

In motor learning, it is hypothesized that groups performing variable or constant practice will show different behavioral outcomes. Specifically, the hypothesis is that varying a given dimension of a task during practice for a group of individuals results in acquisition of a structure that facilitates behavior on this same dimension varied when comparing to the situation in which no variability is induced by the experimenter (Braun et al., 2010; Schmidt, 1975). A recent study (Pacheco & Newell, 2017b) proposed that, even within the same condition of practice, individuals had the possibility to diverge in learning in a way that the transfer performance would not be dependent on the practice condition but on the individual solution learned during practice. It raises the question of whether the practice condition performed by a group is sufficient to predict performance in a transfer test. Nevertheless, Pacheco and Newell (2017b) only conducted analysis in a constant practice condition. The present study tests whether individual characteristics would

[16] This study is in preparation to be submitted to *Experimental Brain Research*. **Abstract:** Different practice conditions (constant/varied practice) are expected to lead to different learning outcomes that are more alike within the same condition than compared to different ones. This would lead to differences in retention and transfer tests. In a recent study, Pacheco and Newell (2017b) showed that within a constant practice condition, individuals showed highly individual outcomes that predicted differences in transfer tests. In light of the contradictory evidence on practice conditions, we tested the idea that, provided task redundancy and different individual tendencies in task, measures of the individual learned outcome (a coordination function) would provide a better explanation for results in transfer tests. Twenty four participants were divided in three groups with different practice conditions (constant, varied distance of the target, and varied angle of the target) and performed a task of throwing for precision for five days. Pre-, post-test, and tests that measured their performance with variable target positions were performed. The results showed that although the group measures could predict some of the results on the after-tests, the coordination function characteristics showed higher levels of explanatory power. This supports the view that individuals learn a specific, individual and generalizable coordination function.

be a better predictor of transfer than the practice condition when different practice conditions are compared.

Variability of Practice

Initially, the variability of practice hypothesis was derived from Schema Theory (Moxley, 1979; Schmidt, 1975). In this context, the system would be organized in terms of general motor programs (GMP) – a movement class with invariant properties – and a schema that would specify the variant parameters of the GMP. Practicing the same GMP with varied requirements would make possible for the schema to integrate various initial conditions, response specification, sensory consequences, and outcomes in a robust rule that could be generalized to other conditions. The idea generated a series of experiments on generalization (see Moxley, 1979; Newell, 2003; Sherwood & Lee, 2003) and provided some support for the hypothesis.

Subsequent theories imported the same idea to their considerations. In general, the idea is that variability of practice allows acquisition of a structure that integrates the variations required during practice into a single unit. A prominent instance of these new views is the structural learning (Braun et al., 2009; Braun et al., 2010). Without the concern to define how the single unit will be (thus, different than Schema theory), it assumes that individuals will find a single rule that characterizes how individuals will perform in new contexts – facilitating (or not) generalization (Ranganathan et al., 2014). Evidence has been provided that practice in a condition where there was variability in a dimension of the task made individuals perform a new context utilizing the same dimension of variation (Braun et al., 2009).

However, since Schema Theory, there is accumulated evidence to question whether the variability of practice hypothesis holds empirically. Van Rossum (1990) provided the most comprehensive consideration on the topic. At the time, subsequent addition of *ad hoc* explanations to the hypothesis (e.g., effect of age, similarity original practice/transfer, etc.) were being posited to accommodate contradictory findings. Van Rossum (1990) reviewed several studies and, controlling for these and other confounding factors (e.g., occurrence of learning), showed that the variability of practice had weak support (see also, Brady, 2008; Hossner, Käch, & Enz, 2016). This lack of support was never fully acknowledged in recent theories but experiments based on similar ideas of variability during practice did not result in better support (Braun et al., 2009; Ranganathan & Newell, 2010; Tuitert et al., 2017).

Special-Purpose Devices and Convergence/Divergence Issues in Practice

The theories that have as consequence the variability of practice hypothesis assume that constant and variable practice schedules would elicit different learning outcomes and, by consequence, different results in transfer tests. Variability in performance between participants that practiced the same condition would be just an effect of confounding factors and individuals within a single group would be more alike than individuals from different groups.

Nevertheless, the assumption might not be valid. Recent studies have shown that, in constant practice, individuals have substantial differences in the way they perform the task resulting in large differences in their performance in transfer tests as well (Pacheco & Newell, 2015, 2017b). From dynamical systems approach to learning, one must understand the initial condition of the individual, the process of change (or search, see Newell et al., 1989; Newell & McDonald, 1992; Newell et al., 1991) that the individual goes through and the task requirements (Beek & van Santvoord, 1992). The observed individual differences seem to emerge from the fact that individuals start (Kostrubiec & Zanone, 2002; Kostrubiec et al., 2012; Zanone & Kelso, 1992, 1994, 1997) and search differently through the perceptual motor workspace (Pacheco, Hsieh, & Newell, 2017; Pacheco & Newell, 2017a). Also, individuals are not restricted to converge to the same solution provided that most tasks are redundant in their nature (i.e., the tasks present more than one solution to achieve the goal). Indeed, these studies have showed that individuals exploit such redundancy in finding different solutions for each.

The argument is that individuals learn a special-purpose device that is specific to the task, individual and generalizable (Pacheco & Newell, 2017b). In learning a solution for a task, individuals find and stabilize a coordination function that is appropriate for the task at hand but can be parameterized to different tasks depending on its characteristics (see Newell, 1985). Nevertheless, although this is specific (functional) to the task and generalizable, the redundancy of the task space allows individuals to find different solutions creating differences between them.

It is an open question whether one can hold that individuals that practiced the same condition during original practice are necessarily more alike than individuals practicing other conditions. The aforementioned studies were performed using constant practice conditions and showed large variability between individuals that were related to transfer performance. Provided the constant condition is not sufficient to constraint individuals to converge to a single solution, one might be tempted to test whether variable practice would be.

Strategy of the Present Study

The main question investigated here is whether variable practice compared to constant practice would result in different characteristics of the coordination function – resulting in differential results in after practice tests. For this we asked participants to perform for five days a throwing for precision task in different practice schedules: variable practice in terms of the distance of the target, variable practice in terms of the angle of target, and constant practice. We analyzed whether the individuals became more alike within than between groups in terms of the characteristics of the coordination function. Also, we asked them to perform after practice tests that *should* advantage a given group if groups indeed lead to differential learning outcomes.

Methods

Participants

Twenty-four college-level students (ages from 22 to 35 years, thirteen females) voluntarily participated in the present study. Informed consent was provided prior to participation with approval from the University of Georgia Institutional Review Board.

Task and Apparatus

The participant's task was to throw a plastic golf ball into a target. Two different targets were used. The target used for practice and transfer tests was an equilateral hexagon with equal angles 10 cm height and 10 cm for each side. The target used for both pre- and post-tests was a square target of 10 cm height, 15 cm each side. These targets were made of cardboard (if the target got worn, it was replaced by a new one). Figure 8 shows the targets and the ball. For each stage, these targets were placed above a table of 73 cm height with their center point at 2.05 m of the center position of which individuals would throw.

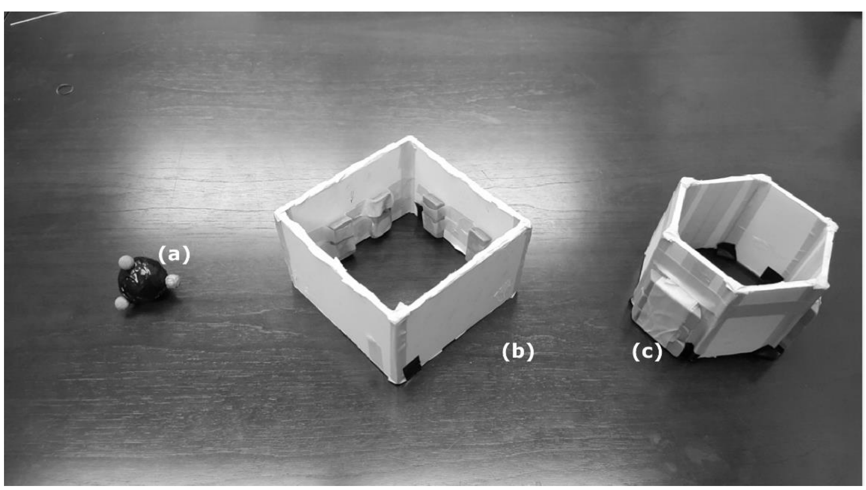

Figure 8. One of the plastic golf balls (a) used with the markers, target of the pre- and post-test (b), and target of the original practice and after-tests (c). (b) and (c) had erasers attached to the target to guarantee that it would not move when hit by the ball.

The shapes of the targets were selected to provide a restricted landing region during practice and transfer tests. This ensured that if the variable practice was to channel the coordination pattern acquired during practice, this was to occur. Four paperboards were attached to each other by the short end and 10 target locations were selected. Five of these locations were selected in a way that if the set of paperboards was placed perpendicular to the antero-posterior direction of the thrower, an arc of radius 2.05 m and 40 degrees would be formed out of the five target positions. The other five locations were selected in a way that if the set of paperboards was placed in the antero-posterior direction of the individual, the center target would be at 2.05 m and the other 4 target locations were separated by $\approx$ 36 cm along the antero-posterior axis. These locations were marked with cardboard restricting the boundaries of the hexagon target. To avoid the balls losing their markers due to hitting the surface of the table, this long paperboard was placed above a mattress foam of 4 cm that covered the table. The foam was rigid enough to maintain a horizontal and plane support for the cardboard and target.

All trials were recorded using the VICON system (Sampling rate: 100 Hz). For this, the individuals wore a dark tight shirt and had markers placed on their right arm and trunk. Following the Plug-in Gait marker localization, the markers were placed at the spinous process of the seventh cervical vertebra, spinous process of the 10^{th} thoracic vertebra, jugular notch where the clavicula meet the sternum, xiphoid process of the sternum, right scapula, acromion-clavicular joint, lower lateral one-third surface of the right arm, lateral epicondyle, lower lateral one-third surface of the right forearm, thumb-side of the wrist, little-finger side of the wrist, and middle knuckle on the right hand. To measure the release parameters, the balls were also marked. The balls were first covered with black tape and four markers were glued to the ball (see Figure 8 (a)).

Instructions and Procedures

On the first day, after getting to the laboratory, individuals read and signed the informed consent form and had the markers placed on their body. The experimenter explained that the goal of the task was to throw the plastic golf balls inside of the target. The instructions emphasized that the participants were not restricted to throw in a specified movement pattern but could explore different movement patterns if this had the goal to improve performance.

The experiment involved a pre-test in the first day, practice for five days (with the first practice session on the same day as the pre-test), a post-test performed right after the last day of practice, and two after-tests performed after a 10 minutes brake. Individuals performed the pre- and post-tests on the square-shaped target for 30 trials each (Figure 8(b)). For practice, individuals performed 210 trials each day (total of 1050 trials of practice) on the hexagon-shaped target (Figure 8(c)). Finally, the two after-tests were also performed on the hexagon-shaped target with each test having 30 trials.

Each group of participants (n = 8) performed a different practice schedule. The constant group (CG) performed all trials aiming at the target at the center position (2.05 m distance at the antero-posterior axis). The angle group (AG) performed the practice with the target position being changed randomly for each trial in terms of the angle (all targets were at 2.05 m distance but different angles from the antero-posterior axis: -20^o, -10^o, 0^o, 10^o, and 20^o). Finally, the distance group (DG) performed the practice with the target position being changed randomly for each trial in terms of the target distance (all targets were placed in the antero-posterior axis but different distances from the participant: 1.33 m, 1.69 m, 2.05 m, 2.41 m, and 2.77 m). For the after-tests, participants performed in order (randomly varied between individuals) the DG and AG conditions for 30 trials each – heretofore the after tests are called DT and AT tests.

To have both a short- and long-term control of performance for individuals, we managed the practice in the following way. We gave them a set of 10 balls to throw every time. After each set, the experimenter counted the number of balls in the target and informed the individual. Also, after 30 trials, the experimenter summed up the performance of 3 sets of 10 balls and told the score to the individual. If any individual required rest, a break of 10 min was provided.

Data Analysis

The procedures described here are the same described in Pacheco and Newell (2017b). There are a few differences given that the design involved more groups than that initial study.

The data of the digitized positions of the markers first passed two filling gaps procedures: Woltring spline for maximum of 10 frames of gaps; and filling based on the trajectories of the other markers of the rigid body for maximum of 25 frames gaps. Then, the trajectories were filtered using the fourth order Butterworth filter at 10 Hz. If any resultant missing trajectory were still present, the trajectories were interpolated by using a spline method (interp1 function in MATLAB). The small occurrence of missing data was due to markers being covered – mainly at the ball when individuals were preparing to start the movement of throwing (a period of usually ten frames). Provided the ball markers were mainly utilized to know the release parameters and the missing period occurred way before the release, we had no problems with missing data. The choice for the cut-off frequency was done after inspection of the spectral distribution of data.

Performance. The performance was analyzed in terms of blocks of 30 trials. For each block, the performance measure was the sum of hits (i.e., ball being thrown inside of target) divided by the number of trials. We performed a linear mixed-effect model (LME) (with a backward method) on performance using as independent variables the day, block and their interaction. The advantage of the LME is that it allows nested data to be modelled (in our case, variables within a given individual) and the independent variables within a given level to vary (in our case, variability between individuals) (see Raudenbush & Bryk, 2002). The initial random variables (i.e., the variables allowed to vary between individuals) were days and blocks with their variances allowed to be full (e.g., the variance of blocks could be related to the variance of days between individuals). By using a backward method, we tested all (fixed and random) effects comparing models with different variables.

We based the maintenance of variables in the equation comparing the Bayesian Information Criterion (BIC, Schwarz, 1978). The models were examined by estimating the parameters using the maximum likelihood estimation and restricted maximum likelihood estimation for fixed and random effects, respectively. The LME was performed using the fitlme code in MATLAB and the backward regression was performed by an algorithm developed for this purpose.

