Training Perceptual Anticipation in Sports: The Case of the Penalty Kick in Football

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0.1 Agradecimientos

Como todos sabemos, una tesis doctoral no puede llevarse a cabo en solitario. Por ello, me gustaría hacer explícito lo profundamente agradecido que estoy a todas las personas que han colaborado de cualquier manera en este proyecto de crecimiento tanto profesional como personal.

En primer lugar tengo y quiero agradecer a David Travieso su papel fundamental en esta tesis, gracias a tu pasión por la ciencia y el debate descubrí la investigación y la convertí también en mi pasión. Para mi, aunque no quede reflejado oficialmente eres mi director de tesis y mucho más. En este sentido agradecer de igual manera a David Jacobs, que ha trabajado de forma incansable desde el primer al último día, con la misma sistematicidad y cercanía. David espero poder seguir aprendiendo a tu lado muchos años. De igual manera, Jorge Ibañez ha sido para mi un pilar fundamental en el desarrollo de este trabajo, agradecerte de corazón tu cercanía, tu completa disponibilidad y tu infinita paciencia. Para mi eres un ejemplo del investigador que quiero llegar a ser.

En este trabajo también han puesto su granito de arena muchas personas que han colaborado directa o indirectamente con el desarrollo de esta tesis. Especialmente Lorena Y Manuel representan el camino que todo joven investigador quiere seguir: comprometidos, metódicos e incansables. También a Carlos, como un igual, compartimos todo lo que hacer una tesis implica. A todos mis compañeros y compañeras del aula PDIF y otros doctorandos compartimos tesis y mucho más, gracias.

Por otro lado quiero agradecer a toda mi familia su apoyo directo o indirecto en estos años. Especialmente a mi madre que, sin saber muy bien de que trata la tesis, ha sido y es un apoyo fundamental en esta y en todas facetas de mi vida. Mi abuela, que sin duda será la persona que más orgullosa guarde y comparta este pequeño libro y mi padre por estar siempre ahí.

También quiero agradecer a mis amigos, mis arnolds. Alejandro, Diego, Fernando, Guillermo, Jorge, Pablo y Salva se que cuento con vosotros para todo, gracias. Dani y Costa estén cerca o estén lejos siempre estaréis ahí, gracias.

I would like also to thank the people of the Human Movement Science in Groningen their amability during my internship. Specially to Claudine to accept my as one more in their group and to Frank to support me during my stay. Frank, I would never forget that "everyone has a plan until they get punched in the mouth" thats a quite accurate deffinition of science.

I have also some words to my beloved vriendin Nienke, thank you for all the support in this thesis and all the perfect moments that we already have and for the ones that we will have.

Finalmente, me gustaría agradecer sinceramente a todas esas personas imprescindibles para llevar a cabo una tesis pero invisibles como el personal de administración y servicio. Gracias también a toda la gente que lucha día a día por los derechos de todos, especialmente por los que luchan por conseguir una ciencia digna en nuestro país.

0.2 Resumen

La anticipación es uno de los factores más relevantes que afectan al rendimiento en situaciones deportivas. Anticipar correctamente el resultado de una acción antes de que ésta suceda aporta una importante ventaja competitiva cuando se refiere a servicios de tenis por encima de los 200 km/h, golpeos en beisbol alrededor de 150 km/h o penaltis en futbol a unos 100 km/h. La anticipación en deporte lleva siendo estudiada en psicología durante los últimos 50 años con avances muy importantes. Sin embargo, algunas cuestiones fundamentales todavía no tienen respuesta incluyendo un enfoque informacional al estudio de la anticipación y la inclusión de los estudios de anticipación en deporte dentro de un marco teórico que guíe la investigación.

El objetivo de esta tesis es contribuir al desarrollo del campo de la anticipación en deporte de forma tanto teórica como práctica, especialmente en la situación de penalti en futbol. Más concretamente se pretende desarrollar un programa de entrenamiento en anticipación en deporte basado en los últimos avances teóricos en psicología ecológica presentados en esta tesis. Para ello, voy a presentar un conjunto de 6 estudios tanto experimentales como teóricos basados en la anticipación de la situación de penalti en futbol y la psicología ecológica.

Los estudios teóricos incluyen una revisión sistemática y una reflexión sobre la teoría del aprendizaje directo como teoría unificada del aprendizaje postcognitivistas. Estos dos estudios permiten basar la propuesta del programa de entrenamiento en anticipación en las últimas evidencias tanto teóricas como en anticipación en deporte. Los estudios experimentales incluyen un conjunto de cuatro experimentos. El primer estudio experimental estudia la situación de penalti desde la perspectiva tanto del portero como del lanzador. El segundo estudio experimental, presenta un estudio de anticipación de penaltis mediante "point light displays" combinado con técnicas de reducción de dimensionalidad. El tercer estudio experimental compara de forma matemática técnicas de reducción de dimensionalidad con técnicas de

clasificación en la tarea de anticipación de penaltis. En el último estudio experimental se propone un programa de entrenamiento novedoso que emplea técnicas de clasificación combinadas con técnicas de reducción de dimensionalidad bajo el paradigma teórico de la psicología ecológica.

Los resultados teóricos mostraron que los experimentos en anticipación deberían ser diseñados siguiendo los últimos avances teóricos y experimentales para asegurar en la medida de lo posible la transferencia del laboratorio a situación de juego real. La metodología de entrenamiento que introducimos en esta tesis sigue esas directrices, basando en aprendizaje en anticipación en información para la percepción. Por otro lado, el entrenamiento de la anticipación en la situación de penalti debe centrarse en la dirección lateral ya que esta puede ser anticipada a partir de los movimientos del lanzador, mientras que la dirección vertical es percibida a partir de la trayectoria del balón.

Los resultados experimentales mostraron que las técnicas de manipulación propuestas en esta tesis mantienen las diferencias en anticipación entre expertos y novatos, justificando el uso de estas técnicas en programas de entrenamiento. Además, los programas de entrenamiento basados en técnicas de reducción de dimensionalidad mostraron resultados positivos mientras que el basado en técnicas de clasificación no. Por ello, aunque todavía no demostrado, el planteamiento teórico planteado en esta tesis es válido: la anticipación en deporte está basada en la detección de información ecológica que puede ser capturada mediante algoritmos de clasificación.

0.3   Abstract

Anticipation is one of the most relevant factors affecting performance in sports situations. Anticipating the outcome of an action before it happens provides a significant competitive advantage when it comes to tennis services above 200 km/h, batting in baseball around 150 km/h and penalties in footbal at about 100 km/h. Anticipation in sports has been studied in psychology during the last 50 years with very important advances in the field. However, fundamental questions have not yet been answered, including an informational approach to the study of anticipation and the inclusion of sports anticipation studies within a theoretical framework that guides the investigation. The objective of this thesis is to contribute to the development of the field of anticipation in sport both from a theoretical and practical point of view, especially in the penalty kick situation of football. More specifically, the aim of this thesis is to develop a training program in anticipation of sport based on the latest theoretical advances in ecological psychology presented in this thesis. This thesis contains a set of 6 studies both experimental and theoretical based on the anticipation of the situation of penalty in football and ecological psychology.

Theoretical studies include a systematic review and a presentation of the theory of direct learning as a unified theory for post-cognitive learning studies. These two studies allow us to base our training proposal in the last evidence in theoretical and anticipatory sports studies. The experimental studies include a set of four experiments. The first experimental study analize the penalty situation from the perspective of both the goalkeeper and the penalty kicker. In the second experimental study, I present a study of anticipation of penalties from "point light displays" combined with dimensionality reduction techniques. The third experimental study mathematically compares dimensionality reduction techniques with classification techniques in the task of anticipating penalties. In the last experimental study, we propose a novel training program that uses a combination of classification and reduction techniques. The desing of this proposal followed the ecological psychology principles.

The theoretical results showed that anticipation experiments have to be designed following the latest theoretical and experimental findings to ensure the transfer of learning from the laboratory to real game situations. The training program proposed in this thesis follows these guidelines, based on ecological psychology principles. On the other hand, anticipation training in the penalty situation should focus on the lateral direction because it can be anticipated from the movements of the kicker, while the vertical direction is perceived mainly from the trajectory of the ball.

The experimental results showed that the manipulation techniques proposed in this thesis maintain the anticipation differences between experts and novices, justifying the use of these techniques in training programs. In addition, the training programs based on dimensionality reduction techniques showed positive results while the ones based in classification techniques did not. Therefore, although not yet demonstrated the theoretical approach proposed in this thesis is still valid: the anticipation in sports is based on the detection of ecological information that can be captured by classification algorithms.

0.4   Publications

Higueras-Herbada, A., Travieso, D., Ibáñez-Gijón, J., & Jacobs, D. (2017). Anticipating the lateral direction of penalty kicks in football from PCA-reduced point-light displays. *Ecological Psychology*, *29(1)*, 23-34. doi: 10.1080/10407413.2017.1270148

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Higueras-Herbada, A., De Paz, C., Jacobs, D., Travieso, D., & Ibáñez-Gijón, J. (2019) The direct learning theory: A naturalistic approach to learning for the post-cognitivist era, *adaptive behavior, 29(1),* 23-34. doi: 10.1080/10407413.2017.1270148

Higueras-Herbada, A., Travieso, D., Ibáñez-Gijón, J., & Jacobs, D. (2019). *Training Perceptual Anticipation in Sports Since the Nineties: A Systematic Review.* Manuscript submitted for publication.

Higueras-Herbada, A., Jose E., Lopes, Travieso, D., Ibáñez-Gijón, J., Araujo, D, & Jacobs, D. (2019). *Height After Side: Goalkeepers Detect the Vertical Direction of Association-Football Penalty Kicks From the Ball Trajectory.* Manuscript submitted for publication.

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Preamble

Chapter 1

Introduction

1.1 Aims of the Thesis

The aim of this thesis is to contribute to the development of an anticipation training program in sport. The thesis proposes a multidisciplinary approach: applying the theoretical principles of the ecological theory of perception and perceptual learning to the analysis of anticipation. This ecological and dynamic approach allows for an empirical and quantitative approach to research in sport psychology. However, this comes at a price: to be able to apply the theoretical principles and methodological tools of the ecological approach it is necessary to have a deep knowledge of the structure of the optical energy surrounding the agent. This structure of energy in the environment is what the ecological approach calls information, the fundamental concept for operationalizing the ecological notion of perception. In this sense, applying this approach to training anticipation in sports is a challenge because optical stimuli in natural conditions have a complex and dynamic structure. This is why it is necessary to employ stimuli presentation techniques that simplify the optical information and to apply dimensionality reduction techniques to these stimuli already-simplified to allow the researcher to interpret and manipulate global optical information structures that underpin the anticipation processes.

Despite this complexity, sport is one of the areas of application where the ecological and dynamic approach has developed its research program with more success (Araujo et al., 2006). This is because sport situations are ecological/natural environments whose conditions are easily controllable by the researcher. This makes it possible to perform experimental manipulations in a natural setup. This favors the design of realistic experiments and whose conclusions can be more easily generalized.

In the combined approach that this thesis proposes, ecological psychology provides a well-develop theoretical framework to studies of anticipation/training in sport. This allows researchers to design experiments to answer relevant questions while interpreting the results within a developed theoretical framework. Studies of anticipation in sport provide a set of experimental situations suitable to contrast hypotheses and developments posed by ecological psychology.

The line of anticipation/training in sport is characterized by being at an intermediate point between psychology and sports science. On the one hand, this line studies phenomena directly related to sport, such as anticipation, performance, speed, or deception. However, all of these measures are directly related to basic psychological processes/constructs such as perception, learning, reaction time, discrimination, etc.

The research of anticipation processes in sport has a history of about 50 years, which has resulted in very relevant research outcomes. The application of research results in anticipation to perceptual learning programs began 30 years ago (Williams & Jackson, 2018).This thesis proposes a new line of research in anticipation/learning in sport using PLDs (Point Light Displays) manipulated with dimensionality reduction techniques like the PCA (Principal Component Analysis) and the LDA (Linear Discriminant Analysis) and using an ecological and dynamic approach to design and interpret the results of the experiments.

1.2 Structure of the Thesis

To achieve our objective, in this thesis we present a series of theoretical and experimental studies that are organized as follows:

The first part, preamble, consists out of two chapters. In Chapter 1, this one, the objectives and organization of the thesis are introduced. Chapter 2 presents the theoretical framework. Independently,

we summarize the line of anticipation in sport, the use of PLDs, the line of dimensionality reduction, ecological psychology and direct learning to conclude by presenting our research proposal.

The second part consists out of two chapters that establish the empirical and methodological basis of this research. Chapter 3 presents a systematic review of perceptual training programs in sport between 1990-2019. It aims to provide a detailed summary of the current and historical trends of anticipation training in sport. With this we can detect weaknesses, propose improvements, and base our proposals on evidence. Chapter 4 presents a study analyzing the situation of the penalty kick in football with a database of 720 penalties from three perspectives: the probability of the goalkeeper to stop the ball, the movements of the penalty taker and the movements of the goalkeeper. This study allows us to establish the informational constraints for the design of the anticipation training program in penalty kicks.

The third part, studies of anticipation, consists out of 3 chapters. Chapter 5 presents the first anticipation study combining PLDs and PCAs. The objective of this study was to validate the methodology used for future steps and to replicate the results obtained in other dimensionality reduction studies. In Chapter 6 we propose the combined use of PCA and LDA. The fundamental difference between the two techniques is the criterion that each technique uses to reorganize the original high-dimensional space. In the case of the PCA what is maximized is the variance explained, while in the LDA, it is the distance between categories. The proposal of this thesis is that this property of the LDA can allow one to relate the components with the information for ecological psychology. In this chapter we present promising mathematical results regarding the added value of applying LDA on PCAs when the goal is to study anticipation. Chapter 7 presents a series of experimental studies with the final aim of implementing an ecological training program in anticipation in sport based on LDA. We will first establish whether learning in this task is possible through an expert-novice study. Afterwards, we will check the possibility of training anticipation of penalty kicks in the lab using an experimental design with feedback. Next, we check whether the neutralization of information of the non-presented modes allows us to achieve the same results, producing learning. As will be explained in the thesis, this step is necessary because the dimensions produced by the LDA are far away from the original action, unlike the dimensions of the PCA, whose maxization of variance yields presentations closer to natural movements, gets presentations closer to natural movements. Finally, and once these prerequisites have been verified, the fourth experiment presents an anticipation training program in penalty kicks and the use of LDA to reorganize the information presented. Because of the unexpected obtained results in this experiment, a fifth manipulation has been carried out to check whether the type of neutralization required by the LDA (other than that used in PCA experiments) could be responsible for the observed results. To do this, we use a methodology based on PCA but using the neutralization used by the LDA. The results of Chapter 7 are discussed within the ecological and dynamic approach to psychology concluding that future studies will need to check whether components obtained through classification algorithms can be related to ecological information. This would allow us to apply the tools proposed by direct learning theory to training programs with the objective to maximize and monitor the learning process.

The fourth part, epilogue, consists of two chapters of a more general and theoretical character. Chapter 8 sets out the role of and ecological theory of learning (direct learning) as a theory of learning for postcognitivism. The proposal of this study is that direct learning should be the starting point for joint research between different postcognitivist approaches to perception and learning. In addition, it contributes to the development of direct learning theory by proposing an extension of the theory to account for the learning of actions with multiple perception-action loops. Chapter 9 presents the overall results of the thesis, limitations and future studies. In this part a joint interpretation of the theoretical and experimental results presented in the thesis is discussed.

Chapter 1

Introducción

1.1 Objetivos de la Tesis

El objetivo de esta tesis es contribuir al desarrollo de un programa de entrenamiento en anticipación en deporte. En la tesis se propone un enfoque multidisciplinar consistente en aplicar los principios teóricos de la teoría ecológica de la percepción y el aprendizaje perceptivo al análisis de la anticipación. Este enfoque ecológico y dinámico permite una aproximación empírica y cuantitativa a la investigación en psicología del deporte. Sin embargo, esto tiene un precio: para poder aplicar los principios teóricos y las herramientas metodológicas del enfoque ecológico es necesario un conocimiento profundo de la estructura de la energía óptica que rodea al agente. Esta estructura de la energía en el entorno es lo que el enfoque ecológico denomina información, el concepto fundamental para operativizar la noción ecológica de percepción. En este sentido, aplicar este enfoque al entrenamiento de la anticipación en deportes es un reto porque los estímulos ópticos en condiciones naturales tienen una estructura muy compleja y dinámica. Por esto es necesario emplear técnicas de presentación de estímulos que simplifiquen la información óptica y técnicas de reducción de la dimensionalidad aplicadas sobre esos estímulos ya simplificados para permitir al investigador interpretar y manipular estructuras globales de la información óptica que sustentan los procesos de anticipación.

A pesar de esta complejidad, el deporte es uno de los ámbitos de aplicación donde el enfoque ecológico y dinámico ha desarrollado su programa de investigación con más éxito (Araujo et al., 2006). Esto se debe a que las situaciones deportivas son entornos ecológicos/naturales cuyas condiciones son fácilmente controlables por el investigador. Esto posibilita manipulaciones experimentales en ambientes naturales, lo que favorece el diseño de experimentos realistas y cuyas conclusiones son más fácilmente generalizables.

En la unión que propone esta tesis, la psicología ecológica provee de un marco teórico contrastado a los estudios de anticipación/entrenamiento en deporte. Esto permite diseñar experimentos para responder preguntas relevantes y a la vez interpretar los resultados dentro de un marco teórico desarrollado. Por su parte, los estudios de anticipación en deporte proveen de un conjunto de situaciones experimentales idóneas para contrastar hipótesis y desarrollos planteados por la psicología ecológica.

La línea de anticipación/entrenamiento en deporte se caracteriza por estar en un punto intermedio entre la psicología y las ciencias del deporte. Por un lado, se estudian fenómenos directamente relacionados con el deporte como, por ejemplo, anticipación, rendimiento, velocidad, o engaño. Pero todas estas medidas están directamente relacionadas con procesos/constructos psicológicos básicos como percepción, aprendizaje, tiempo de reacción, discriminación, etc.

La investigación de los procesos de anticipación en deporte cuenta con una historia de unos 50 años, habiendo dado lugar a resultados muy relevantes. Por su parte, la aplicación de los resultados de la investigación en anticipación a programas de aprendizaje perceptivo comenzó hace 30 años (Williams & Jackson, 2018). En esta tesis se propone una nueva línea de investigación en anticipación/aprendizaje en deporte utilizando PLDs (Point Light Displays) manipulados con técnicas de reducción de dimensionalidad como el PCA (Principal Component Analysis) y el LDA (Linear Discriminant Analysis) y empleando un enfoque ecológico y dinámico para diseñar e interpretar los experimentos.

1.2 Estructura de la Tesis

Para conseguir nuestro objetivo, en esta tesis presento una serie de estudios tanto teóricos como experimentales organizados de la siguiente manera:

La primera parte, preámbulo, consta de dos capítulos. En el capítulo 1, este mismo, se introducen los objetivos y organización de la tesis. En el capítulo 2 se presenta el marco teórico. De forma independiente

se resumen la línea de anticipación en deporte, el uso de los PLD, la línea de reducción de dimensionalidad, la psicología ecológica y el aprendizaje directo para concluir presentando nuestra propuesta de investigación.

La segunda parte está compuesta por dos capítulos que establecen las bases empíricas y metodológicas de esta investigación. En el capítulo 3 se presenta una revisión sistemática de programas de entrenamiento perceptivo en deporte entre 1990-2019. Tiene como objetivo conocer en profundidad las tendencias actuales e históricas de los entrenamientos de anticipación en deporte. Con ello podemos detectar puntos débiles, proponer mejoras y basar nuestra propuesta en evidencias. En el capítulo 4 se presenta un estudio analizando la situación del penalti en futbol con una base de datos de 720 penaltis desde tres perspectivas: la probabilidad del portero de parar el balón, los movimientos del lanzador y los movimientos del portero. Este estudio nos permite establecer las constricciones informacionales para diseñar un entrenamiento de la anticipación en lanzamientos de penalti.

La tercera parte, estudios de anticipación, consta de 3 capítulos. El capítulo 5 presenta el primer estudio de anticipación de penaltis combinando PLDs y PCA. El objetivo de este estudio es validar la metodología empleada para los pasos futuros y replicar los resultados obtenidos en otros estudios de reducción de dimensionalidad. En el capítulo 6 proponemos el uso combinado de PCA y LDA. La diferencia fundamental entre ambas técnicas es el criterio que emplean para reorganizar el espacio de variables original. En el caso del PCA lo que se maximiza es la varianza explicada, mientras que en el LDA es la distancia entre categorías. La propuesta de esta tesis es que esta propiedad del LDA puede permitir relacionar los componentes con la información en términos de la psicología ecológica. Para ello, en este capítulo presentamos resultados matemáticos prometedores con respecto al valor añadido de aplicar LDA sobre los PCAs cuando el objetivo es estudiar anticipación. En el capítulo 7 se presentan una serie de cinco estudios experimentales encaminados a implementar un programa ecológico de entrenamiento en anticipación basado en LDA. Para ello, primero estableceremos si es posible el aprendizaje en esta tarea por medio de un estudio expertos-novatos. Después, comprobaremos la posibilidad de entrenar la anticipación en lanzamientos de penaltis en el laboratorio utilizando un diseño experimental con feedback. A continuación, comprobamos si la neutralización de la información de los modos no presentados permite obtener los mismos resultados que la eliminación de los mismos que se usó en los experimentos anteriores (como se explica más adelante, este paso es necesario porque las dimensiones producidas por el LDA se alejan mucho de la acción original, al contrario que las dimensiones del PCA, ya que al intentar contener el máximo de varianza, consigue presentaciones más próximos a los movimientos naturales). Finalmente, y una vez comprobados estos requisitos previos, el cuarto experimento consiste en un programa de entrenamiento de la anticipación en lanzamientos de penalti y el uso de LDA para reorganizar la información presentada. Debido a los resultados inesperados obtenidos en este experimento, se ha realizado una quinta manipulación para comprobar si el tipo de neutralización requerida por el LDA (distinta de la utilizada en los experimentos con PCA) podría ser responsable de los resultados observados. Para ello, utilizamos una metodología basada en PCA pero utilizando la neutralización usada en por el LDA. Los resultados del capítulo 7 se discuten en el marco la psicología ecológica y dinámica concluyendo que futuros estudios deberán comprobar si los componentes obtenidos mediante algoritmos de clasificación se pueden relacionar con la información ecológica. Esto permitiría aplicar a programas de entrenamiento las herramientas propuestas por la teoría del aprendizaje directo con el objetivo de maximizar y monitorizar el proceso de aprendizaje.

La cuarta parte, epílogo, consta de dos capítulos de un carácter más general y teórico. En el capítulo 8 se plantea el papel de la teoría ecológica del aprendizaje (direct learning) como una teoría del aprendizaje para el postcognitivismo. La propuesta de este estudio es que direct learning puede ser el punto de partida para futuras líneas de investigación conjunta entre distintas aproximaciones postcognitivistas a la percepción y el aprendizaje. Además, se contribuye al desarrollo de la teoría del aprendizaje directo proponiendo una extensión de la teoría para dar cuenta del aprendizaje de acciones con múltiples bucles de percepción-acción. En el capítulo final, 9, se presentan los resultados globales de la tesis, limitaciones y futuros estudios. En esta parte se realiza una interpretación conjunta de los resultados teóricos y experimentales presentados en la tesis.

Chapter 2

Theoretical Background

This chapter introduces the theoretical background that constitutes our proposal. In chapters 3 and 8, anticipation in sport and ecological psychology/direct learning will be further developed.

2.1   Anticipation in Sport

Anticipation is one of the key factors affecting performance in sport. In time constrained situations, the ability to anticipate what your opponent is going to do next is a competitive advantage. According to Williams and Jackson (2018), researchers have been studying anticipation in sport for the last 50 years. After 50 years of research that there are some concepts and evidences clearly established in sports anticipation field[1]. For recent narrative reviews we recommend Williams and Jackson (2018), Farrow (2013), Broadbent et al. (2015), Dicks et al. (2015), Miles et al. (2012). For a more detailed summary of expert novice differences see Mann et al. (2007). Now, a brief summary of the main findings of the anticipation in sport literature will be provided.

First of all, the aim of this thesis is to propose methodological tools and to contribute to the design of perceptual training programs for the penalty kick situation. Therefore, it is important to consider the methodologies used in the literature of anticipation in sports. Most anticipation studies used video occlusion and expert-novice paradigms (Jones & Miles 1978, as cited in Williams & Jackson, 2018; Abernethy & Russell, 1987; Abernethy, 1988). Occlusion technique is an experimentally induced reduction of the availability of information for the performer, typically using standard video recordings. Information can be occluded in time and in space, that is, information can be removed either in specific areas of the display or during specific time-lapses. The two types of occlusion can be combined, but temporal occlusion alone is the most common manipulation in the literature. As a consequence, the results obtained are constrained by the coarse granularity of video-occlusion techniques (see Figure 2.1 for an example of the spatial and temporal occlusion of handball shots). As can be seen in the lower panels of Figure 2.1, the whole dynamic patterns of the action are affected by occlusion. I would like to highlight that for both spatial and temporal occlusion there is an important subjective component concerning the decision about what and when to occlude. This process is typically made without using specific temporal landmarks that define the exact frames or positions that will be occluded. This makes video occlusion difficult to replicate (although one may question whether such subtle changes affect performance, and to what extent, the process is clearly rough).

The expert-novice paradigm has been widely used in sport anticipation. Expert-novice differences inform about what dimensions of anticipation skill are susceptible to be learned. Experts use fewer and longer eye fixations in more relevant areas of the display when compared to novices (Mann et al., 2007). There is evidence showing differences of brain activation between experts and novices when facing an anticipation task (Bishop et al., 2013), even when only kinematic information is presented using PLDs (Wright et al., 2011).

Secondly, various sources of information are combined or used as compound variables to anticipate an action. At least, individuals seem to use kinematic as well as situational information (Loffing & Cañal-Bruland, 2017; Cañal-Bruland & Mann, 2015). Situational information refers to information about the occurrence of certain events in the past that affects anticipatory behavior. The combination of kinematic and situational information used for anticipation depends on the profile of the performers (Navia Manzano & Ruiz Perez, 2013) and the constraints of the task (Mann et al., 2014).

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[1] The thesis is focused on fast ball sports, concretely on the penalty kick because this is the stimuli used in the experimental studies. However, all the points are applicable for most of the situations in sport anticipation.
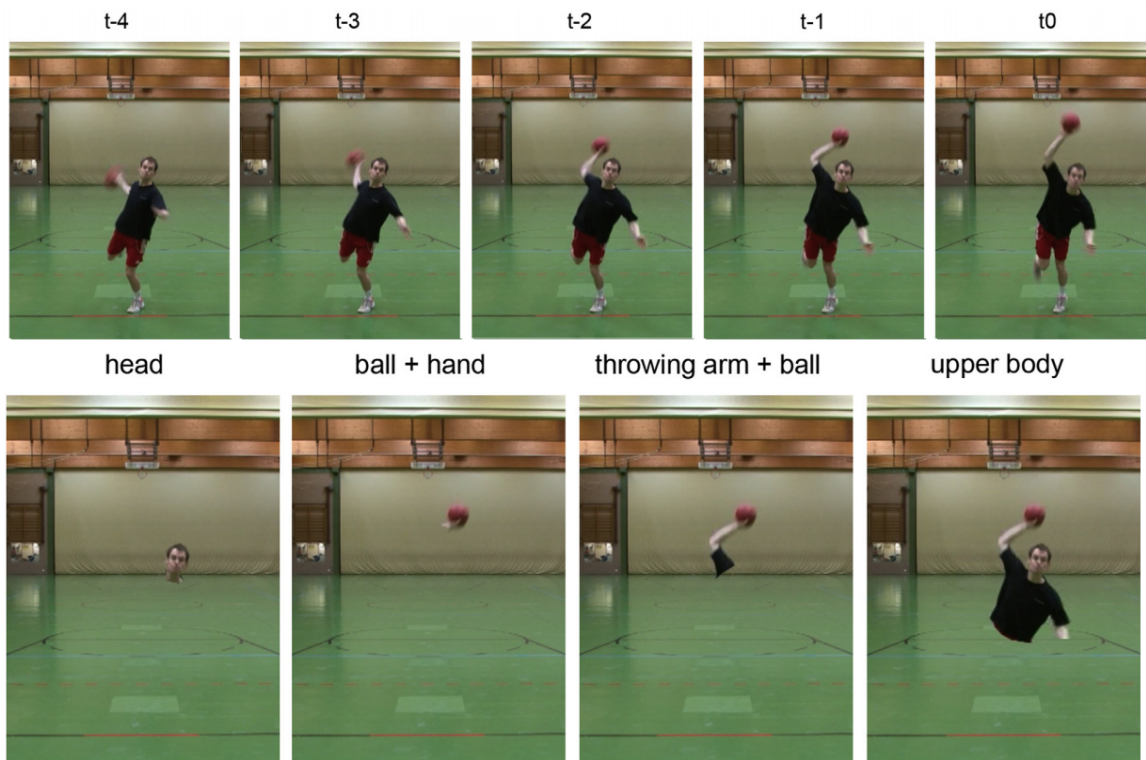
Figure 2.1: The upper panels show five temporal occlusion conditions of a handball shot. The indicated times correspond to the ball release (t0), 40 ms before ball release (t1), 80 ms before ball release (t2), 120 ms before ball release (t3), and 160 ms before ball release (t4). The lower panel shows four spatial occlusion conditions of the final frame of a handball shot. Adapted from Loffing & Hagemann (2014), with permission from Elsevier.

In third place, crucial information for anticipation is often located around the end effector (Williams et al., 2009). In the penalty kick situation, information is located in the lower part of the body, especially in the kicking leg and the non-kicking foot (Lopes et al., 2014). Deceptive movements tend to occur early. The movements converge to genuine ones close to the end of the action (Lopes et al., 2014). Consequently, the final moments before the action finishes are the most informative ones. However, if a defending player waits too long, it is likely that there will not be enough time to react (Lopes et al., 2014; Dicks et al., 2010). In the penalty kick situation, the goalkeeper has to initiate the movement around 120 ms before the kicker contacts the ball (Dicks et al., 2010, 2011; Franks & Harvey, 1997). One of the crucial advantages of expert players is that they respond faster and wait longer to respond than novices (Piras et al., 2014). As a consequence, expert players have access to more reliable information and are less susceptible to deception (Güldenpenning et al., 2017; Brault et al., 2012).

Despite the progress made in anticipation in sports in the last few decades, there are weaknesses that need to be overcome (Williams & Jackson, 2018; Huys et al., 2008; Dicks et al., 2015): the issue of transfer, the nature of information for anticipation, and the lack of a theoretical background in sports psychology studies.

The transfer of acquired improvements in anticipation performance from laboratory training environments to real-word tasks is still an unresolved issue. Back in 1994, in their seminal article "Can We Hasten Expertise by Video Simulations?", Starkes & Lindley, 1994 thought over the issue of the transfer of anticipatory skills from videos in the laboratory to on-court performance. After analyzing 4 available studies, Starkes and Lindley concluded that, when assessing transfer, anticipation training studies using video techniques tend to fail. Most training programs in the laboratory with videos show performance improvements. It may be assumed that the final aim of perceptual training studies in the laboratory is transfer to on-field performance. However, in many cases, improvements in anticipation performance are not transferred to on field performance (the issue of transfer will be discussed in chapter 3).

A second issue in anticipation research is that most of the studies lack a theoretical background to guide the research. As we will see in chapter 3, anticipation-training programs are characterized by heterogeneity in the quantities that are measured (amount of training, type of training, etc.). This may indicate a lack of a theoretical program that guides the research designs. We believe that the use

of a solid theoretical background, provided by ecological psychology, might help to solve the issue of transfer and generate future relevant research questions. In addition, the clear definition of information that is provided by ecological psychology might be useful for studies that aim to discover what kind of information is used for anticipation (as will be discussed in a next section).

Finally, the occlusion paradigm has answered questions regarding where and when information for anticipation is located. However, what kind of information is used for anticipation is still a pending issue. With traditional video occlusion studies, it is not possible to find the information that differentiates between the outcomes of an action (left-right direction in the case of the penalty kick). Several correlational studies that have been reported go beyond the classical occlusion paradigm and aim to identify the information for anticipation. In the case of the penalty kick, Díaz et al. (2012) used PCAs to determine if information for anticipation is local or global. They concluded that global information contributes more than local information to the anticipation of penalty kicks. Lopes et al. (2014) performed a correlational study using 720 deceptive and non-deceptive penalties. They reported that a linear combination of variables was most useful to predict the lateral direction of penalty kicks. However, these biomechanical variables are not information in the ecological sense. Rather, they structure the light in the environment in which the ecological information is to be found. A more direct exploration of the structure of the optical energy that is generated by biological motion may use PLDs. With this approach it is possible to find what information is used for anticipation. Identifying the information for anticipation will facilitate the design of training programs based on information for learning, allowing one to maximize the learning process over time.

2.2 Point Light Displays and Dimensionality Reduction

In 1973 Johansson pioneered a method to isolate kinematic information of human motion from pictorial information. Johansson (1973) recorded a person walking in a dark environment with reflective markers attached to the joints. When reproduced, the videos caused an immediate impression of a person walking, although only moving white dots corresponding to the position of the joints were visible. In the words of Johansson, this method can be used for "isolating information in motion patterns from information in form patterns". PLDs can isolate the kinematics of the movement from the pictorial information about textures. Once the kinematics are isolated it is easier to obtain the invariant patterns in the light produced by biological motion.

PLDs have been used to show that the kinematics of a person are informative about gender, intention, mood, and deception (Runeson & Frykholm, 1983). PLDs are widely used in research on anticipation in sports (see Shim, 2000, and Ward et al., 2002, for early examples). These early studies demonstrated that kinematics contain enough information to anticipate sport actions. After confirming that information for anticipation is indeed present in the kinematics of the actor, the next issue was to identify what information is actually used for anticipation in sports.

In the last few years, the development of motion-capture systems has allowed the registration, use, and analysis not only of videos containing PLDs, but also of the trajectories of the joints over time in 3D space. This technical advance has allowed the application of dimensionality-reduction techniques over the information in PLDs. With the advent of dimensionality-reduction techniques, a more quantitative approach to research on anticipation in sports has emerged.

PCA is the simplest and most common technique to reduce the dimensionality of a dataset. PCA is an algebraic transformation that reorganizes a dataset of correlated variables into a new dataset of independent/orthogonal modes. These modes are organized from the mode that explains most variance of the original dataset to the one that explains least variance. PCA is most often used in anticipation research to reduce the high-dimensional kinematic datasets used in PLDs. The space produced by the PCA can explain more than 95% of the variance in the original dataset using only 6 modes (Huys et al., 2008; see Daffertshofer et al., 2004 for a tutorial on how to use PCA). In addition, it is sometimes easier to interpret and manipulate the independent and linear PCA components than the original dataset. This allows researchers to manipulate or combine the amount of information in different experimental conditions to test what the nature of information for anticipation is.

The first study that we are aware of that combined PLDs with dimensionality-reduction techniques was Troje (2002) studying gender recognition based on modified gait patterns. Troje (2002) performed a two-stage PCA with a sinusoidal fit using Fourier series in between, and finally performed the classification via LDA over gait patterns[2] recorded on a treadmill. He observed that the dynamics of the motion contains more information about gender than the structural relations between body parts (mainly the hip-shoulder relation), in the classification as well as in the psychophysical test.

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[2]An interactive and representative example can be found here https://www.biomotionlab.ca/html5-bml-walker/

Huys and collaborators (2008) introduced this paradigm in the study of anticipation in sports. Since 2008 it has been applied to tennis groundstrokes (Cañal-Bruland et al., 2011; Huys et al., 2008, 2009; N. Smeeton, Huys, & Jacobs, 2013), handball penalty shots (Bourne et al., 2011, 2013), and football penalty kicks Diaz et al., 2012; Higueras-Herbada et al., 2017a, chapter 5 of this thesis).

Combining PLDs and PCA in anticipation in sports has produced relevant results. The information used for anticipation is global/distributed, dynamical, and low dimensional (Huys et al., 2008; Bourne et al., 2013; Diaz et al., 2012). Information used for anticipation is contained in the first few modes of the PCA (around 6 modes), which contain more than 95% of the variance in the original data; (Huys et al., 2008; Higueras-Herbada et al., 2017a). As discussed later in this thesis, it is important to remark that variance explained and information for anticipation are not the same quantity. PCA studies found non-significant differences in performance between the original stimulation and stimulation reconstructed with the first 6 PCA modes. This means that the PCA modes contain information for anticipation, but it does not mean that any of the modes can explain successful performance.

On the contrary, there have been some attempts to assess whether individual PCA components can distinguish between different outcomes of an action. For example, Bourne et al. (2011) compared PCA results as a function of the target location of handball shots and observed no significant differences between the PCA components of shots to different locations. This indicates that there were no dynamical differences captured by the PCA as a function of the outcome of the action. In the case of handball penalties, individual PCA components did not capture the information relevant to distinguish the shots. Huys and collaborators (2008) found that neither shot direction nor shot depth were uniquely characterized by a PCA component for tennis shots. They found that the differences between different tennis shots were found across modes and over the body-racquet.

Despite the contribution to anticipation in sports of this research program, some questions remain unanswered. First, as we will see in the next chapter, most of the studies on anticipation-training in sports lack a clearly defined theoretical background to guide the research. Second, a number of studies confirm that the information for anticipation is contained in a few PCA modes, but researchers still do not know what the information is.

For that reason, one of the aims of this thesis is to contribute to the design of training programs that used LDA instead or combined with PCA. The main advantage of this proposal is that the LDA components will be more closely related to information for anticipation. LDA defines components that best distinguish between left and right penalties. As a consequence, these components are directly relevant to the anticipation of the direction of penalty kicks. Relatedly, the LDA components are defined with respect to the to-be-perceived properties under the ecological framework discussed in the next section.

2.3   Ecological Psychology

Ecological psychology is an approach to perception and action that was developed during the second half of the twentieth century by James Gibson (Gibson, 1979). It was developed in opposition to the hegemony of the cognitivist approach proposed in the 1950s. There are at least three key characteristics that define ecological psychology as a radical theory: the status of the proximal stimulation, the active nature of perception, and the ecological level of analysis.

According to the status of the proximal stimulation, Gibson (1960) reviewed the role of the stimulus in psychology. He observed that cognitive psychology considers that the information provided by the proximal stimulation, received by our senses, is too poor to produce veridical perception. Cognitivism defends that the information that reaches our senses does not specify properties of the environment, meaning that this information needs to be processed to produce veridical perception. Consequently, for cognitivism perception is a process of enrichment, carried out by the brain, of the poor proximal stimulation with the goal to produce veridical perception. Given that this process may fail, cognitive psychologists focus a substantial proportion of their efforts to research on perceptual errors.

In contrast, Gibson based his theory of perception on the fact that animals are most of the time successfully adapted to their ecological niches. Gibson postulates the information that animals detect is rich enough to produce veridical perception. The available information specifies properties of the environment that are relevant to the perceiver, affordances. Gibson coined the term affordance as the substantiation of the verb to afford. An affordance is what the environment offers to the animal, the possibilities of action. Affordances are the objects of perception for ecological psychologists. This conceptualization has several consequences for the field of anticipation in sports. It implies that the ambient energy array contains information that specifies the relevant properties to act (in our case to anticipate the direction of a penalty kick). Therefore, the first task of a researcher aiming to develop an anticipation-training program is to describe in detail the informational basis of the penalty kick situation. This is the aim of the first part of the thesis, which provides a detailed study of the penalty kick situation from various

perspectives.

One of the main critics that have been made to the field of sports psychology is the lack of representative designs. In this sense, experiments designed at the ecological level of analysis tend to be more representative. The active nature of perception is a key contribution of ecological psychology. Cognitive psychologists often consider perception a passive act of receiving and processing information to produce a motor response. In contrast, for ecological psychologists, perception is an active process. Animals exploit the lawful relations between information and the properties of the environment only when they can move/act in the environment. To emphasize this relationship ecological psychologists use the term perception-action coupling to state that to perceive we need to act, and to act we need to perceive.

According to Gibson, the psychological phenomena should be studied at the ecological level of analysis. As Gibson described in his study of the stimuli, cognitive psychologists measure the stimuli in abstract physical units such as meters, kilograms, and the like. These physical properties are not directly relevant to the animals. However, affordances are relevant to animals. For example, animals do not perceive distance in meters. They perceive it in the relative magnitudes of the interaction with the environment. For ecological psychologist the study of perception should be carried out at the ecological level of analysis, where relevant variables for the animal are defined. Considering the ecological level of analysis as the appropriate level to study anticipation in sports implies getting closer to representative designs.

2.4 Direct Learning

In the original formulation of Gibson, learning was conceived as the education of attention, although he acknowledged that the possibilities of learning are unlimited. In Gibson's words: "The process of pickup is postulated to be very susceptible to development and learning. The opportunities for educating attention, for exploring and adjusting, for extracting and abstracting are unlimited" (Gibson, 1979; p. 250). The education of attention is the process of convergence to more useful informational variables with practice. In the late twentieth century, some authors claimed that the approach to learning of ecological psychology was not concrete enough to provide a full understanding of this complex process (C. Michaels & Beek, 1995; Strelow, 1985).

The direct learning theory considers two levels of analysis: the short timescale of perceiving and acting and the long timescale of learning (D. Jacobs & Michaels, 2007). Jacobs and Michaels applied the principles of direct perception, described in the previous section, to the longer timescale of learning so as to respond the above-mentioned critique. Ecological psychology conceives perception as informationally guided. Likewise, direct learning claims that learning is a single-valued function of structured patterns that emerge from the interaction of the organism with its environment. Therefore, under both approaches, neither perception nor learning require inferential or representation-mediated processes. According to the theory of direct learning, learning may be due to the education of attention, calibration, and/or the education of intention.