Release parameters. To identify the release parameters, we determined the moment at which the distance between ball and hand crossed a threshold. For each trial, we averaged the three markers that relate to the hand (thumb-side of the wrist, little-finger side of the wrist, and middle knuckle on the right hand) to have a single 3D location of the hand in space. We did the same for the ball. Then, the Euclidean distance between hand and ball was calculated. To identify the ball-hand distance before the release, we ran a moving window through the ball-hand distance time-series and identified a moment in which the average (the 'cut') could describe a window of 10 frames with a squared error smaller than 2 cm^2. Then, to identify the release point, we identified the point in which the ball-hand distance was above the cut value by 2 cm.

Describing the coordination function. As argued in Pacheco and Newell (2017b), we described the coordination function in terms of the release parameters. They reflect the timing of release in terms of the joints being moved and by a direct relation, reflect where the landing will be – where the task was defined and modified. To describe the coordination function, a principal component analysis (PCA) was run on the release parameter data of each individual pre- and post-tests (separately). To do this, we had to consider how to deal with two different units (position is in m and velocity is in m/s). We verified whether individuals' results were mainly dictated by velocities or positions. To do this, we observed how much variance in position and velocity altered the landing position of the ball. Using this approach, we found that velocities had 2 to 4 times more influence on the result than position. Accordingly, the PCA was run on the velocity release parameters of the pre- and post-test trials.

The coordination function characteristics were its sensitivity, tuning and angle of the projection in the landing plane. Sensitivity refers to the change that variations in the eigenvalues result for the landing position. For this, we projected the eigenvector of the first and second PCs (the ones that covered about 90% of variance) into the landing plane (constituted of the antero-posterior and medio-lateral axes at the target height) and varied the eigenvalues (from -0.15 to 0.15) and observed the total distance that the eigenvectors when projected covered in the landing plane. Tuning refers to the relation between the outcome and changes in the coordination function. For this, we correlated the change within each component with distance of throw. Distance of throw was calculated from the release parameters of each trial. The change was calculated as the difference between the trial t+1 and trial t. Finally, angle of the projection in the landing plane was measured by the angle that the projection of the eigenvector made with the landing plane – taking as 0 degrees the antero-posterior axis.

Coordination Function and Groups. The expectation of different practice schedules is that these would lead to different learning outcomes. Thus, one would expect that individuals within a given practice schedule would become more alike than when compared to individuals from other groups of practice in the end of practice. To analyze this, we performed cluster analyses in the coordination function measures (sensitivity, tuning and angle) of the pre- and post-test and observed whether the resultant cluster had any association with the groups of practice. This was done for all three groups and for the two variable groups (without the constant group). The latter was because it is possible that the constant group was not constrained to a given learning outcome but the two groups (because of variable practice) would be.

To identify the best number of cluster to describe the data, we evaluated the best number of clusters by evaluating solutions that ranged from one to ten clusters using a hierarchical cluster analysis. The evaluation was performed using the evalclusters code from matlab using the Calinski-Harabasz criterion. Also, we also performed clusters imposing as the number of clusters three (when the three groups were considered) or two (when only the variable groups were considered). This was done with the k-means cluster analysis (using kmeans code from matlab) with 10 replications (different initial cluster centroid positions).

Transfer Analyses. To compare groups and coordination function measures in terms of their explanatory power, we performed the LME functions using either the coordination function measures or the groups to observe which would explain the transfer results more properly. As dependent variables, we used either the performance in each condition (AT and DT) and the performance per target. In both cases, we used the backward method to observe whether the results would be dependent on the group or coordination function measures. The backward method was based on the BIC.

Results

Performance

Figure 9 shows the performance for each group per day during practice and the performance in the pre-, post- and after-tests. Table 5 presents the results from the LME analyses for practice and pre-/post-tests comparison. For practice, the LME showed that performance improved for both days (p = .001) and blocks (p < .001) with a significant variation in how individuals improved per day. The group variable was not found to be necessary for the model. For pre-/post-test comparison, the LME showed that individuals performed the pre-test with an average of 9.25 hits (p < .001) and increased the performance by 5.70 hits (p < .001). Individuals varied in term of their pre-test performance. The group variable was not found to be necessary for the model.

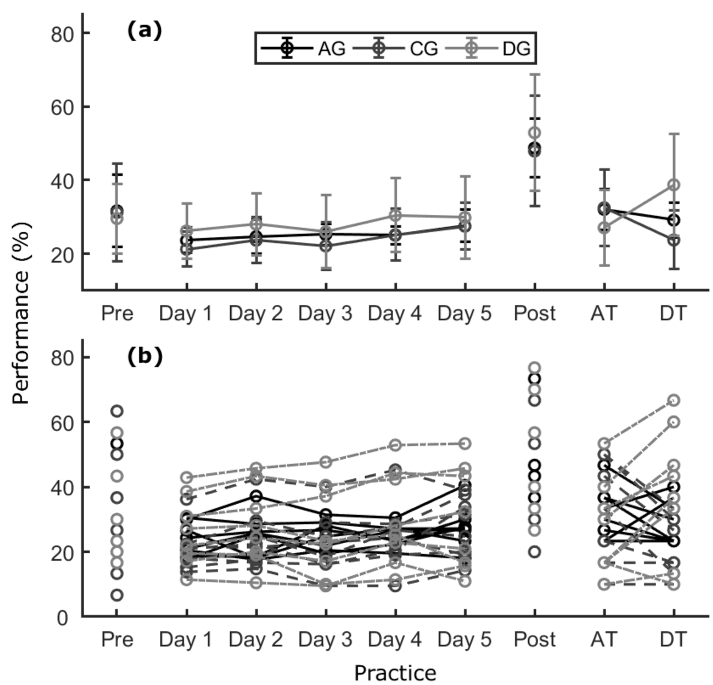

Figure 9. Performance as a function of practice days: (a) Average and 95% confidence interval of group performance; (b) Average performance for each individual;

Table 5. LME for performance over days and blocks in practice and change between pre- to post-test.

	Practice		
p (full)[a] = .624		*p* (intercept)[b] < .001	(R^2 = 0.60)
	Fixed Effects		
	Estimate (± S.E.)	*t*-stat	*p*-value
(Intercept)[c]	5.39 (± 0.53)	10.12	< .001
Day	0.32 (± 0.09)	3.22	.001
Block	0.34 (± 0.04)	8.70	< .001
	Random Effects		
	Estimate	Lower Boundary	Upper Boundary
(Intercept)	2.32	1.69	3.18
Day	0.40	0.27	0.60
Residual	2.28	2.17	2.40
	Pre-/Post-tests		
p (full)[a] = .949		*p* (intercept)[b] < .001	(R^2 = 0.42)
	Fixed Effects		
	Estimate (± S.E.)	*t*-stat	*p*-value
(Intercept)[c]	9.25 (± 1.01)	9.08	< .001
Δ	5.70 (± 1.23)	4.61	< .001
	Random Effects		
	Estimate	Lower	Upper
(Intercept)	2.54	1.14	5.62
Residual	4.28	3.23	5.69

[a] Comparison with the full model. A non-significant *p*-value indicates that the final model (with fewer variables) explains similarly the data as the full model; [b] Comparison with the model including only the intercept. A significant *p*-value indicates that the final model explains better the data as the full model; [c] The intercept relates to the first day/first block performance and the pre-test performance, respectively; S.E.: Standard Error.

Transfer per Groups

Figure 10 shows the results per target. Table 6 presents the results from the LME analysis considering transfer per condition and per target. The model including the groups showed a strong fitting for transfer performance per condition and a moderate fitting per target. The model per condition shows that those who had a better performance in the post-test had better results at both conditions and that the DG group was better at the DT condition – as it would be expected. Note, however, that no differences were found in AT. In the model per target, only differences in distance were found but no differentiation per target in terms of groups. The only difference between groups was that individuals from DG showed more influence of the post-test performance on transfer.

Table 6. LME for performance during transfer tests.

Per Condition			
p (full)[a] = .111	BIC: 258.71	*p* (intercept)[b] < .001	(R^2 = 0.72)
Fixed Effects			
	Estimate (± S.E.)	*t*-stat	*p*-value
(Intercept)[c]	8.66 (± 0.56)	15.30	< .001
Post-test	0.42 (± 0.098)	4.30	< .001
DG*Condition	2.99 (± 1.02)	2.91	.005
Random Effects			
(Intercept)	2.09	Residual	2.29
Per Target			
p (full)[a] = .055	BIC: -83.32	*p* (intercept)[b] < .001	(R^2 = 0.33)
Fixed Effects			
	Estimate[d] (± S.E.)	*t*-stat	*p*-value
(Intercept)[e]	0.29 (± 0.012)	23.35	< .001
Distance	-0.099 (± 0.012)	8.20	< .001
Post-test*DG	0.021 (± 0.003)	6.25	< .001
Random Effects			
(Intercept)	N.S.	Residual	0.18

[a] Comparison with the full model. A non-significant *p*-value indicates that the final model (with fewer variables) explains similarly the data as the full model; [b] Comparison with the model including only the intercept. A significant *p*-value indicates that the final model explains better the than when compared to the simplest possible model; [c] The intercept relates to performance of the Angle Transfer condition for the Constant Group (CG) with all independent variables at their average value; [d] The dependent measure used in this analysis was the percentage of hits (there were different number of attempts per target); [e] The intercept relates to performance of the center target for the Constant Group (CG) with all other independent variables at their average value; S.E.: Standard Error; N.S. not significant.

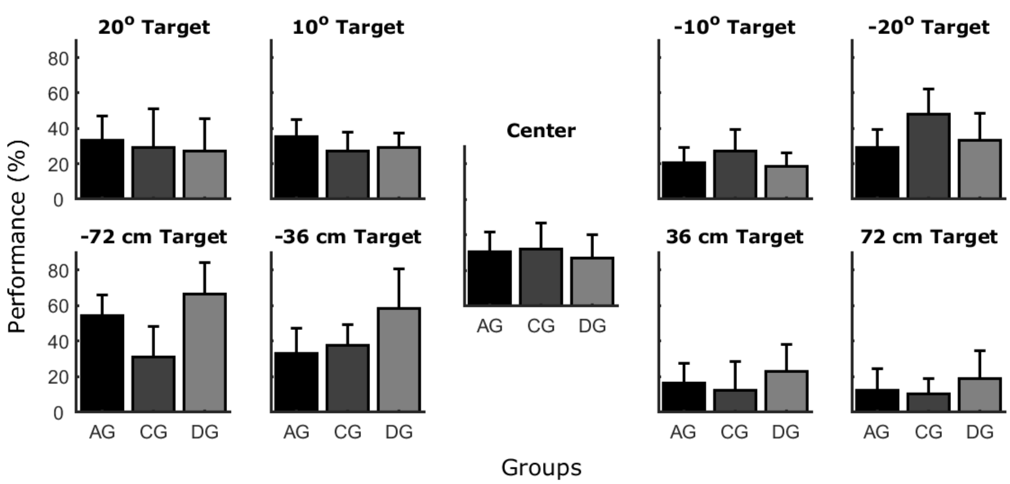

Figure 10. Group average (± 95% C.I.) performance per target combining DT and AT tests

Coordination Function and Practice Schedule Groups

The first point advocated here was that is possible that different practice schedules would not lead to different coordination functions necessarily. Using the projected eigenvectors from the PCA analyses as a measure of the coordination function (see the Introduction section), we analyzed whether the groups differentiated the individuals in terms of the measures of coordination function.

Figure 11 shows the groups in terms of the coordination function measures. As can be observed, the groups do not differentiate between them when coordination functions are considered. The cluster analyses showed that when including only the variables expressing the tuning, sensitivity and angle of projection, there would be a high number of clusters for post-test (= 10) when the linkage method was used. When we selected the number of groups (three) for the *k*-means method, the results were that, when considering three groups, neither the pre-test ($\chi^2[4]$ = 7.91; *p* = .094) nor the post-test ($\chi^2[4]$ = 0.93; *p* = .918) showed association between groups and clusters. Considering two groups (differentiating AG and DG), again, neither the pre-test ($\chi^2[1]$ = 0.25; *p* = .614) nor the post-test ($\chi^2[1]$ = 0.29; *p* = .589) showed an association between groups and clusters.

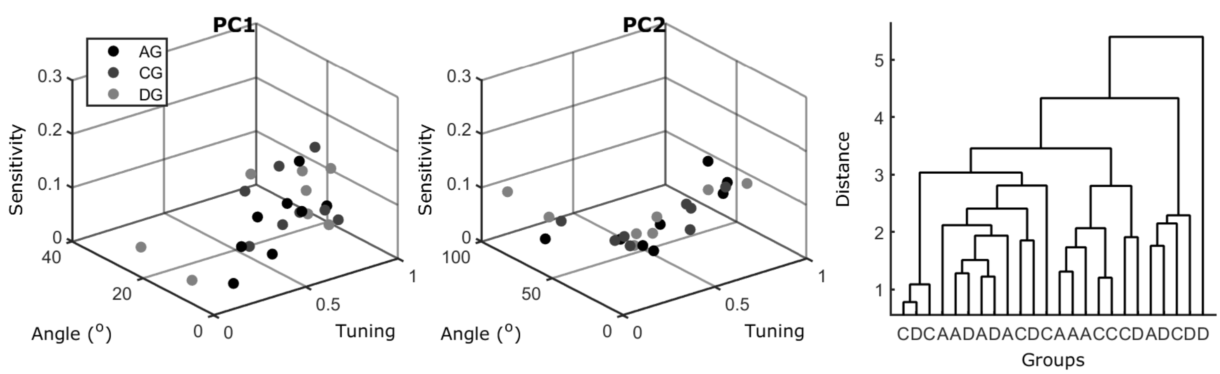

Figure 11. Distribution of individuals in sensitivity, projected angle and tuning of PC1 (left) and 2 (middle) and the dendrogram based on the similarity of individuals on these measures.