The education of intention refers to the process by which a learner chooses what action should be performed. As mentioned in the previous chapter, the ecological approach is a quantitative approach to perception and learning. Consequently, the intention of the learner will determine the ambient energy array that is relevant for the task; in terms of the direct learning theory, the information space that is relevant to the task. During learning, while maintaining the intention unchanged, agents converge toward the use of more useful variables to perform a task (as we have seen in the case of sports, experts use more useful variables to anticipate the opponent's behavior). This process of convergence from less useful to more useful variables is what Gibson referred to as the education of attention (1979). The third process described in the theory of direct learning is calibration. The ecological approach conceives perception and action as single-valued functions of informational variables. Changes in the single-valued function itself are referred to as calibration. For anticipation in sports, calibration would account for two performers who have different levels of anticipation when detecting the same informational variable.

Learning implies changes over the time in the single-valued function, in the intention, and/or in the variables that are detected. To account for these changes, the theory of direct learning makes use of ordinary differential equations and introduces several new concepts. Ordinary differential equations are one of the most powerful tools to describe processes that change over time (Strogatz, 1994; Haken et al., 1985), such as learning.

One of the concepts in the theory of direct learning is the information/calibration space. The concept of information/calibration space was introduced to represent the richness of the ambient energy array. An information space is a n-dimensional space in which every point represents a higher order property of the ambient energy array. Information spaces have been used to describe the informational basis of a task and to show the convergence toward useful variables during the learning process (as we will see in chapter 8). Another relevant concept is the usefulness function. The usefulness function is a function that

represents the maximum performance that can be achieved as a function of the informational variables used to perform a task.

A final concept introduced by the theory of direct learning is the concept of information for learning. Information for learning is an informational quantity that can be identified in the agent-environment interaction when an agent is performing a particular task, and that specifies the movement in the information space. Information for learning can be represented with vector fields in information spaces, connecting the theory of direct learning to the theory of ordinary differential equations. A vector field in an information space is a description of a system of ordinary differential equations. The solutions to the system of differential equations are the learning paths that agents are predicted to follow in a learning task (if information for learning is guiding the learning process). The existence of information for learning implies that there is no need for inferences or mental representations in the learning process, which is to say, learning is direct under this framework as perception is direct for ecological psychology.

In sum, Jacobs and Michaels (2007) developed a theory of learning that does not rely on representations and mental processes. Learning is specific to detectable properties of the ambient energy array, information for learning. There are at least three processes of learning: education of attention (changes in variable use), education of intention (changes in the intention of the agent), and calibration (changes in the single-valued function that describes the perception-action coupling). In chapter 9, the theory of direct learning will be further developed.

The aim of this thesis is to develop the methodological tools needed to apply the theory of direct learning to an anticipation-training program in the penalty kick situation. To achieve our aim, a series of studies was performed. In first place, a detailed study of the penalty kick situation itself both from the kicker and goalkeeper's point of view. In second place, a reduction of the information in the penalty kick situation is needed as explained in chapter 1. Thirdly, classification techniques were used to provide an informational description of the penalty kick situation from the perspective of the goalkeeper. And finally, PCA and LDA techniques will be presented and tested that may be useful for the design of anticipation training programs. Applying this methodology to anticipation-training programs will allow researchers to design more efficient and informationally guided training programs.

Part II

Introductory Studies

Chapter 3

Training Perceptual Anticipation in Sports Since the Nineties: A Systematic Review

The[1] training of perceptual anticipation in sports is of great interest to coaches, athletes, and scholars. The present article provides the first systematic review of the large literature concerning this topic. By a combination of removing duplicates, reading abstracts and titles, and full-text reading, 11668 original search results from four databases were reduced to the 42 studies that were included in the review. These studies were evaluated on aspects related to their design, training, and dependent measures. Positive aspects of the reviewed literature include the variety of the considered sports, the expertise of the players used to create stimuli, and, especially for on-field studies, the high proportion of action-related measures of performance. Negative aspects include the high proportion of novice participants in the training programs and the general lack of transfer from laboratory training to on-field performance. The article is concluded with ten recommendations for future training programs, concerning placebo and control groups, expert participants, on-field training, neutralization techniques, deception, standardized training programs, contextual information, informational variables, process-tracing techniques, and representative design.

3.1   Introduction

Anticipation performance in sports has been studied extensively in the last 50 years (Williams & Jackson, 2018). Being able to anticipate what your opponent will do provides a decisive competitive advantage. The superior anticipation performance of experts is at least partly based on skills such as an improved task-specific information detection and a more focused gaze behavior (Mann et al., 2007). In addition, experts are less susceptible to deception (Güldenpenning et al., 2017) and respond faster and more accurately in time-constrained situations (Piras et al., 2014). There is also evidence that shows differences in brain activation between experts and novices when confronted with situations in which anticipation is crucial (Bishop et al., 2013; Wright et al., 2011). Evidence for the existence of expert-novice differences can be found for a wide variety of sports.

Although the existence of differences between experts and novices is well documented, the details of how these differences emerge during the learning/training are less well understood. Experts spend more time doing sport specific training and they perform activities that novices do not perform as often, including video training, individual sessions, and competitions (Baker et al., 2003a,b). Which aspects of these and other activities are the most crucial ones in order to achieve expertise? Related to this question, many perceptual training programs have been designed with the aim to facilitate the process by which novices graduate toward expert performance (Starkes & Lindley, 1994; Williams & Grant, 1999).

A first group of training programs focused on unspecific visual skills, referred to as *visual hardware*. These skills include processes such as depth perception, color perception, and dynamic acuity. The training programs were based on the belief that the basic visual skills of experts are superior to those of novices (Williams & Grant, 1999). Nowadays, however, most researchers believe that unspecific visual-skill training does not improve perceptual-motor performance in sports (Abernethy & Wood, 2001; Wood

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[1] This chapter is submitted to publication to International Reviews of Sports and Exercise Psychology under the following tittle: Training Perceptual Anticipation in Sports Since the Nineties: A Systematic Review5. Higueras-Herbada, A., Travieso, D., Ibáñez-Gijón, J., & Jacobs, D. M. (2019)

& Abernethy, 1997). Instead, most recent studies focus on those processes that are commonly referred to as *visual software* (Williams & Grant, 1999). In the present context, focusing on the visual software means directly addressing the perceptual skills that one aims to improve. Among the skills that may be addressed are the detection of information and gaze behavior.

Most of the early training programs concerning the (commonly-named) visual software have used video training in combination with occlusion techniques (Williams & Jackson, 2018). A relatively recent trend in the field is to move toward more representative designs using virtual environments (VEs), on-field training, or other techniques that do not alter the dynamic characteristics of the task as much as occlusion does (Araujo et al., 2006; Broadbent et al., 2015; Dicks et al., 2017). Experts are able to extract global dynamic patterns from the opponent's kinematics (Huys et al., 2009). In this sense, neutralization techniques may be preferred over occlusion, because neutralization alters the dynamic patterns to a lesser extent than occlusion, and, therefore, has a less detrimental effect on performance (N. Smeeton, Huys, & Jacobs, 2013).

Several narrative reviews of the literature on the training of perceptual anticipation have been carried out since the nineties. A first review that we are aware of is the one by (Starkes & Lindley, 1994). These authors claimed that transfer tests do not reach significance when videos are used as stimuli in the training. On the other hand, Williams & Grant (1999) reviewed 10 training studies and concluded that video training may be useful when combined with other instructional approaches. The claim that the field of perceptual training in sports should move toward more representative designs has been made by several authors. Examples can be found in the review by Farrow (2013), who concluded that training in VEs should replace video-based training, and in the one by Broadbent et al. (2015).

Other narrative reviews have focused on specific aspects of perceptual training. Jackson & Farrow (2005) considered the implicit-explicit dichotomy, suggesting that this distinction should in fact be seen as a continuum. According to Jackson and Farrow, implicit anticipation training has a greater effect on performance than explicit training when the situation is complex or the performer is under stress. Miles et al. (2012) analyzed the literature on the training of ball sports in VEs, focusing on the psychological and technical factors that have to be considered before using VEs. They concluded that successful VEs should provide a realistic rendering of the scene, allow for a real-time response, and include a natural user interface. Dicks et al. (2015) reviewed perceptual learning studies performed under the ecological approach. Their main conclusion was that experimental methods that allow learners to interact with their environment give rise to better results.

Despite the generally large interest in the training of perceptual anticipation in sports, we are not aware of the existence of systematic reviews of the literature. As detailed above, rather than systematic reviews, one can find narrative reviews and reviews that focus on particular aspects of perceptual training. Notwithstanding the relevance of narrative reviews, the risk of bias is high, because the search strategy and the inclusion/exclusion criteria are not explicit. In addition, it is not possible to replicate the literature search of narrative reviews. The need for a systematic review of this field is further indicated by the heterogeneity of the results of the training programs (e.g., Williams & Grant, 1999)[2]

The present article presents a systematic review of the literature on the training of perceptual anticipation in sports from 1990 to 2018. The review contributes a critical summary of the literature, addressing issues such as the type of stimuli that are used, the level of skill of participants, the inclusion of control and placebo groups, and whether studies include quantitative measures of performance, retention, and transfer. We hope that the results of the review will be useful for training programs that may be developed in the future.

3.2 Method

3.2.1 General Information

To elaborate this review, we followed the guidelines from the Preferred Reporting Items for Systematic reviews and Meta-Analyses Protocols (PRISMA-P; Moher et al., 2015). The search was performed in January 2019, using the following databases: PsycINFO, PsycARTICLES, SPORTDiscus, and Web of Science. Three groups of descriptors were used, joined by AND operators: anticipation related terms (Anticipation OR Perception OR Prediction OR Estimation OR Judgement), training related terms (Learning OR Training OR Skill Acquisition OR Perceptual Training OR Visual-Perceptual Training OR Instruction OR Perceptual Learning OR Perceptual-Skill Training), and a sport related term (Sport).

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[2]The systematic review that we are aware of that is most closely related to perceptual anticipation is the one by Brand & de Oliveira (2017). Brand and Oliveira, however, addressed the specific concept of recalibration and did not focus on sports. As a consequence, none of the studies that were included in their review is included in ours, and vice versa.

These terms were selected as the most commonly used keywords in perceptual-training studies in peer-reviewed journals.

3.2.2   Inclusion Criteria

The criteria to include a study in the review were: (a) the study was published in English, (b) the study was published in a peer-reviewed journal, (c) the study tested perceptual learning in sports with performance measures, and (d) the performance measures were reported before and after the intervention (in a pretest and a posttest). Therefore, studies about expert-novice differences were excluded, as well as conference presentations and studies that reported only decision times or gaze behavior.

3.2.3   Study Selection

Figure 3.1 illustrates the literature search. A total of 11668 studies were identified with the above-mentioned combination of keywords. Of these studies, 6348 were obtained with PsycINFO, PsycARTI-CLES, and SPORTDiscus (combined using EBSCO) and 5320 with Web of Science. As indicated at the top right of the figure, six studies were added to this initial selection on the basis of the references of the studies that were fully read at a later phase of the process. After removing duplicates with RefWorks, 8421 studies remained, which were all screened based on the title and abstract. After this screening, 8315 studies were excluded, leading to 106 studies that were eligible for full-text reading. After the full-text reading, 64 further studies were excluded, meaning that a total of 42 studies were included in the review.
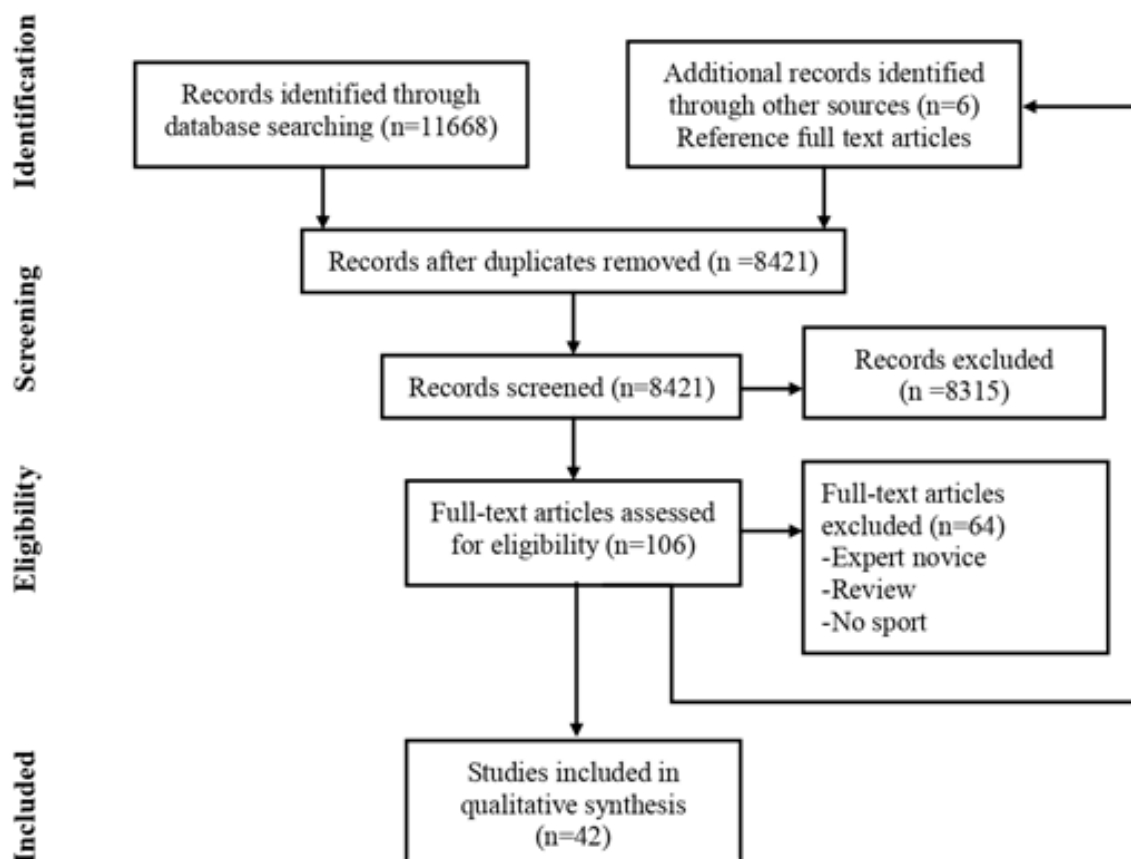

Figure 3.1: Flow diagram of literature selection.

3.2.4   Quality Assessment

The selected studies were submitted to a quality assessment with Crowe Critical Appraisal Tool 1.4 (CCAT; Crowe & Sheppard, 2011a,b). This tool was designed to rate research papers on the basis of eight categories: preliminaries, introduction, design, sampling, data collection, ethical matters, results,

and discussion. For each category the maximum score is five, meaning that the maximum total score is 40. These total scores were transformed into percentages. Using CCAT for the evaluation of research articles improves consistency, absolute agreement, and reliability when compared to an informal evaluation (Crowe et al., 2011, 2012).

3.2.5 Data Analysis

Three groups of descriptors were extracted from the articles: design (quality assessment, sample, sport, stimuli, and response type), training (amount and type of training), and dependent measures (performance, retention, transfer, and other dependent measures). The extracted data were double-checked at different moments by the first author. When the information concerning a particular descriptor was not clear, the measurement was omitted and treated as missing data. The results are reported as percentages, centralization and dispersion measures (mean, median, mode, and standard deviation), and correlations.

3.3 Results

3.3.1 Design

Quality Assessment. Table 3.1 shows the results of the quality assessment with CCAT. The average quality of the studies was 68.69%. More recent studies tended to punctuate higher in the assessment, indicating higher general standards in recent research. The poorest results were observed in the sections concerning sampling, 2.19, and ethical matters, 2.10. In general, the sampling method and the target sample for the perceptual training were not sufficiently well defined. In addition, a few studies did not report information about ethical committees, funding, or potential conflict of interest.

Sample. Table 3.2 (Appendix B) summarizes the information that was extracted from the 42 studies that were reviewed. A total of 1701 participants in 48 experiments were exposed to different types of perceptual training or control conditions. Four studies consisted of more than one experiment: two experiments were included in Schorer et al. (2015) and Broadbent et al. (2017) and three experiments were included in Memmert et al. (2009) and N. Smeeton, Huys, & Jacobs (2013). In the remaining part of this review, we describe the results in terms of number of experiments rather than number of studies.

The average number of participants per experiment was 35.44 (max = 104, min = 1; only one study reported a single-case training). Of the 1701 participants, 222 were high-skill players (professionals, semi-professionals, and players with extensive experience), 449 were medium-skill players (recreational players; intermediate-level players; and highly-skilled participants not performing at their usual position, such as field players behaving as goalkeepers), and 1030 were low-skill players (novices; in most cases students participating in research for course credit)[3].

Sports. As can be observed from the third column of Table 3.2, 10 sports were assessed in the experiments reviewed: tennis (n = 13), badminton (n = 9), football (n = 8), volleyball (n = 5), basketball (n = 3), karate (n = 2), handball (n = 2), cricket (n = 2), squash (n = 2), softball (n = 1), and hockey (n = 1). All situations involved a decision-making task in an individual or team situation from the perspective of the player that had to decide.

Stimuli. The quality of the stimuli is an important factor in relation to the quality of a training program. For example, training without sufficient variability in the stimuli may result in mere adaptation to personal characteristics of the player that is shown in the stimuli, and hence in a type of learning that does not generalize (Hagemann & Memmert, 2006). In this review, we used two characteristics to indicate the quality of the stimuli: the number of players that were used to create the stimuli and the level of expertise of those players.

In 37 of the 48 experiments, expert players were used as performance models in the stimuli. In four other experiments, the performance models had a similar level of expertise as the participants in the training (in three cases a low skill level and in one case a medium skill level). Five studies did not report information about the players that were used as models in the stimuli. The model performers in the remaining two studies were either amateur players or several players with different levels of expertise. All except one of the studies that reported this information used more than one player to create the training stimuli.

Response Type. All studies measured performance before and after the training intervention, which, in fact, was an inclusion criterion. However, there were large differences in the dependent variables used to assess performance. Of the experiments, 19 used a movement as dependent measure, 13 used a keyboard

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[3]This classification in three levels was performed by the first author of the review. In the original articles, the level of expertise of participants was indicated in different ways. The terminology that was used in the original articles included the words: novices, students, recreational/college players, regional/national/international level, (semi-)professionals, less/low/intermediate/highly skilled, or trained/experienced participants.

	Preliminaries	Introduction	Design	Sampling	Data Collection	Ethical Matters	Results	Discussion	Total (40 max)	Total (%)
Christina et al. (1990)	4	4	3	1	3	0	2	3	20	50.0
Williams (1993)	2	5	3	3	2	0	2	2	19	47.5
Singer et al. (1994)	5	5	3	3	2	1	3	4	26	65.0
McMorris & Hauxwell (1997)	3	5	3	1	2	0	0	3	17	42.5
Farrow et al. (1998)	5	5	3	3	4	0	3	4	27	67.5
Abernethy et al. (1999)	3	5	3	3	3	2	4	4	27	67.5
Moreno et al. (2002)	3	3	1	3	3	0	2	1	16	40.0
Farrow & Abernethy (2002)	4	5	3	3	3	3	3	3	27	67.5
Williams et al. (2002)	5	4	4	2	4	1	4	4	28	70.0
Williams et al. (2003)	3	5	4	3	4	1	4	4	28	70.0
Williams et al. (2004)	4	5	4	3	4	1	4	5	30	75.0
Poulter et al. (2005)	5	5	4	1	3	1	4	3	26	65.0
Smeeton et al. (2005)	5	5	4	3	4	3	4	3	31	77.5
Hagemann et al. (2006)	5	3	3	3	2	0	4	3	23	57.5
Hagemann & Memmert (2006)	4	5	3	1	2	1	3	4	23	57.5
Caserta et al. (2007)	5	5	4	3	5	1	4	4	31	77.5
Gabbett et al. (2007)	5	5	4	3	4	1	4	3	29	72.5
Gorman & Farrow (2009)	5	5	4	3	3	1	4	5	30	75.0
Votsis et al. (2009)	4	4	4	1	4	0	3	4	24	60.0
Memmert et al. (2009)	5	5	4	1	2	1	4	3	25	62.5
Savelsbergh et al. (2010)	5	5	3	3	3	3	4	4	30	75.0
Hopwood et al. (2011)	5	5	4	2	5	0	4	4	29	72.5
Lola et al. (2012)	4	5	3	0	3	1	3	3	22	55.0
Abernethy et al. (2012)	4	5	3	2	3	0	4	5	26	65.0
Smeeton et al. (2013)	5	5	4	3	3	3	4	3	30	75.0
Ryu et al. (2013)	5	5	4	0	3	4	5	4	30	75.0
Smeeton et al. (2013)	5	5	4	1	3	5	4	5	32	80.0
Milazzo et al. (2014)	4	5	4	3	5	4	4	4	33	82.5
Murgia et al. (2014)	5	5	5	3	4	2	3	4	31	77.5
Schorer et al. (2015)	5	3	4	3	3	2	4	4	28	70.0
Tzetzis & Lola (2015)	4	5	3	2	3	1	5	3	26	65.0
Nimmerichter et al. (2015)	4	3	4	2	2	3	4	4	26	65.0
Klostermann et al. (2015)	4	4	3	1	4	5	4	4	29	72.5
Milazzo et al. (2016)	5	4	4	2	4	4	5	4	32	80.0
Alder et al. (2016)	5	5	4	2	3	4	4	3	30	75.0
Alsharji & Wade (2016)	4	5	4	2	4	1	5	4	29	72.5
Ryu et al. (2016)	4	5	4	1	3	5	5	4	31	77.5
Broadbent, Ford, et al. (2017)	5	5	3	4	3	4	4	5	33	82.5
Broadbent, Causer, et al. (2017)	5	5	4	1	5	5	5	5	35	87.5
Dicks et al. (2017)	4	5	4	2	5	4	3	3	30	75.0
Ryu et al. (2018)	5	5	4	1	4	5	5	5	34	85.0
Hüsdünker et al. (2018)	5	5	4	5	5	5	5	5	39	97.5
Average	4.40	4.69	3.60	2.19	3.40	2.10	3.76	3.76	27.48	68.69

Table 3.1: Quality Assessment With CCAT

response, 8 an oral response, 7 a mouse response, 3 a pen and paper answer, and 2 a joystick response. One may note that the sum of the response types is 52 while we reviewed 48 experiments. This is so because four studies used two ways to assess performance.

The aim of several studies was to compare performance as a function of response mode. Farrow & Abernethy (2002) compared coupled responses (movements) to uncoupled responses (oral predictions). They found that prediction accuracy was better for the coupled responses when ball-flight information was presented. Milazzo et al. (2016) also compared coupled and uncoupled conditions, for karate, and found that both groups improved from pretest to posttest. Williams et al. (2004) compared perception and perception-action types of training in an on-court situation. They observed that both types of training led to significant improvements, without observing significant differences between the types of training. Alder et al. (2016) asked participants to execute a movement and to give an oral response, but only the oral response was used as dependent variable (the movements were used to increase the fidelity of the task).

In 44 of the 48 experiments, anticipation was evaluated in the laboratory (i.e., four experiments performed all phases on the field). Fifteen experiments tested at least some aspects of performance on the field. Of those 15 experiments, 14 evaluated performance in real match situations or with real

movements, in one experiment participants were asked to move but not to execute the real competitive movement, and in one experiment participants were asked to provide oral responses and real movements as different conditions (Farrow & Abernethy, 2002).

Control and Placebo. When testing a training program, the use of control and placebo groups is important in order distinguish actual effects of the intervention from other effects. Control groups typically do not receive any intervention and are used as a standard comparison. Placebo groups receive an intervention that is not hypothesized to produce beneficial effects, hence providing a measure of mere expectancy effects.

Control and placebo groups were used in 33 and 13 of the 48 experiments, respectively. The aim of several experiments was to compare different training conditions. In such cases, control and placebo groups are not strictly necessary; even so, it would still be advisable to include them. The control groups were used in two ways. In 12 of the 33 experiments with a control group, this group received a training intervention that differed from the experimental one (in four cases, participants' regular training). The other 21 experiments with a control group used a control group that did not receive any kind of training. All experiments that included a placebo group used this group to control expectancy effects (the placebo groups performed the same amount of training, but performing a different task).

3.3.2   Training

Type of Training. We observed large differences with respect to the types of training that were performed in the studies. This may be related to the existence of different theoretical approaches to perceptual learning. Although the final aim of all perceptual training programs is to improve performance, theoretical and practical assumptions lead to the use of different intervention methods. This subsection summarizes the interventions of several studies.

Video-based stimuli were used during the training phase in at least one of the experimental groups in 44 of the 48 experiments. As also mentioned in the subsection Response Type, the remaining four studies performed all the phases on the field. Some type of on-field training was used in 10 of the 48 experiments, including the four experiments that did not use video-based stimuli at all.

From the total of 92 experimental groups, 28 used explicit instructions to guide the participants' anticipation behavior during the task. We use the term explicit instruction in the sense of Jackson & Farrow, 2005 (2005, p. 315), indicating instructions that "explicate a causal relationship between particular cues and/or patterns of movement and a relevant behavioral outcome." The remaining 64 experimental groups used implicit instructions. Implicit-instruction groups used a wide variety of methods, including secondary tasks, guided discovery, practicing with important information highlighted, watching videos without further instructions, or physical training.[4].

Other training methods that were used in the experimental groups of the reviewed experiments included: mental/physical quickness (n = 1), random/easy-to-hard order of stimuli (n = 1), feedback/no feedback (n = 1), occlusion (n = 14), imagery (n = 1), neutralization of information (n = 3), learning by analogy and metaphor (n = 1), slow motion videos (n = 1), local or global masks (n = 1), stroboscopic training (n = 1), and spatial frequency manipulation (n = 1).

Amount of Training. We analyzed three measures related to the amount of training: the number of trials that were performed during the intervention, the duration of the intervention in minutes, and the duration of the intervention in days[5]. As indicated by the blank spaces in Columns 6 to 8 of Table 3.2, 20 of the 144 duration-related measurements were not reported. As shown in Table 3.2, the average intervention duration was 263.9 trials, 17.0 days, and 179.1 minutes. The variability of the measurements was high; therefore, the median and mode are also reported in the table. In experiments with more than one experimental group, the groups received comparable amounts of training (see subsection Control and Placebo).

3.3.3   Dependent Measures

Performance. Performance improvements are defined as significant changes from pretest to posttest in a positive direction. Of the 28 experimental groups with explicit instructions, 19 reported improvements; and of the 64 experimental groups with implicit training, 44 reported improvements. This means that explicit and implicit procedures showed a similar rate of success: 67.9 and 68.8%, respectively. To test if performance improvements were related to the amount of training, point biserial correlations between

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[4]A representative example of an explicit indication is the one concerning a drop shot in tennis (N. J. Smeeton et al., 2005): "Look at the player's backswing, see how small the backswing is in comparison to other shots." Implicit training instructions may be defined in opposition to explicit instructions, meaning that participants are not given explicit rules about the relationship between body movements and action outcomes.

[5]To compute the duration in days we used the following approximation: 1 week = 7 days, 1 month = 28 days.

	Trials	Days	Minutes
Mean	263.9	17.0	179.1
STD	188.8	20.4	206.1
Mode	360	1	120
Median	240	7	120

Table 3.2: Amount of Training in the Studies Reviewed

improvements (yes/no) and the three measures of the amount of training were computed (for implicit and explicit training independently). Table 3.3 shows the results: no significant correlations were observed.

		Trials	Days	Minutes
Implicit	r	0.16	-0.08	0.14
	p	0.38	0.63	0.53
Explicit	r	0.04	-0.05	0.33
	p	0.88	0.83	0.22

Table 3.3: Point Biserial Correlations Between Improvement with Training (Yes/No) and the Three Measures of Amount of Training with Associated p Values for Implicit and Explicit Training Conditions

Retention. Retention tests are performance tests a certain time interval after the posttest. The underlying idea is to test whether improvements with practice are preserved over time. Of the 48 experiments, 16 performed a retention test. On average, those tests took place 19.6 days after the posttest (SD = 33.1; min = 1, max = 140). All retention tests except one took place in laboratory settings. One study included retention tests on the field as well as in the laboratory (Gabbett et al., 2007). The posttests and retention tests were identical in all studies. The large majority of the studies (14 out of 16) reported that performance was maintained from posttest to retention test for at least one of the experimental groups.

Transfer. Transfer is defined as the generalizability of learning to situations other than the learning environment. In perceptual training in sports, the most relevant case of transfer relates to the question whether performance improvements in the laboratory are maintained when tested on the field. Our analysis of transfer included 44 instead of 48 experiments, because four studies performed all phases on the field (Caserta et al., 2007; Dicks et al., 2017; Williams et al., 2004; Hülsdünker et al., 2019). Transfer tests were performed in 11 of the 44 experiments. The transfer reached significance in at least one experimental group in 4 of those 11 experiments. We next briefly describe the four studies that performed all phases on the field.

Williams et al. (2004) compared two types of training: perception based and perception-action based. All stages took place on the tennis court (pretest, training, and posttest). No differences between the types of training were observed; in a posttest, both experimental groups outperformed a technical-instruction control group. The authors concluded that both types of training enhance perceptual skills. Caserta et al. (2007) experimental groups performed all stages on the tennis court. There were three experimental groups: perceptual-cognitive skills, footwork training, and a no-training control. The average age of the participants was 56.6 years. The authors observed superior posttest performance for the perceptual-cognitive skills training as compared to the other experimental groups. Dicks et al. (2017) performed an on-field training for football penalty kicks based on reduced-usefulness training (N. Smeeton, Huys, & Jacobs, 2013) for football penalty kicks. They reported that this training is more beneficial than traditional practice when facing non-deceptive penalty kicks. Hülsdünker et al. (2019) performed a 4-week on-field stroboscopic training for top-level badminton players. The stroboscopic-training group performed significantly better in the posttest than a normal-vision control.

Other Dependent Measures. In addition to the measures of performance addressed in the sub-

section Response Type, several studies measure other variables. Decision time was measured in 22 of the 48 experiments, explicit rule formation in 10, gaze behavior in seven, and stress, deception, movement time, and EEG were all measured in one experiment.

Decision time was measured in the pretests and posttests of those 22 experiments. In 17 experiments, the decision time decreased after the training for at least one of the experimental groups. The remaining five studies did not report a decrease in decision time. Improvements in decision time and performance were not always related. Five experiments showed improvements in performance but not in decision time; and of the 17 experiments that showed improvements in decision time, three did not show improvements in performance.

Explicit rule formation is a free-recall test that assesses explicit knowledge of the cues and/or rules used to anticipate the outcome of the situation. This procedure was used in 10 experiments. In four of the experiments, the explicit group recalled more explicit rules than the other groups. Remember, however, that the explicit groups received explicit instructions, making it less surprising that these groups recalled more explicit rules. Only one study controlled for the similarity between the rules that were provided during the explicit training and those that were recalled by participants; no significant differences were observed when only self-generated rules were taken into account (N. Smeeton, Hibbert, et al., 2013).

Gaze behavior was analyzed in seven experiments, using different measures: fixation duration, saccadic amplitude, areas of interest, breadth of search relative to the relevant actor, spatiotemporal differences of gaze between pretest and posttest, gaze entropy, number of fixations, and visual pattern learning. In general, studies reported an increase in fixation duration and a decrease in the total number of fixations. Only one article did not analyze any of the previously mentioned variables. Klostermann et al. (2015) defined functional and dysfunctional color cueing during training sessions and observed that only dysfunctional cueing led to changes in gaze behavior.

3.4 Discussion

This article reports a systematic review of the literature on the training of perceptual anticipation in sports. The review spans the period from 1990 to 2018 and addresses issues such as the type of training, skill level of participants, experimental design, performance variables, or whether the studies included retention and transfer measures. The remaining part of the article discusses the positive and negative aspects of the reviewed literature and the heterogeneity of the encountered methods. We conclude with a list of 10 recommendations for future training programs.

Let us first mention, however, that the quality assessment with CCAT (Crowe et al., 2011; Crowe & Sheppard, 2011a) indicated that ethics and sampling were the categories with the lowest scores. A substantial proportion of the studies did not provide sufficient information about the ethics-related items such as informed consent, equity, confidentiality/anonymity, ethical approval, funding, or conflict of interest. With respect to sampling, few studies informed about the suitability of the sample size; performing, for example, a priori power analyses.

3.4.1 Positive Aspects: Sports, Stimuli, and Measures of Performance

Positive remarks about the reviewed literature can be made with regard to the variety of sports, the quality of the stimuli, and the methods used to measure performance. Concerning the first of these issues, a wide variety of sports were used to test perceptual training, including individual and team sports, racket and ball sports, and martial arts. In general, the results in terms of performance improvements in the laboratory were promising. This may encourage researchers to keep investigating how perceptual learning can be enhanced.

Concerning the stimuli, 77.1% of the experiments used expert players to create the stimuli for the training programs. In this sense, the average quality of the stimuli was high, exposing learners to genuine information patterns of expert performance. Hagemann & Memmert (2006) pointed out that when transfer is the final aim of a training program, training with experts is an important feature. The variety of players used as models is also a positive factor in the quality of the stimuli: all but one of the studies used more than one player to create the stimuli.

Concerning the ways to measure performance, 93.3% of the on-field experiments asked participants to perform a real movement, and 39.6% of the laboratory experiments asked them to perform a movement similar to the ones in an on-field situation. The type of performance measure affects the way in which participants approach a task. For example, Lappi et al. (2017) observed different gaze patterns between laboratory experiments and real-world tasks, and Roca et al. (2014) observed that the nature of the response affects the used processing strategies. In a meta-analysis, Travassos et al. (2013) demonstrated that expert-novice differences are more pronounced on the field than in the laboratory. Perceptual

anticipation training should, therefore, use experimental responses that are as similar as possible to actual competitive situations.

3.4.2   Negative Aspects: Skill Level of Participants and Transfer

The majority of the research that we reviewed addressed the early stages of the learning process: 60% of the participants were novices and 13% experts. Researchers tend to assume that the same principles of training apply to experts and novices (Williams et al., 2008). Even so, novices are arguably not the target population of the training programs. In this sense, it is relevant to recall the claim of Ward et al. (2008) that "only limited specific evidence is available to those wishing to enhance the performance of highly skilled and elite athletes" (p. 82). To improve research on perceptual anticipation in sports, it is therefore recommendable to perform additional research with professionals and other highly skilled players as participants in the training programs.

A second aspect of the literature that may be classified as negative is the issue of transfer. Transfer tests evaluate whether laboratory training is useful when facing actual competitive situations. Of the reviewed experiments, 25% included a transfer test; of those, 36% demonstrated positive transfer. We are not aware of specific differences between the training programs in our review that led to positive transfer and those that did not. It has been claimed that perceptual video training is useful only when traditional training is not possible, for example when athletes are injured (Starkes & Lindley, 1994; Williams & Grant, 1999). Even so, most of the studies in the review used video as perceptual training method. Only 21% of the experiments performed on-field training. In any case, given the proportion of non-positive results shown in this review, and the general agreement about the importance transfer (Broadbent et al., 2015; Starkes & Lindley, 1994), the research field on the training of perceptual anticipation should increase its focus on transfer.

3.4.3   On the Heterogeneity of Design in the Reviewed Literature

Several aspects of the reviewed literature are difficult to classify as positive or negative. We included these aspects in this subsection on the heterogeneity of design in order to emphasize the large variety of training methods that were encountered in the review. The issues that will be discussed in this subsection are retention, amount of training, control and placebo groups, and representative design.

A substantial proportion of the retention tests in the reviewed studies (more than 87%) showed that performance improvements are maintained over time. This may be interpreted as a positive aspect of the literature. However, the variability in the time interval between the posttests and retention tests was high: this interval ranged from 1 to 140 days. With such variability, it is difficult to extract general conclusions. Also, in our view retention tests are often misapplied. This is so because, in many cases, no regular training is performed between the posttest and the retention test. Expert athletes, however, rarely stop training. It would therefore be relevant to test if performance advantages are maintained while participants continue with their regular training.

A next relevant issue is the training duration. Williams & Grant (1999) encountered studies with one session of training that led to improvements in performance and others with more sessions that did not. Our review showed a similar landscape; for example, an experimental group with one day of training (90 min; 48 trials) showed improvements and one with 28 days of training (240 min; 600 trials) did not. Moreover, we did not observe significant correlations between improvements in performance and the amount of training. We believe that this may be attributed to the heterogeneity of the training programs. Such heterogeneity makes comparisons difficult. In our view, future lines of research should establish more standardized protocols to facilitate the comparison of training interventions.

Control groups were used in 69% of the reviewed studies and placebo groups in 27%. This latter percentage is an improvement with regard to the percentages that can be found in Williams & Grant (1999): 1 out of 10 of the studies that were reviewed by these authors used a placebo group. In addition, 36% of the control groups received some type of intervention (physical/motor training, home training, videos). For that reason, these groups might also be considered placebo groups. However this may be, the percentage of studies that do not control expectancy effects remains high.

A final issue is the one of representative design—a key factor in sports training (Dicks et al., 2009). Representative designs should include as many real-world constraints on performance as possible, which may include fatigue, anxiety/pressure, deception, ecological information, and perception-action coupling (Williams & Jackson, 2018). Said with more precision, representative designs should include all factors that affect performance in competitive situations. Not surprisingly, no study is perfect in this regard, and the studies in this review that were performed on the field tended to be more representative than the ones performed in the laboratory.

3.4.4 Recommendations for Future Training Programs

Combining the results of our systematic review and other recent research in sport science, we propose 10 insights for future training programs:

1. There is a need to include control and placebo groups in research on anticipation training in order to properly control expectancy effects. Even when different training conditions are compared, no-practice control and placebo groups may be relevant.

2. Given that experts are the main target population of many training programs, future research should increase the number of experts in the samples (Williams & Grant, 1999; Ward et al., 2008)

3. To overcome the issue of transfer, on-field perceptual training should be preferred over laboratory training when testing new methods (Dicks et al., 2017; Hülsdünker et al. 2018).

4. In laboratory settings, the neutralization of information should gradually replace traditional occlusion and cueing techniques (N. Smeeton, Huys, & Jacobs, 2013). The use of VEs facilitates neutralization techniques and would be recommendable.

5. The role of deception should be considered in training programs. Only three of the studies in this review addressed deception (actually indicating that there is less improvement when training with deception).

6. There should be an effort to develop standardized training programs that can be tested with different sports and with different samples, allowing better comparisons among training methods (Farrow & Abernethy, 2002; Williams & Jackson, 2018).

7. None of the training programs in this review considered contextual information, despite its demonstrated relevance for anticipation (Cañal-Bruland & Mann, 2015). Future studies should test if and how the use of contextual information can be trained.

8. Training programs based on occlusion and gaze registration have focused on the spatiotemporal location of information (Williams & Jackson, 2018). Future programs should focus on what the used information is.

9. As suggested by Williams & Jackson (2018), perceptual training programs should pay attention to what changes occur in the performer during the learning process, using process-tracing techniques such as, for example, think-aloud, verbal reports, movement registration, or neuroimaging (Hülsdünker et al., 2019).

10. Finally, there should be an effort to create as representative designs as possible to train anticipation in sports, in on-field training programs as well as in programs performed in laboratories.

Chapter 4

Height After Side: Goalkeepers Detect the Vertical Direction of Association-Football Penalty Kicks From the Ball Trajectory

In[1] the present research we analyzed the relation between the height of penalty kicks in association football and (a) the probability that goalkeepers stop the ball, (b) the kinematics of the kicker, and (c) the movements of the goalkeeper. The analyzed data were previously collected in an experiment with professional and semi-professional players that focused on the relation between the kinematics of the kicker and the horizontal direction of the penalties (Lopes et al., 2014). The present research complements the current understanding of the penalty kick with three main observations. First, goalkeepers save penalties at middle heights more often than low and high penalties. Second, the height of penalties is predicted less clearly than their horizontal direction from the kinematics of penalty takers. Third, goalkeepers tend to initiate the horizontal component of the saving action before the moment of ball contact, but they initiate the vertical component of the action about 245 ms after the penalty taker contacts the ball. Taken together, these results support the view that goalkeepers make the left-right decision at least partly focusing on the kinematics of the kicker, and that they dynamically decide the vertical aspects of the movement later, focusing on the ball trajectory.

4.1   Introduction

In association football, the goalkeepers' probability to avoid a goal in a penalty situation is highly dependent on the direction of the ball (Bar-Eli & Azar, 2009)—among several other issues, such as the goalkeepers' displacement capacity and body height (Dicks et al., 2010) and the timing of the saving action (van der Kamp et al., 2018). How do goalkeepers perceive the direction of penalty kicks and control their saving actions accordingly. The answer to this question depends on the aspect of the direction that one has in mind. Goalkeepers do not perceive and control the horizontal and vertical aspects of the penalty situation in the same way. A full understanding of the saving action requires a consideration of both directions.

Most research has focused on the horizontal direction of the penalty kicks (Diaz et al., 2012; Dicks et al., 2010; Franks & Harvey, 1997; Lees & Owens, 2011; Lopes et al., 2014). For the horizontal direction, time constraints mandate that goalkeepers should not wait until after the moment ball contact. Indeed, goalkeepers typically initiate their action before ball contact (Dicks et al., 2010; Franks & Harvey, 1997; McMorris & Hauxwell, 1997; van der Kamp et al., 2018). To enhance the probability of choosing the correct side, goalkeepers rely on anticipatory information from the biomechanics of the penalty taker, probably complemented with situational information about the preferred shooting side of the opponent (Navia et al., 2013). Biomechanical variables that covary with the horizontal direction of penalty kicks include the non-kicking foot angle, knee angle of the kicking leg, speed of the kicking foot, kicking foot angle, hip angle, and movement direction of the kicking foot (Diaz et al., 2012; Lees & Owens, 2011; Lopes et al., 2014).

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[1]This chapter is submitted to publication to Human Movement Sciences under the following tittle: Height After Side: Goalkeepers Detect the Vertical Direction of Association-Football Penalty Kicks From the Ball Trajectory. Higueras-Herbada, A., Jose E, Lopes, Travieso, D., Ibáñez-Gijón, J., Araujo, D, & Jacobs, D. M. (2019)

In addition to the horizontal direction, the height of penalty kicks is relevant in the sense that it exerts a strong influence on the outcome of penalty kicks (Bar-Eli & Azar, 2009). The percentage of correct anticipation from the biomechanics of the penalty taker is substantially lower for the vertical than for the horizontal direction (Causer et al., 2017; Bar-Eli & Azar, 2009; McMorris et al., 1993; Savelsbergh et al., 2005). In addition, the improvement with learning is less for the vertical direction (Poulter et al., 2005cf. McMorris & Hauxwell, 1997). Particularly interesting are the results of Williams (1993). These authors reported that the percentage of errors in judging the location of penalty kicks that was attributable to the height aspect of the judgments was high (between 67% and 71%) when videos of penalty takers were occluded at 120, 40, or 0 ms before the moment of ball contact. This percentage dropped remarkably (to 41%) when the first 40 ms of the ball trajectory was shown. On the basis of these results, Williams and Burwitz recommended goalkeepers to use the initial part of the ball trajectory to adjust the height of their saving action.