We decided to add also the explained variance of the first PC for velocity, explained variance of the first PC for position and their correlation. This was done to provide a full picture of the coordination function and to observe whether that would result in a more reasonable number of clusters. Using the linkage method, the number of clusters was still high for post-test (= 10). When we selected the number of groups (three) for the *k*-means method, neither the pre-test ($\chi^2[4] = 6.85$; $p = .114$) nor the post-test ($\chi^2[4] = 2.38$; $p = .665$) showed association between groups and clusters. Considering two groups (AG and DG), neither the pre-test ($\chi^2[1] = 0.25$; $p = .614$) nor the post-test ($\chi^2[1] = 0.29$; $p = .589$) showed association between groups and clusters.

We also performed tests in terms of all coordination function measures between groups and comparing first and second PCs. Table 7 shows the results of the coordination function for each group. For tuning, all groups had similar values ($p = .556$) with the first component being more correlated with the change in distance ($r = 0.48$) than the second component ($r = 0.31$) ($F(1,21) = 4.55$, $p = .045$). For angle of the projected eigenvector, using Watson-Williams tests, we found no differences between groups ($p > .508$) but a significant difference (using Wilcoxon Signed Rank) between components with the first PC more in line to the antero-posterior variation (median angle: 5.44) when compared to the second PC (median angle = 9.68) ($Z = 2.71$, $p = .007$). The sensitivity of the projected eigenvector did not differ between groups ($p = .429$) and components ($p = .990$). The explained variance of the first component did not differ between groups ($p = .126$).

Table 7. Coordination function characteristics (derived from the first and second components of the PCA analysis)

Part.	Group	R1[a]	R2[a]	A1[b] (º)	A2[b] (º)	L1	L2	E1 (%)
1	AG	0.25	0.62	4.95	9.78	0.08	0.15	57.55
2	AG	0.34	0.54	1.40	9.59	0.07	0.22	53.91
3	AG	0.31	0.18	3.70	1.37	0.14	0.10	52.87
4	AG	0.20	0.61	4.81	6.28	0.02	0.17	58.00
5	AG	0.62	0.11	8.24	69.74	0.19	0.03	64.51
6	AG	0.72	0.07	5.35	10.18	0.11	0.12	54.04
7	AG	0.54	0.11	3.41	0.29	0.12	0.12	68.44
8	AG	0.63	0.29	12.20	11.28	0.10	0.12	65.96
1	CG	0.70	0.03	1.48	3.38	0.10	0.14	87.98
2	CG	0.46	0.40	14.93	4.91	0.13	0.11	46.19
3	CG	0.58	0.45	5.92	10.97	0.11	0.14	64.76
4	CG	0.46	0.15	5.54	14.60	0.21	0.09	67.63
5	CG	0.47	0.59	4.80	4.49	0.10	0.17	61.38
6	CG	0.64	0.01	2.14	6.97	0.12	0.13	77.61
7	CG	0.36	0.42	8.41	9.44	0.06	0.15	84.42
8	CG	0.67	0.35	6.31	89.53	0.22	0.02	74.94
1	DG	0.48	0.28	14.47	89.04	0.16	0.03	59.58
2	DG	0.05	0.57	8.51	13.48	0.03	0.16	77.80
3	DG	0.64	0.15	0.61	9.52	0.10	0.12	85.72
4	DG	0.61	0.25	5.56	11.86	0.15	0.11	53.17
5	DG	0.07	0.74	24.37	8.64	0.04	0.16	69.83
6	DG	0.59	0.22	3.98	5.27	0.11	0.15	60.02
7	DG	0.66	0.29	1.49	29.16	0.20	0.06	58.69
8	DG	0.65	0.06	9.08	89.27	0.17	0.10	71.48

[a] These are the absolute values for correlation; [b] These are the values confined within 0 and 90 degrees.

These analyses support our position that the practice schedule per group does not imply in different coordination functions learned. Nevertheless, the groups did show explanatory power on the results of transfer. The next step is to analyze whether the coordination function measures can explain more (and better) the results of transfer.

Coordination Function and Transfer

We performed the LME analyses to investigate whether the coordination function characteristics could predict the transfer results. Before running the analyses, we found that sensitivity of the second component was strongly correlated to both sensitivity of the first component (r = -0.83) and the angle of the second component (r = -0.73); we took this variable from the full model. Also, tuning of the first component was strongly correlated with the tuning of the second component (*r* = -0.76); we took the tuning of the first component out of the full model. The choice between variables to be taken from the model was made to maintain an equal number of variables from each component. Table 8 shows the results and Figures 12 and 13 show the fitted results for each equation.

For transfer in terms of conditions, the coordination function showed better fitting values with similar BIC when compared to the group model. This indicates that the ratio of number of variables and explanatory power is similar between both but the explanatory power of the coordination function characteristics is higher. In terms of the model itself, both characteristics of PC1 and PC2 revealed a relation to performance. Participants who showed a decreased sensitivity in the first PC had better results in both transfer conditions – with this effect being affected by the angle of the projection. In terms of the second PC, in AT, those who showed higher tuning values showed worse results for lower angle values. For DT, those who showed lower values of tuning, with higher values of angle, showed better results. Finally, the performance in the post-test acted as a moderator of these effects (not shown in the Figure).

These results need to be interpreted considering that both components were somewhat related to each other. Thus, although the results of tuning of the second component seems at odds to the definition of tuning (i.e., it is related to correction), the results might imply that the tuning of the first component might be related to better results. So, those who could modify the most variable component (first component) to correct distance changes in the outcome (tuning), showed better results in transfer for both AT and DT, with higher influence in DT. The influence of sensitivity of the first component is in line to what we expected.

Table 8. LME for performance during transfer tests in terms of the measures of coordination function.

Per Condition			
p (full)[a] = .390	BIC: 258.78	p (intercept)[b] < .001	(R^2 = 0.91)
Fixed Effects			
	Estimate (± S.E.)	t-stat	p-value
(Intercept)[c]	9.97 (± 0.47)	20.79	< .001
A1	-0.38 (± 0.12)	3.15	.003
A2	0.13 (± 0.026)	5.06	< .001
L1	-66.81 (± 12.14)	5.49	< .001
R2*A2	0.43 (± 0.11)	3.72	< .001
A1*L1	-13.20 (± 3.14)	4.19	< .001
R2*Condition	-16.08 (± 3.71)	4.33	< .001
A2*Condition	0.040 (± 0.017)	2.27	.029
A1*L1*Post-test	0.94 (± 0.37)	2.52	.016
R2*A2*Condition	1.14 (± 0.25)	4.43	< .001
R2*Post-test *Condition	-5.98 (± 0.95)	6.28	< .001
L1*Post-test *Condition	-17.99 (± 2.23)	8.04	< .001
R2*A2*Post-test *Condition	-0.30 (± 0.056)	5.30	< .001
Random Effects			
(Intercept)	1.64	Residual	1.40
Per Target			
p (full)[a] = .154	BIC: -87.97	p (intercept)[b] < .001	(R^2 = 0.40)
Fixed Effects			
	Estimate[d] (± S.E.)	t-stat	p-value
(Intercept)[e]	0.30 (± 0.012)	23.91	< .001
A2	0.004 (± 0.0006)	6.38	< .001
Distance	-0.099 (± 0.011)	8.71	< .001
R2*A2	0.016 (± 0.003)	4.91	< .001
A1*L1	-0.284 (± 0.060)	4.68	< .001
A1*Post-test	-0.001 (± 0.0002)	4.80	< .001
L1*Post-test	-0.14 (± 0.020)	6.93	< .001
Random Effects			
	Estimate	Lower	Upper
(Intercept)	N.S.	Residual	0.17

[a] Comparison with the full model. A non-significant p-value indicates that the final model (with fewer variables) explains similarly the data as the full model; [b] Comparison with the model including only the intercept. A significant p-value indicates that the final model explains better the data than when compared to the simplest possible model; [c] The intercept relates to performance of the Angle Transfer condition for the Constant Group (CG) with all independent variables at their average value; [d] The dependent measure used in this analysis was the percentage of hits (there were different number of attempts per target); [e] The intercept relates to performance of the center target for the Constant Group (CG) with all other independent variables at their average value; S.E.: Standard Error; N.S. not significant.

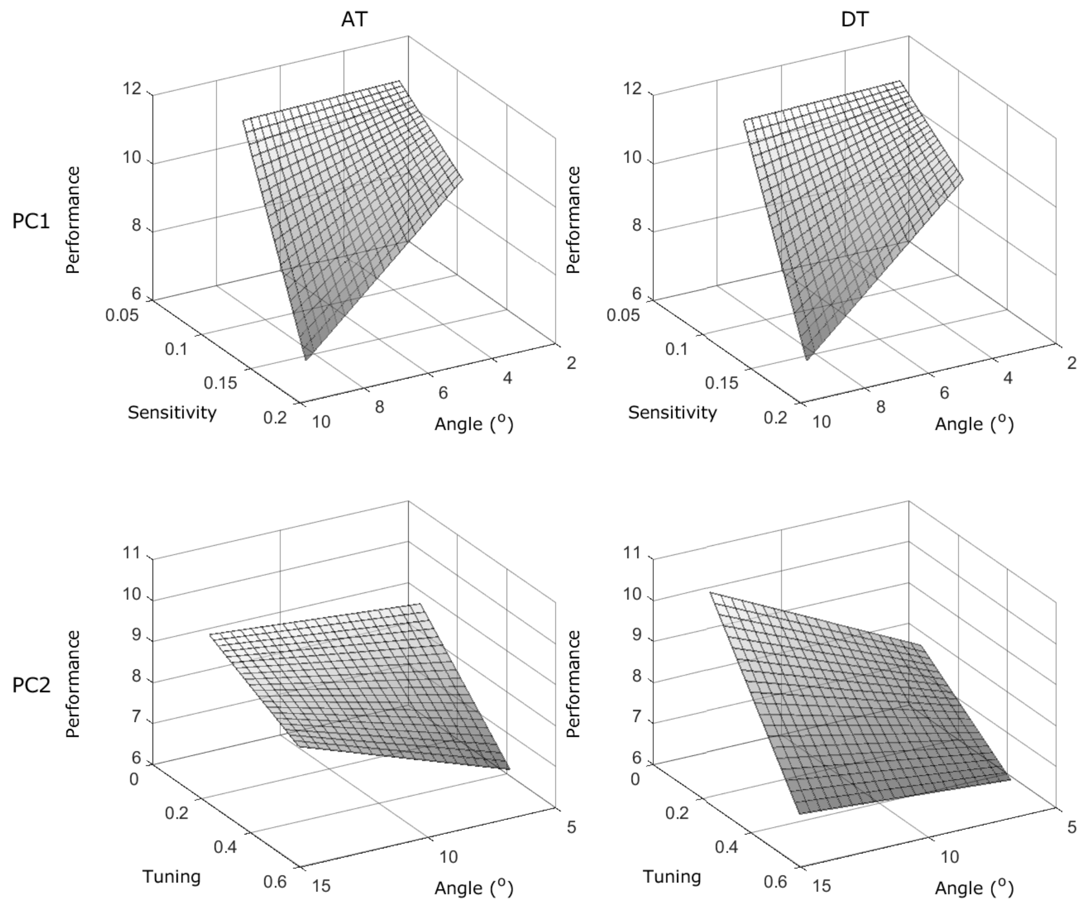

Figure 12. The relation between performance in AT and DT with the results of the fitted regression with tuning and projected angle variables of the first and second PCs.

For transfer in terms of each target, as for the group modeling, the fitting values decreased to a moderate value. Nevertheless, as for the model of conditions, the coordination function showed higher explanatory power (i.e., higher R^2) and, here, a better ratio between variables and explanatory power (i.e., lower BIC). This result, together with the results of the previous model, supports our expectation that the coordination function would be able to explain the transfer results better than the groups.

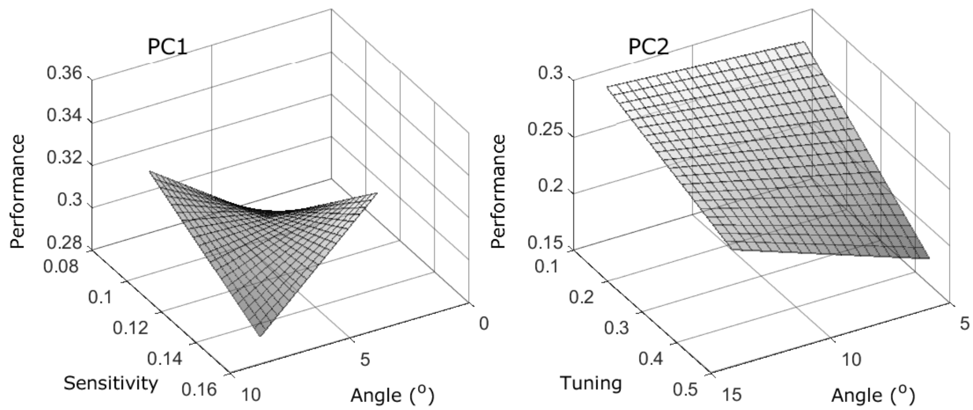

Figure 13. The general relation between performance in all targets with the results of the fitted regression with tuning and projected angle variables of the first and second PCs.

The coordination function characteristics did not show any interaction with distance or angle of the target. The distance as expected, decreased the performance as it increased. In terms of the coordination function, we see similar patterns as the model per condition: those who showed lower tuning for the second component showed better results – which again might refer to a good tuning of the first component. Those who showed lower sensitivity of the first component with higher values of angles showed better results. The opposite, lower angles with high sensitivity, was also true – which is surprising. Finally, those who performed better in the post-test showed even higher influences of the low sensitivity and angle of the first component.

Discussion

The present study tested whether different practice conditions in terms of variability of practice would result in individuals performing and learning solutions that are more alike within a given practice condition when compared to different practice conditions. This is a strong assumption underlying the variability of practice hypothesis (e.g., Schmidt, 1975; Braun et al., 2010) that has not been challenged so far. In following Pacheco and Newell (2017b), we posited that individuals start, change and learn differently from each other provided different initial conditions (i.e., intrinsic dynamics, Kelso, 1995; preferences, see King et al., 2012), individual search-strategies (Pacheco et al., 2017; Pacheco & Newell, 2017a; Withagen & Michaels, 2005), and availability of redundant solutions in the task. Thus, there was possibility for individuals of the same group to diverge in terms of the coordination function learned even when the task condition was similar (e.g., Pacheco & Newell, 2015). Our results support the position in showing that the performance acquired in the tests after practice were better explained by the coordination function characteristics (based on the individual) rather than by the group variables.

Individuality in Learning

From a dynamical systems approach to motor learning, the learning situation should be investigated considering the initial tendencies of the individual, the path and laws of change (search-strategies) and the required goal (cf. Beek & van Santvoord, 1992). Pacheco and Newell (2017b), taking these aspects into account, suggested that provided evidence on different initial tendencies in the task (Kostrubiec & Zanone, 2002; Kostrubiec et al., 2012; Zanone & Kelso, 1992, 1994), differential motion through the perceptual-motor workspace (Michaels et al., 2017; Pacheco et al., 2017; Withagen & Michaels, 2005) and the possibility of task redundancy, individuals had no constraint to converge to the same solution and, thus, to understand transfer, one should assess the learned solution of each individual to predict transfer rather than the task condition itself. This solution is representative of what Newell (1985) referred as the coordination function, and argued by these authors as a special-purpose device that is specific to the task, individual and generalizable. Their results, together with previous work on transfer differences provided individual paths in learning (Pacheco & Newell, 2015), supported such a notion.

The question that we raised here was whether different practice conditions in terms of variability of practice would elicit differences between groups that would surpass the differences between individuals within a single practice condition – as it is assumed in the literature. Although we found significant differences between groups in the DT test, the explanatory power of the group variables was much smaller than when the coordination function measures were considered. As well, the groups did not show differences in terms of the coordination function measures when clustered or compared. If these measures, related to the main axes of variance, are indeed representative of the coordination function (as some of the theories currently assume, see Balasubramaniam & Turvey, 2004; Haken, 1996; Newell & Vaillancourt, 2001), then, the variable practice does not *always* lead to individuals being channeled to a given pattern that would differentiate them from other practice conditions.

Most of the literature that addresses variability of practice over emphasize elaborative, constructive, cumulative, etc. processes in learning (see, for instance, Magill & Hall, 1990). That is, a given representation, schema or other structure is strengthened by variations leading to differential results between different practice conditions and schedules. Nevertheless, one should note that despite the claims posited by these theories, most of reviews on the topic show many empirical studies that do not confirm these expectations (e.g., Brady, 1998; Schmidt & Young, 1987; Van Rossum, 1990). For instance, our results add to the problem in showing that variable practice in angle did not result in better results for this group in the same condition and that random practice did not elicit differences between groups during the acquisition.

Our position deviates from these over representative theories in highlighting the search processes that occur in learning that lead to individual solutions (Newell et al., 1989; Newell & McDonald, 1992; Newell et al., 1991; Pacheco & Newell, 2015). Current studies have shown that individuals deviate from each other in terms of their reliance on perceptual variables (Withagen & Michaels, 2005; Withagen & van Wermeskerken, 2009), their motion through movement possibilities (Pacheco & Newell, 2017a), and how they act in terms of the information provided (Pacheco et al., 2017). Some of these studies show that these indeed result in different end-points of the perceptual-motor workspace even when the conditions are highly similar (e.g., Pacheco & Newell, 2015). The current results add to these studies in highlighting individual differences in learning and its importance to understand learning itself.

Coordination Functions Measures in Learning and Transfer

Pacheco and Newell (2017b) observed that measures of the coordination function predicted the results in the transfer tests. Although the transfer definition cannot be applied here[17], we provided that the coordination function evaluated at the post-test predicted the performance of the individuals in the after tests that included variations in both distance and angle of the target. This supports the point that the used measures (sensitivity, tuning and angle of the projection) indeed represent features of the learned solution and its generalization possibilities.

Nevertheless, the measures that resulted in the regression model here were different than Pacheco and Newell (2017b). There, the transfer tests modified the tolerance for variation in the outcome in either the antero-posterior or medio-lateral directions of the landing plane. The variance accounted for the first component, the sensitivity and the angle of projection of the first and second components were related to the results in transfer. The relation was that those individuals who either relied mainly on the first component and showed smaller sensitivity of the second component or relied on the second component with large tuning showed better results when the condition did not tolerate variation in the antero-posterior direction of the landing plane (the more challenging condition). Here, when considering both results (per condition and per target),

[17] The DG group already performed the DT condition during practice and the AG group already performed the AT condition during practice.

we found that high tuning and lower sensitivity of the first component predicted the results. In both experiments, the angle of projection interfered in the performance on the tests.

These differences are expected to some degree provided the differences between the task conditions and the groups involved. In Pacheco and Newell (2017b), there was a single group performing a constant practice with a larger target. Here, we had three different groups under different practice conditions performing with smaller targets. In both studies, the first component showed lower sensitivity than the second and predicted better results but the tuning, that was, for most individuals in Pacheco and Newell (2017b), based on the second component, was much more varied in the present study in terms of importance – with more individuals using the first component to correct for distance changes. These differences probably changed what was to be expected in the relation of the coordination function and the after tests.

The correlation between measures were also different from Pacheco and Newell (2017b). There, tuning of the first component was highly correlated to several variables of the coordination function and the sensitivity and tuning of the second component were also correlated. Here, we found sensitivity of the second component was highly correlated to sensitivity of the first component and angle of the second component, and the tunings of both components were also correlated. Thus, the structure of variation of these characteristics also changed between both studies.

Although a specific explanation for each of these differences would be highly speculative, they are necessary. The current study is limited to demonstrate that individual characteristics could not be predicted by practice conditions performed in different groups and that these characteristics must be considered to understand learning and transfer. It supports the view that individuals learn a coordination function that is specific to the task, individual and generalizable depending on the coordination function characteristics. However, a development of the theoretical basis of these individual characteristics of the learned solution is warranted.

Especial Skill, Variability of Practice and Task Constraints

Ranganathan and Newell (2013) argued that constant and variable practice would elicit learning of different solutions in the perceptual-motor workspace. While variable practice would result in individuals learning to control a single coordination function that generalizes to the dimension on which the practice varied, constant practice would result in exploiting the redundant space that the task affords. The long practice on the same condition could even result in the observed effect of Especial Skill (roughly, a disproportionate better performance in a given situation because of massive practice) (cf. Keetch, Lee, & Schmidt, 2008; Keetch, Schmidt, Lee, & Young, 2005).

Such a position did not hold here. First, as observed in Table 3, most individuals showed main variation in the movement patterns (coordination function) that, when projected to the landing plane, was along the antero-posterior dimension – irrespective of their group. This shows that the dimension that individuals allowed variation to occur was independent of the variability induced by the experimenter. Theoretically, it could be that the coordination function is not even the same for all variations elicited in practice. In terms of the dynamical systems approach, in some cases the coordination function might lose stability when the dimension of variation achieves a critical value and a new coordination pattern will be observed for such situations (see Kelso, 2009). Second, despite the large number of trials (1050) during practice, the constant group did not develop a superior performance at the center target. This is observed in the results of transfer and Figure 3. Note that the amount of practice provided here was more than provided by Breslin, Hodges, Steenson, and Williams (2012) that elicited the effect to appear in basketball shooting (300 trials).

The possibility is that, as argued earlier, the task itself is not constraining enough to result in the effects observed in other studies. That is, one should clearly consider the possibilities for exploration of the task space that each individual can perform. In the case of the Especial Skill, although novices do not perform with the proficiency and movement pattern consistency that experts show, the movement pattern of the sport is known by many and might have constrained the practice of the basketball shooting to a single coordination pattern. This probably did not occur in our experiment. Individuals could explore different movement patterns over time provided they had no external influence on the movement pattern choice. For variable practice, Braun et al. (2009) showed the effect of varying a given dimension in directing behavior to explore this dimension preferentially. Nevertheless, the effects were observed in reaching tasks in which it is questionable how much redundancy could be exploited in the outcome to result in divergence between individuals.

Thus, as occurred in the comparison between the current experiment and the results of Pacheco and Newell (2017b), the task constraints might elicit important differences that must be considered before stating general principles. This adds to our considerations on the individuals and reinforces the position advocated in the dynamical systems approach to motor behavior that behavior is an emergent property from organismic, task and environmental constraints (Newell, 1986).

CHAPTER 5

GENERAL DISCUSSION

The goal of this dissertation was to propose and investigate a hypothesis on what is learned with practice. We followed the general framework of the dynamical system approach to propose that an individual learns a special-purpose device that is specific to the task, individual and generalizable depending on the properties of the learned device and the new task requirements. We then proposed that one could investigate the properties of the special-purpose device understanding that this is a low-dimension structure that restricts the available degrees of freedom to a functional acting device, namely, a coordination function. This coordination function is functionally tuned to the informational variables present in the task at hand allowing precision in task outcome that can be parameterized to achieve new task goals.

From this, I performed two experiments using transfer paradigms to test whether, as hypothesized, the properties of the coordination function would predict how individuals would adapt to new situations. The two experiments provided qualitatively similar results in showing the explanatory power of the coordination function properties to predict performance in new situations. The findings supported the hypothesis that the characteristics of the learned coordination function of each individual are representative of their transfer possibilities. Quantitatively, the experimental results differed indicating the influence of task constraints on learning and transfer.

In the next few sections, I discuss the theoretical importance of the present findings with an outlook of the necessary steps for further development of the view.

Unification of the Dynamical Systems Approach

Special-Purpose Device Hypothesis as a Consequence

The dynamical systems approach can be said to have emerged as a reaction to the centralist point of view of motor behavior by integration of lessons written by James Gibson (1966; 1986) on ecological psychology and Nikolai Bernstein (1967) on neurophysiology and motor behavior. By understanding the organism as an open system far from equilibrium, non-linear dynamics was the framework that developed the approach in subsequent years (see Kugler et al., 1980 and Haken et al., 1985).

The general position promoted in DSA allowed many paradigms and specific concerns to emerge. Beek and van Santvoord (1992) identified three different approaches to learning that were based on DSA and, as I highlighted in Chapter 2, one could even identify a fourth approach (i.e., synergetic, search-strategies, Beek's approach, and intentional dynamics). Three years later, Michaels and Beek (1995) identified three different general sub-approaches in DSA that had their own experimental paradigms, hypotheses and guidelines (i.e., direct perception, kinetic theory, and pattern dynamics). Today, one could clearly expand those lists including direct learning (Jacobs & Michaels, 2007), ecological dynamics (e.g., Araújo, Davids, & Hristovski, 2006), dynamic field theory (Schöner et al., 2016) and others. There are still other approaches that are clearly influenced by Bernstein' ideas but are not exactly in line to the initial considerations of Kugler et al. (1980) or Turvey (1977), such as the equilibrium-point hypothesis (Feldman, 1986), and synergies (Latash et al., 2002; Santello et al., 2016), etc.

The special-purpose device presented here differs from all these positions advocated in DSA by not being something *different* from what was presented before in other sub-approaches. The special-purpose device is a *consequence* that should be observed in learning when all these approaches are considered as one. Specifically, the SPD considers several findings from these different approaches. The synergetic/coordination dynamics approach (Haken et al., 1985; Kelso, 1995) in learning (Zanone & Kelso, 1992, 1994, 1997) provides the influence of the intrinsic dynamics and bifurcations (annihilation/creation of attractors). The early ideas (Kugler et al., 1980, 1982; Turvey, 1977) and current expansions (e.g., Warren, 2006) provide the requirements of low-dimensional spaces and tuning to informational variables in achieving a functional organization for the task at hand (also Bingham, 1988; Fowler & Turvey, 1978). The early (Newell et al., 1989; Newell & McDonald, 1992; Newell et al., 1991) and current experiments on search-strategies approach (Pacheco et al., 2017; Pacheco & Newell, 2017a), and direct learning (Jacobs & Michaels, 2007; Michaels et al., 2017) provide that learning is about a search process, rather than accumulating experiences, which can be individual depending on how individual pick up a given informational variable and move in terms of it. Finally, in considering the current findings on individuals exploiting task redundancy (Sternad et al., 2014) or body degeneracy (see Edelman & Gally, 2001), the SPD arises as a natural consequence.

The fact that the current dissertation provided supporting results to the individual nature of learning supports the SPD hypothesis and corroborates with the body of work cited above. The fact that the properties selected to represent the learning of each individual resulted in robust explanations of the data shows that the theoretical background used to sustain the SPD hypothesis is sufficiently robust to hold empirically when extended into a new hypothesis (as the SPD). But mainly, the current dissertation demonstrates the usefulness of bringing the DSA into a unified framework.

Integration in Skill Acquisition

A missing step in the unification of DSA and, a necessary development that should be taken for the current proposition, is the understanding of the learning process. Although there is a clear description of *parts* of learning on DSA, this is not sufficient to understand their interactions. For instance, one can identify some interesting principles that relate initial and final status of the intrinsic dynamics (cf. Kostrubiec et al., 2012) when following the synergetic approach but hardly one understands how a learner challenges the initial tendencies of the system and stabilize new attractors. This probably can be approached if advances in search-strategies (Newell et al., 1989), direct learning (Jacobs & Michaels, 2007) and intentional dynamics (Shaw & Alley, 1985) are implemented. Nevertheless, none of these alone could integrate all the findings into a single framework or theory of learning.