An obvious aspect that has to be mentioned with regard to the relative difficulty to perceive the height of penalty kicks is that standard football goals have a width of 7.32 m and a height of 2.44 m. The limited variability in the height of penalties, and the associated difficulty in detecting height, have led several authors to claim that "postural cues relating to the height of the penalty kick are more subtle and harder to pick up than those responsible for conveying the correct side" (?, p. 284-285) and that "critical cues for determining ball height may not be available until late in the moment, or as suggested in previous research, until the first portion of ball flight is visible" (Causer et al., 2017, p. 8). We are not aware of studies on the biomechanics of penalty takers that confirm that the height of penalty kicks is more difficult to predict than the horizontal direction.

At a coaching level it is widely accepted that kickers should lean forward or backward depending on whether they want to direct the ball to a lower or higher location. Williams (1993) showed that soccer players who are asked to anticipate the direction of penalty kicks share the believe that the trunk angle is crucial. Participants in their above-mentioned experiment judged this variable to be the most important predictor of the height of penalties. Prassas et al. (1990) analyzed biomechanical differences for low and high kicks (not penalty kicks, hence having different task constraints; Araujo et al., 2006). In this study, the mean backward lean was 17.5 degrees for high kicks and 13.3 degrees for the low kicks. This difference was significant, providing at least partial support for the coaching recommendation concerning forward or backward lean. However, Prassas et al. reported significant differences for a substantial number of other variables, related to the kicking foot and leg, the non-kicking foot and leg, and the trunk and hip segments. Their overall conclusion was that the main determinant of performing a low or high kick is the height at which the ball is contacted with respect to its horizontal midline.

In sum, our knowledge about the behavior of penalty takers and goalkeepers is more substantial for the horizontal than for the vertical direction. In part this is so because research that relates the biomechanics of kickers to height has only been performed with kicks other than the penalty kick. To date, the movements of the goalkeeper have not been analyzed with regard to height. The present study addressed the height dimension in the specific case of the penalty kick. We used data from an experiment reported in Lopes et al. (2014). In the analyzed experiment, twelve players took 60 penalties each, using a standard size goal and a standard distance. The movements of the penalty takers were registered with movement-registration equipment. The original analyses focused on the biomechanics of the kicker in relation to the horizontal direction. In the present research, we supplemented those analyses with analyses on height and on the time at which goalkeepers initiate the horizontal and vertical aspects of their saving action.

Our analyses can be divided into three parts. First, we determined the efficacy of penalties shot at different heights, expecting to replicate the finding that the height of a penalty is related to its outcome (Bar-Eli & Azar, 2009). Second, we used the movement-registration data from the kickers to determine the predictive value of different kinematic variables with respect to height. We expected height to be more difficult to predict from the body kinematics than the horizontal direction, and we expected the height of the kicking foot and the trunk angle at ball contact to be among the better predictors. Third, we analyzed the regular video recordings of the goalkeepers to determine when their hand positions diverge for penalties shot to the left and right and for penalties shot low and high. We expected the positions to diverge before ball contact for the horizontal direction and substantially later for the vertical direction, reflecting that goalkeepers' decisions occur substantially later for the vertical than for the horizontal direction.

4.2   Method

4.2.1   Participants

The participants in the experiment that we further analyzed (Lopes et al., 2014)[2] were twelve male professional and semi-professional field players (M_{age}= 21.2 years; SD = 4.6 years) and five young but experienced non-professional goalkeepers from the same football club (M_{age}= 17.4 years; SD = 0.9 years). At the time of the experiment, all participants played in the Portuguese National Second Division or in the Portuguese National Junior Second Division.

4.2.2   Materials

An indoor setting was used. Two pieces of red and green tissue that spanned the full height of the goal were placed at the sides of the goal (Figure 1a). The experiment was recorded with a standard video camera (25 Hz; DCR-HC23, Sony Corporation, Tokyo, Japan) and a four-camera infrared system (150 Hz; Qualisys AB, Gothenburg, Sweden). Figure 4.1b shows the positions of the cameras. Goalkeeper data from the standard video camera were digitized with PhysMo software (Barraclough, 2011). The infrared system recorded 16 markers on the penalty taker. Twelve of these markers were attached to the head, shoulders, elbows, wrists, hips, and knees. The remaining four markers were attached to the shoes: one on the backside of each shoe and one on the outer side (near the fifth metatarsal bone).
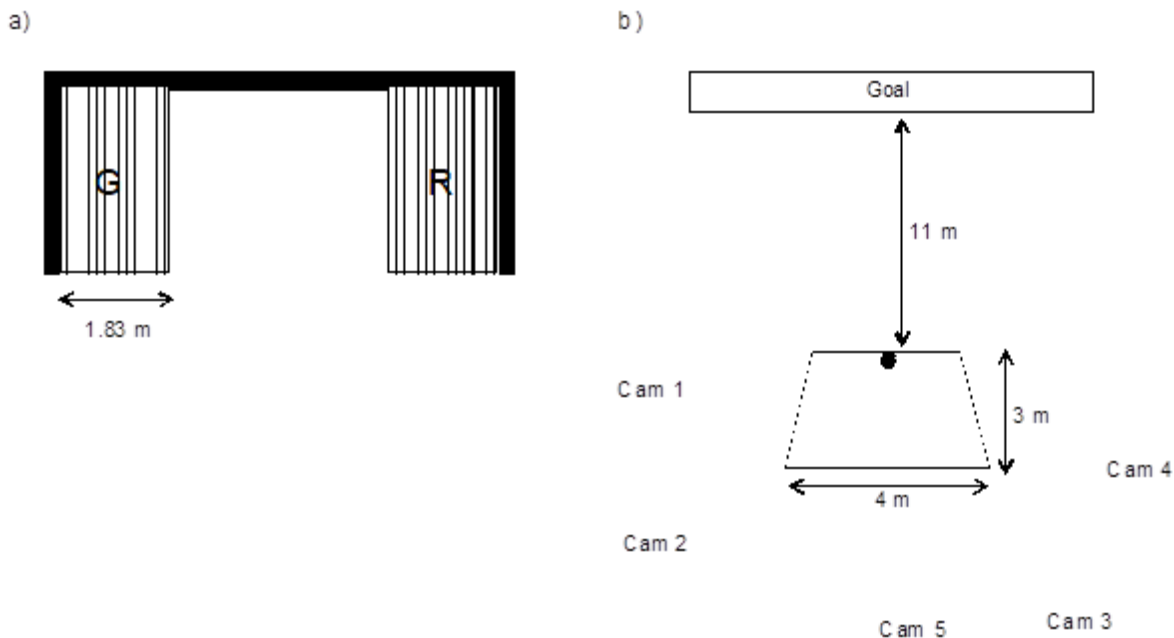
Figure 4.1: Experimental scenario. (a) Goal used in experiment with green (G) and red (R) target areas. (b) The trapezoid area around the penalty kick mark (black filled circle) represents the volume covered by the four Qualisys cameras (Cam 1 to 4). A standard video camera (Cam 5) recorded the trials from frontal perspective. For left-footed kickers the camera positions were mirror-reversed.

4.2.3   Design and Procedure

Trials differed with regard to the side of the penalty (left/green vs. right/red) and with regard to the deception condition (with vs. without deception). This led to the following instructions: "shoot to green without simulating", "shoot to red without simulating", "shoot to green but simulate shooting to red", and "shoot to red but simulate shooting to green". Penalty takers received the instructions before each

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[2]The focused of Lopes et al., (2014) was on the kinematics of the kicker and their relation to the horizontal direction of the penalty. The current experiment focuses on the height dimension and the goalkeepers' saving actions (outcome of the penalties per height category, the relation between the kinematics of the kicker and the height of the penalty kicks, and the movements of the goalkeepers regarding the lateral and height dimensions). Thus, the data that we re-use was the kinematics of the penalty takers and the outcome of the penalties to be related to the height dimension instead of the horizontal direction addressed in (Lopes et al., 2014).

trial. They performed fifteen penalty kicks per condition. The height of the penalties was not mentioned in the instructions.

4.2.4 Data Analysis

Penalty outcome per height category. To measure the horizontal and vertical directions of the ball for a particular trial, we first determined the frame from the standard video at which the ball touched the tissue just after the goal line or was contacted by the goalkeeper (hereafter referred to as the end of the trial). The horizontal and vertical coordinates, referred to as x and y coordinates, were then measured on the screen and transformed to real-world distances. The penalties were categorized as left or right according to the x coordinate (left: x < 0; right: x > 0), and as low, medium, or high according to the y coordinate (low: 0 < y < 81.3 cm; medium: 81.4 < y < 162.7 cm; high: 162.8 < y < 244 cm). Our first set of analyses concerned the efficacy of the penalties as a function of the three height categories via Chi-squared test.

    Kinematics of penalty taker. The second set of analyses aimed to determine the value of several kinematic variables computed from the markers on the penalty takers in predicting the penalty heights (the non-categorized y coordinates). This was done with product-moment correlations (Lopes et al., 2014; cf. Jacobs, Runeson, & Michaels, 2001). The variables that were selected for presentation in this article were: the dominant foot height (the height of the marker on the front part of the foot), the dominant foot speed (the speed of the marker on the front part of the foot), the dominant foot angle (the angle between a vector orthogonal to the floor and the imaginary line connecting the dominant foot markers), the non-dominant foot distance (the horizontal distance between the marker on the font part of the foot and the imaginary line that is parallel to the goal line and that crosses the penalty kick mark), the shoulder-hip-wrist angle for the dominant foot side (the angle formed at the shoulder by the imaginary lines from shoulder marker to wrist and hip markers, respectively), and the trunk angle (the angle between a vector orthogonal to the floor and the segment from the middle between the two hip markers to the middle between the two shoulder markers). This selection of variables was based on literature findings relating the variables with the vertical direction of the ball in other types of kicks and on coaching recommendations related to kicking technique and the control of ball height. One sample $t-test$ were computed on the Fisher z transformations of the correlations for each penalty taker to test whether the correlations differed from zero.

    Timing of saving action. For the third set of analyses we digitized the standard videos from one frame before the moment of ball contact until the frame corresponding to the end of the trial. These analyses included the penalties (a) that were classified as low or high, (b) in which the goalkeeper dove to the side of the kicked ball, and (c) in which the goalkeeper clearly intended to stop the ball with both hands. In total, 88 penalties fulfilled those conditions. For those penalties, the x and y positions of both hands were determined from the videos and averaged over the two hands, obtaining one trajectory per trial. Those trajectories, which differed in length in terms of frames for penalties with different flight durations, were aligned with respect to the end of the trial. The reported analyses were run on the hand trajectories that were further averaged, for each kicker, per side (left, right) or per height (high, low). The aim of these analyses was to examine when the hand trajectories diverged for left and right and for high and low penalties, and hence to reveal the moments at which the goalkeepers' left-right and high-low decisions became apparent.

4.3 Results

4.3.1 Penalty Outcome per Height Category

Table 4.1 presents the percentage of penalties, for each penalty taker and averaged over all penalty takers, that fell in each of the height categories. The number of trials in each category is also shown (bottom row of table). Overall, 31.3% of the penalties fell in the low category, 36.0% in the middle category, and 32.7% in the high category.

    Next, the outcome of the penalties was added to the analysis, in terms of goal or no goal. Table 4.1 presents the percentages of penalties for each of the height categories separated for outcome. A chi-square test showed that ball height and outcome are associated variables: $\chi^2(2, N = 638) = 24.40$, $p < .001$. Scored penalty kicks were above the level of 33.3% for high penalties (residual = 4.1), whereas scored penalties were below that level for medium penalties (residual = -4.5). Given these results, it becomes important to clarify the reasons for which the medium category registered more than the expected number of missed penalty kicks. For this purpose, the outcome variable was considered in three categories: 1 = save; 2 = goal despite goalkeeper touching the ball; and 3 = goal without goalkeeper touching ball. The result of a chi-square test was: $\chi^2(4, N = 638) = 45.83$, $p < .001$. Saves by goalkeepers were particularly

	Ball Height		
	Low	Medium	High
Penalty Taker			
1	34.0	35.8	30.2
2	23.7	43.6	32.7
3	35.1	42.1	22.8
4	26.9	38.5	34.6
5	33.4	31.2	35.4
6	38.6	38.6	22.8
7	26.8	28.6	44.6
8	9.8	37.3	52.9
9	44.1	30.5	25.4
10	27.1	35.4	37.5
11	50.0	25.0	25.0
12	25.9	44.4	29.7
Average	31.3	36.0	32.7
n	200	230	208

Table 4.1: Percentages of Penalties per Height Category

frequent for the medium category (residual = 6.3). This finding was further supported by an analysis that included only the subset of the trials in which the lateral ball direction and goalkeeper's dive direction were identical. In this case the chi-square test showed that: $\chi^2(4, N = 364) = 54.09$, $p < .001$, with an adjusted residual of 6.5 for saved penalty kicks at medium ball height.

Additional analyses were performed focusing on the saved penalty kicks. The numbers of saved penalty kicks for the low (n = 33), medium (n = 77), and high (n = 19) categories were taken as a percentage of the number of penalty kicks directed to each of these height categories (200 for low, 230 for medium, and 208 for high). As shown in the bottom row of Table 4.2, the percentage of saves was higher for penalty kicks with a medium height (33.5%) than for low and high penalty kicks (16.5 and 9.1%, respectively).

4.4   Results

4.4.1   Kinematics of Penalty Taker

The time-evolution of the correlations between the candidate kinematic variables and height are presented in Figure 4.2. An examination of the figure indicates that earlier than about 0.1 s before ball contact, the relations between the kinematic variables and height were weak or nonexistent. Around the moment of ball contact, the kinematic variables that correlated with ball height were the dominant foot height and the dominant foot angle (left column in the figure). The correlations for these variables differed significantly from zero in that period. However, with average correlations of at most about r = .3, the individual kinematic variables (as registered by us), explained less than 10% of the variance in height.

4.4.2   Timing of Saving Action

The average ball flight time for the 88 penalties that were analyzed in this subsection was 525 ms (SD = 64). The mean horizontal position of the ball at the end of the trials was -227 cm (SD = 64) for penalties shot to the left and 233 cm (SD = 81) for penalties shot to the right. The upper panel of Figure 3 shows the horizontal hand position of the goalkeepers for penalties shot to the left and right as a function of the time before the end of the trial. As shown by the asterisks in the figure, the hand positions already differed significantly for left and right penalties at the first video frame that was included in the analyses (i.e., 640 ms before the end of the trial and hence 115 ms before the average moment of ball contact). The

	Ball Height					
	Low		Medium		High	
	Goal	No Goal	Goal	No Goal	Goal	No Goal
Penalty Taker						
1	33.3	35.7	33.3	42.9	33.3	21.4
2	26.1	11.1	41.3	55.6	32.6	33.3
3	32.6	42.9	39.5	50.0	27.9	7.1
4	23.0	38.5	38.5	38.5	38.5	23.0
5	38.9	16.6	27.8	41.7	33.3	41.7
6	34.1	53.8	38.6	38.5	27.3	7.7
7	21.1	38.9	21.1	44.4	57.8	16.7
8	12.8	0.0	23.1	83.3	64.1	16.7
9	47.6	35.3	31.0	29.4	21.4	35.3
10	33.3	0.0	25.7	77.8	41.0	22.2
11	54.3	38.5	17.1	46.2	28.6	15.3
12	28.2	20.0	30.8	80.0	41.0	0.0
Average	32.1	27.6	30.7	52.4	37.2	20.0
n (%)	153 (24.0)	47 (7.4)	149 (23.3)	81 (12.7)	177 (27.7)	31 (4.9)
n (%) of saves	33 (16.5)		77 (33.5)		19 (9.1)	

Table 4.2: Percentages of Penalties per Height Category Separated for Goal and No Goal

mean height of the ball at the end of the trials was 37 cm (SD = 24) for low penalties and 203 (SD = 27) for high penalties. The lower panel of Figure 4.3 shows the vertical hand position of the goalkeepers for low and high penalties. The hand positions differed significantly for low and high penalties from 280 ms before the end of the trial until the end of the trial (Table 3 shows size effects for significant differences). With mean flight durations of 525 ms, this indicates that the height difference became evident around 245 ms after ball contact.

4.5   Discussion

This investigation aimed to extend our understanding of the penalty kick situation with an analysis that focused on height and on the timing of the goalkeepers' saving action. Said with more precision, we analyzed to what extent performance of goalkeepers is affected by variation in ball height, how variables of the penalty takers' kinematics relate to ball height, and the moments at which left-right and height differences in the kicks become evident in the goalkeepers' hand position. These respective issues are addresses in the following three subsections. We claim that goalkeepers use information from the kinematics of the kicker for the horizontal aspects of their saving actions and information from the ball trajectory for the vertical aspects of the saves. A final subsection of this Discussion relates this claim to research on the gaze direction of goalkeepers.

4.5.1   Prenalty Outcome Per Height Category

A first key issue to consider is the preference of penalty takers in what concerns the height of the kicks. The percentages of penalties directed to the different height categories that we observed were: 31.3%
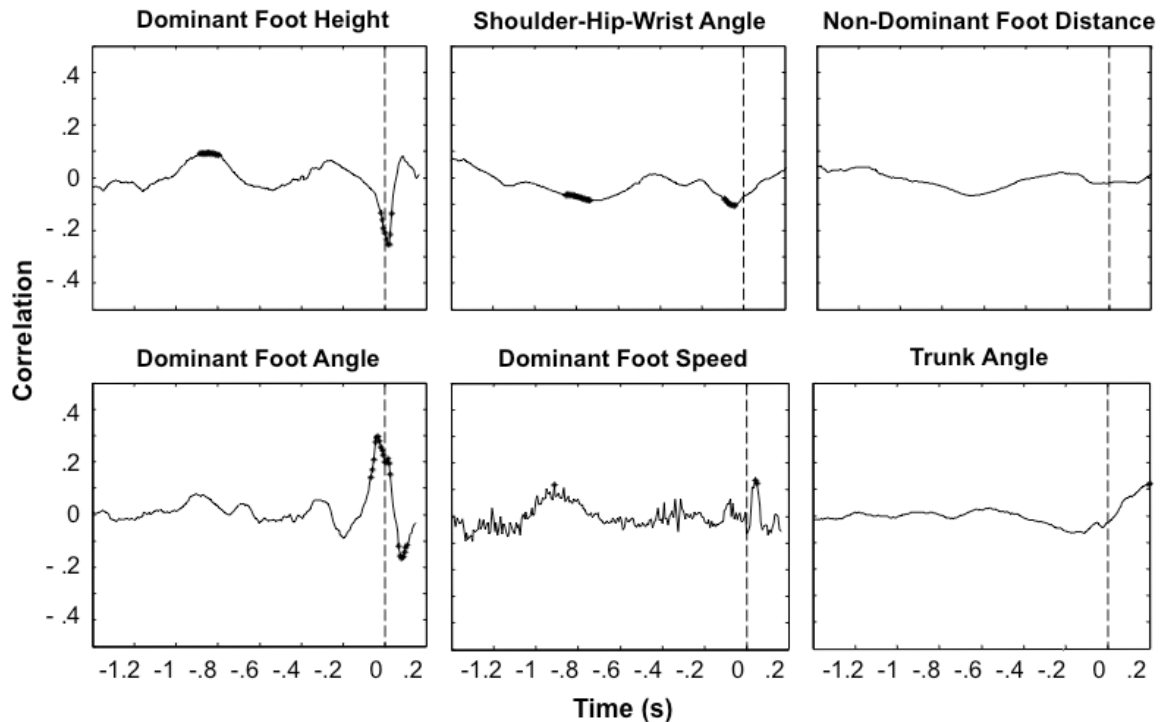
Figure 4.2: Time-evolution of correlations between single kinematic variables and ball height. Each panel gives the results for one kinematic variable. Curves represent correlations computed per penalty taker and averaged over the twelve penalty takers. The moment of ball contact is indicated with dashed vertical line segments. Asterisks indicate significance levels of $p < .05$ obtained with t tests.

for low penalties, 36.0% for medium penalties, and 32.7% for high penalties. Bar-Eli & Azar (2009) analyzed 311 penalty kicks from professional leagues and championships of national teams and reported 56.6%, 30.4%, and 12.9%, respectively, for low, medium and high penalties. Hence, we observed more high penalties and less low penalties. This difference may be related to the psychological pressure on the penalty takers, which was much lower in our study than in the one of Bar-Eli and Azar. Under high pressure, penalty takers may want to avoid the risk of shooting penalties too high.

For the percentages of penalties in which goalkeepers prevented a goal, we observed 16.5% for low, 33.5% for medium, and 9.5% for high penalties. For the same categories, Bar-Eli & Azar (2009) reported 19.8%, 12.6%, and 0.0%, respectively. Our results hence replicate (a) that goalkeepers' possibilities to save penalties depend on the height of the penalties and (b) that high penalties are difficult to save. Despite this broad similarity, we observed more saves overall and relatively more saves in the high and medium areas. In this regard it may be relevant to mention that the goalkeepers in our experiment were junior goalkeepers. For the experimenters it was easy to observe that the experimental situation—with the senior field players of their own football club and in close collaboration with the coach of the senior team—was extremely motivating for these goalkeepers.

4.5.2   Kinematics of Penalty Taker

We next addressed the relation between the penalty takers' movements and the height of the penalties. A first noteworthy result was that the observed correlations were never higher than about 0.3. The laws of physics mandate that the biomechanics of the kicker should determine the direction of the ball. This means that the moderate or low correlations that we obtained should at least partly be attributed to issues such as the selection of the analyzed variables or the precision of our measurements. The low correlations are revealing, however, if one compares them with the fact that the same measurements and the same type of analysis led to substantially higher correlations for the horizontal direction (Lopes et al., 2014). For the horizontal direction, the correlations were well above 0.8 for the dominant foot angle, hip angle, and dominant foot movement direction (see Figure 4 of Lopes et al.). Such high correlations are in line with the high reliability of perceptual variables for the horizontal direction that has been observed
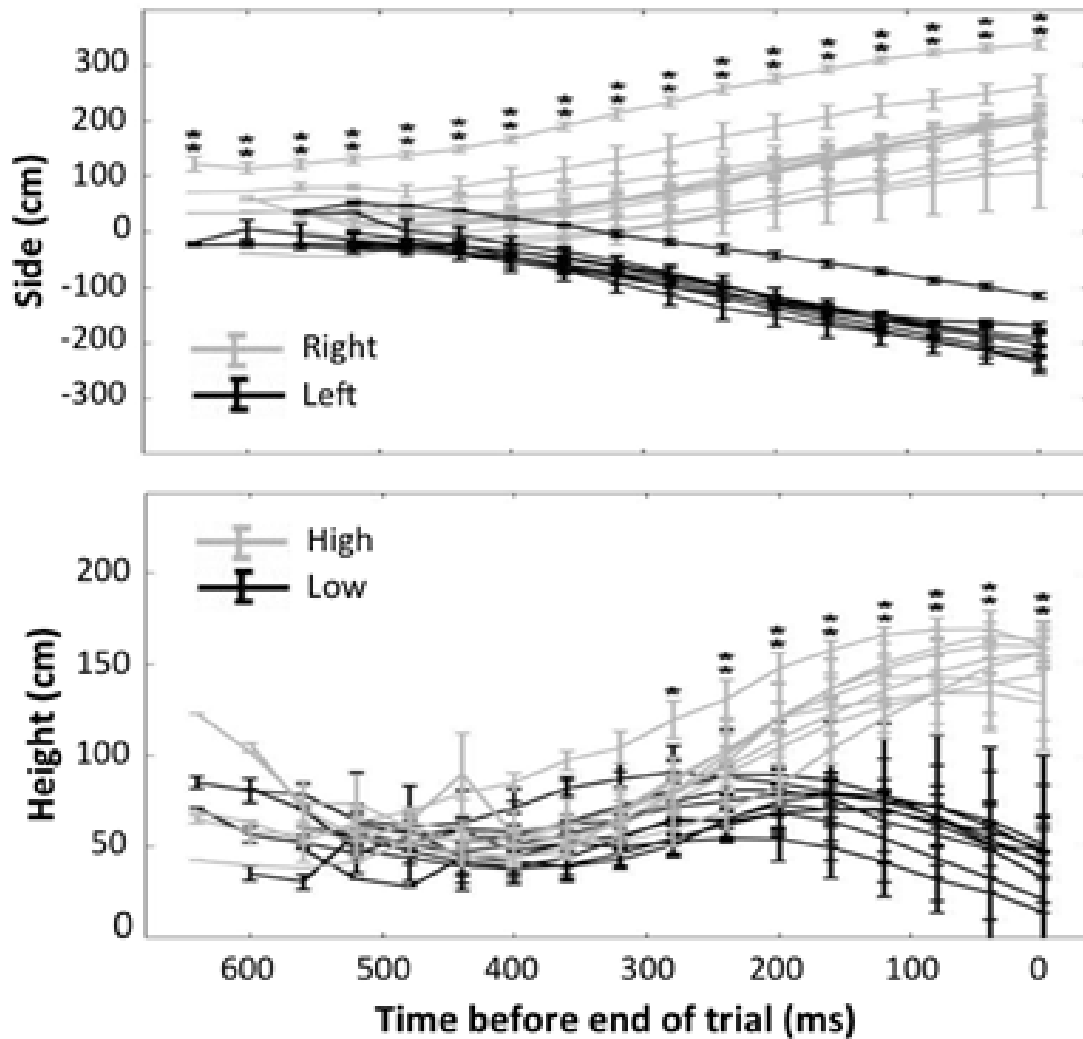
Figure 4.3: Mean horizontal position of the goalkeepers' hands for left and right penalties (upper panel) and for high and low penalties (lower panel) as a function of the time until the ball reaches the goal. The results of single-tailed t tests on the average positions per penalty taker are indicated in each panel with asterisks. One asterisk means $p < .05$; two asterisks means $p < .01$.

in other studies (Franks & Harvey, 1997; Diaz et al., 2012). The results of the present study therefore provide evidence for the common claim that the biomechanical predictors are more subtle for height than for the horizontal direction, and are hence most probably more difficult to detect and use (Causer et al., 2017; Savelsbergh et al., 2002).

The variables that correlated moderately and significantly with height were the dominant foot height and the dominant foot angle. The negative correlations for dominant foot height indicate that the higher the foot the lower the ball direction, as stated in the literature for this variable (Asai et al., 2005; Prassas et al., 1990). For the dominant foot angle, a higher angular value (a less vertical foot position) corresponded to a higher ball trajectory. Although this is the expected direction, the significant correlation may be surprising in the sense that a similar effect did not reach significance in the study by Prassas et al. We did not observe a significant correlation for the trunk angle and hence did not obtain evidence in favor of the common recommendations about trunk angle by coaches and the opinions expressed by football players (Williams, 1993).

4.5.3 Timing of the Saving Action

We believe that the main contribution of this research concerns the differentiated timing for the horizontal and vertical aspects of the goalkeeper saves. In this sense our research is aligned with the approach forwarded by van der Kamp et al. (2018). These authors argued that research on the penalty situation

has "disproportionally focused on understanding the informational basis of spatial control (p. 170)". Although we did not address the informational basis of the temporal control, we agree with van der Kamp et al. that research on the penalty kick has had a too limited focus, and we aimed to broaden the scope with an analyses of height in addition to side, and with an emphasis on the temporal aspects of the goalkeepers' control in both directions.

With respect to the horizontal direction, the hand positions evidenced that goalkeepers took the shot direction into account more than 640 ms before the ball reached the goal, which corresponds to more than about 115 ms before the moment of ball contact. This is consistent with previous findings (Dicks et al., 2010; Franks & Harvey, 1997; Kuhn, 1988; McMorris & Hauxwell, 1997). A contribution of our research is that we demonstrated the finding with a novel methodology, focusing on the actual movements of the goalkeeper. In spite of several exceptions (e.g., Dicks et al., 2010), reviews indicate that the majority of studies on goalkeeper behavior in the penalty kick task have analyzed judgments or gaze behavior of participants who observed videos of penalty takers that were previously recorded from the point of observation of the goalkeeper (Lopes, Araújo, Peres, Davids, & Barreiros, 2008; cf. van der Kamp et al., 2018).

With respect to the vertical direction of the kicks, the goalkeeper positions diverged for low and high penalties around 280 ms before the end of the trial. At that moment, on average, the ball had been in flight for about 245 ms. Given a small perceptual-motor delay (55-130 ms, ?; 80-144 ms, Franks & Harvey, 1997), such a timing allows goalkeepers to rely on the ball trajectory. Moreover, the low predictive value of the kinematics of the kicks with respect to height seems to make the use of trajectory information the better option. The use of trajectory information is also consistent with our results concerning the penalty outcomes. This is so because more saves are to be expected at middle heights if goalkeepers initiate their actions aiming for middle heights and then later adapt the actions on the basis of height information from the ball trajectory. In sum, the type of information and control of the height aspect of the saving action may at some level be similar to the types of information and control that have been proposed in ball interception tasks (Bootsma et al., 1997; Craig et al., 2009; D. M. Jacobs & Michaels, 2006; Morice et al., 2010).

4.5.4   Gaze Direction and Information Usage

A final line of evidence that supports the different types of control—on the basis of the biomechanics for the horizontal direction and on the basis of the ball trajectory for height—can be found in the literature on the gaze direction of goalkeepers. In their training method, aimed at novice goalkeepers, Savelsbergh et al. (2010) proposed a standard fixation pattern from the initiation of the run-up until ball contact. Based on previous studies on the gaze behavior of goalkeepers (Savelsbergh et al., 2002, 2005), Savelsbergh et al. (2010) argued that goalkeepers should start fixating the head of the penalty taker and then lower their gaze, first to the trunk and hip region and then to the leg-foot region. Such a fixation pattern until ball contact is compatible with the claim that goalkeepers control the horizontal direction of their saving action, which is initiated before ball contact, at least partly on the basis of the biomechanics of the kicker.

Around ball contact, association football goalkeepers fixate the ball region more frequently than earlier during the run-up (Savelsbergh et al., 2002, 2010), and this is more so when they actually perform the saving action than when they merely observe the penalty taker (Dicks et al., 2010; cf. Navia et al., 2013. Less is known about the gaze behavior during the ball flight. Although they considered a different sport, for the ball flight phase it is tempting to consider a study by (Navia et al., 2017). These authors showed that, for 6 m and 10 m penalty kicks, during the run-up futsal goalkeepers frequently fixate the body of the penalty taker. Shortly before ball contact, the variation in fixation behavior among goalkeepers is reduced, and the fixation invariantly turns to the ball. For the 10 m kick, Navia et al. (2017) claimed that "goalkeepers tended to track the ball trajectory via a smooth pursuit gaze pattern" (p. 791). Given our results concerning timing, if such results would be true also for association football goalkeepers, they would provide an additional piece of evidence for the claim that the height aspect is indeed adjusted on the basis of the detected ball trajectory.

Part III

Anticipation Studies

Chapter 5

Anticipating the Lateral Direction of Penalty Kicks in Football From PCA-Reduced Point-Light Displays

The[1] anticipation of the direction of football penalty kicks was assessed using Point Light Displays (PLDs). To that end, Principal Component Analyses (PCAs) were applied on previously registered penalty kicks. The PCAs provided an accurate description of the kicks: an average of 98.7% of the variance was explained with the first 6 PCA modes. The results of the PCAs were used to create 7 stimulus conditions, showing PLDs of the kicks as seen from the perspective of the goalkeeper. The first condition included all PCA modes and hence used PLDs of the original penalties. The remaining 6 conditions used all PCA modes until Mode 1, 2, 3, 4, 5, or 6, respectively. Participants observed the PLDs until the moment of ball contact and judged the lateral direction of the kicks. The percentages of correct judgments per condition revealed that the information for the anticipation of penalty kicks is contained in relatively few PCA modes. This confirms previous results obtained with tennis ground strokes (Huys, Smeeton, Hodges, Beek, & Wiliams, 2008), although for tennis ground strokes even fewer PCA modes seemed to be required to achieve accurate anticipation. The relevance of the ecological notion of information for the PCAmotivated body of research is discussed.

5.1 Introduction

In his seminal research on the visual perception of biological motion, Johansson (1973) recorded a person with reflective markers on body locations near the joints while the person walked in a dark environment. Only bright moving dots, corresponding to the reflective markers, were visible during the reproduction of the recorded videos. The videos caused an immediate impression of a walking person on people who observed them. Such an impression was not caused by static images of the bright dots. Johansson's videos isolated the kinematic information of a human in motion from the pictorial information and showed the importance of the kinematic information. The displays used by Johansson are currently known as Point Light Displays (PLDs). Since Johansson's original study many research directions made possible by PLDs have been explored (Runeson & Frykholm, 1983), including the study of anticipation in sports (Ward, Williams, & Bennett, 2002).

This study focuses on the anticipation of the lateral direction of penalty kicks in football (also known as association football or soccer). A substantial number of studies on the football penalty kick use regular video presentations. In many cases, the video presentations are combined with occlusion techniques in which some location of a stimulus video is occluded during some temporal interval (McMorris & Hauxwell, 1997; Poulter et al., 2005). Notwithstanding the numerous advances that have been achieved with occlusion techniques, it has been argued that such techniques are limited in the sense that they lead to conclusions about spatial and temporal aspects of the used information but not about other aspects of the information (Huys et al., 2008). In addition, occluding local regions of a stimulus is less useful if—as argued by proponents of the ecological approach—information is to be found in global rather than local patterns (Huys et al., 2009; C. F. Michaels & Carello, 1981; Williams, Ward, Knowles, & Smeeton, 2002).

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[1] This article is published under the following reference: Higueras-Herbada, A., Travieso, D., Ibáñez-Gijón, J., & Jacobs, D. M. (2017) Anticipating the Lateral Direction of Penalty Kicks in Football From PCA-Reduced Point-Light Displays, *Ecological Psychology, 29(1)*, 23-34, doi: 10.1080/10407413.2017.1270148

The use of PLDs instead of regular videos allows experimental manipulations other than occlusion techniques. Before we can explain this, we need to describe how Principal Component Analysis (PCA; Daffertshofer et al., 2004) can be applied to biological motion. Consider Johansson (1973) example: a walking person with reflective markers on different body locations. In such cases, the different markers move to some extent in similar ways. A large forward movement, for instance, is shared by all markers. This means that the time series that describe the individual marker trajectories contain redundancies. A PCA takes advantage of such redundancies so as to achieve a more efficient description of the movement. Instead of describing the movement with a large number of redundant time series (the x, y, and z coordinates of the original marker trajectories), a PCA searches for a description with fewer time series that are less redundant.

We next provide a more mathematical description of PCA using the specific properties of this study. In our study, each PCA was applied to a 16 (markers) $\times$ 3 (x, y, and z coordinates) $\times$ 10 (penalties) = 480 dimensional data set. This means that 480 time series were used to describe the data set. These original time series, denoted as $q_1(t), ..., q_{480}(t)$, can be interpreted as describing a curve $\mathbf{q}(t) = q1(t)\mathbf{e}_1 + ... + q_{480}(t)\mathbf{e}_{480}$ in a 480-dimensional space[2]. A PCA computes alternative base vectors, denoted as $\mathbf{v}_1, ..., \mathbf{v}_{480}$, and associated time series, denoted as $\zeta_1(t), ..., \zeta_{480}(t)$. These alternative vectors and time series minimize the difference between the original data and the curve

$$\tilde{\boldsymbol{q}} = \sum_{k=1}^{M} \zeta_k(t)v_k \tag{5.1}$$

Said differently, the alternative vectors and time series are optimized so that (a) the approximation $\tilde{\boldsymbol{q}}(t)$ is equal to the original curve $\boldsymbol{q}(t)$ if all base vectors $\boldsymbol{v}_k$ are used (M = 480) and (b) this approximation is the best possible approximation of $\boldsymbol{q}(t)$ if less than 480 vectors are used (M $\leq$ 480). The vectors $\boldsymbol{v}_k$ are referred to as *modes* or *eigenvectors* and the time series $\zeta_k(t)$ as *projections*.

After performing a PCA on a biological movement, which implies a decomposition of the movement in different modes, one can reconstruct the movement in ways that lead to interesting differences between the original and reconstructed movements. In the reconstruction one may for instance use only the first few modes of the PCA, omitting the higher, less relevant modes. One may also use all modes in the reconstruction but average some of them over relevant conditions Huys et al. (2008). If one does not use all modes in the reconstruction, or if one somehow averages during the reconstruction, then the reconstructed movement differs from original one.

The difference between the original and the PCA-reconstructed movements makes the combination of PCAs and PLDs useful and elegant. This is so because, in contrast to regular videos, the use of PLDs allows the experimenter to present PCA-modified movements to participants and hence to assess the perceptual consequences of PCA-based manipulations. This combination of PLDs and PCAs was pioneered by Troje (2002), who studied gender recognition on the basis of walking patterns. The combination of PLDs and PCAs was introduced in the literature on anticipation in sports by Huys et al. (2008).[3]

Huys et al. (2008) addressed the perception of the direction of forehand ground strokes in tennis. In a first experiment, they registered 18 markers on the body and the racket of a player who executed the ground strokes. PCAs were performed on the registered shots. With the first five modes, 96.2% of the variance was explained. In a second experiment of Huys et al. (2008), participants judged the side of shots on the basis of PLDs that were created using the registered shots. The PLDs contained the unmodified original shots or shots reconstructed with different combinations of the PCA modes. The perception of the direction of the shots deteriorated with respect to the unmodified shots if only the first mode or only the first two modes were included. Performance did not deteriorate if the first three, four, or five modes were included. These results indicate that the information for the anticipation of ground strokes in tennis is contained in the first few PCA modes.

Since the research of Huys et al. (2008), multiple advances have been achieved in the understanding of anticipation behavior with the combination of PLDs and PCAs. The majority of these advances were based on the same task: anticipating the direction of ground strokes in tennis (Cañal-Bruland, van Ginneken, van der Meer, & Williams, 2011; Huys et al., 2009; N. Smeeton & Huys, 2011; N. Smeeton, Huys, & Jacobs, 2013; see Bourne, Bennett, Hayes, & Williams, 2011, and Bourne, Bennett, Hayes, Smeeton, & Williams, 2013, for an exception). We believe that applying these techniques to other anticipation tasks may, on the one hand, improve our understanding of such other tasks and, on the other hand, establish the generality of the conclusions. This study applies the techniques described in

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[2] Note that the vectors $\mathbf{e}_1, ..., \mathbf{e}_{480}$ are the standard base vectors of the 480-dimensional space and that, following common convention, we use boldface instead of regular print to indicate quantities that are vectors instead of scalars.

[3] One may want to note that, in contrast to Johansson (1973),Troje (2002), Huys et al. (2008) connected the dots in their stimuli with lines.

Huys et al. (2008) to the anticipation of the direction of penalty kicks in football. Apart from the task used, our design closely matches the one of the aforementioned second experiment of Huys et al. (2008).

The only previous study that we are aware of that used PLDs and PCAs to study the anticipation of the direction of penalty kicks is the one by Diaz, Fajen, & Phillips (2012). That study, however, differs from ours among other reasons because participants observed only unmodified PLDs, whereas in our experiment PCA modes were selectively removed from the stimuli. Another difference is that the penalties that we used to create the PLDs were registered in an experiment with a more representative design than the experiment of Diaz et al. (2012). As an additional indication of the contribution of the present study, let us mention that, although it has inspired further research in the anticipation of tennis ground strokes, the aforementioned second experiment of Huys et al. (2008) has not been replicated with the tennis task either.

5.2 Method

5.2.1 Participants

Fifty-two students of the Universidad Autónoma de Madrid (38 male, 14 female) with a mean age of 20.5 years ($SD = 1.2$) participated in the experiment. Participants were divided into two equal-size groups that judged penalties of different kickers. Participants were compensated with coupons for a university bookstore. The research was approved by the local committee for ethical research (CEI 52-957). All participants gave written informed consent before participating in the experiment. After performing the experiment, we asked participants if they had experience playing football. The large majority of them reported that they had occasionally played football as a recreational activity. None of them, however, played in an official competition. Their experience facing football penalties was therefore low.

5.2.2 Stimuli

Lopes, Jacobs, Travieso, & Araújo (2014) registered 60 penalties for each of 12 professional and semiprofessional football players. For these penalties, the three-dimensional position of 16 markers was registered at 150 Hz. The markers were located on the head, shoulders, elbows, wrists, hip, knees, and on the back and front of the feet of the kicker. Just before each trial, the kickers received the instruction to try to deceive or not to deceive the goalkeeper with respect to the shooting direction. For this study we selected 20 of the penalties that were registered by Lopes et al. (2014): 10 penalties for each of two kickers. For each kicker, 5 of the 10 penalties were shot to the left and five to the right. In all of the selected penalties, the instruction was the one of not deceiving the goalkeeper. All markers were correctly registered in the relevant parts of the time series for all penalties in our selection.

We used penalties from these particular two kickers because we expected that their penalties might be relatively easy to judge. This expectation was based on a reanalysis of data from a preliminary study that included two nondeceptive penalties from 10 kickers (Higueras-Herbada, Travieso, & Jacobs, 2015). The percentages of correct side judgments for these two kickers (76.5% and 77.0%, respectively) were higher than for the other kickers. Given that removing modes from the penalties may be expected to reduce the percentages of correct judgments, aiming to select relatively easy penalties may avoid floor effects near chance level.

Self-developed MATLAB routines transformed the registered three-dimensional body movements to two-dimensional PLDs of these movements. Participants in our experiment observed the penalties with approximately the same projective structure as the goalkeepers in the original experiment. The parts of the time series that were included in the stimuli (and considered in the PCAs) started at the second last maximum height before ball contact of the marker on the front part of the nonkicking foot and ended at the moment of ball contact. Figure 5.1 illustrates the time series. The used parts of the time series lasted 1.1 s ($SD = 0.06$) for the first kicker and 1.0 s ($SD = 0.08$) for the second kicker.