In considering adaptation, learning and development as processes that obey similar principles in different time-scales (Newell, 1991), other researchers under DSA already highlighted the requirement for unity. Specifically, when reviewing the eclectic area of motor learning, Karl M. Newell stated that "there is no prevailing theoretical view of motor skill acquisition; indeed, there has not been one since Hull's theory fell from favor during the 1950s" (Newell, 1991, p. 215). Newell and McDonald (1994) provided some general guidelines and principles by invoking the search-strategies approach and its relation to other constructs under DSA – in a similar argument as advocated here. However, for some reason, a dynamical systems account of practice is still lacking.

Theoretical Advances From and For a Special-Purpose Device Hypothesis

Coordination Function: Specifics

In this dissertation, I proposed that individuals learn a SPD that is specific to the task at hand and individual provided the redundancy afforded by the task and generalizable depending on the properties of the SPD and the transfer test (or new situation). The experiments of the dissertation provided empirical results supporting the claim. The individuality and the consequent individual aspect of generalizability of the SPD were the parts of the definition emphasized in our results (further discussed in the next sections). Nevertheless, there is more to the SPD that must be understood. Here I consider the "specific to the task" part of the definition.

In the dissertation, I followed the ideas of Bingham (1988) and Fowler and Turvey (1978) who followed the position that the human movement system does not work in a *general* mechanism that applies to all conditions and contexts, but learns and find solutions that are functional and *specific* to the task at hand. The idea can be translated as the human movement system being able to become a specialized tool in acting when necessary. That is, if necessary, the arm can act like a mass-spring system that maintains oscillation around a point modulating "stiffness" and "damping" if necessary.

Two points result from this approach. The first is that learning is about picking up informational variables and modulating movement in a way that is specific to the task at hand – the task is a central constraint in how the system is organized. The second is that in invoking general principles of change (for learning, development, etc.), the variations between tasks must be considered to not promote a task dependent principle that ends up being non-generalizable to change as a whole.

There are two more considerations that must be considered when discussing the characteristics of the coordination function. Abbs et al. (1984) reviewed several papers on speech gestures revealing features that are currently accepted as a cornerstone for coordination of many-degrees-of-freedom actions. By employing perturbation paradigms and observing many trials of the same movements, they demonstrated that coordinated movements of the body showed a strong reliance on task constraints. For instance, when individual tries to pronounce "apa" and the jaw is suddenly perturbed avoiding motion, the lower and upper lip compensate the perturbation by modifying their movements but maintaining the pronunciation similar (see also, Kelso et al., 1984). This is not observed when the individual is pronouncing "aza" or "afa" – which results in compensation of the tongue or no compensation, respectively. These adjustments after the perturbations occurred according to the time necessary to make the pronunciation correct – sometimes being faster than the established reaction times. Thus, the coordination of a given task was highly functional to the task at hand – being robust against several different perturbations.

Another feature is the correlated activity in different joints or muscles over repeated attempts that can occur in tasks while still realizing the task outcome (Arutyunyan et al., 1969). This is currently called as a task-synergy (Latash, 2010), covariation (Müller & Sternad, 2004), etc. This phenomenon reveals that there is not a single muscle activation or joint configuration that the central nervous system tries to maintain when performing a given task. Rather, if the task outcome is maintained, the underlying levels of analysis can vary within certain parameter ranges (see, also, Todorov & Jordan, 2002).

These two characteristics, namely robustness against perturbations and covariation, highlight main features of the coordination function that is acquired with practice. They reflect the high reliance on task constraints of the SPD. Nevertheless, how such features are acquired is not well understood. How do the contractions in an otherwise independent muscle counteract unexpected perturbations in a second muscle in order to maintain a task goal? Abbs et al. (1984) hold that this is a result of learning – which seems intuitive. However, how does learning result in such a well-organized function? The answer to these questions is, I believe, still unknown and there is no robust theoretical formulation capable to provide a principled guess.

Individual as the Level of Analysis for Behavior

The whole consideration of SPD that diverges from previous literature in learning is the consideration of individuals as the *only* level of analysis to assess learning. Originally, it is assumed that variance between individuals is just *noise* in the sense of confounding factors that are unimportant for the phenomenon at hand. There are two arguments counter to that. The first is based on the point that the individual differences shown here *are* the source of information for the researcher to understand learning. The second is based on mathematical problems that arise when non-ergodic systems are treated as ergodic systems.

The first argument is based on the possibility of divergence during practice – and empirical results supporting such divergence. Specifically, if individuals start differently, search differently and the task affords many solutions, there is no expectation of convergence. I examined the convergence/divergence issue in the discussion of Experiment 1 (Chapter 3) and provided that if one considers all concepts being advocated in motor behavior (tolerance, noise, covariation, see Sternad et al., 2014) there is no necessity for convergence to occur. Also, in following the results of other areas, such as evolutionary dynamics (e.g., Alfaro et al., 2004; Anderson & Patek, 2016; Young et al., 2007), convergence is the exception rather than the rule. If the convergence does not occur, then individuals are learning different solutions even under the same practice condition. If this is the case, to consider the group (that practiced the same condition) as the source of information is to suppress differences into a non-representative measure.

In Chapter 3, I showed that individuals with the same performance at the end of practice performed the task utilizing different movement patterns and showed large differences in the transfer tests. In both experiments these characteristics could predict performance in tests performed after practice. The results support, then, the point in showing that not only the individual differences are there, but also that they are the differences to be observed in understanding learning. The claim is even stronger when, observing Chapter 4 (second experiment), practicing in a given practice condition did not make individuals more alike than when comparing to different practice conditions.

The second argument is provided by Molenaar (2004) in that learning and development are non-ergodic systems and, because of that, inter-individual characteristics cannot be generalized to intra-individual processes. The point is that for inter- and intra-individual dynamics to have similar properties (and thus averaging be a non-problematic procedure), the system must be ergodic (i.e., the process must be stationary and all individuals must obey the same dynamics). In learning, both criteria cannot be met. Problems from averaging can be exemplified by the literature of learning curves (see, Newell, Mayer-Kress, & Liu, 2006). In short, a set of exponential curves from different individuals and different time-scales could lead to an average that is closer to a power-law than the actual exponential.

Why, then, do so many experiments in motor behavior (and learning) showed systematic results analyzing data using groups? Note that, as considered in Chapter 4, it is possible that some practice conditions channel the behavior of different individuals in a way that make them more alike (than when compared to other groups) which leads to results being “explained” by the practice conditions. In Chapter 4 (Experiment 2), this was not the case in that the cluster analyses did not associate with the groups (see Figure 11) but this is possible – a possibility also considered in Chapter 3. Nevertheless, the consistency of the "group-based" results is highly dependent on whether individuals had "time" to converge (considering that each might converge to the same solution with different amount of practice) and whether the task is sufficiently constraining. Even considering such possibility, note that the situation is just a special case of the general claim that individuals are the source of information to understand learning. That is, groups can be used as the source of information *if* individuals are channeled by the group. The lack of results in "complex" tasks (tasks that involve many degrees of freedom) in terms of some of factors studied under the assumption of convergence (cf., Brady, 2008, Wulf & Shea, 2002) point to the possible conclusion that some of these factors are just robust under simplistic task paradigms (but see Pacheco et al., 2017 for an example where divergence occurred in single-aiming tasks).

Generalization and Prediction

A general point advocated in the present dissertation was that individuals would learn different solutions during the task and the performances on a new context would depend on the relation between the new context and the individual learned solution. This solution is a coordination function that can be characterized in terms of its properties. I assumed that properties such as sensitivity, tuning, and main axes of variation (explained variance and angle of the projected eigenvector) of these coordination functions would be *the* properties to explain transfer performance[18]. In both experiments, these parameters showed predictive power on the transfer tests supporting the SPD hypothesis.

[18] One could assess other properties (e.g., stability). I did not consider stability provided that the range of parameter variations in the transfer tests (both Chapter 3 and 4) were within the variations of the original practice. This is not sufficient for stability to be maintained but we preferred to maintain the number of properties to a minimum.

A point to be further discussed (it was briefly discussed in Chapter 4) is the fact that both experiments diverged in terms of correlations of the coordination function between individuals, the roles of each component (e.g., the tuning of the second component was higher in the first experiment but was not in the second), and the predictions (relation between coordination function and transfer performance). It was interpreted that these differences reflected the specificities of each task and coordination function relation to the transfer tests employed. Although I hold on this argument to explain the differences between the results, this cannot explain why the relations are the way they are. That is, for instance, why explained variation of the first component and sensitivity of the second component are the main predictors in the first experiment and no other variables inserted into the model?

As an answer, I do not know. Several factors impede an interpretation that is not highly speculative. The first is that the Experiment 1 (Chapter 3), for instance, although less variable in terms of the role of each component (i.e., the sensitivity was lower for the first component and the tuning was higher for the second component), provided the existence of a single group, the number of participants required a stepwise method in the regression to avoid over-fitting. That is, even if all parameters in that study were to explain the transfer, I had to avoid over-fitting by using the most rigorous criterion in the backward method. Using the BIC, for instance, would make all variables to stay in the model. Thus, methodological limitations might have undermined all possible contributions[19].

A second factor relies on the problem of correlation between measures. Both Experiments 1 and 2 had properties of both components being correlated that provided a double-meaning for

[19] Note that I also chose to not have interactions between the properties of the two components. This choice was based on the idea that these components are independent of each other and the number of independent variables was too high already. It is clearly possible that the interaction of the components' properties could have provided a better solution but this will await a study with many more participants.

some variables. For instance, in Experiment 1, the relation between explained variance in the first component and sensitivity in the second component was reported as referring to both sensitivity *and* tuning of the second component (two correlated variables). Although I provided a reason to believe in the double-meaning in terms of the relation between tuning and the explained variance, it raises questions on whether the researcher is choosing the explanation that fits the theory at the moment. Note, however, that the correlation between properties can occur theoretically in a way that the double-meaning explanation is correct. In the second experiment, the correlation did not provide a double-meaning, but one variable was interpreted as if it was another (sensitivity of the second component was interpreted as tuning of the first component). Nevertheless, in all cases, although one of possible interpretations of the result would be contrary to the interpretation provided, this would not be contrary to the hypothesized relation between coordination function and transfer performance and it would also be harder to justify in light of the literature.

Although I still hold on the results and interpretations provided, a more definitive relation must be hypothesized to provide more robust tests. In the current experiments, I tested whether individual variables related to the learned coordination function would show *a* relation to performance in transfer tests. This does not specify *the* relation that is to be expected. The literature, however, does not point out such a relation specifically neither. For instance, although Sternad and colleagues (Cohen & Sternad, 2009; Müller & Sternad, 2004; Sternad et al., 2014) provide tolerance, noise and covariation as principles that guide learning, they have no predictions in terms of how these relate to transfer. The same limitation holds for other related theories. Thus, a research agenda must be planned to provide more insights on what should be expected in terms of the properties highlighted of the coordination function and their relation to transfer.

Learning as Search

Finally, a necessary development comes from the question raised on some of the sections above and in other Chapters: how does one can understand learning in a way that the properties of the coordination function are predicted? That is, the area requires a new theory of skill acquisition. A theory that encompasses how different perceptual-motor initial tendencies affect search, and how different search-strategies interact with initial tendencies to give rise to the solutions observed. This requires, as advocated above, a change in focus from groups to individuals to understand general principles of change. But mainly, a change from the established way that the problem of learning is being conceptualized.

Motor learning is, indeed, "a set of processes associated with practice or experience leading to relatively permanent changes in the capability for movement" (Schmidt & Lee, 2005; p. 302). The position that must be reconsidered is *what are the processes* that are advocated. The majority of theories assume that learning is an accumulation of experiences enriching a representation that becomes stronger and more powerful (e.g., Adams, 1971, see J. J. Gibson & Gibson, 1955 for a discussion). Although *a* process of change might require continuing modification (something that acts *similarly* to reinforcement as postulated in Shaw & Alley, 1985), learning is *mainly* about **search**. Individuals do not start and maintain the same strategy that is shaped better and better. Individuals distance themselves from their initial state by changing (in a positive feedback sense) to a new never previously performed movement pattern. This requires avoiding previous attempts, not "enriching" them. Although the literature that emphasized dynamical systems made this point clear long time ago (see Kugler et al., 1982 showing that negative feedback systems *cannot* increase complexity), learning is still thought as an enriching-representation process. I strongly support the view that, in seeing motor learning (and motor behavior as a whole) as a "repetition without repetition" process (Bernstein, 1967), we will understand how individuals acquire the special-purpose device.

REFERENCES

Abbs, J. H., Gracco, V. L., & Cole, K. J. (1984). Control of multimovement coordination: Sensorimotor mechanisms in speech motor programming. *Journal of Motor Behavior, 16*(2), 195-231. doi:10.1080/00222895.1984.10735318

Abernethy, B., & Sparrow, W. A. (1992). The rise and fall of dominant paradigms in motor behaviour research. In J. J. Summers (Ed.), *Approaches to the study of motor control and learning* (pp. 3-45). North-Holland: Elsevier Science Publishers.

Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior, 3*(2), 111-149. doi: 10.1080/00222895.1971.10734898

Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychological Bulletin*, *101*(1), 41-74. doi:10.1037/0033-2909.101.1.41

Adolph, K. E. (2005). Learning to learn in the development of action. In J. J. Rieser, J. J. Lockman, & C. A. Nelson (Eds.), *Action as an organizer of learning and development* (Vol. 33, pp. 91-122).

Adolph, K. E., Berger, S. E., & Leo, A. J. (2011). Developmental continuity? Crawling, cruising, and walking. *Developmental Science, 14*(2), 306-318. doi:10.1111/j.1467-7687.2010.00981.x

Adolph, K. E., Eppler, M. A., Marin, L., Weise, I. B., & Clearfield, M. W. (2000). Exploration in the service of prospective control. *Infant Behavior & Development*, *23*, 441-460.

Alfaro, M. E., Bolnick, D. I., & Wainwright, P. C. (2004). Evolutionary dynamics of complex biomechanical systems An example using the four-bar mechanism. *Evolution, 58*(3), 495-503.