As illustrated in Figure 2a, the stimuli consisted of 16 black dots of a point-light kicker and a black circle corresponding to the ball. The point-light figure subtended approximately 8° of visual angle, nearly the same as a kicker in the field situation. The background was uniformly white. Figure 2b shows that a chin rest was used, located at a distance of 1 m from the 24-in. (0.61-m) screen. The eyes were located approximately at the same height as the center of the screen.

5.2.3 Experimental Conditions

Before applying the PCAs, the considered parts of the 480 registered time series (16 markers x 3 coordinates x 10 penalties) were mean subtracted and divided by their standard deviation. This normalization
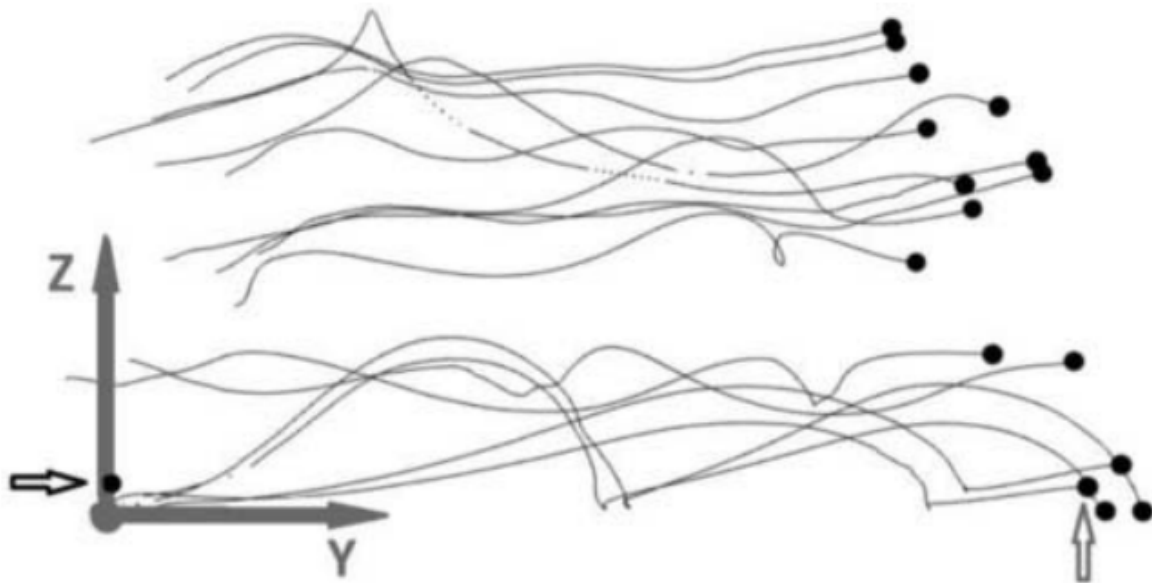
Figure 5.1: Lateral view of the considered parts of the marker trajectories. The x coordinate, not shown in the figure, is orthogonal to the y and z coordinates. The dots at the right indicate the position of the body markers at the first frame of the time series. The vertical arrow at the bottom right indicates the event that defined the beginning of the intervals: the second last maximum height of the marker on the front part of the nonkicking foot. The horizontal arrow at the left indicates an additional marker at the position of the ball.
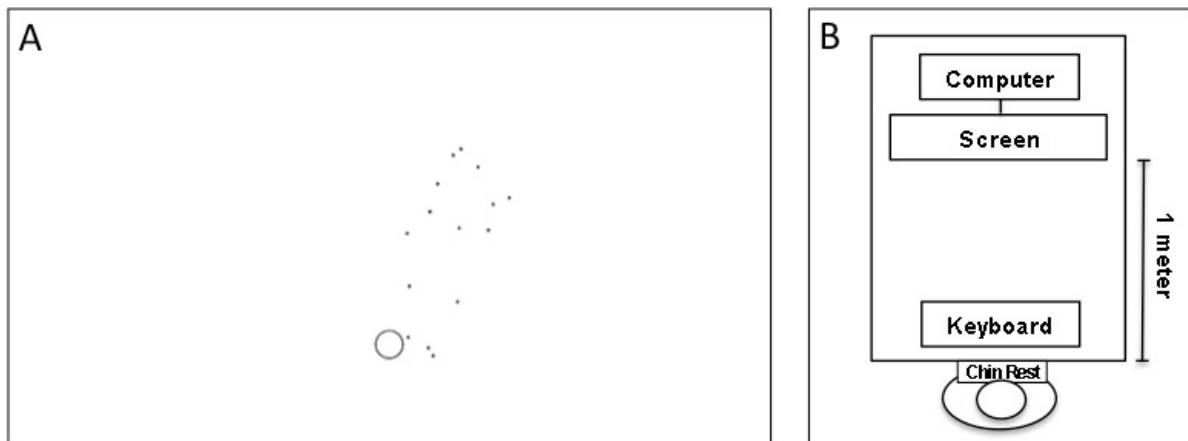

Figure 5.2: A: Single frame of a stimulus video for an unmodified penalty. This frame is close to the moment of ball contact. The black dots correspond to the registered marker positions. The ball is represented with an open circle. Only the markers that were occluded by the ball were not visible in the stimulus videos. B: Experimental setup.

was performed to avoid that markers with large movement amplitudes had disproportionally large contributions to the higher PCA modes (Daffertshofer et al., 2004). The time series were also resampled to a uniform length of 100 frames. A separate PCA was performed for each of the two kickers. This led to relatively homogeneous time series per PCA, performed without time warping.

After performing the PCA-based decomposition in modes, we reconstructed the movements of the kicker using different combinations of the modes. Said more precisely, for each experimental condition we computed the approximation $\tilde{q}(t)$ with a different value of M (see Equation 1). The values of M that

were used in the seven conditions were 480, 1, 2, 3, 4, 5, and 6, respectively. When M was set at 480, all modes were used in the reconstruction, and hence PLDs of the original penalties were computed. This condition was referred to as M_{all}. Setting M at any value between 1 and 6 means that only the modes until the value of M were used; these six conditions were referred to as $M_1, M_2, M_3, M_4, M_5, and M_6$. Being purposefully redundant, the penalties used in condition M3, for instance, were approximations of the actual penalties based on Modes 1 to 3 of the PCAs.

The reconstructed data, $\tilde{q}(t)$, consisted of 480 time series with a uniform length of 100 frames. To undo the normalization, each time series was multiplied by its original standard deviation, and its original mean was added. The resampling of the time series to 100 frames was also undone. At the end of the PCA procedure for each kicker, we obtained approximations of the 48 time series of each of the 10 penalties in each of the seven conditions, giving $10x7 = 70$ penalties to be used as stimuli. The stimuli were presented with a frequency of 60 Hz.[4]

5.2.4   Procedure

Participants were informed that they would be shown 70 penalties from the perspective of the goalkeeper and that some of these penalties had a peculiar an appearance. The penalties that looked peculiar were the ones that were reconstructed with few modes (varying in degree but approximately until M_3 or M_4). The participants were asked to indicate the direction of the kicks with the right- or left-arrow key. The penalties were presented in a random order. Each participant observed the penalties of one kicker. Each penalty was shown twice before the participant responded. Optional breaks were suggested after each 10 trials. The experiment took approximately 15 min.

5.2.5   Data Analysis

For all ANOVAs, whenever the sphericity assumption was violated, Huynh-Feldt corrections were performed and the corrected degrees of freedom are reported. Fisher's least significant difference tests were used as post hoc tests.

5.3   Results

5.3.1   PCA Results
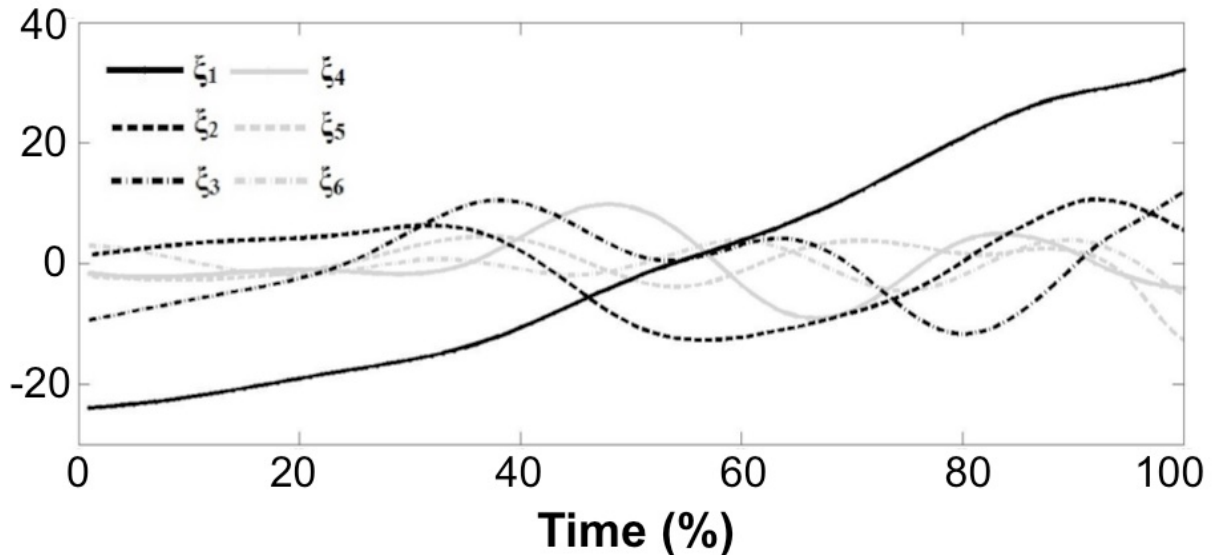
Figure 5.3: Projections associated to the first six modes of the Principal Component Analysis for the first kicker. The projections for the second kicker were similar.

For the first kicker, the first six modes explained 67.9%, 11.9%, 9.8%, 5.0%, 2.5%, and 1.7% of the variance, respectively. For the second kicker, these modes explained 71.4%, 10.8%, 8.6%, 4.6%, 2.3%,

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[4]A   video   with   a penalty   from each   of   the   seven PLD   conditions   can   be   found   at http://www.uam.es/gruposinv/gipym/HiguerasHerbadaEtAl2017.m4v

and 1.1% of the variance. For both kickers, the first six modes together explained 98.7% of the variance.

Figure 5.3 illustrates the projections corresponding to the first six modes. Figure 5.4 illustrates the contributions of the markers and coordinates to the modes. Note from Figures 5.3 and 5.4 that the projection of Mode 1 increased monotonically and that the coordinates that contributed to Mode 1 were mainly x and y. Mode 1 captured the overall approach of the kicker to the ball. Given that the overall approach was in the horizontal direction, the contribution of the z coordinate was minor. The remaining projections in Figure 5.3 indicate that Modes 2 to 6 concerned more cyclic movements. Figure 5.4 shows that the z coordinate was the main contributor to these cyclic modes.

The variance explained by Mode 1 (around 70%) was much higher than the variance explained by the other modes (between 1 and 12%). The information provided in Figures 5.3 and 5.4 allows one to understand this difference. The overall horizontal approach concerned a larger movement than the cyclical fluctuations in the vertical direction around the approach trajectory. Furthermore, although all markers contributed about the same to the overall approach, the marker contributions to the cyclic fluctuations were less homogeneous. The latter contributions were more concentrated in the extremities.
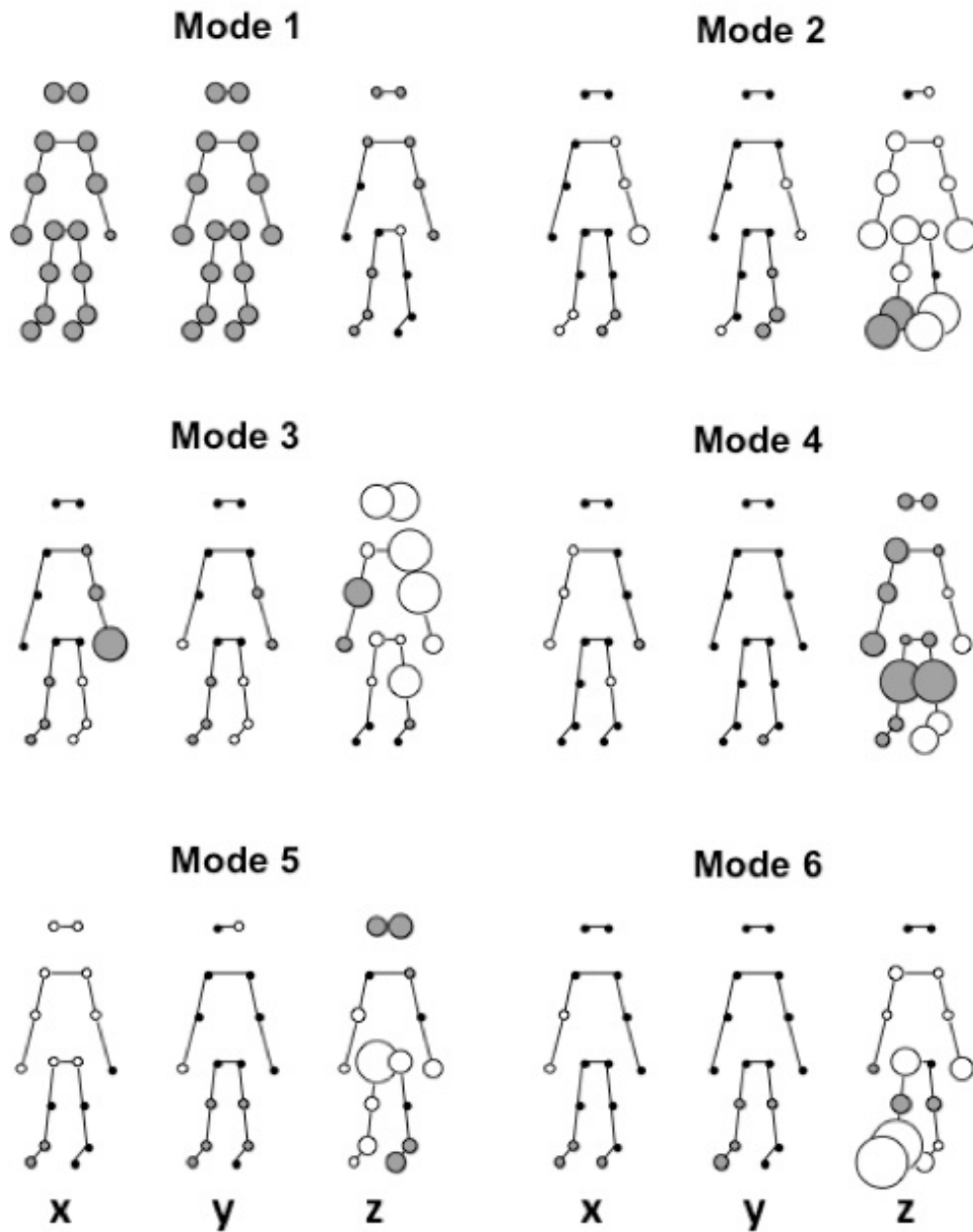
Figure 5.4: Coefficients of the mode vectors for Modes 1 to 6 of the first kicker. For each mode, 48 average coefficients are represented: 16 markers x 3 coordinates. Each average represents 10 coefficients, corresponding to the 10 penalties of this kicker. Grey and white fills of the circles indicate positive and negative averages, respectively. The absolute value of the averages is indicated by the size of the circles. Large circles indicate markers and coordinates that contribute importantly to the considered modes. The results for the second kicker were similar.

5.3.2 Experimental Results

5.3.3 Overall Performance

Figure 5.5 shows the percentage of correct side judgments in the different conditions per kicker (left panel) and averaged over the two kickers (right panel). We performed an ANOVA with condition as a within-subjects variable and kicker as a between-subjects variable on the percentage of correct judgments. The ANOVA revealed signficant main effects of condition, $F(5.5, 273.1) = 3.79$, $p < .01$, $\eta_p^2 = .07$, and kicker, $F(1, 50) = 31.33$, $p < .001$, $\eta_p^2 = .39$, and a significant interaction, $F(5.5, 273.1) = 3.06$, $p < .01$, $\eta_p^2 = .06$.
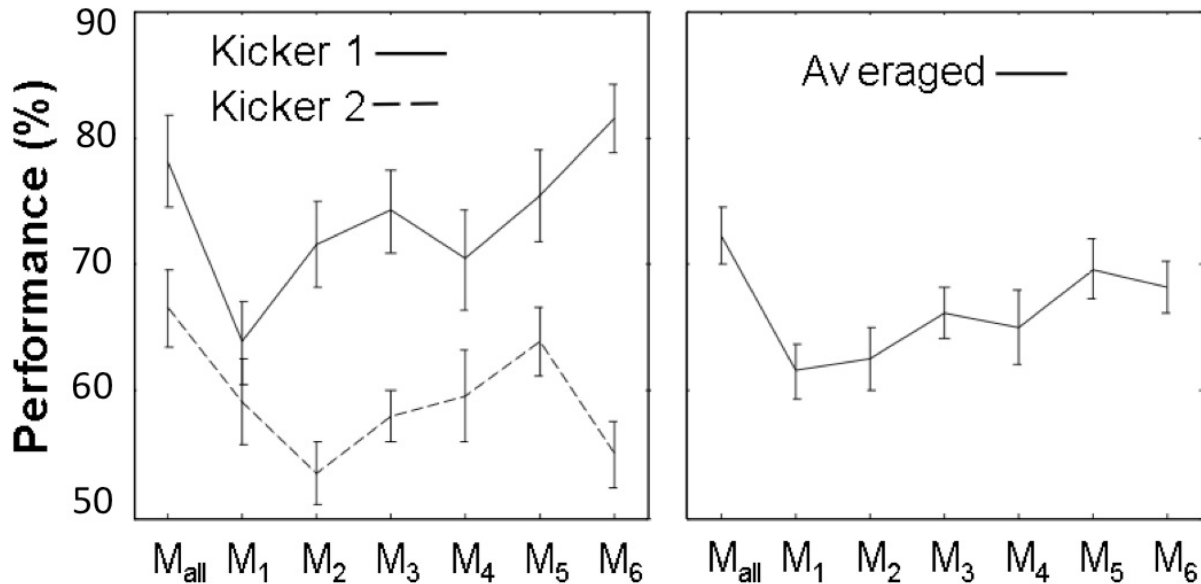

Figure 5.5: Percentage of correct judgments as a function of experimental condition for the first and second kicker (left panel) and averaged over the two kickers (right panel). Error bars indicate standard errors of the mean.

The accuracy of anticipation in the condition with the original penalties, indicated by M_{all}, was 78.1% for the first kicker and 66.5% for the second kicker, leading to an average of 72.3%. The average performance largely showed the expected profile over conditions: The percentage decreased steeply from Mall to M1 and then slowly increased with the successive inclusion of modes (from M_2 to M_6). The curves for the individual kickers showed deviations from the expected profile. Most remarkably, for the first kicker, performance increased by 6.2% with the inclusion of Mode 6, whereas, more surprisingly, for the second kicker performance decreased by 8.8%. We do not have an explanation for this latter finnding. Our further analyses focused on the performance averaged over the two kickers.

A one-way ANOVA on the averaged percentages showed a significant effect of condition: $F(6, 150) = 3.63$, $p < .01$, $\eta_p^2 = .13$. Post hoc analyses indicated that the average anticipation in the condition Mall was significantly better than in the conditions M1, M2, and M_4 ($ps < .05$). Furthermore, performance in the conditions M_5 and M_6 was signficantly better than in the condition M_1 and performance in the condition M5 was significantly better than in the condition M_2 ($ps < .05$). No other significant differences among conditions were observed. The averaged performance was above chance level in all conditions ($ps < .001$).

The variability was high: the standard deviations per condition and kicker varied between 10.6% and 20.3%. This high variability motivated us to visually inspect the profiles of individual participants. Following the interesting results of this initial inspection, the next subsection reports more formal analyses for subgroups of participants selected on the basis of their performance.

5.3.4 Hihg- and Low-performing Individuals

For this analysis, we first ordered the participants for each kicker according to their performance in the condition M6. Participants with equal performance for M_6 were subordered using their performance for M_5 and then using M_4. After this ordering, performance was averaged over the kickers per pair of participants. The 13 highest- and 13 lowest-performing pairs were analyzed as the high- and low-performing groups. We used this ordering procedure because we wanted our grouping criterion to be

independent of the subsequently applied statistics. Using the conditions with the higher modes for the grouping allowed us to statistically compare the groups using the conditions with the lower modes together with the condition with the unmodified penalties.
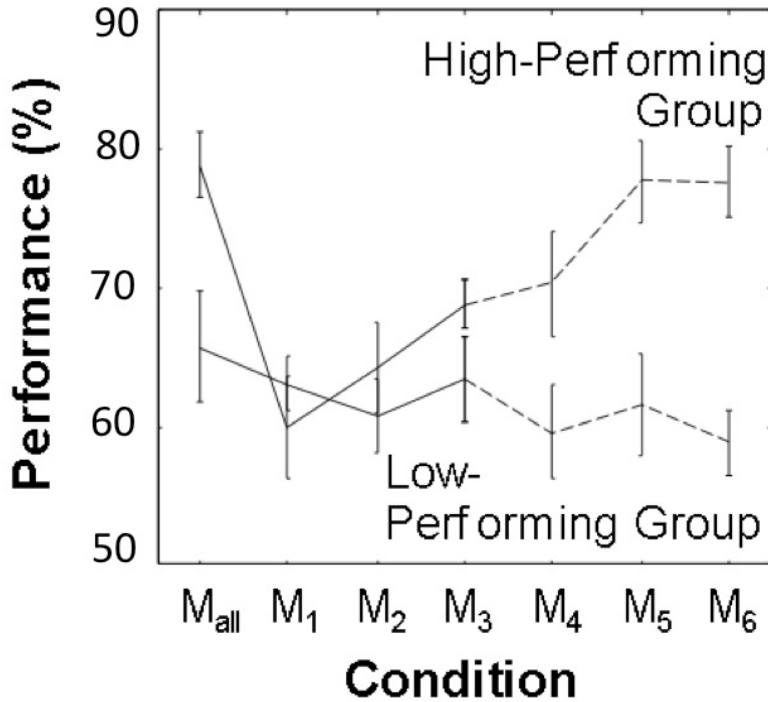

Figure 5.6: Percentages of correct judgments as a function of experimental condition for groups with high- and low-performing individuals. The dashed segments at the right indicate that conditions M_4 to M_6 were used to define the groups.

Figure 5.6 shows the performance of the obtained groups. We performed a mixed ANOVA with condition (M_{all}, M_1, M_2, and M_3) as a within-subjects variable and group (high performance, low performance) as a between-subjects variable on the percentage of correct judgments. The ANOVA revealed a significant main effect of condition, $F(3, 72) = 5.85$, p = .001, $\eta_p^2 = .20$, superseded by a significant interaction, $F(3, 72) = 3.12$, p = .03, $\eta_p^2 = .12$. The effect of group did not reach significance, $F(1, 24)$ = 2.79, $p = .11$, $\eta_p^2 = .10$. Post hoc tests indicated that, for the high-performing group, the performance in Mall was significantly higher than in the other conditions ($ps < .05$). Furthermore, for this group, performance in M_3 was significantly higher than in M_1 ($p < .05$). No significant differences were observed for the low-performing group.

5.4 Discussion

This study investigated the accuracy of anticipation on the basis of PLDs reconstructed with different numbers of PCA modes. The design of our experiment was inspired by Experiment 2 of Huys et al. (2008), but where Huys et al. (2008) addressed ground strokes in tennis, we used penalty kicks in football. The average anticipation accuracy for the unmodified PLDs was 72.3%. This relatively high percentage is in line with previous studies. It demonstrates that PLDs contain information for the perception of biological motion (Johansson, 1973) and, in particular, for anticipatory behavior in sports (Diaz et al., 2012; Higueras-Herbada et al., 2015; Huys et al., 2009, 2008). The percentage of variance explained by the PCAs was high, reaching an average cumulative 97.4% with the first five modes and 98.7% with the first six modes. These results are similar to the ones reported by Huys et al. (2008), who found that the percentage explained by the first five modes was 96.2%. Likewise, Troje (2002) pioneering study showed that more than 98% of the variance in walking patterns was explained with four PCA modes. These results confirm that biological motion contains redundancies and thereby highlight the usefulness of dimensionality reduction techniques such as PCAs. The main pattern of results over our experimental conditions with and without PCAbased manipulations replicates the main pattern reported by Huys et al. (2008). We observed a drop in anticipation performance from the condition with the unmodified penalties to the condition with penalties that were reconstructed only on the basis of the first mode as well as an increase in performance with the successive inclusion of the higher modes. This overall pattern

shows that a substantial part of the information that is used for the anticipation of penalties in football is contained in penalties that are reconstructed on the basis of few PCA modes.

A difference between our results and the ones concerning ground strokes in tennis is that performance appears to recover more quickly with the inclusion of modes in the case of the ground strokes. This difference is easily appreciated from a comparison of the overall shape of the curve in the right panel of our Figure 5 and the overall shape of Figure 7 of Huys et al. (2008). In the considered experiment of Huys et al. (2008), performance in the condition with the unmodified shots was significantly better than performance in the equivalents of our conditions M_1 and M_2 (indicated by Model and Model-2 in Figure 7 of Huys et al., 2008). In our experiment, a signficant difference in the average performance was observed also for M_4

Another noteworthy result of our experiment is that we observed differences between separately analyzed high- and low-performing groups. Individuals in the perceptually skilled group anticipated better in the condition with the original penalties than in conditions with fewer PCA modes. For individuals in the perceptually less skilled group there were no significant differences among the conditions. This result may indicate that highly skilled individuals, in contrast to less skilled ones, are able to extract higher order invariants: Their performance suffers in the conditions with fewer modes, where these invariants are not available. This interpretation is consistent with studies that show that gaze patterns tend to change with experience (Ward et al., 2002; Williams et al., 2002). The interpretation is also consistent with ecologically motivated approaches to learning, which attribute improvements with practice to changes in variable use (D. Jacobs & Michaels, 2007).

The previous remarks bring us to a weakness of many of the studies in the PCA-based body of research, including the present one. Although it is shown that information for perception is contained in actions that are reconstructed with relatively few modes, and it may even be shown which modes are the more relevant ones, it is not shown what the information is. To appreciate this point, one may note that typical ecological claims about the use of informational variables—such as the inertia tensor (Solomon & Turvey, 1988), optical acceleration (C. F. Michaels & Oudejans, 1992), or some fractional-order derivative (D. M. Jacobs, Vaz, & Michaels, 2012)-allow precise predictions about performance. In contrast, claiming that information for perception is contained in a few PCA modes does not. Our claim that six PCA modes are sufficient, for instance, does not allow us to predict whethera particular penalty will be perceived as being shot to the left or to the right.

To indicate why candidate variables from typical ecological research allow more precise predictions than the dimensionality reduction reported in the majority of PCA-based studies, we need to address a crucial aspect of the ecological notion of information. In the ecological view, information for perception is information about to-be-perceived properties (C. F. Michaels & Carello, 1981). To-be-perceived properties are therefore a necessary part of any ecological inquiry on the informational basis of perception. In contrast, PCAs search for dimensions that describe the global structure of the action independent of to-be-perceived properties. That is, the optimization performed by PCAs is unrelated to to-be-perceived properties and, therefore, to a large extent unrelated to the ecological notion of information. This implies that after having reduced the dimensionality, one still has to identify the information about to-be-perceived properties that is contained in the dimensionality-reduced action.

To identify the information in the dimensionality-reduced action, one may compare PCA results for actions with different values of the to-be-perceived property (Huys et al., 2008). Such attempts, however, have not always been successful (Bourne et al., 2011). To conclude this article, let us more speculatively indicate an alternative route for researchers who are interested in dimensionality reduction and information usage. We believe that such researchers may want to consider discriminant analyses instead of (or in addition to) PCAs. Rather than searching for dimensions that best describe the action as a whole, discriminant analyses search for dimensions that best distinguish categories (Xiang, Fan, & Lee, 2006; cf. Troje, 2002). If one takes these categories to be the to-be-perceived properties (e.g., the left vs. right direction), then the modes of the discriminant analyses are inherently related to the to-be-perceived properties. This may make the modes obtained with discriminant analyses better suited to the ecological notion of information than the modes obtained with PCAs.

Chapter 6

Information in Complex Biomechanical Actions: A Linear Discriminant Algorithm

6.1 Introduction

Point-light[1] allow scientists to present kinematic information isolated from pictorial information. Principal component analyses (PCAs) can be used to obtain low-dimensional approximations of intrinsically highdimensional point-light actions (Daffertshofer, Lamoth, Meijer, & Beek, 2004). Many point-light actions are well described with 4-6 dimensions. For example, with five dimensions one can describe more than 97% of the variance in tennis shots (Huys, Smeeton, Hodges, Beek, & Wiliams, 2008), football penalty kicks (Higueras-Herbada, Travieso, Ibáñez-Gijón, & Jacobs, 2017b), and walking patterns (Troje, 2002).

Dimensionality-reduced point-light actions can be used as stimuli in psychophysical experiments. Observers may be asked to judge outcomes of the actions, such as the final direction of tennis shots or penalty kicks. Consistent with the finding that 4-6 dimensions describe much of the total variance of many actions, stimuli constructed on the basis of 4-6 dimensions lead to judgments that are not significantly different from stimuli that contain all variance (Higueras-Herbada et al., 2017b; Huys et al., 2008).

The above-described psychophysical results demonstrate that a substantial part of the information that is used for the anticipation of the outcome of actions is contained in the dimensionality-reduced actions. But what is that information? Related to this question, several authors have analyzed the results of PCAs that were performed separately per action outcome. Such analyses have not always revealed clear differences. As an example of this, Bourne, Bennett, Hayes, & Williams (2011) claimed that "the dynamical structure underpinning the handball penalty shot does not differ greatly across locations (p. 40)".

In Higueras-Herbada et al. (2017b) we have argued that PCAs are not perfectly suited to distinguish actions according to their outcomes, and hence that PCAs are not closely related to information about the outcomes. This is so because PCAs search for dimensions that best explain the overall variance in datasets. In contrast, linear discriminant analyses (LDAs) search for dimensions that best explain differences between subsets of the total dataset (Xiang, Fan, & Lee, 2006). LDAs might therefore be more closely related to the ecological notion of information than PCAs.

The present chapter describes a novel LDA algorithm. The algorithm was applied to football penalties. The used penalties were registered by Lopes, Jacobs, Travieso, & Araújo (2014). These penalties were also used in a PCA-based psychophysical experiment reported in Higueras-Herbada et al. (2017b).

6.2 Method

Our initial dataset consisted of 48 timeseries: 3 Cartesian coordinates of 16 registered markers. Each timeseries contained 1000 datapoints: 100 datapoints per penalty for 10 registered penalties. The 100 datapoints per penalty were the resampled timeseries that were registered between the second last maximum

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[1]This chapter is published under the following reference: Higueras-Herbada, A., Travieso, D., Ibáñez-Gijón, J., & Jacobs, D. M. (2017, June). Information in Complex Biomechanical Actions: A Linear Discriminant Algorithm. In Studies in Perception and Action XIV: Nineteenth International Conference on Perception and Action (p. 13). Taylor & Francis. Psychology Press.

height of the non-kicking foot and ball contact.

Before computing the LDA, a PCA was used to reduce the dimensionality from 48 to 6. With this PCA we obtained 6 dimensions, or PCA modes, and the projections of the original data on these modes. The PCA computed the 6 dimensions so that these explained as much variance of the total dataset as possible. See Daffertshofer et al. (2004) for more detail on the application of PCA to biological movement.

Within the 6 dimensional dataset obtained with the PCA, our LDA searched for new dimensions, the LDA modes. The LDA algorithm maximized the differences between the averaged projections for penalties to the left (first 500 datapoints of the timeseries) and right (last 500 datapoints). The optimization considered a time window between approximately .56 and .11 s before ball contact (i.e., between frames 60 and 90 of the resampled projections). Detecting information during this interval may permit goalkeepers a timely reaction.
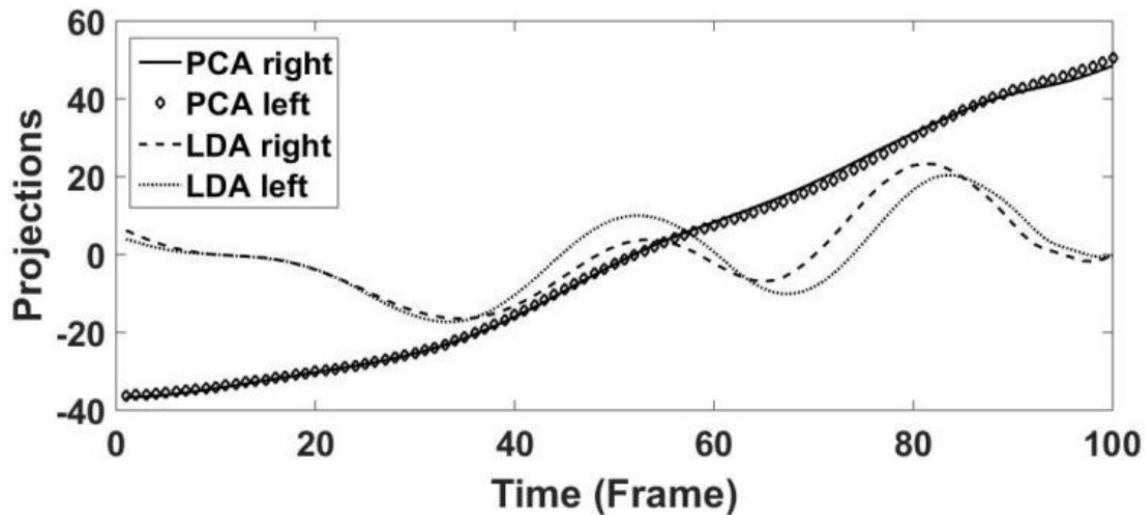

Figure 6.1: Projections of first PCA and LDA modes averaged for left and right penalties.

6.3 Results and Discussion

Figure 6.1 shows the projections for the first PCA and LDA modes. For the PCA, these projections increased monotonically. This increase corresponds to the forward movement of the kicker, which constitutes a large part of the overall variance. The LDA captured the overall approach in its higher modes: the projections for the first mode were cyclic. In contrast to the PCA projections, the LDA projections for left and right penalties differed substantially between frames 60 and 90. We next analyze this difference for all modes. The upper panel of Figure 6.2 shows the above-mentioned difference in the projections, which was optimized in the LDA, for all six PCA and LDA modes. The difference was large for the first LDA mode and lower for the higher modes. The decay over successive modes indicates the extent to which the LDA was successful in concentrating the left-right differences in the first modes. For the PCA, rather than decreasing over modes, the difference was maximal for Mode 3, followed by Modes 2 and 4. The lower panel of Figure 2 shows the variance explained by the different PCA and LDA modes. This quantity was optimized in the PCA. As expected, the first PCA mode explained much variance and the explained variance was lower for the higher PCA modes. For the LDA, Mode 4 explained most variance, followed by Mode 3 and Mode 1. The variance that was explained by the six modes together was high: 98.2%. As a consequence of our methodology, this percentage was identical for the PCA and LDA.

In short, differences between penalty kicks to the left and right are distributed over PCA modes. LDA-based reorganizations of the PCA-reduced subspace concentrate the differences in the first few modes. One may therefore hypothesize that the information that observers use to anticipate the action outcome is included in the first few LDA modes while it is distributed over most PCA modes. Psychophysical research is needed to test this hypothesis.
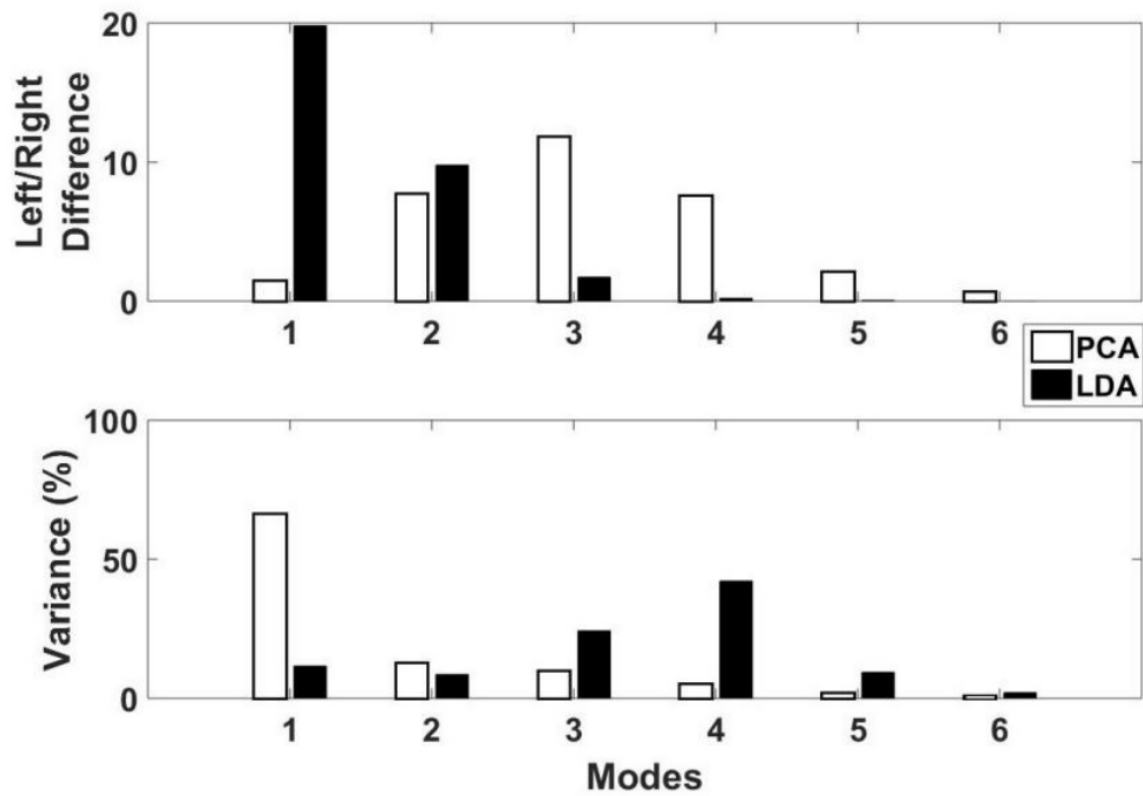
Figure 6.2: Upper panel: Mean differences between the projections of left and right penalties for PCA and LDA in the optimized interval. Lower panel: percentage of variance explained by PCA and LDA modes.

Chapter 7

Toward the use of LDA in PLD experiments: Training anticipation in the penalty kick situation

7.1 General Introduction

Anticipation has been a research topic in sports psychology since the sixties (Williams & Jackson, 2018). Proper anticipation skills can provide an important competitive advantage in team and individual sports situations. Recent studies indicate that experts outperform novices in picking up task-specific information, and have shorter response times and more focused gaze behavior (see Mann et al., 2007 for a meta-analysis). In this chapter we analyze expert-novice differences and learning in the penalty kick situation, keeping in mind the future objective of designing an ecologically inspired training program that can accelerate the transition toward expert levels of performance.

As we have seen in chapter 3, researchers have designed and evaluated different perceptual training programs to improve novice anticipation performance. Most anticipation training programs use occlusion techniques (Williams & Jackson, 2018). A relatively recent trend in the field is to move toward more representative designs using manipulation techniques that do not disturb the dynamical characteristics of the kinematics as much as occlusion does (Broadbent et al., 2015; Dicks et al., 2017; N. Smeeton, Huys, & Jacobs, 2013; chapter 3 of this thesis). The aim of this chapter is to contribute to the development of an ecological anticipation-training program, using the experimental framework presented so far in this thesis. More specifically, the basis for this training program is formed by PLDs and dimensionality reduction techniques.

As we have explained in chapter 5, PCA-modified PLDs have successfully been used to study anticipation in different sports: tennis (Huys et al., 2008; Cañal-Bruland et al., 2011; Huys et al., 2009; N. Smeeton & Huys, 2011; N. Smeeton, Huys, & Jacobs, 2013), handball (Bourne et al., 2011, 2013), and penalty kicks (Diaz et al., 2012; Higueras-Herbada et al., 2017b). To our knowledge, Troje (2002) was the first study that combined PCA reduction techniques with a classification algorithm, linear discriminant analysis (LDA), demonstrating that this technique can successfully be applied in a gender recognition task.

These experiments have contributed to the knowledge about the anticipation process in sports in multiple ways. It has been shown that PCAs over PLDs contain enough information for anticipation in sports. When presenting 5-6 PCA modes, performance does not differ from the performance that is observed with the original high-dimensional data (Huys et al., 2008; Higueras-Herbada et al., 2017b). In most task situations, around 6-7 PCA modes contain at least about 95% of the variance in the original data. The experiments with PCAs and PLDs have also corroborated the results of the spatial and temporal occlusion studies about when and where information for anticipation is available. In sum, PCA anticipation experiments have shown that there is an important source of information for anticipation in global, dynamical, and low-dimensional patterns of the kinematic time-series.

Despite these contributions, the explanatory framework used to guide research in sports anticipation studies is not sufficiently well developed. For example, one can observe an excess of heterogeneity in anticipation training programs. In chapter 3 we reviewed 42 studies and we found 10 training methods that were only applied in one study. This chapter, and this thesis in general, applies the ecological approach to perception and perceptual learning to study anticipation in sports. In chapter 6 we suggested how such an application could be performed using PLDs in penalty kicks. In a nutshell, an ecological research program for anticipation should be built around the concept of ecological information.

A fundamental question regarding anticipation training with PCA over PLDs remains unanswered: what information is used to guide anticipation? Most of the PCA over PLDs anticipation experiments concluded that the information for anticipation is contained in a few PCA modes. Other studies have shown similar performance levels when comparing anticipation with original stimuli and with PCA-modified stimuli (Huys et al., 2008, for tennis, and Higueras-Herbada et al., 2017b, for penalty kicks). These results indicate that there is enough information for anticipation in the first six modes of the PCA subspace. However, researchers still do not know what information is actually used. We argue that this is a consequence of the way in which PCA works.

The PCA searches for dimensions that best describe the action as a whole. Without any knowledge of the existence of different categories in the dataset, the PCA is blind to the informational differences that can be used to guide anticipation. On the contrary, different discriminant analyses search for dimensions that best distinguish between pre-defined categories. These pre-defined categories are selected because they are directly related to the aim of the action. In other words, they are directly related with the to-be-perceived properties (e.g., the differences in the kicker's kinematics for left and right penalty kicks). As a consequence, the modes obtained with discriminant analyses are more related to the ecological notion of information than the modes obtained with PCAs. The discriminant analysis that is focused on in chapters 6 and 7 is a linear discriminant analysis (LDA).

In chapter 6 we compared the results obtained via PCA and via LDA (using the left/right direction of the penalty kicks as the pre-defined categories). For each PCA and LDA mode we used two measures: the explained variance of the action as a whole and the differences between the pre-defined left and right categories. The total variance explained by the PCA and the LDA was the same 98.2% of the original dataset. As expected, the first PCA modes explained progressively less variance, but for the LDA the explained variance was distributed over the modes (see lower panel of Figure 6.2). In contrast, for the LDA the differences between left and right projections were concentrated in the first three modes (see upper panel of Figure 6.2). This indicates that the LDA worked as expected and that LDA modes may be closely related to the ecological notion of information.

In sum, the future aim that motivates this chapter is the development of an LDA-based anticipation-training program on the basis of low-dimensional spaces whose dimensions are more closely related to information about to-be-perceived properties than the more traditional PCA-based methods. A series of five experiments is presented. As we will see, not all of the experiments confirmed our hypotheses. Even so, we believe that the series of experiments is valuable because it successively validates different steps of the method and thereby clarifies the conditions that are required for LDA-based training programs.

The first experiment addresses expert-novice differences in the anticipation of penalty kicks. The design of this experiment replicates that of the experiment of chapter 5, with the difference that we also tested an expert population in an expert-novice experimental paradigm. In chapter 5 we observed that having only Modes 1 and 2 in a PCA over PLD presentation of stimuli does not provide enough information to perform better than random. Thus, we expect that experts have higher anticipation performance than novices in the conditions of stimulation that include at least three modes. In any case, a higher performance of experts would demonstrate the possibility of training perceptual anticipation.

The second experiment analyzes the effects on performance of training with feedback. The experiment uses a pretest-posttest design, with four training sessions in between, otherwise replicating the manipulations on stimuli and the experimental conditions used in the two previous experiments (chapter 5 and Experiment 1 of chapter 7). Following the reasoning explained above, we expect that the training will improve anticipation performance for the conditions of stimulation that contain at least three modes. This would confirm that training with feedback can be used to improve performance in the laboratory and hence that it makes sense to study how such training may be optimized with PCA and LDA methodology.

The third study tests the effect on performance of a PCA-based methodology that neutralizes the information in the modes whose information should not be presented, rather than omitting these modes altogether as was done in Experiments 1 and 2. Omitting the higher modes is not feasible in LDA-based procedures because it would produce PLDs whose movements are too different from the natural movement. Therefore, to use LDA-based techniques it is important that neutralization is used. In contrast, in previous PCA over PLDs the higher modes could be removed rather than neutralized because the obtained postures still resembled identifiable movements. We expect the same overall profile of results with neutralization (Experiment 3) as with the omission of modes (Experiments 1 and 2). This would show that PCA over PLD training programs that use neutralization to restrict information might improve performance in the laboratory.

The fourth experiment tests performance changes with feedback using an LDA-based method. As shown in chapter 6, the first three LDA modes contain almost all the differences between left and right penalties. Thus, we expect that the performance with LDA-reduced stimuli will be similar to performance with natural stimuli using only the first three modes of the LDA. To anticipate, Experiment 4 did not lead to the expected results, which may be due to the particular type of neutralization that was used in

the LDA method (of projections rather than of modes).

The fifth experiment tests whether the neutralization of projections that is used by our LDA may explain the unanticipated results in the fourth experiment. We applied the neutralization that was used in the LDA of Experiment 4 to the PCA-based method. We expect a similar profile of performance as the one observed with the LDA-based method in Experiment 4. This would demonstrate that we need an alternative approach to neutralization, or an alternative LDA algorithm that allows for the neutralization of modes rather than the neutralization of projections.

7.2 Experiment 1: PCA and Expert-novices Differences

The first experiment replicates the design of the experiment on anticipation from PCA-reduced penalty kicks that was presented in chapter 5. The modes that were not presented were omitted. In the present experiment, we use PCA-reduced penalty kicks to compare expert and novice performance. Expert-novice differences have been a recurrent topic in the anticipation literature (see Mann et al., 2007 for a meta-analysis). In our case, the objective of this comparison is to elucidate the existence of perceptual differences between experts and novices in anticipation tasks using PCA over PLD as stimulation. We expect that experts outperform novices in the conditions that include at least three modes.

7.2.1 Method

Subjects and Ethics. The experiment was approved by the local committee for ethical research (CEI 52-957). All participants were given a written informed consent before participating in the experiment. Forty-five subjects participated. Twenty-seven of them were novices, 10 men and 17 women. All novice participants were students participating in the experiment in exchange of course credits. The novices had limited experience in the penalty kick situation. Eighteen participants were experts playing in official teams in Madrid with football experience of at least 15 years. Of the eighteen experts, three were goalkeepers. All experts had extensive experience in the penalty kick situation.

Procedure and Design. The procedure was the same as in chapter 5. We used the same penalties in the same conditions with the same setting and procedure.

7.2.2 Results and Discussion

Figure 7.1 summarises the results of Experiment 1. We performed a repeated measures ANOVA with condition as within-subject factor and expertise as between-subject factor. The ANOVA revealed significant main effects of condition, $F(7,37) = 10.70$, $p < .001$, $\eta_p^2 = .28$, and expertise, $F(1,43) = 12.08$, $p < .001$, $\eta_p^2 = .37$, and a non-significant interaction effect, $F(7,43) = 5.04$, $p = .94$.
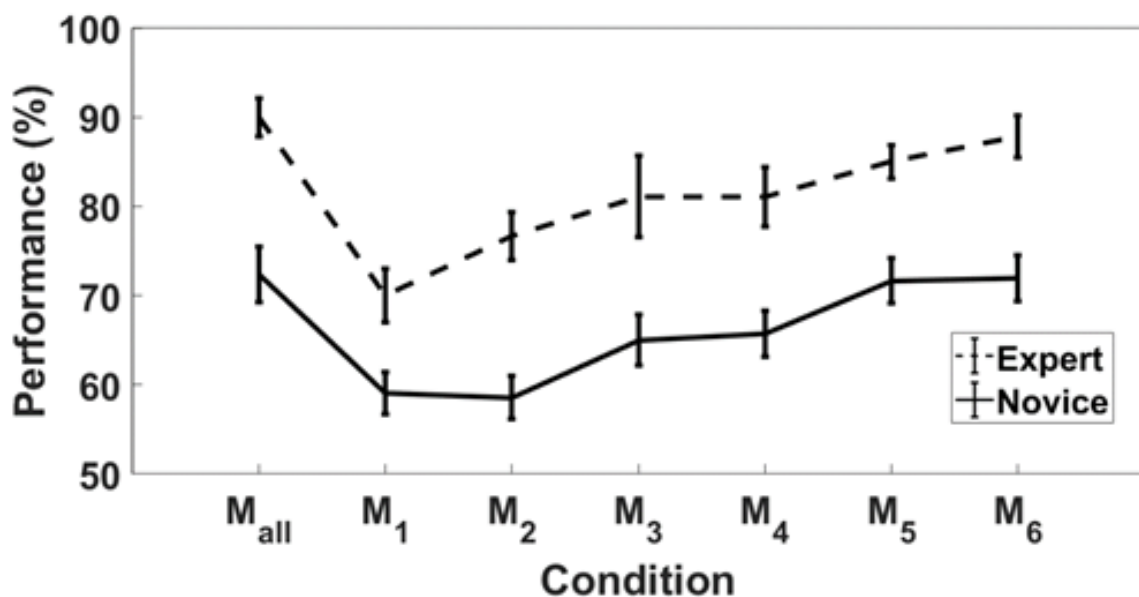

Figure 7.1: Performance (%) as a function of experimental condition for the Experiment 1. Error bars indicate standard error of the mean.

Post hoc analysis indicated that novice performance in condition M_{all} and M_6 was significantly higher than Post hoc analysis indicated that novice performance in the conditions M_{all} and M_6 was significantly higher than performance in the conditions M_1 and M_2. For the groups of experts, performance in the conditions M_{all} and M_6 was higher than performance in the condition M_1. The performance of experts was significantly higher than that of novices in all conditions except M1. in conditions M_1 and M_2. For the groups of experts, performance in conditions M_{all} and M_6 was higher than performance in condition M_1. Performance of experts was significantly higher than novices in all conditions except M_1.

These results indicate that experts outperformed novices in all conditions, except when only the first PCA mode was presented. Conversely, the first mode does not provide enough information for expert anticipation. It is interesting that the profile of the two curves is similar, with the best performance in the condition Mall, followed by a decay in performance in M1 and a progressive recovery with the addition of modes. In sum, expert-novice differences can indeed be observed using PCA-reduced PLD as stimuli. This encourages us to think that perceptual-training in a laboratory can be a useful tool to achieve expert performance.

7.3 Experiment 2: PCA and Training With Feedback

The results obtained so far indicate that PCA over PLDs methodology can provide information for anticipation in penalty kicks when at least the first two modes are present. We have also confirmed that with PCA over PLDs significant differences between expert and novice anticipation performance can be observed. The aim of this experiment is to test with PCA-based methods if training with feedback improves novice performance after practice in the laboratory.

7.3.1 Method

Subjects and Ethics. The experiment was approved by the local committee for ethical research (CEI 52-957). All participants were given a written informed consent before participating in the experiment, and all of them were students participating in research for course credits. The experience of the participants facing penalty kicks was low. Seven subjects participated in this experiment, 1 man and 6 women.

Procedure and Design. As were the other experiments, this experiment was performed using self-developed MATLAB routines and Psychtoolbox-3. Participants were informed that they would be shown a series of penalty kicks from the perspective of the goalkeeper. The participants were asked to indicate the direction of the kicks with the right- or left-arrow key. The penalties were presented in a random order. Each penalty was shown twice before the participant responded. Optional breaks were suggested after each 10 trials.

The training program was divided into 3 different days: Day 1 (pretest and Training 1), Day 2 (Training 2 and Training 3), and Day 3 (Training 4 and posttest). The total duration of the experiment was approximately 180 min. We selected 18 penalties (9 left and 9 right) of the ones recorded by Lopes et al. (2014). Twelve of the 18 penalties were manipulated in the different conditions of the pretest and posttest. In each training session, the 18 original penalties were presented 5 times.

The pretest and posttest consisted of eight conditions referred as M_{all}, M_0, M_1, M_2, M_3, M_4, M_5, and M_6. These conditions differed in the amount of information presented. M_{all} corresponds to the original penalties with all the information. In the M_0 condition none of the PCA modes were presented. This means that no dynamical information was used and hence that there was only static information available for anticipation. Static information refers to the means and standard deviations of the time-series; it contains side-specific differences although dynamical information has been claimed to be more relevant for anticipation (Bourne et al., 2011; N. Smeeton & Huys, 2011). The condition M_1 contains the first PCA mode, M_2 the first and the second, M_3 the first three, etc.

7.3.2 Results and Discussion

Figure 7.2 shows the results for the PCA training program. We performed a ANOVA with condition and time as within subject variables. The ANOVA revealed significant main effects of condition, $F(7,70) = 3.42$ p $< .01$, $\eta_p^2 = .025$, a non-significant time effect, $F(1,10) = .40$ p $= .039$, np2 $= .14$, and a non-significant interaction effect, $F(7,70) = .41$, p $= .75$. The post hoc analysis indicates that there were no significant differences between the conditions in pre-test. For the post test, condition M_5 was anticipated significantly higher than condition M_1. A one-way ANOVA for training blocks did not reach significance, $F(3,18) = 0.93$, p $= .93$.

These results tentatively indicate that anticipation training with feedback may improve performance. The only significant difference was between M5 and M1 in the posttest, but there were close to significant
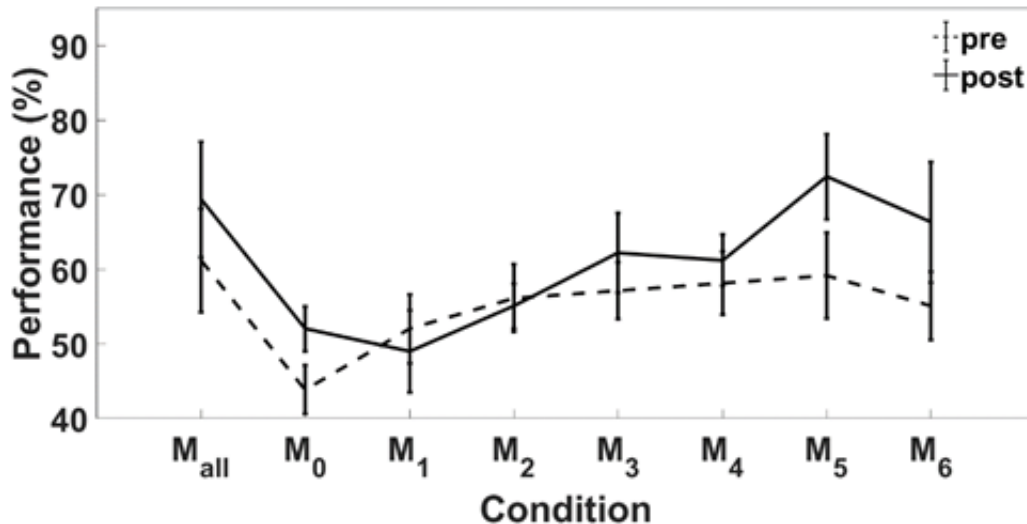
Figure 7.2: Shows performance (%) as a function of experimental condition in pre- and post-training for the PCA training program of experiment 2. Error bars indicate the standard error of the mean.

differences between M5 and M6 when comparing pretest and posttest. The obtained profile was similar to the one shown in other PCA anticipation experiments (Huys et al., 2008; Higueras-Herbada et al., 2017b). A limitation of this experiment is the sample size. Due to the small sample size (and the variance in the data) some differences that should have been significant were not.

7.4 Experiment 3: PCA and the Neutralization of Modes

PCA provides a subspace that maximizes the variance explained by the modes. In contrast, LDA provides a space that maximizes the differences between left and right penalties. Therefore, as shown in the video of chapter 5, PCA reconstructed penalties can be recognized as a natural biological movement when the first 3-4 modes are presented. This is not the case with the LDA reconstructed penalties, because more than 50% of the variance is contained in the last 3 modes. For that reason, LDA-based stimulus presentations must neutralize rather than remove the discarded dimensions. Let us explain in more detail why neutralization is relevant for LDA over PLD experiments (Huys et al., 2009).

Neutralization cancels out the dynamical differences between left and right outcomes by averaging PCA or LDA modes for each marker (N. Smeeton, Huys, & Jacobs, 2013). After neutralization, PCA or LDA mode-averages can be added without adding side-specific information to the stimuli. This allows researchers to add individual modes to test performance, while having visually appealing stimuli. For example, if we want to test anticipation performance using only the first mode of the PCA with a smooth movement, we can add the information of Mode 1 and neutralize the remaining 5 modes. The resulting stimuli will contain the information to distinguish between left and right penalties of the first mode but not the information of the remaining ones, because, for the other modes, it will contain the averaged, side-neutral dynamics.

This third experiment analyzes the effect of training with feedback on anticipation performance using PCAs with neutralization to restrict the availability of information. If PCA-neutralized stimulation can retain the performance gain observed with PCA-omitted stimuli, future LDA-based training programs may be able to increase performance. In addition, with neutralization a wide variety of new anticipation studies are possible. For example, it would be possible to neutralize certain areas or time-windows as occlusion studies did, but without disrupting the dynamics of the movement (N. Smeeton, Huys, & Jacobs, 2013).

7.4.1 Method

Subjects and Ethics. The experiment was approved by the local committee for ethical research (CEI 52-957). All participants were given a written informed consent before participating in the experiment. All of them were students participating in research for course credits. The experience of the participants facing penalty kicks was low. Nine subjects participated in this experiment (2 men and 7 women).

Procedure and Design. This experiment replicates the manipulations performed and the stimuli used in Experiment 2 with one exception. The information in the modes that are restricted in a certain condition are neutralized rather than omitted. More precisely, after performing the PCA-based decomposition in modes, we reconstructed the movements of the kicker using different techniques in the two experiments: neutralization (Experiment 3) and omission (Experiment 2). For each experimental condition we computed the approximation $q(t)$ with a different value of M (see Equation 5.1). The values of M that were used in the eight conditions were 480, 0, 1, 2, 3, 4, 5, and 6, respectively. When M was set at 480 (M_{all}), all modes were used in the reconstruction, and hence PLDs of the original penalties were presented. Setting M at any value between 1 and 6 means that only the modes until the value of M were used. These six conditions were referred to as M_1 to M_6.

For the omission condition (Experiment 2), only PCA modes corresponding to the included conditions were added to the stimuli. For instance, penalties of condition M4 were approximations of the actual penalties based on Modes 1 to 4 of the PCAs. In contrast, for the neutralized condition, in addition to the modes that were included with side-specific information as in the omission experiment, we added a neutralized version of the remaining modes. The neutralized version of each mode was computed by averaging the base vectors, v, for each marker coordinate and for left and right penalties.

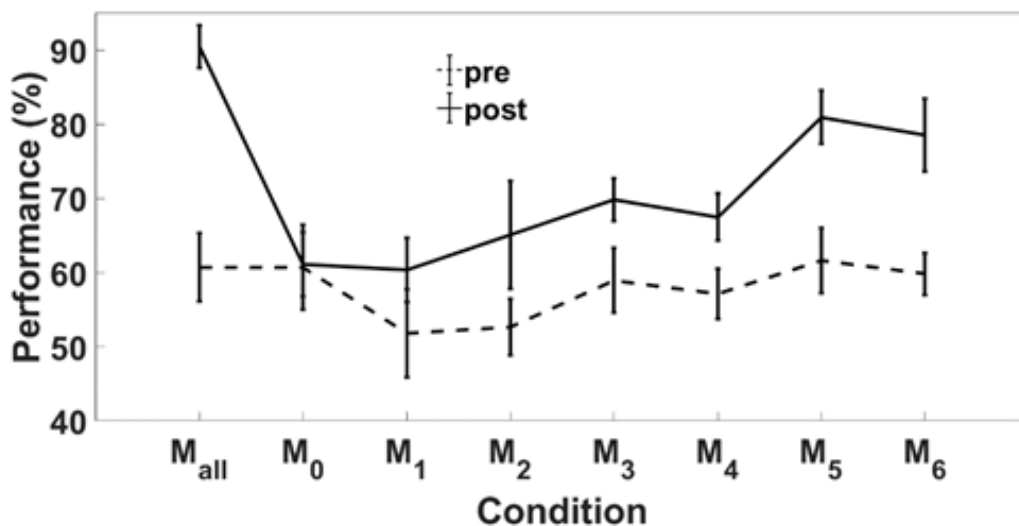## 7.4.2   Results and Discussion

Figure 7.3: Shows performance (%) as a function of experimental condition in pre- and post-training for the PCA with neutralization training program of experiment 3. Error bars indicate the standard error of the mean.

Figure 7.3 shows the results for the PCA PCA with neutralization training program. We performed a ANOVA with condition and time as within subject variables. The ANOVA revealed a significant effect of condition, $F(7,105) = 2.14$ p $< .01$, $\eta_p^2 = .25$, a significant time effect, $F(1,15) = 18.58$ p $< .001$, $\eta_p^2 = .55$, and a significant interaction effect, $F(7,105) = 2.15$, p $< .05$, $\eta_p^2 = .13$. The post-hoc analysis indicates that there were no significant differences between the conditions in pre-test. For the post-test there were significant differences between condition mall and conditions M_0, M_1, M_2, M_3 and M_4; there were also significant differences between M_5 and M_{0-1}. There were significant differences between the pre- and post-test in the conditions M_{all}, M_4, M_5 and M_6. A one-way ANOVA for training blocks reached significance $F(3,24) = 1.06$, p $= .39$. The post hoc analysis indicated that there were no significant differences.

These results indicate that anticipation training with feedback shows as much or more improvement in performance when evaluated with PCA and neutralization as compared to traditional PCA and omission. The same profile of results was observed as in the previous experiments and in other PCA anticipation studies (Huys et al., 2008; Higueras-Herbada et al., 2017). As was the case with the previous experiment, a limitation of this experiment is the sample size. Possibly related to this limitation, and to the high observed variance, some differences that were expected to be significant in the pretest were not. Nevertheless, the expected profile was significant in the posttest, in which performance was similar to

the expert performance in Experiment 1. The validation of the neutralization manipulation allows us to proceed to the LDA methodology.

7.5 Experiment 4: LDA and the Neutralization of Projections

The positive results of the previous experiments allow us to test the LDA algorithm that was discussed in chapter 6 in a psychophysical anticipation experiment. The previous experiments showed that neutralization works properly, with similar or even better levels of performance than conditions that omit modes. In addition, the first experiment shows an interesting profile by comparing expert and novice anticipation performance. In this experiment the LDA algorithm is used. We expect that, in contrast to the PCA, performance would increase in a greater amount with the addition of only the first modes.

Next we present the LDA algorithm. The first step is to obtain a low-dimensional space via PCA. We used a low-dimensional space with the six modes that explain most of the variance (around 95% of the total variance). Before presenting the LDA algorithm we need to explain some differences between how PCA is implemented (as in chapter 5 and in previous experiments) and how LDA is implemented.

To apply the PCA that was used in previous experiments to the dataset we organized the penalties in columns. A similar organization was used by Daffershofer et al. (2004), Huys et al. (2008), and Higueras-Herbada et al. (2017). In our penalty kick case, this means that each row of the dataset contained a full 100-frame-long time-series of one of the 16 markers in one of the three coordinates. This leads to a total of 576 rows (i.e., dimensions): 16 (markers) x 3 (x, y, and z coordinates) x 12 (penalties). To more easily understand the following paragraph, note that each of our penalties provides 48 rows with time-series. That is, each penalty provides a 48x100 matrix with recorded data. Using an organization in columns, then, means that the 48x100 matrices of the 12 penalties were placed below each other.

In contrast, to apply the LDA explained in chapter 6, the dataset was organized in rows. This means that each row of the dataset contains all time-series (all trials from both left and right categories) of one of the 16 markers in one of the three coordinates. This gives a total of 48 rows: 16 (markers) x 3 (x, y, and z coordinates), each row being of length 1200 (100 [time-series length] x 12 [penalties]). In other words, rather than placing the 48x100 data blocks per penalty below each other, they are now placed next to each other. We chose this organization because discriminant analyses typically distinguish categories of data-points (i.e., columns) rather than categories of dimensions (i.e., rows). With an organization in rows, the left and right categories are indeed applicable to columns.

As mentioned above, to facilitate the computations that underlie the algorithm that performs our LDA search we first reduced the original 48-dimensional dataset to a 6-dimensional dataset. To do so, we applied a PCA to the 48x1200 matrix. All but the first 6 dimensions of the PCA were discarded. Our application of the LDA algorithm consisted in a recursive numerical search for a new base vector in the 6-dimensional space that was obtained with the PCA. The new base vectors were successively chosen so as to maximize the distance (that is, the aggregated differences) between the projections for the left and right penalties. The search process was repeated until the original space was exhausted (in this case, until the sixth LDA mode was obtained). The reconstruction of the time-series (t) with M base vectors was similar to the PCA reconstruction (Equation 1 in chapter 5). The only difference of relevance to the reconstruction, in fact, was that the LDA resulted in different modes and hence different associated projections.

Let us provide some more detail about the optimization criterion that we used in the numerical search process. Instead of minimizing the distance between the approximation and the original dataset, as is done in a PCA, we optimized the search in a way that maximized the distance between left and right projections on the space spanned by the base vectors. This optimization was performed in a time window that goes from frame 76 to frame 100 of the length-normalized time-series. Given that the time-series lasted about 1 second each, this interval goes from 240 to 0 ms before ball contact (which corresponds to the relevant time window identified by previous studies on the anticipation of penalty kicks; Dicks et al., 2011). The used optimization equation reads as follows:

$$\tilde{q} = \boldsymbol{w_k}(t) \sum_{k=1}^{M} \zeta_k(t) v_k \tag{7.1}$$

For some readers it may be helpful to note that we obtained this equation by modifying the equation that is used in the traditional PCA optimization (e.g., Equation 3 of Daffertshofer et al., 2004). The process of searching the best-separating base vector was applied recursively until the original space dimensionality was reached. To that end, after a maximal-distance dimension was obtained its information was removed from the time-series as described in Equation 9 of (Xiang et al., 2006). We hence obtained

six base vectors, the LDA modes, which were ordered according to their capacity to distinguish left and right penalties.

In this experiment we used a similar procedure as in Experiments 2 and 3 (PCA with omission and PCA with neutralization, respectively), using the newly developed LDA instead of PCA. Neutralization was used to generate the stimuli, because using omission in LDA leads to visibly awkward and unrecognizable movements. Due to the organization of the dataset in rows, the neutralization could not be performed on the modes themselves. This is so because each coefficient of an LDA mode is related to both left and right time-series. On the contrary, in the PCA-based method used in Experiments 1, 2, and 3, some of the coefficients of a mode correspond to time-series from shots to the left and other coefficients correspond to time-series from shots to the right. As a consequence, in Experiment 3 it was possible to perform the neutralization on the modes themselves (i.e., averaging the mode coefficients for the left and right penalties). In the LDA-based method used in this experiment, rather than the modes, we neutralized the projections of the time-series on the LDA dimensions. That is, in reconstructing the penalties, the to-be-neutralized modes were added with projections averaged over left and right penalties.

Considering that LDA modes maximize the differences between left and right penalties, we expected that with the addition of the first modes (1-3) performance would reach the same level as with the original stimuli.

7.5.1   Method

Subjects and Ethics. The experiment was approved by the local committee for ethical research (CEI 52-957). All participants were given a written informed consent before participating in the experiment, and all of them were students participating in research for course credits. The experience of the participants facing penalty kicks was low. Twenty-three subjects participated in this experiment (5 men and 18 women).

Procedure and Design. The procedure and design were the same as in Experiments 2 and 3. The only difference was that we used the LDA-based method explained above instead of the PCA-based method used in Experiments 2 and 3.

7.5.2   Results and Discussion

Figure 7.4: Performance (%) as a function of experimental condition for experiment 4. Error bars indicate standard error of the mean. Solid horizontal lines indicate performance of each training session.

Figure 7.4 shows the results of the LDA training. We performed an ANOVA with condition and time (pre-post) as within-subject variables. The ANOVA revealed significant main effects of condition, $F(7,196) = 8.92$, $p < .001$, $\eta_p^2 = .24$, and time, $F(2,28) = 6.00$, $p < .05$, $\eta_p^2 = .18$, and a significant interaction effect, $F(7,196) = 2.38$, $p < .05$, $\eta_p^2 = .08$. The post hoc analysis indicated that for the pretest there were no significant differences between conditions. Performance in the post-test of condition M_{all} was significantly better than in all other conditions. There were significant differences in conditions M_{all}, M_1, and M_6 between pre-test and post-test.

Average performance for the training blocks was 66.35, 67.14, 67.62 and 71.41% respectively for each training session. One-way ANOVA for training blocks reached significance F(3,17) = 21.31, p < .001, η_p^2 = .56. Results indicated significant differences between all training sessions except between train 2 and train 3.

We expected that with only 1-3 modes of the LDA performance would be at the level of the original penalties. The obtained results did not follow the expected profile. A flat or decreasing profile was seen in the pretest and posttest, except for the condition Mall (original penalties). These results and the fact that performance in the training blocks were similar to the ones obtained in the other training experiments made us think that the neutralization of the projections that we implemented, in order to apply the LDA-based method, generates problematic sets of stimuli for perceptual anticipation. In the next experiment we explored this possibility using a PCA-based method with the matrix organization of the LDA-based method. As a consequence, it uses the neutralization of projections of the LDA-based method, and can help us identify the role of this neutralization in the failure of LDA-based training[1].

7.6 Experiment 5: PCA and the Neutralization of Projections

The results of the LDA methodology did not follow the profile that we expected. There were no significant differences among the conditions in the pretest and posttest, except for the original penalties (the unmodified conditions). The fact that only the condition Mall and the training sessions showed the expected profile indicates that the problem could be due to the neutralization of projections (rather than modes) that we used for our LDA-based method. In this fourth experiment we wanted to verify this explanation. To that end, we designed a PCA-based method that replicates the matrix organization and the neutralization of the LDA-based method.

As explained in chapter 5 and the previous experiment, in order to apply the PCA to the dataset, we organized the data in columns. This means that each row of the dataset contained the time-series of one of the 16 markers in one of the three coordinates, given a total of 576 dimensions: 16 (markers) x 3 (x, y, and z coordinates) x 12 (penalties). In contrast, to apply the LDA, as explained in chapter 6 and the previous experiment, the dataset was organized in rows instead of columns. That means that each row of the dataset contained all time-series (all trials from both left and right penalties) of one of the 16 markers in one of the three coordinates, giving a total of 48 dimensions: 16 (markers) x 3 (x, y, and z coordinates). As can be seen, the difference in the organization of the data between PCA and LDA is that for the LDA all the trials (penalties) for each coordinate and marker are in the same row and for the PCA they are not.

Experiment 5 tested the results of training with feedback using PCA modified penalty kicks with the matrix organization that was used for the LDA in Experiment 4. If our hypothesis is correct, and the organization of the dataset affects performance, we expect a performance profile similar to Experiment 4.

7.6.1 Method

Subjects and Ethics. The experiment was approved by the local committee for ethical research (CEI 52-957). All participants were given a written informed consent before participating in the experiment, and all of them were students participating in research for course credits. The experience of the participants facing penalty kicks was low. Nineteen subjects participated in this experiment (3 men and 16 women).

Procedure and Design. The procedure and design were the same as in experiment 1 and 4.

7.6.2 Results and Discussion

Figure 7.5 shows the results of the PCA columns neutralization training. We performed an ANOVA with condition and time (pre-post) as within-subject variables. The ANOVA revealed a non-significant main effects of condition, F(7,273) = 1.89, p = .07, η_p^2 = .05, and a significant effect of time, F(1,39) = 8.72, p < .05, η_p^2 = .18, and a non-significant interaction effect, F(7,273) = 1.39, p = .21, η_p^2 = 0.03. Post hoc analysis indicates that there were no significant differences between conditions in the pre-test and post-test. There were significant differences between pre- and post-training conditions Mall, M3, M4 and M6. Performance in training blocks was 64.7, 70.8, 73.7 and 75% respectively for each training block. One-way ANOVA for training blocks reached significance F(3,19) = 5.57, p < .05, np2 = .23. Results indicate significant differences between training 1 and training 4.

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[1] After observing the results of this experiment, we have checked the programming of the LDA method as carefully as possible. However, we did not encounter programming errors that may be related to the unexpected pattern of results.
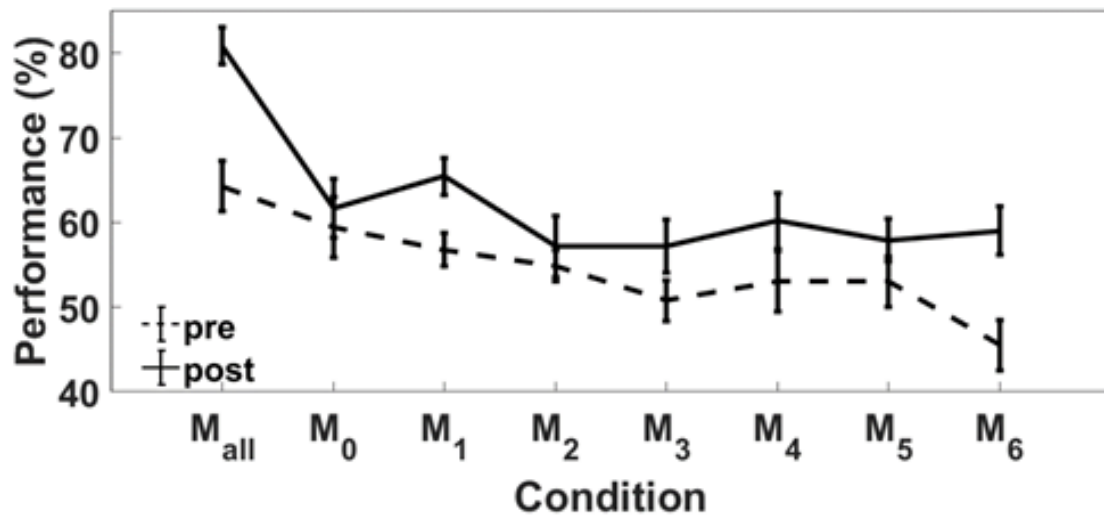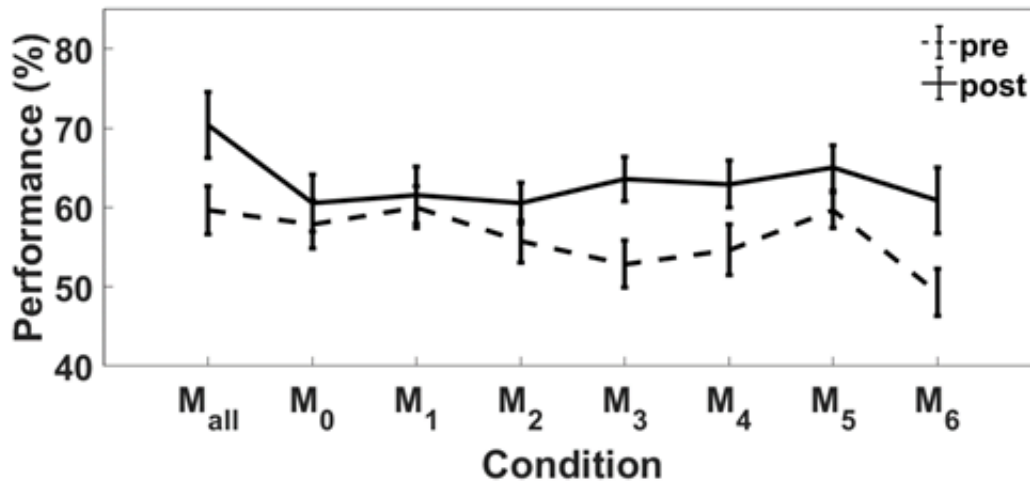
Figure 7.5: Performance (%) as a function of experimental condition for the experiment 4. Error bars indicate standard error of the mean. Error bars indicate standard error of the mean. Solid horizontal lines indicate performance of each training session.

To summarize, an almost flat performance profile was observed for pretest and posttest. There were significant pretest-posttest differences only for conditions Mall, M4, and M6. This means that the neutralization of projections has a greater detrimental effect on performance than the neutralization of modes (used in Experiment 3). These results are similar to the ones obtained in Experiment 4 for the LDA method: performance in the Mall condition and during training sessions (with original stimuli) showed improvement with practice. This means that the unexpected results of the LDA methodology may be due to the neutralization of projections.

7.7　General Discussion

In this chapter, we presented a series of experiments with PCA-LDA modified PLDs of penalty kicks. The objective of the series of experiments was to work toward an LDA-based anticipation-training program for penalty kicks.

Experiment 1 replicated the experimental setup used in chapter 5, but this time comparing expert and novice samples. Expert-novice differences can provide information about the nature of the learning process, as well as about peculiarities of expert performance that are relevant to training programs. With two or more PCA modes, the experts outperformed the novices. These results indicate that PCAs over PLDs maintain expert-novice differences in the anticipation of penalty kicks. In addition, expert and novice anticipation performance follows the same profile. The best performance for both groups was observed for the original penalties, followed by a decay in performance, which slowly recovered with the inclusion of modes until the conditions M5 and M6 that did not differ in performance from the original penalties.

Experiments 2 and 3 compared omission and neutralization conditions in a training-with feedback setting. The neutralization of the information that is not presented in each experimental condition was a pre-step needed to apply LDA in a training program. This is related to the quantities that are optimized in each algorithm. PCA maximizes the explained variance of each mode. Therefore, the first mode is the one that explained most variance, and with the addition of the subsequent modes, the action cannot be distinguished from the original data, both from the perceptual and performance point of view.

In contrast, our LDA maximizes the distance between the projections of left and right penalties. This distance is not directly related to the amount of explained variance. Consequently, when LDA-modified stimuli are presented and not included modes are omitted, a large number of modes are needed to present a smooth biological movement. Neutralization allows researchers to present information of individual PCA or LDA modes with a visual appealing stimulus.

The results of Experiments 2 and 3 showed that performance can be enhanced with feedback-based practice and that either neutralization or omission can be used to selectively remove information. Results were similar to previous studies in anticipation from PCAs, with a drop in anticipation performance from the condition with the original penalties to the condition with penalties that were reconstructed only

on the basis of the first modes, as well as an increase in performance with the successive inclusion of the higher modes (Huys et al., 2008; Higueras-Herbada et al., 2017). This pattern was followed in the omission and in the neutralization conditions.

As can be seen by comparing Figures 7.2 and 7.3, performance in the neutralization experiment was higher for all conditions compared to the omission condition. This indicates that neutralization is a proper way to present individual PCA modes. It also shows that neutralization can eliminate information of the stimulation in a way that is less disrupting for the general dynamics than other techniques such as omission or occlusion (Smeeton et al., 2013). We expected that with a larger sample size the results of Experiment 2 would have been stronger. However, the general pattern is clear and sufficient to allow us to continue with the planned series of experiments.

Experiment 4 concerned the LDA methodology. The aim was to test the LDA algorithm, which was mathematically tested in chapter 6, in a psychophysical experiment. The advantage of using LDA instead of PCA is that LDA searches for dimensions that best distinguish between left and right penalties. Consequently, these dimensions will be more closely related to ecological information for anticipation.

Results of the experiment did not show the expected profile. In the posttest, there were only significant differences between the condition Mall and the other modified conditions. Performance did not increase with the addition of the LDA modes in the pretest and posttest. However, performance significantly increased in the training sessions and from pretest to posttest for the condition Mall. Thus, the conditions that showed an increase in performance were the ones that were not LDA modified. For that reason, we suspected that there could be problems with the LDA treatment.

Because each coefficient of an LDA mode is related to time-series of both left and right penalties, the neutralization could not be performed on the modes themselves. On the contrary, in the PCA-based method used in Experiment 2, some of the coefficients of a mode correspond to time-series for shots to the left and other coefficients correspond to time-series for shots to the right. As a consequence, in Experiment 2 it was possible to perform the neutralization on the modes themselves, whereas for the LDA-based method used in this experiment we neutralized the projections of the time-series on the LDA dimensions.

To test if peculiarities of the neutralization method that was used for the LDA could be affecting performance, in Experiment 5 we designed a methodology that used a new PCA-based method, replicating the organization of the dataset and the neutralization used in the LDA-based methodology. With this experiment we wanted to check whether performance was affected by the neutralization method.

The overall profile of the results in Experiment 5 was similar to the one obtained in Experiment 4. There were no significant differences among the conditions in the pretest or posttest. Hence, for the PCA with the dataset organized in rows, performance did not follow the profile typically followed in PCA anticipation experiments. This profile is characterized by a drop in anticipation performance from the condition with the original penalties to the condition with penalties that were reconstructed only on the basis of the first modes, as well as an increase in performance with the successive inclusion of the higher modes.

The fact that the results of Experiment 5 did not replicate the typical results of PCA anticipation experiments makes us think that at least part of the problems with the LDA could be due to the neutralization method. We can also speculate that another difference between the PCA and LDA implementations may affect performance. PCA provides an analytical solution to optimize the variance explained, whereas our LDA implements a numerical solution.

Another problem may be related to the fact that we performed the classification via LDA over time-series data projections. We made this decision because we wanted the algorithm to work with real-world coordinates. Troje (2002) performed a similar experiment based on gender recognition from gait patterns. In his approach, Troje performed a two-stage PCA with a sinusoidal fit using Fourier series in between, and finally performed the classification via LDA. In this case, the linear classifier was applied on variables that related either to one or to the other category, and therefore a mode-based neutralization could be used.

In our case, we did not use the two-stage PCA, followed by the sinusoidal fit used by Troje (2002), because our data does not behave like treadmill gate recorded data. According to Troje (2002) treadmill recorded gait data can be "nicely modeled with pure sine functions". Four sinusoids captured both the fundamental frequency of the walking and the second harmonic explaining, on average, around 95

With penalty kicks 4 sinusoidal modes explained around 75% of the total variance, 20% less than for gait patterns. If one compares Figure 5.1 with Figure 3 of Troje (2002), differences between gait and a penalty kick are evident. For the gait pattern, the movement is perfectly cyclical and hence can be perfectly modeled by sinusoidal functions. In addition, when recording on a treadmill, the variation in the y-coordinate is very low, meaning that there is no real displacement. In contrast, for a penalty kick there is movement in the y-coordinate. Actually, this movement provides a substantial proportion of the total variance (corresponding to the approach to the ball; see chapter 5). Finally, the movement of a

penalty kick is clearly not cyclical.

In sum, the LDA methodology put forward in this chapter as a basis for future training programs was not as successful as we had expected. Even thought, in the process we obtained valuable information for anticipation research. First, we demonstrated that expert-novice differences can be observed with PCA-based PLD stimulation. Next, we demonstrated that training with feedback improves anticipation performance, in a pattern over PCA modes that closely resembles the one observed for experts and novices. The improvement with feedback can be demonstrated if information in the unavailable modes is either removed or neutralized. Finally, we provided a possible explanation for the failure of the LDA methodology. We demonstrated that a PCA-based method in which neutralization is performed on the projections, as in the LDA method, has similar results to the ones obtained in the LDA method. The theoretical claim that inspired this study remains valid, though still unproven: anticipatory behavior is based on perceiving low-dimensional and ecologically relevant information. In this sense, we are already testing other methods to perform simultaneous categorization and dimensionality reduction in ways that are similar to the here-tested LDA, but without the detected shortcomings.