Anderson, P. S. L., & Patek, S. N. (2016). Mechanical sensitivity reveals evolutionary dynamics of mechanical systems. *Proceedings of the Royal Society B: Biological Sciences*, *282*, 1-9. doi:10.1098/rspb.2014.3088

Araújo, D., Davids, K., & Hristovski, R. (2006). The ecological dynamics of decision making in sport. *Psychology of Sport and Exercise*, *7*(6), 653-676. doi: 10.1016/j.psychsport.2006.07.002

Arutyunyan, G. A., Gurfinkel, V. S., & Mirskii, M. L. (1969). Organization of movements on execution by man of an exact postural task. *Biofizika*, *14*(6), 1103-1107.

Aune, T. K., Pedersen, A. V., & Ingvaldsen, R. P. (2008). Dominant paradigms in motor behavior research: The motor-action controversy revisited. *Perceptual and Motor Skills, 106*(2), 573-578. doi:10.2466/pms.106.2.573-578

Balasubramaniam, R., & Turvey, M. T. (2004). Coordination modes in the multisegmental dynamics of hula hooping. *Biological Cybernetics*, *90*(3), 176-190. doi:10.1007/s00422-003-0460-4

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychological Bulletin, 128*(4), 612-637. doi:10.1037//0033-2909.128.4.612

Beek, P. J., & van Santvoord, A. M. (1992). Learning the cascade juggle: A dynamical systems analysis. *Journal of Motor Behavior*, *24*(1), 85-94. doi:10.1080/00222895.1992.9941604

Bennett, S., & Davids, K. (1995). The manipulation of vision during the powerlift squat: Exploring the boundaries of the specificity of learning hypothesis. *Research Quarterly for Exercise and Sport, 66*(3), 210-218. doi:10.1080/02701367.1995.10608835

Bennett, S., & Davids, K. (1997). The effect of task constraints on the manipulation of visual information and the implications for the specificity of learning hypothesis. *Human Movement Science*, *16*(4), 379-390. doi:10.1016/S0167-9457(97)00002-X

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. New York: Pergamon Press.

Berthouze, L., & Goldfield, E. C. (2008). Assembly, tuning, and transfer of action systems in infants and robots. *Infant and Child Development, 17*, 25-42. doi:10.1002/icd.542

Bilodeau, E. A., & Bilodeau, I. M. (1961). Motor-Skills Learning. *Annual Reviews of Psychology*, *12*, 281-310. doi:10.1146/annurev.ps.12.020161.001331

Bingham, G. P. (1988). Task-specific devices and the perceptual bottleneck. *Human Movement Science*, *7*(2-4). doi:10.1016/0167-9457(88)90013-9

Bizzi, E. (1980). Central and peripheral mechanisms in motor control. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 131-143). North-Holland, Netherlands: Elsevier.

Brady, F. (1998). A theoretical and empirical review of the contextual interference effect and the learning of motor skills. *Quest, 50*(3), 266-293. doi:10.1080/00336297.1998.10484285

Brady, F. (2008). The contextual interference effect and sport skills. *Perceptual and Motor Skills*, *106*(2), 461-472. doi:10.2466/pms.106.2.461-472

Braun, D. A., Aertsen, A., Wolpert, D. M., & Mehring, C. (2009). Motor task variation induces structural learning. *Current Biology, 19*, 352-357. doi:10.1016/j.cub.2009.01.036

Braun, D. A., Mehring, C., & Wolpert, D. M. (2010). Structure learning in action. *Behavioural Brain Research, 206*(2), 157-165. doi:10.1016/j.bbr.2009.08.031

Breslin, G., Hodges, N. J., Steenson, A., & Williams, A. M. (2012). Constant or variable practice: Recreating the especial skill effect. *Acta Psychologica, 140*(2), 154-157. doi:10.1016/j.actpsy.2012.04.002

Buchanan, J. J., Kelso, J. A. S., DeGuzman, G. C., & Ding, M. (1997). The spontaneous recruitment and suppression of degrees of freedom in rhythmic hand movements. *Human Movement Science, 16*(1), 1-32. doi:10.1016/S0167-9457(96)00040-1

Cohen, R. G., & Sternad, D. (2009). Variability in motor learning: relocating, channeling and reducing noise. *Experimental Brain Research, 193*(1), 69-83. doi:10.1007/s00221-008-1596-1

Connolly, K. J. (1977). The nature of motor skill development. *Journal of Human Movement Studies, 3,* 128-143.

Easton, T. A. (1972). On the normal use of reflexes: The hypothesis that reflexes form the basic language of the motor program permits simple, flexible specifications of voluntary movements and allows fruitful speculation. *American Scientist, 60*(5), 591-599.

Edelman, G. M. (1987). *Neural Darwinism: The theory of neuronal group selection*. New York, NY: Basic Books.

Edelman, G. M., & Gally, J. A. (2001). Degeneracy and complexity in biological systems. *PNAS, 98*(24), 13763-13768. doi: 10.1073/pnas.231499798

Feldman, A. G. (1986). Once more on the equilibrium-point hypothesis (λ model) for motor control. *Journal of Motor Behavior, 18*(1), 17-54. doi: 10.1080/00222895.1986.10735369

Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of human learning*. San Diego, CA: Academic Press.

Fleishman, E. A., & Rich, S. (1963). Role of kinesthetic and spatial-visual abilities in perceptual-motor learning. *Journal of Experimental Psychology*, *66*(1), 6-11. doi:10.1037/h0046677

Fontaine, R. J., Lee, T. D., & Swinnen, S. P. (1997). Learning a new bimanual coordination pattern Reciprocal influences of intrinsic and to-be-learned patterns. *Canadian Journal of Experimental Psychology, 51*(1), 1-9. doi:10.1037/1196-1961.51.1.1

Fowler, C., & Turvey, M. T. (1978). Skill acquisition: An event approach with special reference to searching for the optimum of a function of several variables. In G. Stelmach (Ed.), *Information processing in motor learning and control* (pp. 1-40). New York: Academic Press.

Fukson, O. I., Berkinblit, M. B., & Feldman, A. G. (1980). The spinal frog takes into account the scheme of its body during the wiping reflex. *Science*, *209*(4462), 1261-1263. doi:10.1126/science.7403886

Gagné, R. M., & Foster, H. (1949). Transfer of training from practice on components in a motor skill. *Journal of Experimental Psychology, 39*(1), 47-68. doi:10.1037/h0063050

Gel'fand, I. M., Gurfinkel, V. S., Tsetlin, M. L., & Shik, M. L. (1971). Some problems in the analysis of movements. In I. M. Gel'fand, V. S. Gurfinkel, S. V. Fomin, & M. L. Tsetlin (Eds.), *Models of the structural-functional organization of certain biological systems* (pp. 329-345). Cambridge, MA: MIT Press.

Gel'fand, I. M., & Tsetlin, M. L. (1962). Some methods of control for complex systems. *Russian Mathematical Surveys*, *17*, 95-116. doi:10.1070/RM1962v017n01ABEH001124

Gel'fand, I. M., & Tsetlin, M. L. (1971). Mathematical modeling of mechanisms of the central nervous system. In I. M. Gel'fand, V. S. Gurfinkel, S. V. Fomin, & M. L. Tsetlin (Eds.), *Models of the structural-functional organization of certain biological systems*. Cambridge, MA: MIT Press.

Gentner, D. R. (1987). Timing of skilled motor performance Tests of the proportional duration model. *Psychological Review, 94*(2), 255-176. doi:10.1037/0033-295X.94.2.255

Gibson, E. J. (1940). A systematic application of the concepts of generalization and differentiation to verbal learning. *Psychological Review, 47*(3), 196-229. doi:10.1037/h0060582

Gibson, E. J. (1942). Intra-list generalization as a factor in verbal learning. *Journal of Experimental Psychology, 30*(3), 185-200. doi:10.1037/h0058505

Gibson, E. J. (2000). Perceptual learning in development: Some basic concepts. *Ecologycal Psychology, 12*(4), 295-302.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. New York, NY: Houghton Mifflin.

Gibson, J. J. (1986). *The ecological approach to visual perception*. New York: Taylor & Francis Group.

Gibson, J. J., & Gibson, E. J. (1955). Perceptual learning: Differentiation or enrichment? *Psychological Review, 62*(1), 32-41. doi:10.1037/h0048826

Goldfield, E. C. (1995). *Emergent forms: Origins and early development of human action and perception*. New York, NY: Oxford Press.

Goldfield, E. C., Kay, B. A., & Warren, W. H., Jr. (1993). Infant bouncing: The assembly and tuning of action systems. *Child Development, 64*(4), 1128-1142.

Haken, H. (1996). *Principles of brain functioning: A synergetic approach to brain activity, behavior and cognition*. Berlin, Germany: Springer-Verlag.

Haken, H. (2004). *Synergetics: Introduction and advanced topics*. Berlin, Germany: Springer-Verlag.

Haken, H., Kelso, J. A., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, *51*(5), 347-356. doi:10.1007/BF00336922

Handford, C., Davids, K., Bennett, S., & Button, C. (1997). Skill acquisition in sport: Some applications of an evolving practice ecology. *Journal of Sports Science*, *15*(6), 621-640. doi:10.1080/026404197367056

Harlow, H. F. (1949). The formation of learning sets. *Psychological Review, 56*(1), 51-65. doi:10.1037/h0062474

Harlow, H. F., & Harlow, M. K. (1949). Learning to think. *Scientific American*, *181*(2), 36-39.

Hasson, C. J., Zhang, Z., Abe, M. O., & Sternad, D. (2016). Neuromotor noise is malleable by amplifying perceived errors. *PLoS Computational Biology, 12*(8), e1005044. doi:10.1371/journal.pcbi.1005044

Hendrickson, G., & Schroeder, W. H. (1941). Transfer of training in learning to hit a submerged target. *Journal of Educational Psychology, 32*(3), 205-213.

Heuer, H. (1991). Invariant relative timing in motor-program theory. In J. Fagard & P. H. Wolff (Eds.), *The development of timing control and temporal organization in coordinated action* (pp. 37-68). North Holland, Netherlands: Elsevier.

Hilgard, E. R., & Bower, G. H. (1975). *Theories of learning*. London, England: Prentice-Hall.

Holding, D. H. (1976). An approximate transfer surface. *Journal Motor Behavior, 8*(1), 1-9. doi:10.1080/00222895.1976.10735049

Hossner, E.-J., Käch, B., & Enz, J. (2016). On the optimal degree of fluctuations in practice for motor learning. *Human Movement Science, 47*, 231-239. doi: 10.1016/j.humov.2015.06.007

Hoyt, D. F., & Taylor, R. (1981). Gait and the energetics of locomotion in horses. *Nature 292*, 239-240. doi: 10.1038/292239a0.

Huet, M., Jacobs, D. M., Camachon, C., Missenard, O., Gray, R., & Montagne, G. (2011). The education of attention as explanation of variability of practice effects: Learning the final approach phase in a flight simulator. *Journal of Experimental Psychology: Human Learning and Memory, 37*(6), 1841-1854. doi:10.1037/a0024386

Iberall, A. S. (1977). A field and circuit thermodynamics for integratice physiology. I. Introduction to the general notions. *American Journal of Physiology, 233*(5), R171 - R180.

Jacobs, D. M., Ibañez-Gijón, J., Díaz, A., & Travieso, D. (2011). On potential-based and direct movements in information spaces. *Ecological Psychology, 23*, 123-145. doi:10.1080/10407413.2011.566046

Jacobs, D. M., & Michaels, C. F. (2007). Direct learning. *Ecological Psychology, 19*(4), 321-349. doi:10.1080/10407410701432337

Jirsa, V. K., & Kelso, J. A. S. (2004). *Coordination dynamics: Issues and trends*. Berlin, Germany: Springer-Verlag.

Kay, H. (1957). Information theory in the understanding of skills. *Occupational Psychology, 31*, 218-224.

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychologial Bulletin, 70*(6), 387-403. doi:10.1037/h0026739

Keetch, K. M., Lee, T. D., & Schmidt, R. A. (2008). Especial skills: Specificity embedded within generality. *Journal of Sport & Exercise Psychology, 30*(6), 723-736. doi:10.1123/jsep.30.6.723

Keetch, K. M., Schmidt, R. A., Lee, T. D., & Young, D. E. (2005). Especial skills: Their emergence with massive amounts of practice. *Journal of Experimental Psychology: Human Perception and Performance, 31*(5), 970-978. doi:10.1037/0096-1523.31.5.970

Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology, 246*(6 Pt 2), R1000-1004.

Kelso, J. A. S. (1995). *Dynamic patterns*. Cambridge, MA: MIT Press.

Kelso, J. A. S. (2009). Coordination dynamics. In R. A. Meyers (Ed.), *Encyclopedia of complexity and systems science*. New York, NY: Springer.

Kelso, J. A. S., & Jeka, J. J. (1992). Symmetry breaking dynamics of human multilimb coordination. *Journal of Experimental Psychology: Human Perception and Performance, 18*(3), 645-668. doi:10.1037/0096-1523.18.3.645

Kelso, J. A. S., & Norman, P. E. (1978). Motor schema formation in children. *Developmental Psychology, 14*(2), 153-156. doi:10.1037/0012-1649.14.2.153

Kelso, J. A. S., Tuller, B., Vatikiotis-Bateson, E., & Fowler, C. A. (1984). Functionally specific articulatory cooperation following jaw perturbations during speech: Evidence for coordinative structures. *Journal of Experimental Psychology: Human Perception and Performance, 10*(6), 812-832. doi:10.1037/0096-1523.10.6.812

King, A. C., Ranganathan, R., & Newell, K. M. (2012). Individual differences in the exploration of a redundant space-time motor task. *Neuroscience Letters, 529*(2), 144-149. doi:10.1016/j.neulet.2012.08.014

Kostrubiec, V., Tallet, J., & Zanone, P. G. (2006). How a new behavioral pattern is stabilized with learning determines its persistence and flexibility in memory. *Experimental Brain Research, 170*(2), 238-244. doi:10.1007/s00221-005-0208-6

Kostrubiec, V., & Zanone, P. G. (2002). Memory dynamics: Distance between the new task and existing behavioural patterns affects learning and interference in bimanual coordination in humans. *Neuroscience Letters, 331*(3), 193-197. doi:10.1016/S0304-3940(02)00878-9

Kostrubiec, V., Zanone, P. G., Fuchs, A., & Kelso, J. A. S. (2012). Beyond the blank slate: routes to learning new coordination patterns depend on the intrinsic dynamics of the learner-experimental evidence and theoretical model. *Frontiers in Human Neuroscience, 6*, 222. doi:10.3389/fnhum.2012.00222

Krinskii, V. I., & Shik, M. L. (1964). Single model motor task. *Biophysics, 9*, 661-666.