7.8 Acknowledgements

Part IV

Epilogue

Chapter 8

The direct learning theory: a naturalistic approach to perceptual learning for the post-cognitivist era

Di Paolo, Buhrmann, & Barandiarán (2017) proposed[1] a list of criteria that post-cognitivist theories of learning should fulfill. In this article we describe the direct learning theory, developed under the ecological approach, and review research performed in this theoretical framework. We argue that the theory of direct learning fulfills most of the criteria put forward by Di Paolo et al. (2017). In this sense, the tools and concepts of the direct learning theory can be useful to other post-cognitivist theories of learning. Direct learning holds that improvements with practice in perception and perceptually-guided action are driven by information for learning. Such information can be found in the dynamic interaction of the organism that performs the action and the environment in which the action is performed. The theory formally describes information for learning as a vector field that spans a space that includes all perception-action couplings that may be used to perform the action. Being located at a point of such a space means using a specific perception-action coupling. Changes in perception-action couplings due to learning can be represented as paths across the space, and can be explained with the vector field of information for learning. Previous research in the direct learning framework considered actions that were best understood with single perception-action couplings. To conclude the article, and inspired by the criteria of Di Paolo et al., we discuss an extension of the theory to actions that are best understood with multiple perception-action couplings.

8.1 Introduction

Post-cognitivist approaches to psychology are a heterogeneous group of theories brought together by their shared rejection of the central assumptions of cognitivism: the poverty of the stimulus doctrine, the representational basis of the mind, and the computer metaphor of the brain. Their origin can be traced back to the early days of cognitive psychology in the 1940s-1950s. Since then, post-cognitivist approaches have independently proliferated on their opposition to the hegemonic cognitivist framework. As a result, the theoretical landscape in psychology has been enriched with a variety of alternative theories of cognition (Calvo & Gomila, 2008).

The cognitivist approach claims that cognition is based on mental representations, that is, symbolic intermediates between the observer and the world. As a consequence, the digital computer is considered as the best model to understand the operations of the mind, and information theory as the best tool to analyze it. In this computational portrait of cognition, perception is a process of enrichment and inference upon the ambiguous sensory stimulation to produce a representation of the most likely state of affairs of the world. Unsurprisingly, the mental operations that bring about veridical perception within the cognitivist explanation are abstract computations over abstract mental representations. Perception is considered, therefore, to be indirect. A practical consequence is that the focus of research in cognitivism is on perceptual errors that might reveal the cognitive processes underlying these errors.

Despite the particularities of the different post-cognitivist approaches, they share crucial commitments (Gonzalez-Grandón & Froese, 2018). The term "4E cognition" refers to embodied, embedded, enacted,

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[1]This article is published under the following reference: Higueras-Herbada, A., De Paz, C., Jacobs, D. M., Travieso, D., & Ibáñez-Gijón, J. (2017) The direct learning theory: A naturalistic approach to learning for the post-cognitivist era, *Ecological Psychology, 29(1)*, 23-34, doi: 10.1080/10407413.2017.1270148

and extended, as the expression of these commitments (Rowlands, 2010, p. 3). The 4E approach to cognition eschews the metaphor of the brain as a processor of information and considers that the agent-environment relation is central to understand cognition. Haugeland (1998) highlighted that the terms embodied and embedded emphasize that "mind, therefore, is not incidentally but intimately embodied and intimately embedded in its world" (p. 237). In addition, enaction emphasizes the importance of what the agent does to perceive meaning and extendedness implies that cognition spans beyond the body, including parts of the environment.

The original formulation of the 4E approach to cognition did not include the ecological theory of perception among its defining members (Gonzalez-Grandón & Froese, 2018; Haugeland, 1998; Kiverstein & Clark, 2009; Rowlands, 2010). However, the main commitments that characterize the 4E approach (the non-representationalism; the extended, embodied, and embedded nature of cognition; and the active role of the agent) are fundamental assumptions of ecological psychology since its inception in the middle of the twentieth century (Gibson, 1979; C. F. Michaels & Carello, 1981). In addition, the ecological approach to perception has a record of more than sixty years of empirical research on perception across the different modalities, on the active role of the perceiver through the perception-action coupling and the analysis of exploratory actions, on motor control including anticipation, and on learning. In sum, we think that the naming of the approach would be equally appealing and more encompassing under the label "5E cognition", with the fifth E standing for ecological.

The absence of ecological psychology in the original 4Es maybe the related to the fact that the 4E notion itself emerged in close relation to philosophical questions. One of the main aims of this article is to help bridge the gap between disciplines to foster interdisciplinary cross-pollination. Ecological psychologists are, first and foremost, experimental psychologists. This primacy of experiments is responsible for our bias toward explanations grounded in real situations with ecological validity. We do appreciate the formal elegance of models, but if one aims to explain cognition as an activity of life, models should refer to actual experiments with real organisms or other situations with ecological validity. Said in other words, abstract models whose equations, symbols, and graphs do not refer to aspects of real actions of organisms in environments are less common and less appreciated in ecological psychology.

Among the different perspectives included under the umbrella of 4E cognition, enactivism is the approach that has moved most from theoretical toy models to more tangible and applied psychological research. Noteworthy examples of experimental psychology performed from an enactive perspective can be found in the field of sensory substitution (Auvray, Hanneton, & O'Regan, 2007; Bermejo, Di Paolo, Hüg, & Arias, 2015; Froese, McGann, Bigge, Spiers, & Seth, 2012; Lenay, Gapenne, Hanneton, Marque, & Genouëlle, 2003; Visell, 2008; cf. Díaz, Barrientos, Jacobs, & Travieso, 2012). As a consequence, we think that enactivism is the most appropriate member of the 4Es for an empirically informed dialogue with the ecological approach. The general relation between ecological psychology and enactivism has extensively been discussed in Fultot, Nie, & Carello (2016) and the associated open peer commentaries (cf. Mossio & Taraborelli, 2008).

The specific focus of the present article is on learning. For the classic cognitive approach, theories of learning are often enrichment theories. Such theories may suppose, for example, that improvements with practice are to be found in the process of stimulus enrichment with inferences using previous knowledge. Under the 4E umbrella, interesting steps toward an account of learning have been made by Di Paolo et al., 2017 (cf. Baggs, 2018, for an ecologically-inspired review of this book). Di Paolo and colleagues indicate that sensorimotor learning is a crucial but neglected aspect of the sensorimotor approach. Among other things, they discuss general principles that a theory of learning should fulfill. To facilitate the interdisciplinary interaction among post-cognitivist approaches, we describe the ecological theory of direct learning (D. Jacobs & Michaels, 2007) and argue that this theory fulfills many of the requirements on learning theories that were identified by Di Paolo and collaborators.

Our article is organized as follows. The first section provides a brief introduction to ecological psychology and enactivism, discussing their theoretical relation. In the second section, we present criteria for theories of learning derived from Di Paolo et al. (2017). The third section reviews the direct learning theory and two exemplar studies that were performed under this theory. The fourth section discusses direct learning from the perspective of the criteria identified by Di Paolo and collaborators. Finally, the last section presents an extension of the theory of direct learning that aims to solve some issues for its application to a more general domain.

8.2 Ecological Psychology and Enactivism

In 1979, James Gibson culminated his development of the theory of ecological psychology with the book "The ecological approach to visual perception" (Gibson, 1979). Gibson challenged, among other things, traditional conceptions about the object of perception and the appropriate level of analysis to

study perception. During the first half of the twentieth century, perceptual theories often defined the object of perception at the level of physical units, characterized by absolute measurements of distance, volume, mass, or force. Gibson defined a new level of analysis, the ecological scale, which contains the organism-environment systems that psychology should be concerned about. A related departure of ecological psychology from classic theories is the use of the concept of information instead of the one of stimulus. The doctrine of stimulus poverty implies an elementaristic, passive, local, and instantaneous concept of the stimulus. For ecological psychology, in contrast, information is to be found in dynamic patterns of environmental energy. Any such pattern is a candidate informational variable that an organism can potentially use to control an intended action. Complex ambient energy patterns that extend over substantial time and space intervals are referred to as higher-order informational variables.

Some informational variables in environmental energy arrays are specific to properties of the environment that are relevant to the organism. Such informational variables and the specified ecological properties are bound by a one-to-one relation. This means that detecting the informational variable equals perceiving the ecological property. In this sense, the notion of information in the ecological theory is not akin to the correlational/probabilistic notion of information theory. The portrayal of perception as active information pickup is typically referred to as direct perception, because representational intermediates and mental processes are not necessary for perception to occur (C. F. Michaels & Carello, 1981). To reiterate this fundamental notion, the specificity between properties or processes of the organism-environment system and informational variables allows perception to be direct, that is, to be based on the detection of information (in the ecological sense).

Enactivism was proposed by Varela & Thompson (1993) as a general theory of cognition and psychological experience that considers cognition as the result of a dynamic organism-environment interaction. Nowadays, the enactive approach encompasses several flavors of the original formulation that share the principle of cognition as organism-environment interaction, but diverge on their preferred location along the organism-environment dipole, which is to say, on their respective emphasis on the organism or the environment (Barandiarán, 2017). The original formulation of enactivism defined cognitive systems as autonomous and operationally closed systems (Varela, Thompson, & Rosch, 1991). This notion of autonomy was inherited from the theory of autopoietic systems (Maturana & Varela, 1987), a biological precursor of enactivism.

Autopoietic systems are the result of a self-sustaining closed network of interactions that constitute the identity of the system as a whole, that is, the autopoietic organization (Maturana & Varela, 1987). The behavior of autopoietic systems is not determined by natural forces, it is the product of the internal agenda of the autopoietic system. An autopoietic system takes advantage of natural causation to fulfill its internally defined goals. In this sense, autopoietic systems are considered autonomous: their interiors are complex enough to bring about a characteristic way of using energetic and material environmental perturbations while perpetuating their organization. In contraposition, the behavior of natural systems is passive-reactive against the laws of nature.

Foundational enactivism considers the nervous system as operationally closed and autonomous and hence focuses on neural dynamics in their explanation of behavior (Varela et al., 1991). The nervous system interfaces sensory and motor tissues in order to provide an adaptive coupling to the environment, but there is nothing of essential interest to be found outside of the closed network of neural interactions other than perturbations. In response to this solipsistic perspective of cognition, and to further reduce the appeal to representationalism, contemporary enactivism has evolved away from the strong internalism of the enactivism of Varela and colleagues (Barandiarán, 2017). This is clear, for example, in the emphasis of some contemporary enactivists on sensorimotor contingencies and on the dynamic role of the external environment that furnishes those contingencies (e.g., O'Regan & Noë, 2001).

Historically, the interaction between ecological psychology and enactivism has not been particularly fluent. Autopoietic enactivism has rejected direct perception since its initial proposal for two reasons. First, it is argued that direct perception overemphasizes the importance of the environment (Varela et al., 1991). Relatedly, the use of the word *information* in the ecological approach is considered by autopoietic enactivism as implying instructive interactions with the environment, thus breaking the principle of operational closure of the organism. Second, enactivism argues that the ecological approach is a form of a physicalism. Such claims remain common in the work of contemporary enactivists (e.g., Di Paolo et al., 2017, p. 81). The examples throughout this article will illustrate that these claims, rather than being faithful with the ecological tradition, highlight a problem of communication between (and understanding of) approaches with different philosophical backgrounds (cf.Baggs, 2018).

Nowadays, researchers can crudely be divided in three different positions regarding the relation between ecological psychology and enactivism (Fultot et al., 2016). The first position holds that the theoretical differences are irreconcilable. Cariani (2016), for example, argues that ecological psychologists defend a direct realism and claim that meaning is in the environment, whereas enactivists defend perspectivist ontologies and claim that meaning is in the head of the agent. A second position is that the theories

complement each other at different levels of analysis. In this sense, Heras-Escribano (2016) proposes that the approaches can be reconciled in a shared research program in which enactivism accounts for the subpersonal processes via neurodynamics and ecological psychology explains the agential level through direct perception (cf. McGann, 2016). A third position holds that there are already bridges between the theories. Stapleton (2016), for example, points to research that joins the ecological concept of affordance and the process of sense-making from enactivism.

Despite the theoretical differences, many points of agreement become obvious if one considers the approaches in the context of specific perceptual-motor problems. Let us illustrate this with two examples. First, walking to a target, which is a rather simple action for humans and other animals. A variable that specifies the direction of motion in the temporal changes of the visual field, the optic flow, is the focus of expansion. If we change our walking direction, we modify what is at the focus of expansion. If we move orthogonally with regard to the direction of a target, the target will not be at the focus of expansion. Walking to a target can be achieved by keeping the focus of expansion at the target. This means that the focus of expansion may used to control locomotion by correcting deviations from the intended direction.

This perceptually-guided behavior can easily be incorporated in an enactive description. Visual expansions are the result of a sensorimotor loop that can be enacted (we can turn right and left and control the focus of expansion). Moreover, its detection does not specify the effect on the organism (it is not instructive) and, therefore, does not break the operational closure principle. In addition, an agent can use the mastery of this sensorimotor contingency. On the other hand, the focus of expansion is a higher-order variable at the ecological scale (it is contained in the time evolution of a substantial part of the optic array). Its behavior is lawful, and it is so because of the laws of optics. It is useful for the prospective control of locomotion and, at the same time, it requires the relative movement of the perceiver, which in the ecological approach is achieved through the perception-action coupling.

As a second example, consider the muscle-based perception through wielding (Turvey & Carello, 1995). Perceiving properties of objects by wielding is a daily activity, as when handling utensils. Individuals can perceive properties such as the length and width of hand-held objects or whether the objects are bent or not. To do so, inertial properties are explored. During wielding, forces and torques are applied, and spatial translations and rotations are obtained as a consequence. For linear movements, the mass of an object is the relation between the total force that is applied and the acceleration that is produced as a result. For rotational movements in three dimensions, a higher-order quantity captures the relation between the rotational forces (i.e., torques) and accelerations: the inertia tensor. The inertia tensor is a nine-dimensional quantity (i.e., a 3×3 matrix) that is based on the distribution of mass along the object (Solomon & Turvey, 1988). Despite its apparent complexity, the inertia tensor describes the relation between forces and movements. As such, the components of the inertia tensor can be detected through wielding, which is to say, by applying forces and observing their relation to the movements.

As indicated in the previous paragraph, wielding objects allows the detection of multiple candidate variables. Later in this article, we will need more precise definitions of three of those variables: mass (M), static moment (SM), and the first principal moment of inertia (I_1; i.e., a main component of the inertia tensor). The following expressions of these variables indicate their close linkage:

$$I_1 = \int \rho(s)\delta(s)^2 dV, \tag{8.1}$$

$$SM = \int \rho(s)\delta(s)dV, \quad and \tag{8.2}$$

$$M = \int \rho(s)\delta(s)dV. \tag{8.3}$$

In these equations, $\rho(s)$ is the mass-density function of the wielded object, $\delta(s)$ the distance to a given axis of rotation, and V the volume of the wielded object over which $\rho(s)$ and $\delta(s)$ are integrated (D. M. Jacobs, Silva, & Calvo, 2009). The mass of an object can be detected through linear exploratory movements or by holding the object still against the effect of gravity. The static moment of an elongated object, such as a rod, can be detected by suspending it horizontally from a single grip and noting the rotational force that is generated. As mentioned above, active exploration with rotational movements allows the detection of the components of the inertia tensor, including the first principal moment.

The fundamental notions required to understand the muscle-based perception through wielding, typically studied from the ecological perspective, are laws that connect a motor component (the forces) to a sensory component (the resulting movements). Such notions can easily be accommodated in an enactive account. Consider, for example, the similarities between muscle-based perception and the enactive portrayal of the perception of softness through exploration of a sponge:

Having the sensation of softness consists in being aware that one can exercise certain practical skills with respect to the sponge: one can, for example, press it, and it will yield under the pressure. The

experience of softness of the sponge is characterized by a variety of such possible patterns of interaction with the sponge, and the laws that describe these sensorimotor interactions we call, following MacKay (1962), laws of sensorimotor contingency (O´Regan, Myin, & Noë, 2005).

8.3   General Principles for 4E-Inspired Theories of Learning

The goal of this section is to explicitly formulate a list of requirements that should ideally apply to any theory of learning that falls under the umbrella of 4E cognition. Without aiming to be exhaustive, our hope would be to obtain a tentative list on which different contributors of the 4E approach may agree. We will first describe requirements that are implied by the 4E concept itself. Following those, we describe requirements that were selected from chapter 4 of Di Paolo et al. (2017)—which we believe to be the main attempt so far from the enactive approach to formalize a learning theory. A final requirement in our list is taken from the ecological approach. In subsequent sections of this article, we will use the obtained list of requirements to assess the contributions of the theory of direct learning.

The most obvious requirements are the ones implied by the name of the 4E approach. That is, a theory of learning from the approach should be consistent with the commitments to describe cognition, and hence learning, as an *embodied, embedded, enacted*, and *extended* process. Relatedly, a learning theory in the 4E approach should be *non-representational*. This means that learning cannot be portrayed as an improvement in syntactic operations or computations on symbolic representations. Less obviously, the processes that are responsible for the improvements with learning should not be based on such computations and representations either.

We next consider elaborations of and additions to these requirements that were formulated by Di Paolo et al. (2017). One of the requirements that these authors mention is that learning should *transform perception* rather than construct perception out of previous processes other than perception. In their words, "the starting point from which perception develops is always already a form of perception" (p. 79). With regard to their specific theory, they claim that the process "starts always from an existing sensorimotor organization" and that it "develops from there into novel forms, differentiated forms, forms that become extinct and replaced by others, and so on" (p. 79).

Another set of requirements on a learning theory mentioned by Di Paolo et al. (2017) is that such a theory should be *action-based* and *world-involving*. With regard to the action-based part, they state that "adaptations only occur in the context of active, personal effort in remastering the visual world" (p. 79). However, it is not the activity of the learner as such that is claimed to be important. Rather, it is the dynamic interaction of the learner with the world. Di Paolo formulate this world-involving part of their requirement by saying that learning "involves a relation to the dynamics of the world beyond the mere supply of sensory input" (p. 80). More passive learning situations would lack "a chance to engage the world and attune to a new form of coupling with it" (p. 80).

Di Paolo et al. (2017) also mention that a theory of learning requires *adaptive mechanisms*, which may be based on a *normative evaluation* that provides the agent with feedback to evaluate if his or her current state of functioning is appropriate in a concrete situation. Related to the requirements of adaptive mechanisms and normative evaluation, Di Paolo et al. write:

"an agent can also learn from the way she fails. *Directed learning* [emphasis added] could rely, for instance, on gradients in the normative evaluation ... or on details of perturbations encountered in failed assimilation attempts" (p. 103).

As we will illustrate in subsequent sections, we believe that this quote—including the wording used to refer to the learning processes—is indicative of the relevance of the direct learning framework to parts of the approach to learning sketched by Di Paolo et al.

Another pair of requirements on theories of learning that we have selected from the chapter by Di Paolo et al. (2017) relate to the fact that *learning never ends*. In the words of Di Paolo et al., for learners "this requires that they never reach strictly stable equilibrium" and that they "must retain a residue of dynamic criticality without which they would simply be unchangeable automatisms" (p. 102). A related requirement is that learning processes are *open-ended*. According to Di Paolo et al., this implies that learning does not have an end point, meaning that novel and un-anticipated perception-action solutions can be arrived at through learning (p. 78 and p. 98).

This brings us to the final requirement of our list, which was anticipated in the introduction. Many theories in the 4E approach agree that the formal aspects of dynamic models can usefully be applied to the understanding of cognitive processes. The theory sketched by Di Paolo et al. (2017) and the direct learning framework are no exceptions. A final requirement for a theory of learning, inspired by common practice within the ecological approach, is that the dynamic models that are inspired by the theory and that aim to illustrate the theory should be formulated at the *ecological scale*, meaning that they should refer to tangible aspects of real-world actions. Let us consider two purposefully simplified models to

illustrate this requirement.

First, let S refer to an organism-environment system that includes all possible perception-action couplings in which the organism can engage. Note that S can be high dimensional. Given that learning implies a change in the organism-environment system and its perception-action couplings, we can refer to learning as the derivative of S. Second, let O be an organism with two action possibilities: it may be at rest or move at a constant speed. In this second case, learning may be portrayed as, say, a change in the rules, or probabilities, by which the organism chooses to move or not.

However simple these models are, they might have some virtues. With respect to the first model, one may argue that it is not wrong in the sense that all types of learning will eventually be some further specification of the model. With regard to the second model, one may argue (or demonstrate) that its behavior has some similarities with human behavior, and hence that the model exemplifies how the considered behavior may arise. Despite these arguments, however, the points, spaces, trajectories, vectors, gradients, etc., that illustrate such models do not refer to tangible aspects of real world actions. Hence, if one accepts the requirement that models are ideally formulated at the ecological scale, one should be suspicious about the contribution of such models to learning theories in the 4E approach.

Di Paolo et al. (2017) state that "several of these principles are already present in other approaches" (p. 103). We believe that the theory of direct learning, not mentioned in the chapter, is a good candidate in this regard. The next section provides a summary of the direct learning theory, including two examples of actions that have been used to elaborate the theory.

8.4   Direct Learning

The direct learning theory has been developed under the principles of the ecological approach (D. Jacobs & Michaels, 2007; cf. D. Jacobs, 2001). With the theory, the authors aimed to respond to the criticism that the ecological approach, at that time, did not provide a sufficiently detailed understanding of learning (Claire & Peter, 1995). The direct learning approach considers two levels of analysis: the one of perceiving and acting and the one of learning (aiming for a theory that is consistent as well with the level of analysis of ecological realism; D. M. Jacobs & Michaels, 2002). The processes that are implied by perceiving, acting, and learning are conceived as multiple continuous and concurrent processes that occur at different timescales. The main research strategy of the direct learning approach is to scrutinize the traditional ecological principles, which were developed to understand perceiving and acting, and to explore how these principles may be interpreted or modified to be applicable to processes at the longer time-scale of learning.

Crucial among those principles, and giving rise to the name direct learning, is the claim of the traditional ecological approach that perceiving and acting are direct or information-based rather than inferential processes. Analogously, direct learning claims that learning is information-based. As does the traditional ecological approach at the level of perceiving and acting, the direct learning approach considers the directness of learning as a methodological doctrine. This means that, rather than aiming to prove or disprove the claim, the approach takes the methodological doctrine as its starting point and asks what else must be true if the doctrine is true. This search has led to a sequence of concepts, ideas, and empirical studies that, we believe, are useful to many members of the 4E approach.

In the framework of direct learning, the level of learning includes at least three processes: the education of intention, the education of attention, and calibration. With regard to the first process, the education of intention, one should realize that many actions are possible in any given situation. If a ball approaches, one may be able to catch the ball, dive away to avoid the ball, or try to hit the ball. The intention of an agent determines which action he or she aims to perform. The *education of intention*, then, refers to the process by which agents improve in choosing which action they aim to perform (or what property they aim to perceive). Assuming an intention is indispensable in the direct learning approach, and in the ecological approach in general, because it allows one to evaluate the environment and the performance of the agent in terms of the goals of the agent. This is related to the normative evaluation often mentioned by proponents of the enactive approach (Hutto, 2005; Di Paolo et al., 2017). A more detailed consideration of intentions and changes therein and their place in the direct learning framework can be found in Arzamarski, Isenhower, Kay, Turvey, & Michaels (2010; cf. Shaw & Kinsella-Shaw, 1988).

To give an example of the need for the concept of intention in the direct learning theory, note that assuming a particular intention is indispensable to evaluate the usefulness of informational variables. Variables that specify the property that an agent intends to perceive or act upon are useful whereas variables that are unrelated to that property, even though they may specify other properties, are not. Empirical evidence shows that, with practice, individuals graduate from the use of less useful variables to the use of more useful variables (e.g., D. M. Jacobs et al., 2001). This gradual process of convergence toward specifying information, even if the intention of the agent is assumed to remain constant, is known

as the *education of attention* (Gibson, 1979). The third process at the level of learning that is considered in the direct learning framework is *calibration.* This process refers to changes in how the informational variable that is operative at a particular moment is carried into perception or action.

To provide a more formal interpretation of these learning processes, needed to outline subsequent aspects of the theory, let us consider the following equation:

$$F = f(I) \tag{8.4}$$

in which I is the informational variable that is used at a particular moment, F refers to a particular action parameter (e.g., a force exerted by the action system; when studying perception, F is substituted for a perceptual parameter, P), and f is the single-valued function that describes how information is carried into perception or action. The equation describes how an action system functions at a particular moment. An intention determines that the system acts the way it does, and therefore sets up the equation as a whole. Even with a constant intention, however, the equation that best describes the functioning of a system changes with practice. In line with our previous description, the education of attention corresponds to changes in the informational variable I and calibration to changes in the single-valued function f.

Equation 3.4 is essentially the same as the traditional ecological concept of *control law* (Warren, 2006), which has frequently been used to formalize aspects of the ecological approach at the level of perceiving and acting. Changes in the equation over time, formalized by the temporal derivatives of f and I, provide a foot into the door of the direct learning theory. To describe further aspects of the theory we need to advance from the disembodied description of Equation 4, without reference to a particular action, to action-related and thereby falsifiable interpretations of the concepts that are implied by the equation. To do so, we have selected two empirical studies on direct learning that we consider particularly relevant to members of the 4E approach.

8.4.1   Learning as Continuous Movement Through a Space: the Pole-balancing Example

D. M. Jacobs et al. (2012) analyzed learning using a cart-pole task (Figure 3.1). The task of participants was to keep the unstable pole on the cart balanced for 30 s. Performing this action requires practice: participants needed between 22 and more than 150 trials to maintain the pole balanced for three consecutive trials. Participants control the force, $F(t)$, that they apply to the cart. In line with the ecological approach, and the concept of control law, Jacobs et al. assumed that the applied force is a function of information detected a short time interval before exerting the force. What information was used? And, what function related that information to the applied force?

To answer these questions, Jacobs et al. (2012) used a version of Equation 4 that is applicable to this particular action:

$$F(t) = k\Theta^a(t - d) \tag{8.5}$$

In this equation, Θ^a is the fractional derivative[2] of order a of the angle of the pole (see Figure 1), d is the perceptual-motor delay, and k is a constant. The quantity Θ^a is the informational variable used in to control the action (I in Equation 4), a is a parameter that changes with changes in the education of attention, and k is a constant that changes with changes in calibration. Both the education of attention and calibration were formalized in ways that were considered as simple as possible to capture the relevant phenomena: both changes were portrayed as single-dimensional. Moreover, the calibration function f in Equation 4 was as simple as a multiplication by a constant. Note that, together with the equations of motion of the physical system, Equation 5 allows one to predict the performance of the agent-environment system as a whole.

We are now in the position to introduce another important aspect of the direct learning approach: learning processes are portrayed as continuous trajectories through a space. Most studies in the direct learning framework considered *information spaces.* D. M. Jacobs et al. (2012) instead used a combined *information-calibration space* (Figure 2). The coordinate axes of this space are the parameters that indicate the education of attention and calibration of an individual at a particular moment, which is to say, the parameters a and k in Equation 5. If one registers the movements of an individual that performs the action, one can determine the parameters a and k that best fit the performance, and hence localize the individual at a point in the space. A substantial number of empirical studies on direct learning show that learning, when analyzed this way, can be described as a process of convergence toward the more

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[2]Jacobs et al. (2012) reviewed the definition of fractional derivatives and discussed advantages of using that concept. To understand the following discussion it is sufficient to know that $\Theta(a)$ is a detectable informational variable that depends on the parameter a.
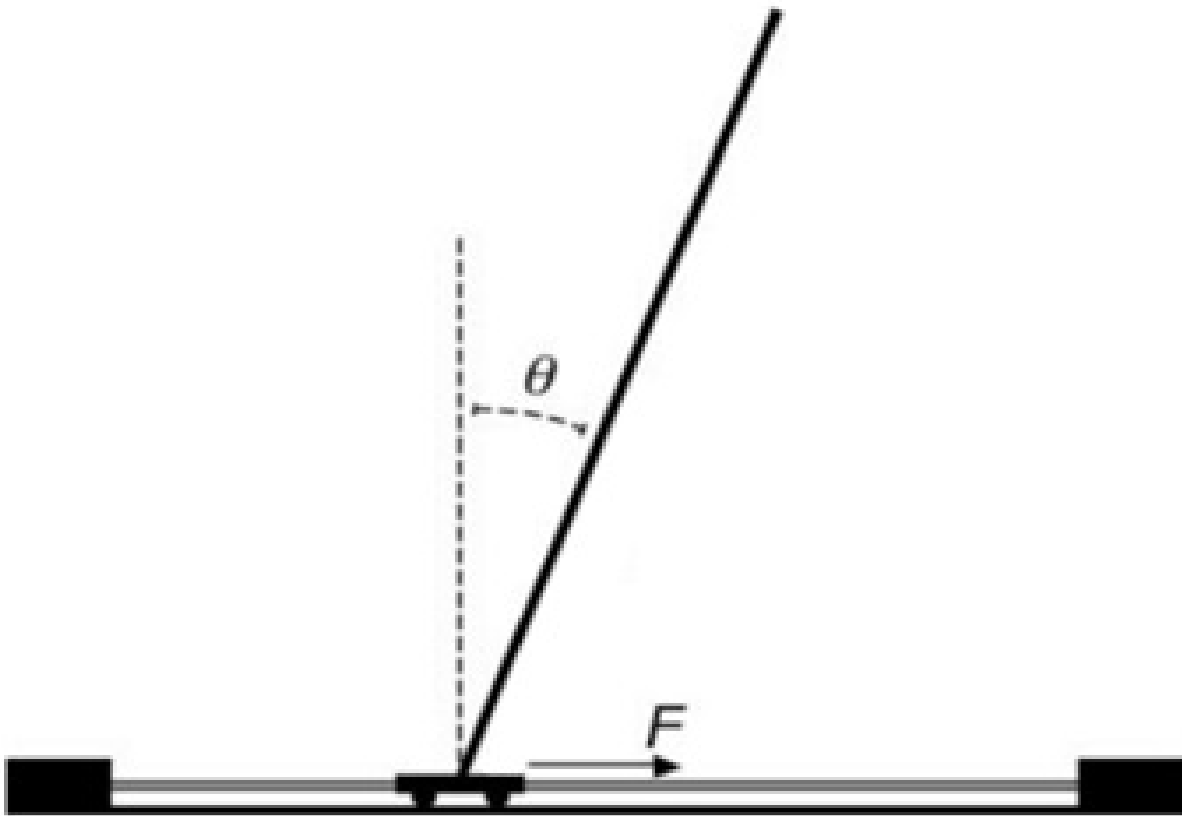
Figure 8.1: Participants moved the cart with their dominant hand along a steel rod with the aim to keep the pole balanced. Adapted form "The learning of visually guided action: An information-space analysis of pole balancing," by D. M. Jacobs, D. V. Vaz, and C. F. Michaels, 2012, Journal of Experimental Psychology: Human Perception and Performance, 38, p. 1216. Copyright by American Psychological Association. Adapted with permission.

useful regions in such spaces (e.g., C. F. Michaels et al., 2008; cf. Abney & Wagman, 2015; Huet et al., 2011; C. F. Michaels & Romaniak-Gross, 2012)

For the pole-balancing task, this convergence toward the more useful regions in the space is illustrated in Figure 2 by the ellipses that summarize the empirically determined locations of the whole group of participants, at different phases of the experiment. Whereas the ellipse that indicates the initial performance (first quarter) is large, showing that individuals were widely distributed over the space, the ellipse indicating performance later in the experiment (fourth quarter) is small, showing that individuals by then had converged toward a more limited region in the space. Jacobs et al. (2012) further showed that the region on which individuals converged is indeed the most useful region. That is, an agent-cart-pole system remains well balanced if one uses the as and ks from this region and simulates the performance of the system using the forces computed with Equation 5 together with the appropriate equations of motion.

So far, we have introduced the education of intention, the education of attention, and calibration, and we have seen how, in the context of particular actions, the latter two processes can be empirically tracked and analyzed as trajectories through information and information-calibration spaces. The claim that learning processes are information-based can now intuitively be understood as the claim that patterns in the dynamic agent-environment interaction that emerges while an agent is localized at a particular point in the space push the agent through the space. In the pole-balancing example, information for learning may be found, for example, in the particular ways that the pole remains balanced or falls down over multiple trails. We next provide more tangible illustrations of how the informational basis of the learning can be defined and analyzed.

8.4.2   Information for Learning: A Dynamic Touch Example

In the previous sections, we have introduced the central claim of the direct learning approach: learning processes are driven by information that emerges from the agent-environment interaction over some time.
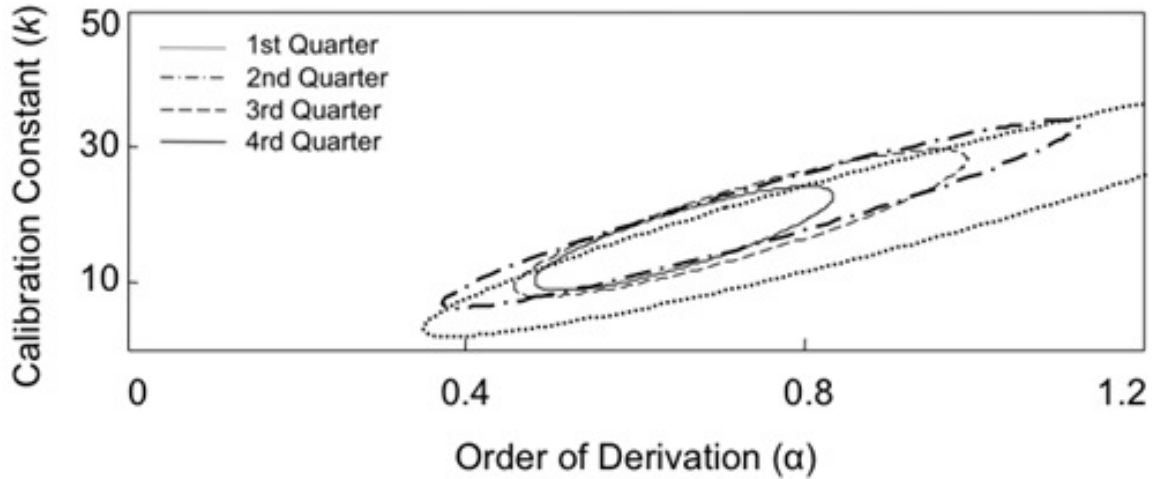
Figure 8.2: Information-calibration space used to study cart-pole balancing. The ellipses indicate the location of the group of participants in the space for each quarter of trials during the experiment. Adapted form "The learning of visually guided action: An information-space analysis of pole balancing," by D. M. Jacobs, D. V. Vaz, and C. F. Michaels, 2012, Journal of Experimental Psychology: Human Perception and Performance, 38, p. 1220. Copyright by American Psychological Association. Adapted with permission.

Whereas the previous section provided an example of how one may analyze and observe the changes due to learning, the present section concerns a study that provides a tangible example of information for learning: the muscle-based mass-perception study by D. M. Jacobs et al. (2009). Participants in that study were asked to freely wield unseen objects (called tensor objects) with their right hand and to judge the mass of those objects as compared to a reference object in their left hand. Instead of Equation 4, we now use the equation:

$$J = f(I) \tag{8.6}$$

in which J is the mass judgment made on a particular trial and I the informational basis of that judgment, which is to be detected from the object through wielding.

For our current purpose, it is sufficient to analyze the education of attention. This means that we need an information space that allows us to track changes in the informational basis of performance (i.e., changes in I). The equation used by D. M. Jacobs et al. (2009) to describe that information space was:

$$I(x, y) = yI_3 + (1 - y) \int \rho(s)\delta(s)^x dV. \tag{8.7}$$

It is crucial to understand that, in this equation, I is an informational variable that can be detected from the object through wielding and that the informational variable depends on two parameters: x and y. For a description of the general shape of the equation, and a motivation for using this one, we refer the reader to Jacobs et al. We provide the full equation here to emphasize that the direct learning theory has been worked out at the level of measurable quantities. Let us further mention, for completeness, that I_3 is the third principal moment of inertia and that the remaining terms are the same as in Equations 1 to 3.

With an informational variable, I, that depends on two parameters, x and y, we have obtained a two-dimensional information space. If x and y are both zero, the equation matches the one for mass (Equation 1). If $x = 1$ and $y = 0$, the equation matches the one for static moment (Equation 2). Other values of x and y correspond to other detectable informational variables. D. M. Jacobs et al. (2009) used this information space to track the information usage with learning of individuals in different experiments and conditions. The upper panel of Figure 3 presents the results for the pretest and posttest for a group of participants who received feedback based on mass. The lower panel presents analogous results for individuals who received feedback based on static moment. Consistent with the results from other studies in the direct learning paradigm, the figure shows that learning goes together with convergence toward the more useful informational variables.

For the relation between direct learning and other 4E theories, it is relevant to note that the informational variables represented by points in information spaces are actively picked up rather that detected
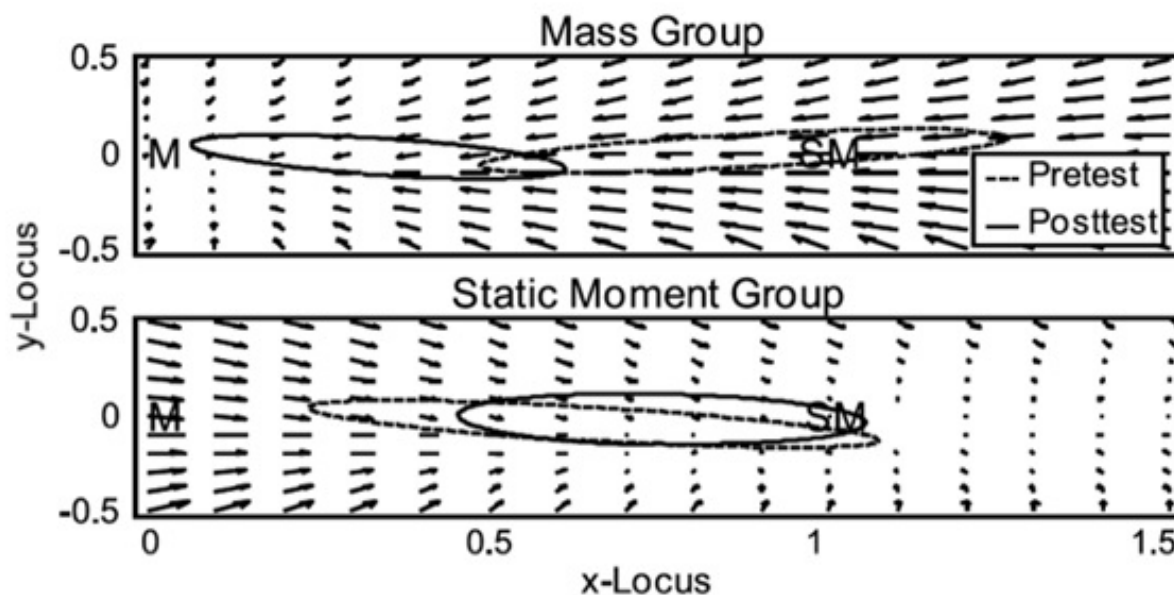
Figure 8.3: Ellipses that indicate the location of individuals in the information space defined by Equation 7, for groups of individuals with feedback on mass (upper panel) and static moment (lower panel), in the pretest (dashed outline) and posttest (continuous outline). The vector fields correspond to the information for learning defined in Equations 8 and 9. M = locus corresponding to mass. SM = locus corresponding to static moment. Adapted form ´´An empirical illustration and formalization of the theory of direct learning: The muscle-based perception of kinetic properties,´´ by D. M. Jacobs, P. L. Silva, and J. Calvo, 2009, *Ecological Psychology, 21*, p. 257. Copyright by Taylor & Francis Group, LLC. Adapted with permission.

in a passive manner. For muscle-based perception this is obvious: participants actively wield the to-be-perceived objects. Furthermore, and related to the traditional ecological claim that perceiving and acting are inseparable processes, the exploration that participants perform to detect the inertial informational variables depends on which variables they detect. To demonstrate this, Michaels and Isenhower (2011; cf. C. F. Michaels & Isenhower, 2011) determined the positions of participants who performed a muscle-based perception task in an information space and analyzed the way in which they wielded. Indeed, being localized at a certain point in the space went together with certain ways to explore (cf. Arzamarski et al., 2010). The continuous changes in what information is detected that are captured by the convergence in information spaces, therefore, should be hypothesized to go together with continuous changes in the exploratory movements that underlie the information detection.

Apart from this short aside on exploratory movements, being able to empirically track the learning of individuals as trajectories through a space allows us to proceed to a next step in the theory of direct learning: explaining the learning itself as an information-based process. As well-known from the theory of differential equations, trajectories through a space are specified by the temporal derivatives of the coordinates of the space at each point in the space. Those temporal derivatives define a vector field on the space. Along with the ellipses that describe the movements through the space with practice, Figure 3 gives vector fields that would predict such movements.

Now consider an individual who is localized at a particular point in the space, performing the wielding and making his or her judgments as determined by the information that is represented by that point in the space (in interaction with the world, or in this case the object that he or she happens to encounter). Such an individual would be predicted to move along the space according to the vector at his or her locus. The remaining question in the direct learning framework is: what informational pattern, detectable over multiple trials from the relation between the judgments, the resulting feedback, and other information detectable through the wielding, would specify the vector that indicates the observed movement at that locus? In the direct learning framework, a detectable informational quantity that specifies the movement through the space for all loci in the space and for all experimental conditions qualifies as *information for learning.*

The information for learning proposed by D. M. Jacobs et al. (2009) is described by the following

equations:

$$x'(t) = -k_1 \quad covariance\{E, SM/M\} \tag{8.8}$$

and

$$y'(t) = -k_2 \quad covariance\{E, I_3\} \tag{8.9}$$

In these equations, k_1 and k_2 are constants, E is the error as indicated by the feedback, and the other variables are as defined earlier in this article. Together, the temporal derivatives on the left hand side of the equations specify a vector in the space, as they should. Jacobs et al. showed that the vectors specified by the detectable quantities on the right hand side correspond reasonably well to the observed movements through the space. In fact, those vectors are the ones plotted in our Figure 3. With this example of detectable information for learning we have completed our description of the central claims of the direct learning theory.

Obviously, it is possible to accept or use some of the tools of the direct learning framework without accepting the entire theory. For example, our portrayal so far argued that learning trajectories are based on vectors, which means that learning is based on detected informational quantities that are as many dimensional as the space that is used to describe the learning. Even from within the framework of direct learning, however, we have tentatively explored the alternative view that learning may be based on single-dimensional potential functions on the space (D. M. Jacobs et al., 2011). Figure 4 illustrates this type of analysis for the information space defined in Equation 7. The surface in the upper panel shows a detectable measure of the maximum level of performance that can be achieved by individuals who use the different loci in the space. The empirically-measured probability density functions shown in the lower panel of the figure indicate that, with practice, individuals move from the less useful to the more useful regions in the space. We cannot rule out that movements through information spaces are causally linked to usefulness functions rather than to vectors that represent information for learning.
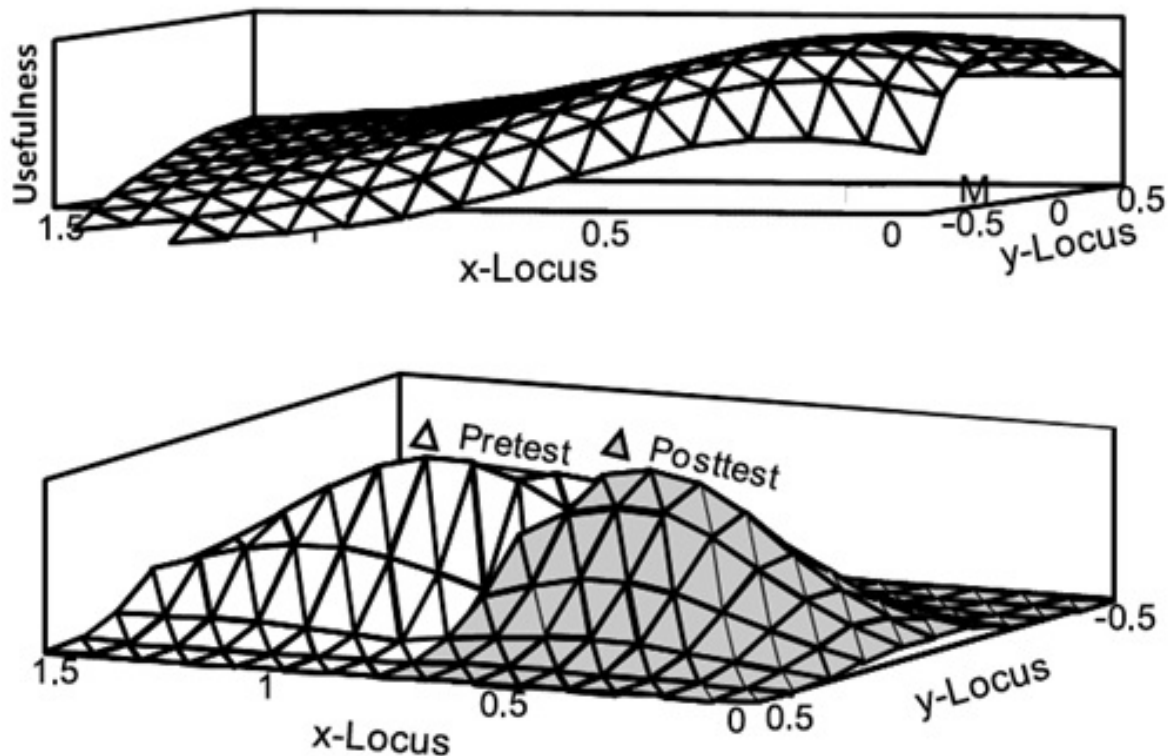
Figure 8.4: Upper panel: Usefulness function for the information space indicated by Equation 7 for a mass-estimation task (the fast condition of Experiment 2 of Jacobs et al., 2009). More useful variables are indicated by a higher surface. Lower panel: distributions functions that indicate the locations of the group of individuals before and after practice. Adapted form "An empirical illustration and formalization of the theory of direct learning: The muscle-based perception of kinetic properties," by D. M. Jacobs, P. L. Silva, and J. Calvo, 2009, *Ecological Psychology, 21*, p. 269. Copyright by Taylor & Francis Group, LLC. Adapted with permission.

One should note that learning based on information that is as many dimensional as the space in which learning takes place, and that specifies a direction, is the more elegant formulation of the direct learning theory. This is so because it takes most advantage of the different time-scales of perception and action and of learning. If learning is slow, the processes of perceiving and acting can generate the learning vectors without noteworthy changes in the locus of the learner; in the extreme, the information for learning can be generated with the learner being located at a single point in the space. If the information for learning is a single-dimensional usefulness function, on the other hand, this function needs to be sampled from several nearby loci in the space to determine a direction of change. This sampling process necessarily mixes movements in the space, which are supposed to be slow, with the perceiving and acting that generates the information about the usefulness, which are supposed to be fast. However this may be, if one assumes that the information vector field is the gradient of a usefulness function, parts of the theory may be illustrated with usefulness functions as well as with information vectors, without bothering about which of the two is causally related to the learning. As such, we will make use of usefulness functions in the remaining part of this article. Note that this part of the direct learning theory shows similarities to the suggestion concerning *directed learning* by Di Paolo et al. (2017) that was quoted in the previous section.

Summarizing the main tenets of the direct learning theory, then, it is claimed that perceiving and acting are fast information-based processes that cause a dynamic interaction of the agent and its environment. In this interaction, the way that the agent perceives and acts at a particular moment has observable consequences. Information that drives the slower learning processes is claimed to be present in the rich higher-order structure over time of these observable consequences.

8.5 Direct Learning and Enactivist Principles for a Theory of Learning

As stated above, the aim of this article is to put forward the theory of direct learning as an empirically supported framework for post-cognitivist approaches to learning. In this section, we assess to what extent the direct learning theory fulfills the requirements that were derived from the analysis of (Di Paolo et al., 2017).

The first set of requirements for such a theory is that it must comply with the basic commitments that characterize the 4E approach, that is, it should portray learning as an embodied, embedded, enacted, and extended process. We added to this general list an explicit commitment to non-representationalism and the need to formulate research questions at the ecological scale (that is, referred to aspects of real-world actions). Direct learning was developed within the ecological approach. In this sense, it assumes the basic tenets of the ecological approach, in particular: the directness of psychological processes that follows from a non-representational stance; the active nature of perception-action that parallels the enactive requirement; and the assumption that the ecological scale is the proper level of analysis for psychological phenomena, which incorporates embeddedness, embodiment, and extendedness at the root of the approach.

The first requirement derived from the analysis of (Di Paolo et al., 2017) is that learning should transform perception, rather than to construct perception out of pre-existing non-perceptual processes. As explained in the previous section, the direct learning theory proposes information and calibration spaces and vector fields of information for learning to account for the changes in perception-action couplings. Every point in such spaces stands for a specific perception-action coupling. In other words, being at a certain point of an information-calibration space means using a specific informational variable, with a specific calibration, to control an action. As such, being at a certain point generates a specific interaction with the environment, which, in turn, contains information that allows the agent to modify its behavior at longer time-scales. This information in the loci-specific interaction with the environment can be formalized as a vector that indicates the direction and magnitude of change for a specific perception-action coupling. In sum, direct learning attempts to establish the laws by which perceiving and acting are transformed.

The next requirements are two intimately related notions: learning should be action-based and world-involving. This means that the actions of the learner or the mere sensory input that follows an action are not important per se. The relevance of action for learning only appears in relation to the dynamic interaction between the learner and the world. Note that this is what information for learning attempts to describe: how the dynamics of the current perception-action coupling constrain the evolution of the coupling itself. A clear example of world-involvedness can be found in (D. M. Jacobs et al., 2012), who included the physical equations of motion of the cart-pole system as an essential part of their portrayal of learning (see their Equations 1 and 2).

(Di Paolo et al., 2017) also highlighted that a post-cognitivist theory of learning requires adaptive mechanisms to determine the change of the current perception-action engagement. These adaptive mechanisms are assumed to be based on a source of normative evaluation that furnishes the agent with feedback to evaluate the appropriateness of its current state of functioning. One should observe that postulating such mechanisms may imply the risk to reintroduce traditional representational thinking in theories, because it may seem to require a traditional representational/inferential agent (or homunculus) that is responsible for the adaptive processes (i.e., for the mastery of sensorimotor contingencies; Noë et al., 2004). Warnings against reintroducing traditional representational thinking in this way can be found in Jacobs and Michaels (2007, p. 330; cf. Hutto, 2005, p. 392). As we have shown, however, the direct learning approach holds that processes such as normative evaluation and behavioral adaptation themselves can be accounted for at the ecological scale without appealing to representations or inferences. This, in fact, is why direct learning received this name: the adaptation due to learning is hypothesized to be information-based, which is to say, specified in the current agent-environment interaction.

The final set of requirements for a theory of learning identified by Di Paolo et al. (2017) are that learning never ends and must be open-ended. In line with these requirements, and with the Gibsonian view that perception itself is extended in time, Jacobs et al. claim that their theory "does not consider learning a process that has a beginning and an end. Learning does not start or stop" (p. 249). Illustrating this view, C. F. Michaels et al. (2008) designed a two-stage learning experiment. The structure of the feedback was changed from the first to the second stage of the experiment so as to modify the usefulness function and the information vectors. At each stage, a movement through the information space was observed that was compatible with the feedback, even though during the first stage near optimal performance was reached. Hence, the claim that learning never ends has always been present in the direct learning theory.

Open-endedness is accommodated to a certain degree. Depending on the particular learning environment, or on the feedback given in an experiment, different loci in information spaces are the more useful ones. It has been demonstrated empirically that learners converge toward those loci that are the most useful ones in their particular task environment, and hence that learning does not have a fixed end point (Huet et al., 2011; D. M. Jacobs et al., 2009; C. F. Michaels et al., 2008). For Di Paolo et al. (2017), however, open-endedness seems to go further. They claim that "the learning and refinement of perception and action skills in some cases, if not unbounded, seems to have no obvious predictable bounds" (p. 101), and that learning is seen as "the combinatorial construction of new patterns of sensorimotor coordination in a potentially ever-growing space of possibilities" (p. 104). They further argue that such open-endedness and lack of predictability requires some degree of randomness. In contrast to this requirement, the direct learning framework implies bounds on learning in the sense that learning cannot extend beyond the considered information and calibration spaces. Likewise, the direct learning framework, in its current state, does not provide an explicit and empirically demonstrated formulation of how randomness affects learning processes.

To summarize, we believe that the theory of direct learning fulfills the large majority of the criteria that post-cognitivist theories should fulfill. Our main claim in this article, therefore, is that the theory would be useful to members of the 4E approach as a starting point for further theorizing about learning. With regard to the criterion of open-endedness, it is fair to say that the direct learning theory encompasses fewer phenomena than the approach to learning that was sketched by Di Paolo et al. (2017). An important advantage that is related to having a less-encompassing theory, however, is that the direct learning theory has been formulated more precisely and has been developed in a much closer relation to empirical research with ecologically-valid tasks.

Finally, to demonstrate with an example that direct learning can be used as the starting point for further theorizing, we conclude this article with a speculative extension of the theory. Even though the theory presented so far is less in need of a representational homunculus that controls or supervises the learning than the to-be-presented extension, and better supported empirically, a few aspects related to open-endedness and randomness may be more easily incorporated in the extension. With this we aim to illustrate that extensions of the theory may be yet better suited to the criteria derived from the chapter by Di Paolo et al. (2017).

8.6   Direct Learning and Multiple Perception-action Couplings

Previous research on direct learning has addressed how experience with a particular task modifies and maintains a single perception-action coupling, or control law. Consider the example of displacing the hand with regard to the body with the aim to intercept an approaching object. Control laws that may be operative in this action have been studied extensively (e.g., Bootsma et al., 1997). To apply the direct learning framework, one would need to analyze the behavior of learners with an information-calibration space, a vector field that represents information for learning, and a usefulness function (cf. D. M. Jacobs

& Michaels, 2006). Given that a single perception-action coupling is addressed, one would need one of each. For example, one would need only a single information-calibration space, independently of how many dimensions that space may have.

Some actions, however, are best described with several perception-action couplings (e.g., van Hof et al., 2006; cf. Lee et al., 1983, p. 343). Consider a hypothetical catching action in which the catcher separately controls three action components: (a) the timing of the initiation of the catch, (b) the displacement of the hand toward the ball, and (c) the timing of the grasp component of the catch. Three control laws may be used to describe this action[3]. If so, to study learning, one may also use three information-calibration spaces, usefulness functions, and quantities that serve as information for learning. The question that would be raised, we believe, is to what extent the learning of the different perception-action couplings would be independent. Said more precisely, the organism-environment interaction may only generate useful and detectable information for learning for one action component if the other action components are performed at least reasonably successfully.

Consider Figure 5. Imagine that the horizontal axis is an information space for the timing of the initiation of the catch. The continuous curve is a hypothetical usefulness function, such as the maximum percentage of correct catches that may be achieved on the basis of the informational variables that are represented in the space. If the other action components would not be controlled in a sufficiently close to optimal way, one could not catch 100% of the to-be-caught balls, not even if one initiates the catches on the basis of the most optimal informational variable. This is illustrated by the dashed usefulness function in Figure 5. In light of the direct learning theory, one should imagine that the lower usefulness function goes together with an information field with shorter and less precise information vectors.

The previous argument implies that a relatively successful control of the hand displacement and of the timing of the grasp may be necessary to guarantee the existence of information for learning for the initiation of the catch. Likewise, a to-some-extent successful initiation of the catch may be necessary to guarantee the information for learning for the other components. Imagine, then, a particular observer that performs each action component on the basis of an informational variable with a very low usefulness. The three usefulness functions related to such a situation might be as the approximately flat curves in Figure 6. To explain the left panel: even if the observer initiates the catch on the basis of a reasonably good variable, he or she will still catch only a few random balls as long as the control of the other components is insufficient. The question becomes: how can a learner get out of such a situation? If, as we have sketched, the overall situation is poor in information for learning, the answer to this question may require more than the direct learning theory as we have described it in earlier sections.

Given that the situation in Figure 6 is poor in information for learning, it invites some random behavior into the theory (and hence some individual differences in learning trajectories; cf. Withagen & Van Wermeskerken, 2009). By trying out different informational variables (i.e., loci) at the initial stages of the learning process, the learner might create a situation in which some slight peaks start to emerge in one of the usefulness functions. These slight peaks may form the beginning of a more deterministic learning process that increases the peaks also in the other usefulness functions. The slowly increasing optimality of the different action components will then guarantee the existence of information for learning for the respective components, which, in turn, allows direct learning. If a certain level of performance is achieved, the different action components may flexibly keep each other in shape, achieving a system that is robust to a wide range of perturbations.

One may speculate that situations such as the one described in Figure 6, in which the percentages of correctly performed actions are very low and some random behavior seems to be required, are more characteristic for infant learning (e.g., Van der Kamp et al., 2003; cf. Kayed & van der Meer, 2007) than for the learning patterns shown by adults. Even for adults, however, some actions may initially be so cognitive/inferential, of such an exploratory nature, and/or so much based on instructions, that one might question the usefulness of the direct learning theory on itself for such actions (cf. Runeson et al., 2000). One could think, for example, about learning to swim a particular stroke, which is even unlikely to occur only on the basis of practice. The theoretical sketch provided in this concluding section may therefore increase the scope of the theory also for adults.

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[3]We use this suggestion only as a convenient way to illustrate the theoretical point that we want to make in this section. With the example we do not aim to take side in the debate about how the initiation of catches, and the other action components, are actually controlled (cf. Bootsma et al., 1997, p. 1287).
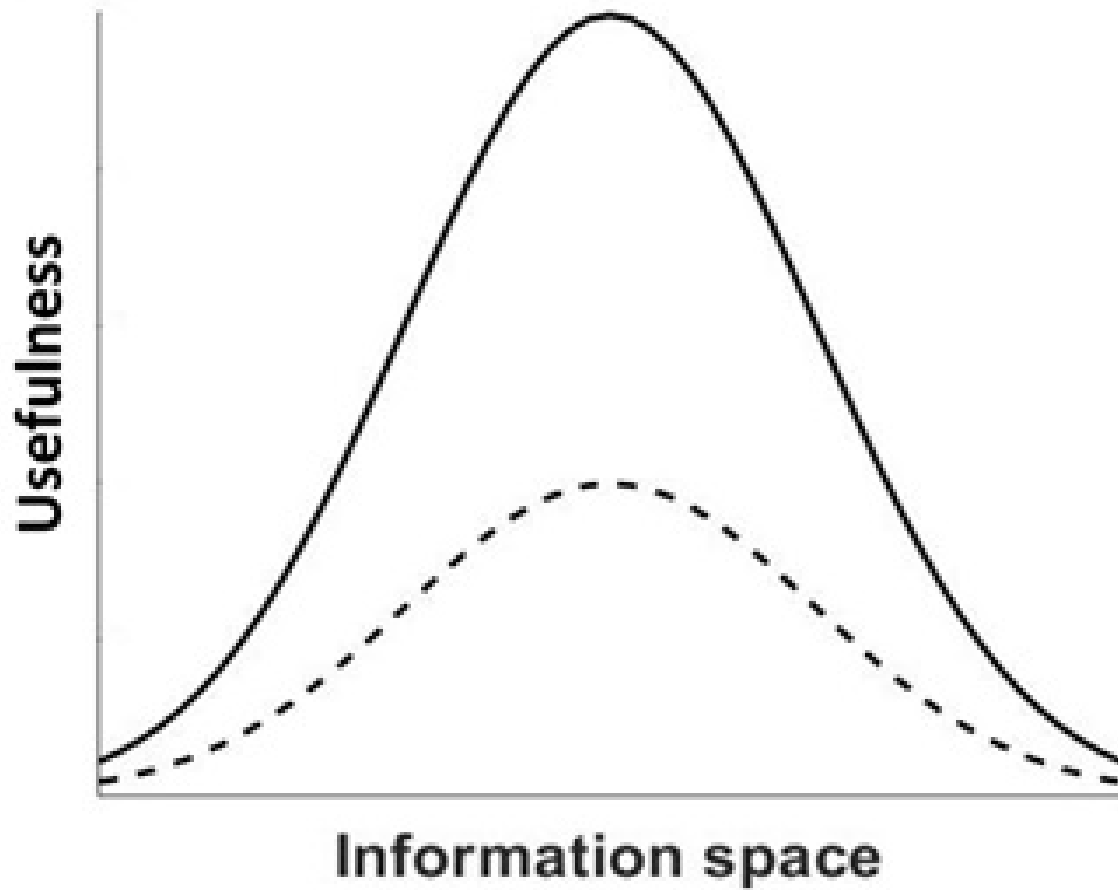
Figure 8.5: Hypothetical usefulness functions associated to an information space for one component of a multi-component action. The solid line stands for a situation in which the other components of the action are performed in a way that is sufficiently close to optimal. The dotted line stands for a situation in which this is not the case.
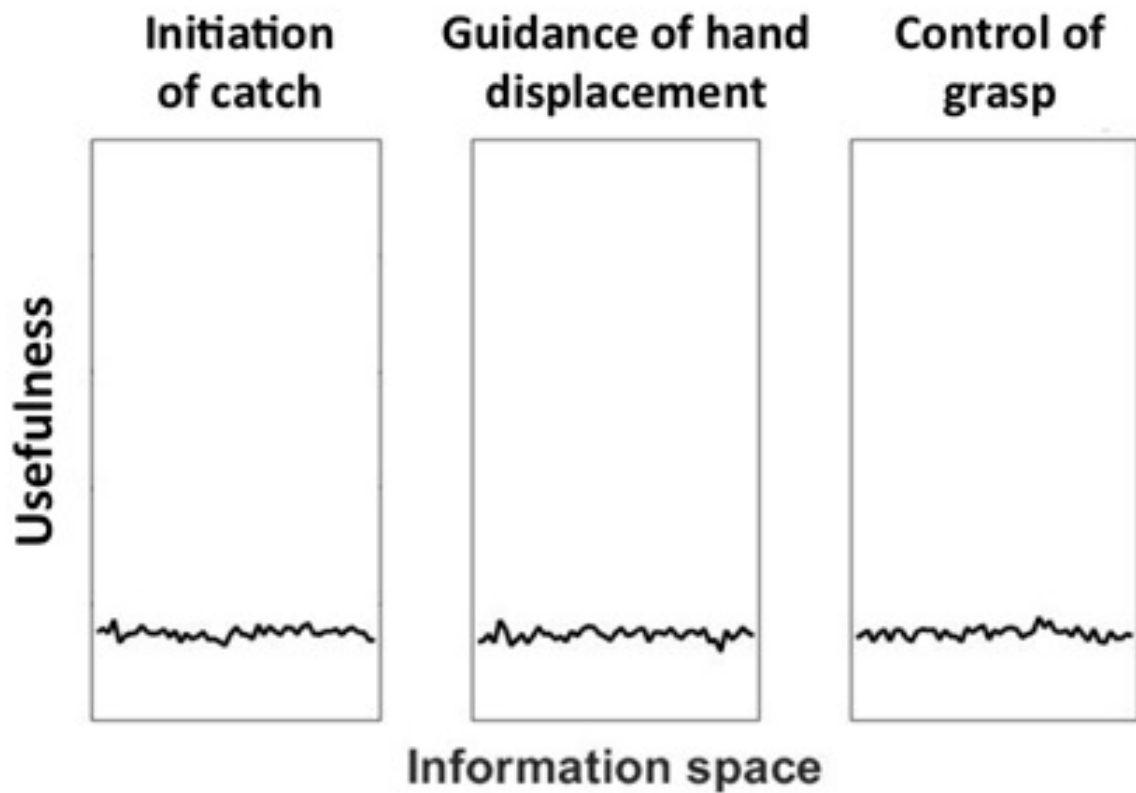
Figure 8.6: Flat usefulness functions that correspond to the components of a hypothetical catching action in which all components are performed in a way that is far from optimal.

Chapter 9

General Discussion and Conclusions

9.1 Global Results

The central theme of this thesis is the study of anticipation in sports for the development of training methods, specifically in the penalty kick situation in football. In this section we will discuss the results of the studies presented in chapters 3 to 8.

The objective of chapter 3 was to conduct a systematic review of anticipation training programs from 1990 to 2019. The results showed that anticipation training programs in the laboratory are generally effective. However, when evaluating performance in a real game situation most studies did not find positive transfer results.

It was discussed that the ultimate goal of an anticipation training program in sports has to be the transfer to the real game. Based on the results obtained in the review of 42 studies, a decalogue of recommendations for future training programs in anticipation was proposed. These results have allowed us to base the design of the training programs that we propose to work toward in this thesis on the current and historical evidence of anticipation training programs.

Chapter 4 presents an experiment analyzing the probability of the goalkeeper to stop the ball, the penalty taker kinematics, and the goalkeeper's movements in a database of 720 penalties of 12 kickers. The obtained results showed that the goalkeeper is more likely to stop the balls going to a medium height, while those that go high or low are almost impossible to stop for the goalkeeper. In addition, predicting the height of a penalty is more difficult than predicting the lateral direction. This is because the correlations between the kicker's movements and the height of the penalty are weak (never higher than .3). Whereas, for the lateral direction, different variables correlate above .8.

For the goalkeeper's movements, the results indicated that the goalkeepers begin their movement toward one of the sides before the kicker hits the ball, about 150 ms, based on the kicker's kinematics. However, the movement relative to the height of the ball starts about 245 ms after contact with the ball, presumably based on the initial trajectory of the ball, being unlikely that there will be any anticipation in this movement. These results indicate that to improve the performance in penalties relative to the height, the fitness of the goalkeeper, as well as its reaction speed would be more important than anticipation variables. All of these results justify that most of the training studies focus on the side direction, including those presented in this thesis.

Chapter 5 presents the first experiment in anticipation of penalties treated with PCA of this thesis. The purpose of this experiment was to check whether the results obtained in tennis and handball (Bourne et al., 2013; Huys et al., 2008) are replicable for the case of penalties in football. The results obtained were similar to those obtained in other anticipation experiments from PCAs, both in terms of variance explained by the components of the PCA and in terms of anticipation by experimental subjects. There were similar anticipation levels with the original stimuli and with 5-6 PCA components. In the end of the chapter we discuss the possibility that by replacing/combining the PCA with LDA the components found will have a closer relationship with the ecological concept of information than those obtained by PCA. The PCA aims to increase the explained variance of its components. Most experiments found that about 6 components contain enough information for anticipation. It was proposed that using an algorithm such as LDA, in which the differences between right and left penalties are maximized, the components obtained will be more related to the properties of the environment relevant to anticipation.

Chapter 6 presents a mathematical analysis comparing PCA and LDA on PCA subspace. The compared variables were the percentage of variance explained and the differences between left and right penalties. The results showed that the total variance explained by the 6 selected components was the same for PCA and PCA-LDA, 98.2%. However, the distribution of the explained variance between the components was different. As expected, for the PCA the variance explained was decreasing, because the

PCA maximizes the variance explained. For LDA the explained variance was distributed more homogeneously among the components, the last 3 components explained about 50% of the variance. As for the differences between left and right penalties on the PCA, those differences were distributed among all components, since the PCA does not work on that variable. For the LDA the differences were concentrated in the first components. These results show that LDA components may be related to relevant environmental properties to anticipate penalties in football.

Chapter 7 consists out of a series of five penalty anticipation experiments aimed to contribute to the development of an ecological training program using LDA. The first experiment replicated the study presented in Chapter 5, with the difference that it compares the performance in anticipation for experts and novices. The goal of this experiment was to test whether anticipation in the penalty kick task mantains expert-novice differences. This also allows us to check if it is possible to train anticipation in the laboratory by comparing the performance profiles in the different conditions between experts and novices after performing the training program. The results showed that experts anticipate better than novices with about 80% of the total variance presented. This indicates that laboratory experiments can capture differences between experts and novices. This demonstrates the utility of performing laboratory training programs to increase anticipation performance. The fact that the effect of the interaction was not significant indicates that the anticipation profile across the conditions comparing experts and novices is similar: higher anticipation on the original penalties, decreasing when presenting only from 1 to 3 PCA modes, and with 4-6 modes no differences were found with the original penalties. The set of results indicates that there are learning possibilities in our experiment of anticipating penalty kicks in the laboratoy.

The second experiment was aimed to check the possibility of training anticipation of penalties using PLDs and PCAs. Experimental conditions replicate those used in the previous experiment and the chapter 5 experiment with 4 training sessions between the pretest and the posttest. The results showed that a training program that evaluated by PCA can improve performance with a profile similar to the one shown in experiments with experts and novices. The third experiment aimed to check if neutralizing unpresented PCA components (in the other experiments the unpresented modes were removed) also allow us to determinets to improvements in anticipation performance. Neutralization is a necessary step to perform the LDA. This is because the components obtained by LDA do not aim to contain as much variance as possible as the components obtained by PCA. The results showed that neutralized penalties are anticipated at the same level as the original penalties when 4-6 PCA components are presented. The positive results in this experiment allow the necessary neutralization to be applied for the LDA stimuli used in the next experiment.

After testing the prerequisites for applying the LDA to the anticipation experiments, the fourth experiment actually uses LDA. The aim of the fourth experiment was to compare the results of the training programs with PCA-LDA. We expected to find that in the case of the LDA the presentation of the first components (1-3) would significantly increase the performance with respect to the PCA, because these first components contain the differences between left and right penalties. The results showed only significant differences between the condition of the original penalties and the others, both in the pretest and in the posttest. To apply the LDA, a different type of neutralization needs to be applied, compared to the one applied with the PCA. In order to check if this difference in the neutralization process could be causing the lack of improvement over components in the LDA experiment, we designed the fifth experiment. The fifth experiment aimed to check if the neutralization used with the LDA was the cause of the lack of performance improvement over components in the previous experiment. In this experiment a PCA method was performed using the neutralization needed for the LDA. The results showed that there was no improvement in anticipation over the manipulated conditions. These results indicate that the neutralization required to perform the LDA adversely affects performance. This is a likely explanation for the lack of improvements over components in Experiments 3 and 4.

Chapter 8 aimed to present the direct learning theory as a unified theory for the study of learning within post-cognitivism theories. The chapter presents ecological psychology and enactivism as the main theories that make advances in the experimental study of perception and learning. Recently, a group of enactivists have proposed a set of requirements that a learning theory should meet. Throughout the chapter the theory of direct learning is presented as the starting point for the study of learning under the post-cognitivist theories of perception and learning. The direct learning theory proposes a quantitative and falsifiable approach to the study of perceptual learning. Under the direct learning theory, learning is an information-driven process that does not require mental representations and inferences. On the other hand, it is shown that the theory of direct learning meets the requirements proposed by the enactivists and the general assumptions of the approximation of the 4Es approach to cognition. Finally, an extension of the theory of direct learning is presented, so that it can account for the learning of actions with multiple loops of perception-action.

9.2   Limitations and Future Work Directions

In this section, we will present some limitations of the studies presented in this thesis, and possible experiments to overcome these limitations. First of all, in chapter 2 we pointed out that a limitation of literature in anticipation in sport is the use of novices/students as experimental subjects. This results in a poor generalization of the conclusions. As we mentioned in chapter 3, some authors go further and propose that experience is an indispensable requirement to carry out an anticipation training program. In any case, all but two experimental studies of this thesis (the study in chapter 4 and experiment 1 of chapter 7) have been conducted with subjects with no experience in anticipating penalty kicks. This is a clear limitation and is one of the possible reasons why, in some cases, we do not obtain the expected results. To overcome this limitation it would be needed to replicate the experiments with experienced participants, as has been done with studies in tennis and handball (Bourne et al., 2013; Huys et al., 2010).

Secondly, in our anticipation experiments we used LDA. This decision is partly based on the previous literature (e.g. Troje, 2002). In this case we did not obtain the expected results, possibly due to the neutralization of the data needed to apply our LDA and the particular characteristics of the movements used (penalty kicks). Troje (2002) conducted the experiment with a cyclic movement, gait, and applied the discriminant analyses on the Fourier coefficients. In our case we applied the LDA to the projections of the original time series in the PCA modes. In the future, it would be relevant to replicate as closely as possible Troje's (2002) process with penalties. In addition, there are multiple algorithms that could perform the same function of dimensionality reduction and clasification. Future studies should test the usefulness of these algorithms in a perceptual training program.

Thirdly, as stated in chapter 3, training programs should get close to representative designs to maximize the transfer of laboratory to on-field performance. Given the manipulations of the data proposed in this thesis, the use of VE would be the most recommended way to get close to more representative desings.

Finally, the conclusions obtained in chapter 3, the systematic review, have to be taken with caution. Since this is a systematic review, we have mostly worked with descriptive statistics. In the future, for the special case of transfer and retention, a meta-analysis could be relevant. A meta-analysis would allow to determine whether the transfer and retention results are significant and their size of the effect, as well as the influence of control variables on performance.

9.3   General Conclusions and Contributions

The objective of this thesis was to contribute to the development of anticipation in sport, in particular in the penalty kick situation in football, and to the theoretical framework of ecological psychology. To this end, we started to develop an anticipation training program in sport, using dimensionality reduction techniques.

First, the systematic review of chapter 3 provides both theoretical and practical conclusions. In this sense we have made a systematic and comprehensive summary of the anticipation training programs published in the last 30 years. With this summary we can conclude that advances, since the early studies in the late 1960s, have been extraordinary (Williams & Jackson, 2019). However, it has not yet been possible to establish the variables that determine transfer between laboratory and on-field settings.

Recent advances in technology (virtual reality, powerful processors and video recorders...) and in theory (such as those presented in chapter 8 of the thesis) indicate that there should be a paradigm shift in anticipation training programs. On the one hand, progress has to be made towards on-field training to ensure transfer to real practice (Dicks et al., 2017; Hülsdünker et al. 2018). On-field training is possible and necessary in most cases, except in cases where manipulations cannot be carried out in a real life environment. In this case, experiments must be conducted in the laboratory (trying to make the design as representative as possible). On the other hand, theoretical advances have shown that it is time to stop using occlusion techniques and start using techniques that are less disrupting to the dynamics of movement, such as neutralization. These techniques combined with virtual reality allow to obtain more representative designs while allowing the experimental manipulations of the laboratory. This last part is the one that has been followed to design the training program proposed in this thesis.

Secondly, Chapter 4 has delved into an understanding of the penalty kick situation from 3 different perspectives, with results directly applicable to the game situation. Concerning the probability of the goalkeeper to stop the ball, the results of previous studies have been replicated, showing that high or low penalties in most cases result in a goal. This has clear practical implications for penalty kickers. If the kicker is able to adjust the kick to the corners, the probability of success is almost guaranteed. On the other hand, it has been shown that the kinematics of the kicker cannot be used to predict the height of

the penalty, while the side direction can. This tells us that the height is anticipated by the goalkeepers from the trajectory of the ball, and the lateral direction is anticipated from the movements of the penalty kicker. This result also justifies that the vast majority of training in anticipation of penalties will focus on the side direction. Finally, and as a consequence of the above, the goalkeeper's movements in the horizontal direction start around 150 ms before the penalty kicker hits the ball; in the vertical direction these movements are evident about 250 ms after the penalty taker has hit the ball.

Thirdly, the series of experiments in chapters 5–7 present a plan to develop an anticipation training program using LDA. Although the results were not positive, the experimental series have value for future work by other researchers in anticipation of sport and for our future experiments in anticipation (we are currently testing other methods of dimensionality reduction and classification that allow to overcome the problems mentioned in chapter 7). The greatest contribution of this thesis is that it establishes the way to start desingning informationally-based anticipation training programs.

As explained in the theoretical framework, ecological psychology proposes the analysis of cognition at the organism-environment level of analysis. This implies that, as proposed in this thesis, the first task of the researcher interested in the study of anticipation is to study the penalty situation in it's natural environment (chapter 4). Secondly, the task should be studied in terms of information for perception (a first approximation is presented in chapters 5-7). Finally, when the information space available to perform the task and the utility of the variables of this space is obtained, it would be possible to apply the direct learning formalisms, resulting in the development of more efficient and goal-driven training programs.

The design of training programs under the ecological psychology and direct learning framework has several implications that allow to overcome the limitations of studies of anticipation in sport. First, the lack of theoretical framework in anticipation studies resulted in a great heterogeneity in the type of studies carried out, being difficult to carry out generalizations, as seen in chapter 3. Studying anticipation within the framework of ecological psychology will help to develop an agenda with common goals to design directly comparable experiments. On the other hand, using ecological theory as a theoretical framework will help generalize the use of representative designs.

Secondly, and the real radical change that has been proposed is to redefine the design of the anticipation studies. This thesis proposes to design anticipation studies on information for perception.The first studies that take a step towards information-based research are the correlational studies and the first dimensionality reduction studies. However, these studies found the problem that the amount of variance explained is not directly related to the information used for anticipation. The greatest contribution of this thesis is the proposal to use classification algorithms that allow researchers to optain components that are closely related to information for anticipation. In the future, this will allow researchers to use tools of the direct learning theory.

From a theoretical point of view, we want to highlight the contribution of chapter 8. In chapter 8 we have presented the theory of direct learning, within the theoretical framework of ecological psychology, as the leading candidate to guide learning studies in the postcognitivist era. Ecological psychology gives special importance to the organism-environment level of analysis to explain goal-oriented behavior. This theoretical framework fits perfectly with the experimental designs and research objectives of anticipation studies in sport (Araujo, Davids & Hristovski, 2006). In this sense we argue that the processes of education of attention, education of intention and calibration defined under the direct learning theory, can be perfectly used in the anticipation learning studies. In this sense, the posibility of relating the components obtained by LDA to informational variables would allow studies in anticipation to model the learning process.

On the other hand, chapter 8 presents an expanded version of the direct learning theory to overcome some limitations detected since its proposal in 2007. Adding the "random behavior" component to the theory of direct learning makes it possible to overcome two limitations. Firstly, given the randomness component, it is possible to account for the fact that different agents have different learning curves or to account for an explanation of children's learning (Withagen & Van Wermeskerken, 2009; Kayed & van der Meer, 2007). Secondly, the randomness component also explains how to move from a situation where utility curves depend on multiple action components, and are flat because one of the action components is not well controlled by the agent. In this case, the randomness component allows for small spikes to appear in utility functions in the early stages of learning that eventually result in information-driven paths for learning.

In conclusion, we believe that the development of the anticipation training programs in the near future will be strongly linked to the use of representative designs and interdisciplinary collaboration between the sport sciences and psychology, enhanced by the use of new technologies. This thesis has helped to start defining the basic process to start studying anticipation from an information point of view.

Chapter 9

Discusión general y Conclusiones

9.1 Resultados globales

El tema central de esta tesis es el estudio de la anticipación en deporte para el desarrollo de métodos de entrenamiento, en concreto en la situación de penalti en futbol. En esta sección se van a discutir los resultados de los estudios presentados en los capítulos 3 al 8.

El objetivo del capítulo 3 era realizar una revisión sistemática de los programas de entrenamiento en anticipación desde 1990 hasta 2019. Los resultados obtenidos mostraron que los entrenamientos en anticipación en laboratorio son, en general, eficaces. Sin embargo, cuando se evalúa el rendimiento en situación de juego real la mayoría de los estudios no encuentran resultados positivos de transferencia.

Se discutió que el objetivo final de un entrenamiento en anticipación en deporte tiene que ser la transferencia al juego real. A partir de los resultados obtenidos en la revisión de 42 estudios se propuso un decálogo de recomendaciones para futuros programas de entrenamiento en anticipación. Estos resultados nos han permitido basar el diseño los programas de entrenamiento propuestos en esta tesis en las evidencias actuales e históricas de entrenamiento en anticipación.

El capítulo 4 presenta un experimento que analiza la probabilidad de que el portero detenga el balón, la cinemática del lanzador y los movimientos del portero en una base de datos de 720 penaltis de 12 lanzadores. Los resultados obtenidos mostraron que es más probable que el portero detenga los balones que van a una altura media, mientras que los que van alto o bajo es casi imposible detenerlos. Además, predecir la altura de un penalti es más complicado que predecir la dirección. Esto se debe a que las correlaciones entre los movimientos del lanzador y la altura del penalti son muy débiles (nunca superiores a .3). Mientras que, para la dirección lateral, distintas variables correlacionan por encima de .8.

En cuanto a los movimientos del portero, los resultados indicaron que los porteros inician su movimiento anticipatorio hacia uno de los laterales antes de que el lanzador golpee el balón, alrededor de 150ms, basándose en la cinemática del lanzador. Sin embargo, el movimiento relativo a la altura del balón se inicia unos 245ms después del contacto con el balón, presumiblemente basándose en la trayectoria inicial de este, siendo poco probable que se produzca algún tipo de anticipación en este sentido. A la luz de estos resultados, para mejorar el rendimiento en penaltis relativo a la altura tendría bastante importancia el físico del portero, así como su velocidad de reacción más que variables de anticipación. El conjunto de estos resultados justifica que la mayoría de los entrenamientos de anticipación en penaltis se centren en la dirección lateral incluyendo los presentados en esta tesis.

En el capítulo 5 se presenta el primer experimento de anticipación en penaltis tratados con PCA de la tesis. El objetivo de este experimento era comprobar si los resultados obtenidos en tenis y balonmano (Bourne et al., 2013; Huys et al., 2008) se dan igualmente en el caso de penaltis en futbol. Los resultados obtenidos fueron similares a los obtenidos en otros experimentos de anticipación a partir de PCAs tanto en términos de varianza explicada por los componentes del PCA como en términos de anticipación por parte de los sujetos experimentales. Se obtuvieron niveles de anticipación similares a los estímulos originales con 5-6 componentes del PCA.

Al final del capítulo se discute la posibilidad de que sustituyendo/combinando el PCA con LDA los componentes encontrados tendrán una mayor relación con el concepto de información de la psicología ecológica que los obtenidos mediante PCA. El PCA tiene como objetivo aumentar la varianza explicada de sus componentes; la mayoría de los experimentos encuentran que alrededor de 6 componentes contienen información suficiente para la anticipación. Se propuso que empleando un algoritmo como el LDA, en el que se maximizan las diferencias entre penaltis lanzados a la derecha y a la izquierda, los componentes obtenidos estarán relacionados más directamente con las propiedades del ambiente relevantes para la anticipación.

El capítulo 6 presenta un análisis matemático comparando el PCA y el LDA sobre el subespacio del PCA. Las variables comparadas fueron: porcentaje de varianza explicada y las diferencias entre penaltis lanzados a la izquierda y a la derecha. Los resultados mostraron que el total de varianza explicada por los 6 componentes seleccionados fue el mismo para el PCA y el LDA sobre PCA, 98.2%. Sin embargo, la distribución de varianza explicada entre los componentes fue diferente. Para el PCA la varianza explicada fue decreciendo, como era de esperar, ya que el PCA maximiza la varianza explicada. Para el LDA la varianza explicada se distribuyó de forma más homogénea entre los componentes, los 3 últimos componentes explicaron alrededor del 50% de la varianza. En cuanto a las diferencias entre penaltis lanzados a la izquierda y a la derecha en el PCA esas diferencias estaban distribuidas entre todos los componentes, dado que el PCA no trabaja sobre esa variable. Para el LDA las diferencias se concentraban en los primeros componentes. Estos resultados muestran que los componentes del LDA pueden estar relacionados con las propiedades relevantes del ambiente para anticipar penaltis en futbol.

El capítulo 7 consiste en una serie de cinco experimentos de anticipación en penaltis que tenía como objetivo contribuir al desarrollo de un programa de entrenamiento ecológico utilizando LDA. En el primer experimento se replicó el estudio presentado en el capítulo 5 comparando el rendimiento en anticipación de expertos y novatos. El objetivo de este experimento era comprobar si la tarea de anticipación en penalti sobre PLDs mantiene las diferencias entre expertos y novatos. Esto permite además comprobar si existe la posibilidad de entrenar la anticipación en laboratorio comparando el perfil de rendimiento en las diferentes condiciones entre expertos y novatos después de realizar el programa de entrenamiento. Los resultados mostraron que los expertos anticipan mejor que los novatos con alrededor del 80% de la varianza total presentada. Lo que indica que este tipo de experimentos en laboratorio puede capturar diferencias entre expertos y novatos. Esto demuestra la utilidad de realizar un programa de entrenamiento en laboratorio para aumentar el rendimiento en anticipación. Que el efecto de la interacción no fuera significativo indica que el perfil de anticipación a lo largo de las condiciones comparando expertos y novatos es similar: anticipación más alta en los penaltis originales, decayendo cuando se presentan solo de 1 a 3 modos del PCA para luego recuperarse y con 4-6 modos no se encontraron diferencias con los penaltis originales. El conjunto de los resultados indica que hay posibilidades de aprendizaje en nuestro experimento de anticipación de penaltis en laboratorio.