Kugler, P. N., Kelso, J. A. S., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior*. North-Holland: North-Holland.

Kugler, P. N., Kelso, J. A. S., & Turvey, M. T. (1982). On the control and co-ordination of naturally developing systems. In J. A. S. Kelso & J. E. Clark (Eds.), *The development of movement control and co-ordination*. New York, NY: Wiley.

Kugler, P. N., & Turvey, M. T. (1987). *Information, natural law, and the self-assembly of rhythmic movement.* Hillsdale, NJ: Lawrence Erlbaum

Kuhn, T. S. (1970). *The structure of scientific revolutions*. Chicago, IL: University of Chicago Press.

Lashley, K. S. (1930). Basic neural mechanisms in behavior. *Psychological Review, 37*(1), 1-24. doi: 10.1037/h0074134

Latash, M. L. (2010). Stages in learning motor synergies: a view based on the equilibrium-point hypothesis. *Human Movement Science, 29*(5), 642-654. doi:10.1016/j.humov.2009.11.002

Latash, M. L., Scholz, J. P., & Schöner, G. (2002). Motor control strategies revealed in the structure of motor variability. *Exercise and Sport Sciences Reviews, 30*(1), 26-31.

Latash, M. L., Scholz, J. P., & Schöner, G. (2007). Toward a new theory of motor synergies. *Motor Control, 11*(3), 275-308. doi:10.1123/mcj.11.3.276

Loftus, G. R., & Masson, M. E. J. (1994). Using intervals in within-subject designs. *Psychonomic Bulletin & Review, 1*(4), 476-490. doi: 10.3758/BF03210951

MacKenzie, C. L., & Marteniuk, R. G. (1985). Motor skill: Feedback, knowledge, and structural issues. *Canadian Journal of Psychology, 39*(2), 313-337. doi:10.1037/h0080064

Magill, R. A., & Hall, K. G. (1990). A review of the contextual interference effect in motor skill acquisition. *Human Movement Science, 9*(3-5), 241-289. doi:10.1016/0167-9457(90)90005-X

McCracken, H. D., & Stelmach, G. (1977). A test of the schema theory of discrete motor learning. *Journal of Motor Behavior, 9*(3), 193-201. doi:10.1080/00222895.1977.10735109

McDonald, P. V., Oliver, S. K., & Newell, K. M. (1995). Perceptual-motor exploration as a function of biomechanical and task constraints. *Acta Psychologica, 88*(2), 127-165. doi: 10.1016/0001-6918(93)E0056-8

Metzler, W. H. (1910). Formal discipline. *The Mathematics Teacher, 3*(1), 9-17.

Michaels, C. F., Arzamarski, R., Isenhower, R. W., & Jacobs, D. M. (2008). Direct learning in dynamic touch. *Journal of Experimental Psychology: Human Perception and Performance, 34*(4), 944-957. doi:10.1037/0096-1523.34.4.944

Michaels, C. F., & Beek, P. J. (1995). The state of ecological psychology. *Ecological Psychology, 7*(4), 259-278. doi: 10.1207/s15326969eco0704_2

Michaels, C. F., Gomes, T. V. B., & Benda, R. N. (2017). A direct-learning approach to acquiring a bimanual tapping skill. *Journal of Motor Behavior, 49*(5), 550-567. doi:10.1080/00222895.2016.1247031

Miller, G. A. (1953). What is information measurement? *American Psychologist*, *8*(1), 3-11.

Mitchell, S. A., & Oslin, J. L. (1999). An investigation of tactical transfer in net games. *European Journal of Physical Education*, *4*(2), 162-172. doi:10.1080/1740898990040205

Mitra, S., Amazeen, P. G., & Turvey, M. T. (1998). Intermediate motor learning as decreasing active (dynamical) degrees of freedom. *Human Movement Science*, *17*(1), 17-65. doi:10.1016/S0167-9457(97)00023-7

Molenaar, P. C. M. (2004). A manifesto on psychology as idiographic science: Bringing the person back into scientific psychology, this time forever. *Measurement: Intersciplinary Research & Perspective, 2*, 201-218. doi: 10.1207/s15366359mea0204_1

Morice, A. H. P., Siegler, I. A., Bardy, B. G., & Warren, W. H. (2007). Learning new perception-action solutions in virtual ball bouncing. *Experimental Brain Research, 181*(2), 249-265. doi:10.1007/s00221-007-0924-1

Moxley, S. E. (1979). Schema: The variability of practice hypothesis. *Journal Motor Behavior*, *11*(1), 65-70. doi:10.1080/00222895.1979.10735173

Müller, H., & Sternad, D. (2004). Decomposition of variability in the execution of goal-oriented tasks: Three components of skill improvement. *Journal of Experimental Psychology: Human Perception and Performance, 30*(1), 212-233. doi:10.1037/0096-1523.30.1.212

Nelson, D. O. (1957). Studies of transfer of learning in gross motor skills. *Research Quarterly . American Association for Health, Physical Education and Recreation, 28*(4), 364-373. doi:10.1080/10671188.1957.10612945

Newell, K. M. (1985). Coordination, control and skill. In D. Goodman, R. B. Wilberg, & I. M. Franks (Eds.), *Differing perspectives in motor learning, memory, and control* (pp. 295-317). North-Holland: Elsevier.

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 341-360). Dordrecht: Kluwer Academic Publishers Group.

Newell, K. M. (1991). Motor skill acquisition. *Annual Review of Psychology, 42*, 213-237. doi: 10.1146/annurev.ps.42.020191.001241

Newell, K. M. (2003). Schema theory (1975): Retrospectives and prospectives. *Research Quarterly for Exercise and Sport, 74*(4), 383-388. doi:10.1080/02701367.2003.10609108

Newell, K. M., & Corcos, D. M. (1993). Issues in variability and motor control. In K. M. Newell & D. M. Corcos (Eds.), *Variability and motor control* (pp. 1-9). Champaign, IL: Human Kinetics.

Newell, K. M., Kugler, P. N., Van Emmerik, R. E. A., & McDonald, P. V. (1989). Search strategies and the acquisition of coordination. In S. A. Wallace (Ed.), *Perspectives on the coordination of movement* (pp. 85-122). North-Holland: Elsevier Science Publishers.

Newell, K. M., Mayer-Kress, G., & Liu, Y.-T. (2006). Human learning: Power laws or multiple characteristic time scales? *Tutorials in Quantitative Methods for Psychology, 2*(2), 66-76.

Newell, K. M., & McDonald, P. V. (1992). Searching for solutions to the coordination function: Learning as exploratory behavior. In G. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior II* (pp. 517-532). North-Holland: Elsevier Science Publishers.

Newell, K. M., & McDonald, P. V. (1994). Learning to coordinate redundant biomechanical degrees of freedom. In S. P. Swinnen, J. Massion, H. Heuer, & P. Casaer (Eds.), *Interlimb coordination: Neural, dynamical, and cognitive constraints* (pp. 515-536). New York, NY: Academic Press.

Newell, K. M., Mcdonald, P. V., & Kugler, P. N. (1991). The perceptual-motor workspace and the acquisition of skill. In J. Requin & G. E. Stelmach (Eds.), *Tutorials in motor neuroscience* (pp. 95-108). Boston: Kluwer.

Newell, K. M., & Slifkin, A. B. (1998). The nature of movement variability. In J. P. Piek (Ed.), *Motor behavior and human skill* (pp. 143-160). Champaign, IL: Human Kinetics.

Newell, K. M., & Vaillancourt, D. E. (2001). Dimensional change in motor learning. *Human Movement Science, 20*(4-5), 695-715. doi:10.1016/S0167-9457(01)00073-2

O'Keefe, S. L., Harrison, A. J., & Smyth, P. J. (2007). Transfer or specificity? An applied investigation into the relationship between fundamental overarm throwing and related sport skills. *Physical Education and Sport Pedagogy, 12*(2), 89-102. doi:10.1080/17408980701281995

Osgood, C. E. (1949). The similarity paradox in human learning: A resolution. *Psychological Review, 56*(3), 132-143. doi:10.1037/H0057488

Pacheco, M. M., Hsieh, T.-Y., & Newell, K. M. (2017). Search strategies in practice: Movement variability affords perception of task dynamics. *Ecological Psychology, 29*(3).

Pacheco, M. M., & Newell, K. M. (2015). Transfer as a function of exploration and stabilization in original practice. *Human Movement Science, 44*, 258-269. doi: 10.1016/j.humov.2015.09.009

Pacheco, M. M., & Newell, K. M. (2017a). Search strategies in practice: Influence of information and task constraints. Manuscript submitted to *Acta Psychologica*.

Pacheco, M. M., & Newell, K. M. (2017b). Transfer as a function of the learned coordination function: Specific, individual and generalizable. Manuscript submitted to *Human Movement Science*.

Park, J.-H., & Shea, C. H. (2003). Effect of practice on effector independence. *Journal of Motor Behavior, 35*(1), 33-40. doi:10.1080/00222890309602119

Polit, A., & Bizzi, E. (1979). Characteristics of motor programs underlying arm movements in monkeys. *Journal of Neurophysiology, 42*(1 Pt 1), 183-194.

Prigogine, I. (1955). *Introduction to thermodynamics of irreversible processes*. New York, NY: John Wiley & Sons.

Proteau, L. (1995). Sensory integration in the learning of an aiming task. *Canadian Journal of Experimental Psychology, 49*(1), 113-120. doi:10.1037/1196-1961.49.1.113

Proteau, L., Marteniuk, R. G., Girouard, Y., & Dugas, C. (1987). On the type of information used to control and learn an aiming movement after moderate and extensive training. *Human Movement Science, 6*(2), 181-199. doi:10.1016/0167-9457(87)90011-X

Proteau, L., Marteniuk, R. G., & Levesque, L. (1992). A sensorimotor basis for motor learning: Evidence indicating specificity of practice. *Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology, 44*(3), 557-575. doi: 10.1080/14640749208401298

Ranganathan, R., & Newell, K. M. (2010). Emergent flexibility in motor learning. *Experimental Brain Research, 202*(4), 755-764. doi: 10.1007/s00221-010-2177-7

Ranganathan, R., & Newell, K. M. (2013). Changing up the routine: Intervention-induced variability in motor learning. *Exercise and Sport Sciences Reviews*, *41*(1), 64-70. doi:10.1097/JES.0b013e318259beb5

Ranganathan, R., Wieser, J., Mosier, K. M., Mussa-Ivaldi, F. A., & Scheidt, R. A. (2014). Learning redundant motor tasks with and without overlapping dimensions: Facilitation and interference effects. *Journal of Neuroscience, 34*(24), 8289-8299. doi:10.1523/Jneurosci.4455-13.2014

Raudenbush, S. W., & Bryk, A. S. (2002). *Hierarchical linear models: Applications and data analysis methods*. Thousand Oaks, CA: Sage.

Reed, E. S. (1982). An outline of a theory of action systems. *Journal of Motor Behavior, 14*(2), 98-134. doi: 10.1080/00222895.1982.10735267

Robinson, E. S. (1927). The 'similarity' factor in retroaction. *The American Journal of Psychology, 39*(1/4), 297-312.

Rosengren, K. S., Savelsbergh, G. J. P., & van der Kamp, J. (2003). Development and learning: A TASC-based perspective of the acquisition of perceptual-motor behaviors. *Infant Behavior & Development*, *26*(4), 473-494. doi:10.1016/j.infbeh.2003.08.001

Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: a review and critical reappraisal. *Psychological Bulletin, 95*(3), 355-386. doi:10.1016/j.humov.2009.07.001

Saltzman, E. L., & Kelso, J. A. (1987). Skilled actions: a task-dynamic approach. *Psychological Review, 94*(1), 84-106. doi: 10.1037/0033-295X.94.1.84

Santello, M., Bianchi, M., Gabiccini, M., Ricciardi, E., Salvietti, G., Prattichizzo, D., . . . Bicchi, A. (2016). Hand synergies: Integration of robotics and neuroscience for understanding the control of biological and artificial hands. *Physics of Life Reviews, 17*, 1-23. doi:10.1016/j.plrev.2016.02.001.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, *82*(4), 225-260. doi:10.1037/H0076770

Schmidt, R. A., & Lee, T. D. (2005). *Motor control and learning: A behavioral emphasis*. Champaign, IL: Human Kinetics.

Schmidt, R. A., & Young, A. (1987). Transfer of movement control in motor skill learning. In S. M. Cormier & J. D. Hagman (Eds.), *Transfer of learning* (pp. 47-79). Orlando, FL: Academic Press.

Scholz, J. P., & Kelso, J. A. S. (1990). Intentional switching between patterns of bimanual coordination depends on the intrinsic dynamics of the patterns. *Journal of Motor Behavior, 22*(1), 98-124. doi: 10.1080/00222895.1990.10735504

Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: identifying control variables for a functional task. *Experimental Brain Research, 126*(3), 289-306. doi:10.1007/s002210050738

Schöner, G. (1990). A dynamic theory of coordination of discrete movement. *Biological Cybernetics, 63*(4), 257-270. doi:10.1007/BF00203449

Schöner, G., Spencer, J. P., & DFT Research Group (2016). *Dynamic thinking: A primer on dynamical field theory.* New York, NY: Oxford University Press.

Schwarz, G. (1978). Estimating the dimension of a model. *The Annals of Statistics, 6*(2), 461-464.

Shaw, R. E., & Alley, T. R. (1985). How to draw learning curves: Their use and justification. In T. Johnston & A. Pietrewicz (Eds.), *Issues in the ecological study of learning* (pp. 275-304). Hillsdale, NJ: Lawrence Erlbaum.

Shaw, R. E., Kadar, E., Sim, M., & Repperger, D. W. (1992). The intentional spring: A strategy for modeling systems that learn to perform intentional acts. *Journal of Motor Behavior, 24*(1), 3-28. doi:10.1080/00222895.1992.9941598

Shaw, R. E., Turvey, M. T., & Mace, W. M. (1982). Ecological psychology: The consequence of a commitment to realism. In W. Weimer & D. Palermo (Eds.), *Cognition and the symbolic processes* (Vol. 2, pp. 159-226). Hillsdale, NJ: Lawrence Erlbaum.

Shea, J. B., & Morgan, R. L. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology: Human Learning and Memory, 5*(2), 179-187. doi:10.1037/0278-7393.5.2.179

Sherwood, D. E., & Lee, T. D. (2003). Schema theory: critical review and implications for the role of cognition in a new theory of motor learning. *Research Quarterly for Exercise and Sport, 74*(4), 376-382. doi:10.1080/02701367.2003.10609107

Slifkin, A. B., & Newell, K. M. (1998). Is Variability in Human Performance a Reflection of System Noise? *Current Directions in Psychological Science, 7*(6), 170-177. doi: 10.1111/1467-8721.ep10836906

Smeeton, N. J., Ward, P., & Williams, A. M. (2004). Do pattern recognition skills transfer across sports? A preliminary analysis. *Journal of Sports Science, 22*(2), 205-213. doi:10.1080/02640410310001641494

Sternad, D., Huber, M. E., & Kuznetsov, N. (2014). Acquisition of novel and complex motor skills: Stable solutions where intrinsic noise matters less. In M. F. Levin (Ed.), *Progress in motor* *control: Advances in experimental medicine and biology* (pp. 101-124). New York, NY: Springer.

Sutton, R. S., & Barto, A. G. (1998). *Reinforcement learning: An introduction*. London, England: The MIT Press.

Tani, G., Correa, U. C., Basso, L., Benda, R. N., Ugrinowitsch, H., & Choshi, K. (2014). An adaptive process model of motor learning: insights for the teaching of motor skills. *Nonlinear Dynamics, Psychology, and Life Sciens, 18*(1), 47-65.

Taub, E., Ellman, S. J., & Berman, A. J. (1966). Deafferentation in monkeys: effect on conditioned grasp response. *Science, 151*(3710), 593-594. doi:10.1126/science.151.3710.593

Taub, E., Goldberg, I. A., & Taub, P. (1975). Deafferentation in monkeys: pointing at a target without visual feedback. *Experimental Neurology, 46*(1), 178-186. doi:10.1016/0014-4886(75)90040-0

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching: Mapping intention and intrinsic dynamics. *Child Development, 64*(4), 1058-1098. doi:10.2307/1131327

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.

Thorndike, E. L. (1931). *Human learning*. New York, NY: Century Co.

Thorndike, E. L., & Woodworth, R. S. (1901a). The influence of improvement in one mental function upon the efficiency of other functions. I. *Psychological Review, 8*(3), 247-261. doi:10.1037/h0074898

Thorndike, E. L., & Woodworth, R. S. (1901b). The influence of improvement in one mental function upon the efficiency of other functions. II. The estimation of magnitudes. *Psychological Review, 8*(4), 384-395. doi:10.1037/h0071280

Thorndike, E. L., & Woodworth, R. S. (1901c). The influence of improvement in one mental function upon the efficiency of other functions. III. Functions involving attention, observation and discrimination. *Psychological Review, 8*(6), 553-564. doi:10.1037/h0071363

Todorov, E., & Jordan, M. I. (2002). Optimal feedback control as a theory of motor coordination. *Nature Neuroscience, 5*(11), 1226-1235. doi: 10.1038/nn963

Tremblay, L., & Proteau, L. (1998). Specificity of practice: The case of powerlifting. *Research Quarterly for Exercise and Sport, 69*(3), 284-289. doi:10.1080/02701367.1998.10607695

Tremblay, L., & Proteau, L. (2001). Specificity of practice in a ball interception task. *Canadian Journal of Experimental Psychology, 55*(3), 207-218. doi:10.1037/h0087367

Tremblay, S., Houle, G., & Ostry, D. J. (2008). Specificity of speech motor learning. *The Journal of Neuroscience, 28*(10), 2426-2434. doi:10.1523/JNEUROSCI.4196-07.2008

Tuitert, I., Bootsma, R. J., Schoemaker, M. M., Otten, E., Mouton, L. J., & Bongers, R. M. (2017). Does practicing a wide range of joint angle configurations lead to higher flexibility in a manual obstacle-avoidance target-pointing task? *PLoS One, 12*(7), e0181041. doi:10.1371/journal.pone.0181041

Tumer, E. C., & Brainard, M. S. (2007). Performance variability enables adaptive plasticity of ‘crystallized’ adult birdsong. *Nature, 450*(7173), 1240-1244. doi:10.1038/nature06390

Turvey, M. T. (1977). Preliminaries to a theory of action with reference to vision. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing: Toward an ecological psychology*. Hillsdale, NJ: Erlbaum.

Turvey, M. T. (1996). Dynamic touch. *American Psychologist, 51*(11), 1134-1152.

Turvey, M. T. (2007). Action and perception at the level of synergies. *Human Movement Science, 26*(4), 657-697. doi:10.1016/j.humov.2007.04.002

Turvey, M. T., Fitch, H. L., & Tuller, B. (1982). The Bernstein perspective: I. The problems of degrees of freedom and context conditioned variability. In J. A. S. Kelso (Ed.), *Human motor control*. Hillsdale, NJ: Erlbaum.

Turvey, M. T., & Fonseca, S. (2009). Nature of motor control Perspectives and issues. In D. Sternad (Ed.), *Progress in motor control: A multidisciplinary perspective*. New York, NY: Springer.

Van Orden, G. C., Holden, J. G., & Turvey, M. T. (2003). Self-organization of cognitive performance. *Journal of Experimental Psychology: General, 132*(3), 331-350. doi:10.1037/0096-3445.132.3.331

Van Rossum, J. H. A. (1990). Schmidt's schema theory: The empirical base of the variability of practice hypothesis. A critical analysis. *Human Movement Science, 9*(3-5), 387-435. doi:10.1016/0167-9457(90)90010-B

Wagner, H., Pfusterschmied, J., Tilp, M., Landlinger, J., von Duvillard, S. P., & Müller, E. (2014). Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike. *Scandinavian Journal of Medicine & Science in Sports, 24*(2), 345-354. doi:10.1111/j.1600-0838.2012.01503.x.

Warren, W. H. (2006). The dynamics of perception and action. *Psychological Review, 113*(2), 358-389. doi:10.1037/0033-295X.113.2.358

Wenderoth, N., Bock, O., & Krohn, R. (2002). Learning a new bimanual coordination pattern is influenced by existing attractors. *Motor Control, 6*(2), 166-182. doi:10.1123/mcj.6.2.166

Whiting, H. T. A., Savelsbergh, G. J. P., & Pijpers, J. R. (1995). Specificity of motor learning does not deny flexibility. *Applied Psychology: An International Review, 44*(4), 315-332. doi:10.1111/j.1464-0597.1995.tb01083.x

Withagen, R., & Michaels, C. F. (2005). The role of feedback information for calibration and attunement in perceiving length by dynamic touch. *Journal of Experimental Psychology: Human Learning and Memory, 31*(6), 1379-1390. doi:10.1037/0096-1523.31.6.1379

Withagen, R., & van Wermeskerken, M. (2009). Individual differences in learning to perceive length by dynamic touch: Evidence for variation in perceptual learning capacities. *Attention, Perception, & Psychophysics, 71*(1), 64-75. doi:10.3758/APP.71.1.64

Wolpert, D. M., & Flanagan, J. R. (2010). Motor learning. *Current Biology, 20*(11), R467-472. doi:10.1016/j.cub.2010.04.035

Wu, H. G., Miyamoto, Y. R., Castro, L. N. G., Ölveczky, B. P., & Smith, M. A. (2014). Temporal structure of motor variability is dynamically regulated and predicts motor learning ability. *Nature Neuroscience, 17*(2), 312-320. doi:10.1038/nn.3616

Wu, Y.-H., Truglio, T. S., Zatsiorsky, V. M., & Latash, M. L. (2015). Learning to combine high variability with high precision: Lack of transfer to a different task. *Journal of Motor Behavior, 47*(2), 153-165. doi:10.1080/00222895.2014.961892

Young, R. L., Haselkorn, T. S., & Badyaev, A. V. (2007). Functional equivalence of morphologies enables morphological and ecological diversity. *Evolution*, *61*(11), 2480-2492. doi:10.1111/j.1558-5646.2007.00210.x

Zanone, P. G., & Kelso, J. A. S. (1992). Evolution of behavioral attractors with learning: Nonequilibrium phase-transitions. *Journal of Experimental Psychology: Human Perception and Performance, 18*(2), 403-421. doi:10.1037/0096-1523.18.2.403

Zanone, P. G., & Kelso, J. A. S. (1994). The coordination dynamics of learning: Theoretical structure and experimental agenda. In S. P. Swinnen, J. Massion, H. Heuer, & P. Casaer (Eds.), *Interlimb coordination: Neural, dynamical, and cognitive constraints* (pp. 637). London: Academic Press.

Zanone, P. G., & Kelso, J. A. S. (1997). Coordination dynamics of learning and transfer: Collective and component levels. *Journal of Experimental Psychology: Human Perception and Performance, 23*(5), 1454-1480. doi:10.1037/0096-1523.23.5.1454

Zelaznik, H. N., Schmidt, R. A., & Gielen, S. C. (1986). Kinematics properties of rapid aimed hand movements. *Journal of Motor Behavior, 18*(4), 353-372. doi: 10.1080/00222895.1986.10735386

APPENDICES

APPENDIX A – EIGENVECTORS OF EXPERIMENT 1

Table A.1 presents the eigenvectors derived from the PCA on velocity release parameters of each individual.

Table A.1 – Eigenvectors derived from the PCA on the velocity release parameters of each individual

	First PC			Second PC		
P1	0.017	-0.671	0.741	0.151	0.734	0.662
P2	-0.068	0.978	0.199	0.831	-0.055	0.553
P3	-0.074	0.997	0.028	-0.140	-0.038	0.989
P4	-0.035	0.959	-0.280	0.430	0.267	0.862
P5	-0.090	0.995	0.038	-0.100	-0.047	0.994
P6	-0.058	0.998	0.037	0.769	0.068	-0.635
P7	-0.022	0.763	-0.646	-0.006	0.646	0.763
P8	-0.110	0.890	0.443	-0.010	-0.447	0.895
P9	-0.039	0.985	0.166	0.075	-0.163	0.984
P10	0.047	0.997	-0.062	0.995	-0.052	-0.088
P11	-0.015	0.995	0.100	0.015	-0.100	0.995
P12	-0.014	0.990	0.143	0.040	-0.142	0.989
P13	-0.124	0.980	0.159	-0.248	-0.185	0.951
P14	-0.062	0.967	0.246	-0.323	-0.252	0.912
P15	0.022	0.996	0.088	-0.067	-0.087	0.994
P16	-0.029	0.979	-0.201	0.028	0.201	0.979
P17	-0.059	0.993	-0.100	0.086	0.105	0.991

APPENDICES

APPENDIX B – EIGENVECTORS OF EXPERIMENT 1

Table B.1 presents the eigenvectors derived from the PCA on velocity release parameters of each individual.

Table B.1 – Eigenvectors derived from the PCA on the velocity release parameters of each individual

	First PC			Second PC		
Group Angle						
P1	0.260	0.965	-0.030	0.947	-0.261	-0.185
P2	0.186	0.967	0.172	0.678	-0.254	0.690
P3	0.113	0.994	-0.011	0.993	-0.113	-0.040
P4	0.178	0.984	-0.029	0.981	-0.180	-0.076
P5	0.037	0.999	-0.013	0.987	-0.034	0.159
P6	0.028	1.000	-0.004	0.995	-0.028	-0.101
P7	0.020	1.000	-0.022	0.922	-0.027	-0.386
P8	0.038	0.999	-0.023	0.989	-0.041	-0.143
Group Constant						
P1	0.994	-0.011	-0.108	0.107	-0.102	0.989
P2	0.999	-0.017	-0.050	0.049	-0.066	0.997
P3	0.988	0.071	-0.135	0.146	-0.178	0.973
P4	0.721	0.020	0.693	-0.692	-0.050	0.721
P5	0.983	0.021	0.183	-0.168	-0.295	0.941
P6	0.992	0.113	-0.048	0.113	-0.693	0.712
P7	0.987	0.054	-0.151	-0.006	0.953	0.302
P8	0.750	0.035	0.661	-0.661	0.083	0.746
Group Distance						
P1	-0.604	-0.034	0.796	0.797	-0.013	0.604
P2	-0.387	0.013	0.922	0.922	-0.003	0.387
P3	-0.373	-0.108	0.921	0.927	-0.012	0.374
P4	-0.300	-0.038	0.953	0.949	0.087	0.302
P5	-0.303	-0.210	0.930	0.950	0.014	0.313
P6	-0.619	-0.063	0.783	0.782	0.049	0.622
P7	-0.268	-0.054	0.962	0.963	0.018	0.269
P8	-0.629	-0.170	0.759	0.773	-0.034	0.633