El segundo experimento tenía como objetivo comprobar la posibilidad de entrenar la anticipación de penaltis utilizando PLDs y PCAs. Las condiciones experimentales replican las empleadas en el experimento anterior y el experimento del capítulo 5 con 4 sesiones de entrenamiento entre el pre-test y el post-test. Los resultados mostraron que un programa de entrenamiento basado en PCA puede mejorar el rendimiento con un perfil similar al mostrado en experimentos con expertos y novatos El tercer experimento tenía como objetivo comprobar si la neutralización de los componentes del PCA no presentados (en los otros experimentos se eliminan los modos no presentados) permite también la mejora del rendimiento en un programa de entrenamiento. La neutralización es un paso necesario para realizar el LDA. Esto se debe a que los componentes obtenidos mediante LDA no tienen como objetivo contener el máximo de varianza posible como los componentes obtenidos mediante PCA. Los resultados obtenidos mostraron que los penaltis neutralizados son anticipados al mismo nivel que los penaltis originales cuando se presentan 4-6 componentes del PCA. Los resultados positivos en este experimento permiten aplicar la neutralización necesaria para el programa de entrenamiento basado en LDA que se presenta en el próximo experimento.

Una vez comprobados los requisitos previos para aplicar el LDA a los experimentos de anticipación, el cuarto experimento presenta el programa de entrenamiento utilizando LDA. El objetivo de este experimento era comparar los resultados del programa de entrenamiento que emplean PCA-LDA. Esperábamos encontrar que con el LDA la presentación de los primeros componentes (1-3) aumentaría significativamente el rendimiento con respecto al PCA ya que en estos primeros componentes se concentran las diferencias entre penaltis lanzados a izquierda y derecha. Los resultados mostraron solamente diferencias significativas entre la condición de los penaltis originales y las demás, tanto en el pre-test como en el post-test. Para aplicar el LDA se necesita aplicar un tipo de neutralización diferente a la aplicada con el PCA. Para comprobar si esta diferencia en la neutralización podría estar causando la falta de mejora en rendimiento en el programa de entrenamiento que emplea LDA diseñados el quinto experimento. El quinto experimento tenía como objetivo comprobar si la neutralización utilizada con el LDA era la causa de la falta de mejora del rendimiento con la práctica. En este experimento se lleva a cabo un entrenamiento con PCAs utilizando el método de neutralización usado en el entrenamiento con LDA. Los resultados mostraron que no existe mejora de la anticipación en las condiciones manipuladas, solo en la condición mostrando los penaltis originales. Estos resultados indican que la neutralización necesaria para llevar a cabo el LDA afecta negativamente a la mejora del rendimiento. Esta es una probable causa de que en el experimento 3 no se apreciaran diferencias en anticipación en las diferentes condiciones.

El capítulo 8 tenía como objetivo presentar la teoría del aprendizaje directo como teoría unificada para estudiar el aprendizaje dentro del post-cognitivismo. En el capítulo se presenta la psicología ecológica y el enactivismo como las principales teorías post-cognitivistas que han avanzado en el estudio experimental

de la percepción y el aprendizaje. Recientemente, un grupo de enactivistas han propuesto un conjunto de requisitos que una teoría de aprendizaje debería cumplir. A lo largo del capítulo se presenta la teoría del aprendizaje directo como el punto de partida para el estudio del aprendizaje bajo el conjunto de teorías post-cognitivistas a la percepción y el aprendizaje. La teoría del aprendizaje directo propone una aproximación cuantitativa y falsable al estudio del aprendizaje perceptivo-motor. Dentro de la teoría del aprendizaje directo el aprendizaje es un proceso guiado por la información que no requiere representaciones mentales e inferencias. Por otro lado, se demuestra que la teoría del aprendizaje directo cumple los requisitos propuestos por los enactivistas y los supuestos generales de la aproximación de las 4Es a la cognición. Finalmente, se presenta una extensión de la teoría del aprendizaje directo para que esta pueda dar cuenta del aprendizaje de acciones con múltiples bucles de percepción-acción.

9.2   Limitaciones y trabajo futuro

En esta sección, se van a presentar algunas limitaciones de los estudios presentados en esta tesis y posibles experimentos para superar esas limitaciones. En primer lugar, en el capítulo 2 señalamos como limitación en gran parte la literatura de anticipación en deporte el uso sistemático de novatos/estudiantes como sujetos experimentales. Esto genera como consecuencia problemas de generalización de los resultados. Como mencionamos en el capítulo 3 algunos autores van más allá y proponen que la experiencia es un requisito indispensable para llevar a cabo un entrenamiento en anticipación con resultados relevantes. En cualquier caso, todos los estudios experimentales de esta tesis excepto dos (el estudio del capítulo 4 y el experimento 1 del capítulo 7) han sido realizados con muestra sin experiencia en anticipación de penaltis. Esto es una clara limitación y es una de las posibles razones por la que, en algunos casos, no obtenemos los resultados esperados. Para superar esta limitación sería suficiente con replicar los programas de entrenamiento en anticipación con PCA con participantes con experiencia en la situación de penalti, como se ha hecho con los estudios en tenis y balonmano (Bourne et al., 2013; Huys et al., 2010).

En segundo lugar, en nuestra primera propuesta para aplicar la teoría del aprendizaje directo a tareas de anticipación en deporte utilizamos LDA. Esta decisión está basada en la literatura previa, principalmente Troje (2002). En este caso no obtuvimos los resultados esperados, posiblemente debido a la neutralización de los datos necesaria para aplicar el LDA y las particulares características de los movimientos que caracterizan los penaltis de futbol. Troje (2002) realizó el experimento con un movimiento cíclico, la marcha, y aplicó el LDA sobre los coeficientes de Fourier que ajustaban las series temporales. En nuestro caso aplicamos el LDA sobre las proyecciones de las series temporales originales en los modos del PCA. En el futuro, sería relevante replicar lo más parecido posible el proceso de Troje (2002) con penaltis. Además, existen múltiples algoritmos que podrían cumplir la misma función de reducción de dimensionalidad. Futuros estudios deberían probar la utilidad de estos algoritmos en un programa de entrenamiento perceptivo.

En tercer lugar, como se defendió en el capítulo 3, se debería avanzar hacia programas de entrenamiento con diseños representativos para maximizar la transferencia del aprendizaje obtenido en laboratorio a situación real. Dadas las manipulaciones de los datos propuestas en esta tesis el uso de VE sería la vía más recomendable para hacerlo.

Por último, las conclusiones obtenidas en el capítulo 3, revisión sistemática, tienen que ser tomadas con cautela. Dado que se trata de una revisión sistemática se ha trabajado, en su mayoría, con estadísticos descriptivos. En el futuro, conforme aumenten los estudios que realicen pruebas de transferencia y retención, sería relevante realizar un metaanálisis. Un meta-análisis permitiría determinar si el conjunto de los resultados de transferencia y retención son significativos y su tamaño del efecto, así como, el posible efecto de variables mediadoras afecten a los resultados.

9.3   Conclusiones generales y contribuciones

El objetivo de esta tesis doctoral era contribuir al desarrollo de la anticipación en deporte, en concreto a la situación de penalti en futbol, y al marco teórico de la psicología ecológica. Para ello se propuso contribuir al desarrollo de un programa de entrenamiento en anticipación en deporte utilizando técnicas de reducción de dimensionalidad que permitan que sus componentes estén más interpretados como variables informacionales que los de los estudios previos en el campo.

En primer lugar, la revisión sistemática del capítulo 3 aporta tanto conclusiones teóricas como prácticas. En este sentido hemos realizado un resumen sistemático y exhaustivo de los entrenamientos en anticipación en los últimos 30 años. Con este resumen podemos concluir que los avances en anticipación desde los primeros estudios a finales de los 60 han sido extraordinarios (Williams & Jackson,

2019). Pero todavía no se ha conseguido establecer cuáles son los criterios para que los efectos de la práctica en laboratorio se mantengan en el tiempo y se transfieran a la práctica real.

Los avances recientes en tecnología (realidad virtual, procesadores y grabadoras de video potentes...) y en la teoría (como los presentados en el capítulo 8 de la tesis) están sentando las bases para un cambio de paradigma en los programas de entrenamiento en anticipación. Por un lado, ha de avanzarse hacia entrenamientos "on-field" para asegurar la transferencia a la práctica real (Dicks et al., 2017; Hülsdünker et al. 2018). Los entrenamientos "on-field" son posibles y necesarios en la mayoría de los casos, excepto cuando existen manipulaciones que no pueden llevarse a cabo en un entorno real y los experimentos han de realizarse en laboratorio (tratando siempre que el diseño sea lo más representativo posible). Por otro lado, los avances teóricos muestran que es el momento de abandonar las técnicas de oclusión por técnicas que perjudiquen en menor medida la dinámica del movimiento, como la neutralización. Estas técnicas combinadas con realidad virtual permiten obtener un diseño representativo al mismo tiempo que permiten la manipulación experimental típica de laboratorio. Esta última parte es la que se ha seguido para diseñar el programa de entrenamiento propuesto en esta tesis.

En segundo lugar, en el capítulo 4 se ha profundizado en la comprensión de la situación de penalti desde 3 perspectivas diferentes con resultados directamente aplicables a la situación de juego. En cuanto a la probabilidad de que el portero detenga el balón, se han replicado los resultados de estudios previos, mostrando que los penaltis altos o bajos en la mayoría de los casos acaban en gol. Esto tiene implicaciones prácticas claras para los lanzadores, si consiguen lanzamientos ajustados a las esquinas la probabilidad de éxito está casi garantizada. Por otro lado, se ha mostrado que la cinemática del lanzador no puede ser utilizada para predecir la altura del penalti, mientras que la dirección lateral sí. Esto nos indica que la altura es anticipada por los porteros a partir de la trayectoria del balón y la dirección lateral es anticipada a partir de los movimientos del lanzador. Este resultado además justifica que la gran mayoría de los entrenamientos en anticipación de penaltis se centren en la dirección lateral. Por último, y como consecuencia de lo anterior, los movimientos del portero en la dirección horizontal comienzan alrededor de 150ms antes de que el lanzador golpee el balón; mientras que en la dirección vertical estos movimientos son evidentes unos 250ms después de que el lanzador haya golpeado el balón.

En tercer lugar, la serie de experimentos de los capítulos 5 al 7 presenta el plan propuesto para terminar con la propuesta de un programa de entrenamiento que emplea LDA. Considero que, aunque el objetivo de aplicar el LDA a un programa de entrenamiento no haya sido exitoso, la serie experimental tiene valor para trabajos futuros de otros investigadores en anticipación en deporte y para nuestros futuros experimentos en la línea (actualmente estamos utilizando otros métodos de reducción de dimensionalidad y clasificación que permiten superar los problemas mencionados en el capítulo 7). La mayor contribución de esta tesis es que se ha presentado la base para emplear la doctrina metodológica del aprendizaje directo en el estudio de la anticipación en deporte.

Como se explicó en el marco teórico, la psicología ecológica propone el análisis de la cognición en el nivel organismo-ambiente. Esto implica que, como se ha propuesto en esta tesis, la primera tarea del investigador interesado en el estudio de la anticipación sea estudiar la situación del penalti en su entorno natural (capitulo 4). En segundo lugar, se debe describir en términos de información para la percepción la tarea que se pretende estudiar (una primera aproximación se presenta en los capítulos 5-7). Finalmente, una vez obtenido el espacio de información disponible para realizar la tarea y la utilidad de las variables de este espacio, sería posible aplicar el formalismo de direct learning para definir la información para el aprendizaje. Con estos espacios de información para el aprendizaje es posible desarrollar programas de entrenamiento más eficientes y dirigidos por objetivos.

El diseño de programas de entrenamiento bajo el marco teórico de la psicología ecológica y el aprendizaje directo tiene varias implicaciones que permiten superar las limitaciones de los estudios de anticipación en deporte. En primer lugar, la falta de marco teórico en los estudios de anticipación tenía como consecuencia una gran heterogeneidad en el tipo de estudios realizados, siendo complicado realizar generalizaciones, como se ha visto en el capítulo 3. El estudio de anticipación dentro del marco de la psicología ecológica va a ayudar a que se desarrolle una agenda con objetivos comunes que permita diseñar experimentos con resultados directamente comparables guiados por la búsqueda y uso de información para la anticipación. Por otro lado, diseñar experimentos desde el enfoque ecológico está directamente relacionado con realizar diseños representativos por lo que utilizar la teoría ecológica como marco teórico ayudará a generalizar el uso de diseños representativos.

En segundo lugar, y el verdadero cambio radical que se ha propuesto es redefinir el diseño de los estudios de anticipación. Esta tesis propone basar los estudios de anticipación en la identificación y uso de información para la percepción. Como hemos visto en el capítulo 3, los entrenamientos en anticipación hablan principalmente de aprendizaje implícito/explícito, pero no de qué es lo que se aprende. Los primeros estudios que dan un paso hacia una investigación basada en la información son los estudios correlacionales y los primeros estudios de reducción de dimensionalidad. Sin embargo, estos estudios se encontraron con el problema de que la cantidad de varianza explicada no se relaciona directamente con la

información utilizada para la anticipación. En este punto se encuentra la mayor contribución de esta tesis, en el empleo de algoritmos de clasificación que permiten reducir la dimensionalidad de la información óptica y cuyos componentes son directamente interpretables como información para la percepción dentro de la psicología ecológica. Esto permite utilizar las herramientas de la teoría del aprendizaje directo y tiene como consecuencia que se podrá, de forma personalizada, explicar, controlar y predecir el proceso de aprendizaje en anticipación.

Desde el punto de vista teórico queremos destacar la contribución del capítulo 8. Por ello en el capítulo 8 hemos presentado la teoría del aprendizaje directo, dentro del marco teórico de la psicología ecológica, como principal candidata a guiar esta línea de investigación. La psicología ecológica da especial importancia a la interacción organismo-ambiente para explicar la conducta orientada a un objetivo. Este marco teórico encaja perfectamente con los diseños experimentales y objetivos de investigación de los estudios de anticipación en deporte (Araujo, Davids & Hristovski, 2006). En este sentido argumentamos que los procesos de educación de la atención, educación de la intención y calibración dentro de la teoría del aprendizaje directo, pueden dar cuenta de gran parte de procesos de aprendizaje en el ámbito de la anticipación. En este sentido, interpretar los componentes obtenidos mediante LDA como variables informacionales para construir una función de utilidad como las vistas en el capítulo 8 permitiría a los estudios en anticipación modelizar el proceso de aprendizaje por medio de ecuaciones diferenciales que mostrarían como la información guía el aprendizaje.

Por otro lado, el capítulo 8 presenta una versión ampliada de la teoría del aprendizaje directo y da cuenta de algunas limitaciones detectadas desde su planteamiento en 2007. Añadiendo el componente que hemos denominado como "random behaviour" la teoría del aprendizaje directo consigue explicar dos limitaciones. En primer lugar, dado el componente de aleatoriedad se consigue dar cuenta al hecho de que diferentes agentes tengan curvas de aprendizaje diferentes o al aprendizaje infantil (Withagen & Van Wermeskerken, 2009; Kayed & van der Meer, 2007). En segundo lugar, el componente de aleatoriedad también permite explicar cómo pasar de una situación en la que las curvas de utilidad dependen de varios componentes de acción y son planas debido a que uno de los componentes de acción no es controlado bien por el agente. En este caso, el componente de aleatoriedad permite que en las etapas iniciales del aprendizaje haya pequeños picos en las funciones de utilidad que, con el tiempo, dan lugar a trayectorias guiadas por información para el aprendizaje.

En conclusión, creemos que el desarrollo en los próximos años de la investigación en anticipación en deportes va a estar fuertemente ligado al uso de diseños representativos y a la colaboración interdisciplinar entre las ciencias del deporte y la psicología, potenciada por el uso de nuevas tecnologías. Esta tesis ha colaborado a presentar las bases metodológicas para poder comenzar a estudiar la anticipación en deporte bajo la teoría del aprendizaje directo. El proceso seguido ha sido el siguiente. En primer lugar, investigar en profundidad como se ha tratado la anticipación en deporte en los últimos años. En segundo lugar, estudiar la situación de penalti desde el punto de vista del portero y el lanzador. Finalmente, desarrollar la metodología para caracterizar la situación de penalti desde la perspectiva del portero de forma informacional empleando algoritmos de clasificación y reducción de dimensionalidad. Permitiendo el diseño de programas de entrenamiento que puedan hacer uso de las herramientas propuestas en la teoría del aprendizaje directo.

Chapter 10

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Appendix A

Published Articles

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Anticipating the Lateral Direction of Penalty Kicks in Football From PCA-Reduced Point-Light Displays

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ABSTRACT

The anticipation of the direction of football penalty kicks was assessed using Point Light Displays (PLDs). To that end, Principal Component Analyses (PCAs) were applied on previously registered penalty kicks. The PCAs provided an accurate description of the kicks: an average of 98.7% of the variance was explained with the first 6 PCA modes. The results of the PCAs were used to create 7 stimulus conditions, showing PLDs of the kicks as seen from the perspective of the goalkeeper. The first condition included all PCA modes and hence used PLDs of the original penalties. The remaining 6 conditions used all PCA modes until Mode 1, 2, 3, 4, 5, or 6, respectively. Participants observed the PLDs until the moment of ball contact and judged the lateral direction of the kicks. The percentages of correct judgments per condition revealed that the information for the anticipation of penalty kicks is contained in relatively few PCA modes. This confirms previous results obtained with tennis ground strokes (Huys, Smeeton, Hodges, Beek, & Williams, 2008), although for tennis ground strokes even fewer PCA modes seemed to be required to achieve accurate anticipation. The relevance of the ecological notion of information for the PCA-motivated body of research is discussed.

In his seminal research on the visual perception of biological motion, Johansson (1973) recorded a person with reflective markers on body locations near the joints while the person walked in a dark environment. Only bright moving dots, corresponding to the reflective markers, were visible during the reproduction of the recorded videos. The videos caused an immediate impression of a walking person on people who observed them. Such an impression was not caused by static images of the bright dots. Johansson's videos isolated the kinematic information of a human in motion from the pictorial information and showed the importance of the kinematic information. The displays used by Johansson are currently known as Point Light Displays (PLDs). Since Johansson's original study many research directions made possible by PLDs have been explored (Runeson & Frykholm, 1983), including the study of anticipation in sports (Ward, Williams, & Bennett, 2002).

This study focuses on the anticipation of the lateral direction of penalty kicks in football (also known as association football or soccer). A substantial number of studies on the football penalty kick use regular video presentations. In many cases, the video presentations are combined with occlusion techniques in which some location of a stimulus video is occluded during some temporal interval (McMorris & Hauxwell, 1997; Poulter, Jackson, Wann, & Berry, 2005). Notwithstanding the numerous advances that have been achieved with occlusion techniques, it has been argued that such techniques are limited in the sense that they lead to conclusions about spatial and temporal aspects of the used information but not about other aspects of the information (Huys, Smeeton, Hodges, Beek, & Williams, 2008). In addition, occluding local regions of a stimulus is less useful if—as argued by proponents of the ecological approach—information is to be found in global rather than local patterns (Huys et al., 2009; Michaels & Carello, 1981; Williams, Ward, Knowles, & Smeeton, 2002).

The use of PLDs instead of regular videos allows experimental manipulations other than occlusion techniques. Before we can explain this, we need to describe how Principal Component Analysis (PCA; Daffertshofer, Lamoth, Meijer, & Beek, 2004) can be applied to biological motion. Consider Johansson's (1973) example: a walking person with reflective markers on different body locations. In such cases, the different markers move to some extent in similar ways. A large forward movement, for instance, is shared by all markers. This means that the time series that describe the individual marker trajectories contain redundancies. A PCA takes advantage of such redundancies so as to achieve a more efficient description of the movement. Instead of describing the movement with a large number of redundant time series (the x, y, and z coordinates of the original marker trajectories), a PCA searches for a description with fewer time series that are less redundant.

We next provide a more mathematical description of PCA using the specific properties of this study. In our study, each PCA was applied to a 16 (markers) × 3 (x, y, and z coordinates) × 10 (penalties) = 480 dimensional data set. This means that 480 time series were used to describe the data set. These original time series, denoted as $q_1(t)$, …, $q_{480}(t)$, can be interpreted as describing a curve $\mathbf{q}(t) = q_1(t)\,\mathbf{e}_1 + \ldots + q_{480}(t)\,\mathbf{e}_{480}$ in a 480-dimensional space.[1] A PCA computes alternative base vectors, denoted as $\mathbf{v}_1$, …, $\mathbf{v}_{480}$, and associated time series, denoted as $\xi_1(t)$ …, $\xi_{480}(t)$. These alternative vectors and time series minimize the difference between the original data and the curve

$$\tilde{\mathbf{q}}(t) = \sum_{k=1}^{M} \xi_k(t)\mathbf{v}_k. \tag{1}$$

Said differently, the alternative vectors and time series are optimized so that (a) the approximation $\tilde{\mathbf{q}}(t)$ is equal to the original curve $\mathbf{q}(t)$ if all base vectors $\mathbf{v}_k$ are used ($M = 480$) and (b) this approximation is the best possible approximation of $\mathbf{q}(t)$ if less than 480 vectors are used ($M < 480$). The vectors $\mathbf{v}_k$ are referred to as *modes* or *eigenvectors* and the time series $\xi_k(t)$ as *projections*.

After performing a PCA on a biological movement, which implies a decomposition of the movement in different modes, one can reconstruct the movement in ways that lead to interesting differences between the original and reconstructed movements. In the reconstruction

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[1]Note that the vectors $\mathbf{e}_1$, … , $\mathbf{e}_{480}$ are the standard base vectors of the 480-dimensional space and that, following common convention, we use boldface instead of regular print to indicate quantities that are vectors instead of scalars.

one may for instance use only the first few modes of the PCA, omitting the higher, less relevant modes. One may also use all modes in the reconstruction but average some of them over relevant conditions (Huys et al., 2008). If one does not use all modes in the reconstruction, or if one somehow averages during the reconstruction, then the reconstructed movement differs from original one.

The difference between the original and the PCA-reconstructed movements makes the combination of PCAs and PLDs useful and elegant. This is so because, in contrast to regular videos, the use of PLDs allows the experimenter to present PCA-modified movements to participants and hence to assess the perceptual consequences of PCA-based manipulations. This combination of PLDs and PCAs was pioneered by Troje (2002), who studied gender recognition on the basis of walking patterns. The combination of PLDs and PCAs was introduced in the literature on anticipation in sports by Huys et al. (2008).[2]

Huys et al. (2008) addressed the perception of the direction of forehand ground strokes in tennis. In a first experiment, they registered 18 markers on the body and the racket of a player who executed the ground strokes. PCAs were performed on the registered shots. With the first five modes, 96.2% of the variance was explained. In a second experiment of Huys et al. (2008), participants judged the side of shots on the basis of PLDs that were created using the registered shots. The PLDs contained the unmodified original shots or shots reconstructed with different combinations of the PCA modes. The perception of the direction of the shots deteriorated with respect to the unmodified shots if only the first mode or only the first two modes were included. Performance did not deteriorate if the first three, four, or five modes were included. These results indicate that the information for the anticipation of ground strokes in tennis is contained in the first few PCA modes.

Since the research of Huys et al. (2008), multiple advances have been achieved in the understanding of anticipation behavior with the combination of PLDs and PCAs. The majority of these advances were based on the same task: anticipating the direction of ground strokes in tennis (Cañal-Bruland, van Ginneken, van der Meer, & Williams, 2011; Huys et al., 2009; Smeeton & Huys, 2011; Smeeton, Huys, & Jacobs, 2013; see Bourne, Bennett, Hayes, & Williams, 2011, and Bourne, Bennett, Hayes, Smeeton, & Williams, 2013, for an exception). We believe that applying these techniques to other anticipation tasks may, on the one hand, improve our understanding of such other tasks and, on the other hand, establish the generality of the conclusions. This study applies the techniques described in Huys et al. (2008) to the anticipation of the direction of penalty kicks in football. Apart from the task used, our design closely matches the one of the aforementioned second experiment of Huys et al. (2008).

The only previous study that we are aware of that used PLDs and PCAs to study the anticipation of the direction of penalty kicks is the one by Diaz, Fajen, and Phillips (2012). That study, however, differs from ours among other reasons because participants observed only unmodified PLDs, whereas in our experiment PCA modes were selectively removed from the stimuli. Another difference is that the penalties that we used to create the PLDs were registered in an experiment with a more representative design than the experiment of Diaz et al. As an additional indication of the contribution of the present study, let us mention that, although it has inspired further research in the anticipation of tennis ground strokes, the

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[2]One may want to note that, in contrast to Johansson (1973), Troje (2002) and Huys et al. (2008) connected the dots in their stimuli with lines.

aforementioned second experiment of Huys et al. (2008) has not been replicated with the tennis task either.

Method

Participants

Fifty-two students of the Universidad Autónoma de Madrid (38 male, 14 female) with a mean age of 20.5 years ($SD = 1.2$) participated in the experiment. Participants were divided into two equal-size groups that judged penalties of different kickers. Participants were compensated with coupons for a university bookstore. The research was approved by the local committee for ethical research (CEI 52-957). All participants gave written informed consent before participating in the experiment. After performing the experiment, we asked participants if they had experience playing football. The large majority of them reported that they had occasionally played football as a recreational activity. None of them, however, played in an official competition. Their experience facing football penalties was therefore low.

Stimuli

Lopes, Jacobs, Travieso, and Araújo (2014) registered 60 penalties for each of 12 professional and semiprofessional football players. For these penalties, the three-dimensional position of 16 markers was registered at 150 Hz. The markers were located on the head, shoulders, elbows, wrists, hip, knees, and on the back and front of the feet of the kicker. Just before each trial, the kickers received the instruction to try to deceive or not to deceive the goalkeeper with respect to the shooting direction. For this study we selected 20 of the penalties that were registered by Lopes et al.: 10 penalties for each of two kickers. For each kicker, 5 of the 10 penalties were shot to the left and five to the right. In all of the selected penalties, the instruction was the one of not deceiving the goalkeeper. All markers were correctly registered in the relevant parts of the time series for all penalties in our selection.

We used penalties from these particular two kickers because we expected that their penalties might be relatively easy to judge. This expectation was based on a reanalysis of data from a preliminary study that included two nondeceptive penalties from 10 kickers (Higueras-Herbada, Travieso, & Jacobs, 2015). The percentages of correct side judgments for these two kickers (76.5% and 77.0%, respectively) were higher than for the other kickers. Given that removing modes from the penalties may be expected to reduce the percentages of correct judgments, aiming to select relatively easy penalties may avoid floor effects near chance level.

Self-developed MATLAB routines transformed the registered three-dimensional body movements to two-dimensional PLDs of these movements. Participants in our experiment observed the penalties with approximately the same projective structure as the goalkeepers in the original experiment. The parts of the time series that were included in the stimuli (and considered in the PCAs) started at the second last maximum height before ball contact of the marker on the front part of the nonkicking foot and ended at the moment of ball contact. Figure 1 illustrates the time series. The used parts of the time series lasted 1.1 s ($SD = 0.06$) for the first kicker and 1.0 s ($SD = 0.08$) for the second kicker.

As illustrated in Figure 2a, the stimuli consisted of 16 black dots of a point-light kicker and a black circle corresponding to the ball. The point-light figure subtended approximately
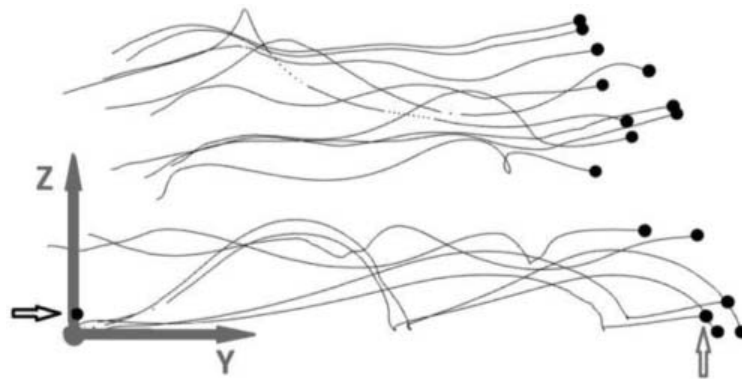
Figure 1. Lateral view of the considered parts of the marker trajectories. The x coordinate, not shown in the figure, is orthogonal to the y and z coordinates. The dots at the right indicate the position of the body markers at the first frame of the time series. The vertical arrow at the bottom right indicates the event that defined the beginning of the intervals: the second last maximum height of the marker on the front part of the nonkicking foot. The horizontal arrow at the left indicates an additional marker at the position of the ball.

8° of visual angle, nearly the same as a kicker in the field situation. The background was uniformly white. Figure 2b shows that a chin rest was used, located at a distance of 1 m from the 24-in. (0.61-m) screen. The eyes were located approximately at the same height as the center of the screen.

Experimental conditions

Before applying the PCAs, the considered parts of the 480 registered time series (16 markers × 3 coordinates × 10 penalties) were mean subtracted and divided by their standard deviation. This normalization was performed to avoid that markers with large movement amplitudes had disproportionally large contributions to the higher PCA modes (Daffertshofer et al., 2004). The time series were also resampled to a uniform length of 100 frames. A separate PCA was performed for each of the two kickers. This led to relatively homogeneous time series per PCA, performed without time warping.

After performing the PCA-based decomposition in modes, we reconstructed the movements of the kicker using different combinations of the modes. Said more precisely, for each experimental condition we computed the approximation $\tilde{\mathbf{q}}(t)$ with a different value of M (see Equation 1). The values of M that were used in the seven conditions were 480, 1, 2, 3, 4, 5, and 6, respectively. When M was set at 480, all modes were used in the reconstruction, and hence PLDs of the original penalties were computed. This condition was referred to as M_{all}. Setting M at any value between 1 and 6 means that only the modes until the value of M were used; these six conditions were referred to as M_1, M_2, M_3, M_4, M_5, and M_6. Being purposefully redundant, the penalties used in condition M_3, for instance, were approximations of the actual penalties based on Modes 1 to 3 of the PCAs.

The reconstructed data, $\tilde{\mathbf{q}}(t)$, consisted of 480 time series with a uniform length of 100 frames. To undo the normalization, each time series was multiplied by its original standard deviation, and its original mean was added. The resampling of the time series to 100 frames was also undone. At the end of the PCA procedure for each kicker, we obtained approximations of the 48 time series of each of the 10 penalties in each of the seven conditions, giving
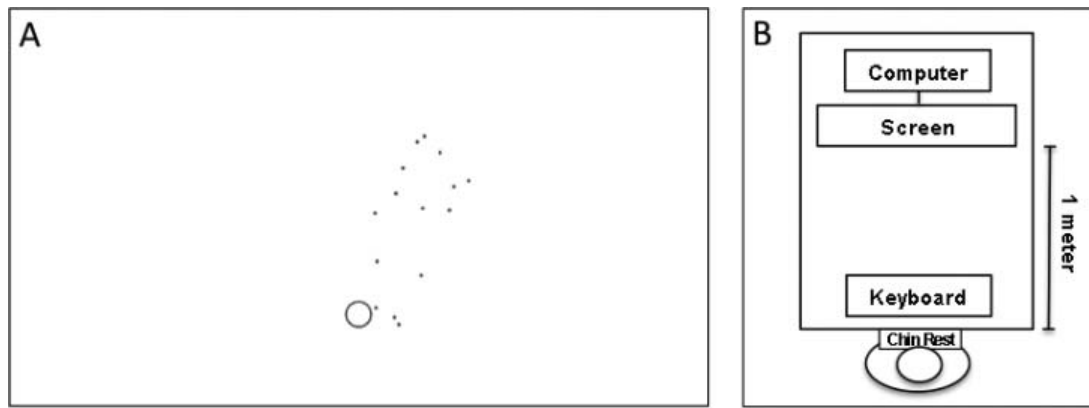
Figure 2. A: Single frame of a stimulus video for an unmodified penalty. This frame is close to the moment of ball contact. The black dots correspond to the registered marker positions. The ball is represented with an open circle. Only the markers that were occluded by the ball were not visible in the stimulus videos. B: Experimental setup.

$10 \times 7 = 70$ penalties to be used as stimuli. The stimuli were presented with a frequency of 60 Hz.[3]

Procedure

Participants were informed that they would be shown 70 penalties from the perspective of the goalkeeper and that some of these penalties had a peculiar appearance. The penalties that looked peculiar were the ones that were reconstructed with few modes (varying in degree but approximately until M_3 or M_4). The participants were asked to indicate the direction of the kicks with the right- or left-arrow key. The penalties were presented in a random order. Each participant observed the penalties of one kicker. Each penalty was shown twice before the participant responded. Optional breaks were suggested after each 10 trials. The experiment took approximately 15 min.

Data analysis

For all ANOVAs, whenever the sphericity assumption was violated, Huynh-Feldt corrections were performed and the corrected degrees of freedom are reported. Fisher's least significant difference tests were used as post hoc tests.

Results

PCA results

For the first kicker, the first six modes explained 67.9%, 11.9%, 9.8%, 5.0%, 2.5%, and 1.7% of the variance, respectively. For the second kicker, these modes explained 71.4%, 10.8%, 8.6%, 4.6%, 2.3%, and 1.1% of the variance. For both kickers, the first six modes together explained 98.7% of the variance.

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[3]A video with a penalty from each of the seven PLD conditions can be found at http://www.uam.es/gruposinv/gipym/HiguerasHerbadaEtAl2017.m4v.
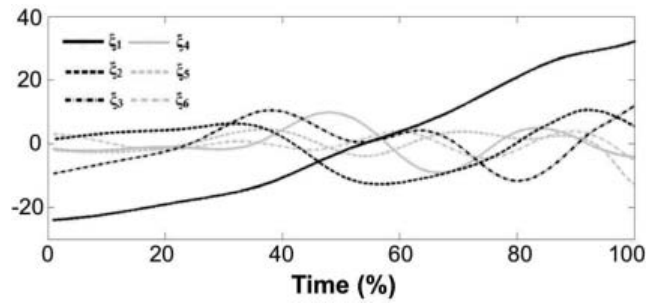
Figure 3. Projections associated to the first six modes of the Principal Component Analysis for the first kicker. The projections for the second kicker were similar.

Figure 3 illustrates the projections corresponding to the first six modes. Figure 4 illustrates the contributions of the markers and coordinates to the modes. Note from Figures 3 and 4 that the projection of Mode 1 increased monotonically and that the coordinates that contributed to Mode 1 were mainly x and y. Mode 1 captured the overall approach of the kicker to
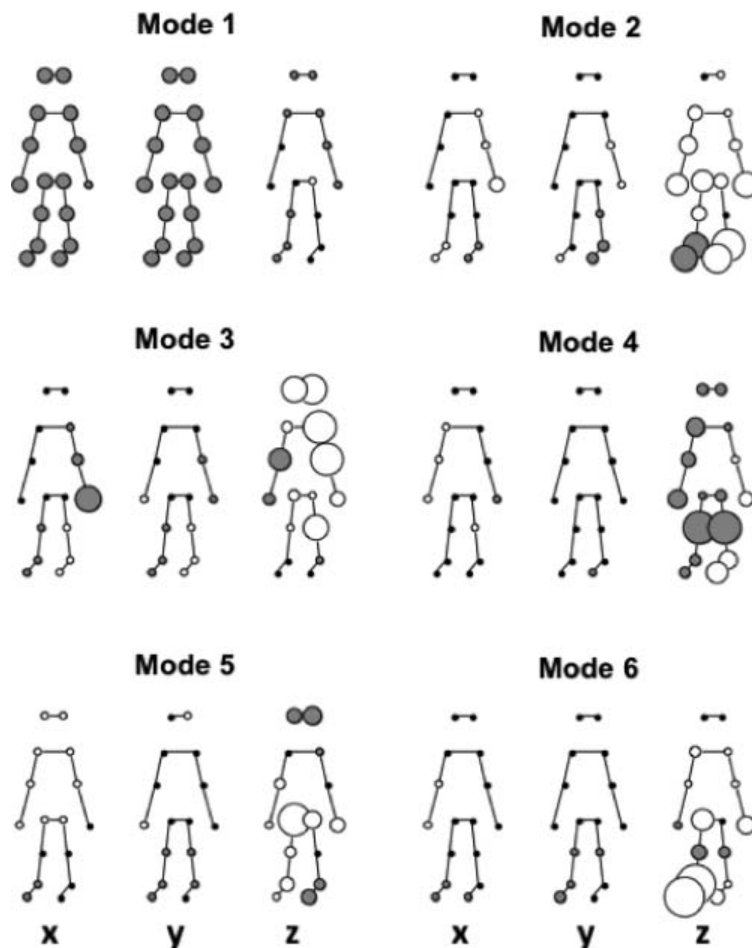
Figure 4. Coefficients of the mode vectors for Modes 1 to 6 of the first kicker. For each mode, 48 average coefficients are represented: 16 markers × 3 coordinates. Each average represents 10 coefficients, corresponding to the 10 penalties of this kicker. Grey and white fills of the circles indicate positive and negative averages, respectively. The absolute value of the averages is indicated by the size of the circles. Large circles indicate markers and coordinates that contribute importantly to the considered modes. The results for the second kicker were similar.

Figure 5. Percentage of correct judgments as a function of experimental condition for the first and second kicker (left panel) and averaged over the two kickers (right panel). Error bars indicate standard errors of the mean.
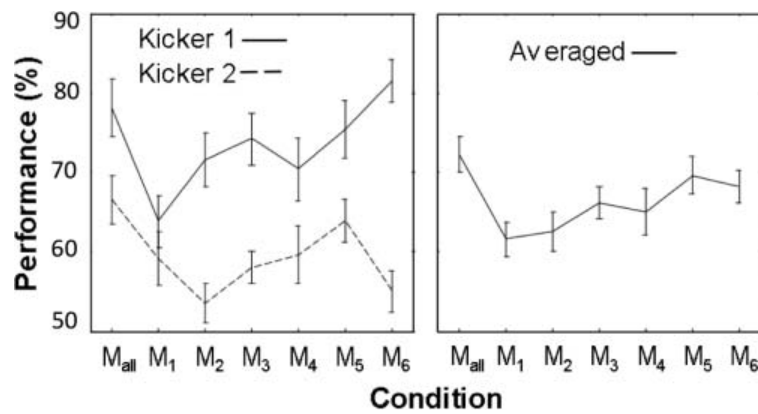
the ball. Given that the overall approach was in the horizontal direction, the contribution of the z coordinate was minor. The remaining projections in Figure 3 indicate that Modes 2 to 6 concerned more cyclic movements. Figure 4 shows that the z coordinate was the main contributor to these cyclic modes.

The variance explained by Mode 1 (around 70%) was much higher than the variance explained by the other modes (between 1 and 12%). The information provided in Figures 3 and 4 allows one to understand this difference. The overall horizontal approach concerned a larger movement than the cyclical fluctuations in the vertical direction around the approach trajectory. Furthermore, although all markers contributed about the same to the overall approach, the marker contributions to the cyclic fluctuations were less homogeneous. The latter contributions were more concentrated in the extremities.

Experimental results

Overall performance

Figure 5 shows the percentage of correct side judgments in the different conditions per kicker (left panel) and averaged over the two kickers (right panel). We performed an ANOVA with condition as a within-subjects variable and kicker as a between-subjects variable on the percentage of correct judgments. The ANOVA revealed significant main effects of condition, $F(5.5, 273.1) = 3.79$, $p < .01$, $\eta_p^2 = .07$, and kicker, $F(1, 50) = 31.33$, $p < .001$, $\eta_p^2 = .39$, and a significant interaction, $F(5.5, 273.1) = 3.06$, $p < .01$, $\eta_p^2 = .06$.

The accuracy of anticipation in the condition with the original penalties, indicated by M_{all}, was 78.1% for the first kicker and 66.5% for the second kicker, leading to an average of 72.3%. The average performance largely showed the expected profile over conditions: The percentage decreased steeply from M_{all} to M_1 and then slowly increased with the successive inclusion of modes (from M_2 to M_6). The curves for the individual kickers showed deviations from the expected profile. Most remarkably, for the first kicker, performance increased by 6.2% with the inclusion of Mode 6, whereas, more surprisingly, for the second kicker performance decreased by 8.8%. We do not have an explanation for this latter finding. Our further analyses focused on the performance averaged over the two kickers.

A one-way ANOVA on the averaged percentages showed a significant effect of condition: $F(6, 150) = 3.63$, $p < .01$, $\eta_p^2 = .13$. Post hoc analyses indicated that the average anticipation

in the condition M_{all} was significantly better than in the conditions M_1, M_2, and M_4 (ps < .05). Furthermore, performance in the conditions M_5 and M_6 was significantly better than in the condition M_1 and performance in the condition M_5 was significantly better than in the condition M_2 (ps < .05). No other significant differences among conditions were observed. The averaged performance was above chance level in all conditions (ps < .001).

The variability was high: the standard deviations per condition and kicker varied between 10.6% and 20.3%. This high variability motivated us to visually inspect the profiles of individual participants. Following the interesting results of this initial inspection, the next subsection reports more formal analyses for subgroups of participants selected on the basis of their performance.

High- and low-performing individuals

For this analysis, we first ordered the participants for each kicker according to their performance in the condition M_6. Participants with equal performance for M_6 were subordered using their performance for M_5 and then using M_4. After this ordering, performance was averaged over the kickers per pair of participants. The 13 highest- and 13 lowest-performing pairs were analyzed as the high- and low-performing groups. We used this ordering procedure because we wanted our grouping criterion to be independent of the subsequently applied statistics. Using the conditions with the higher modes for the grouping allowed us to statistically compare the groups using the conditions with the lower modes together with the condition with the unmodified penalties.

Figure 6 shows the performance of the obtained groups. We performed a mixed ANOVA with condition (M_{all}, M_1, M_2, and M_3) as a within-subjects variable and group (high performance, low performance) as a between-subjects variable on the percentage of correct judgments. The ANOVA revealed a significant main effect of condition, $F(3, 72) = 5.85$, $p = .001$, $\eta_p^2 = .20$, superseded by a significant interaction, $F(3, 72) = 3.12$, $p = .03$,

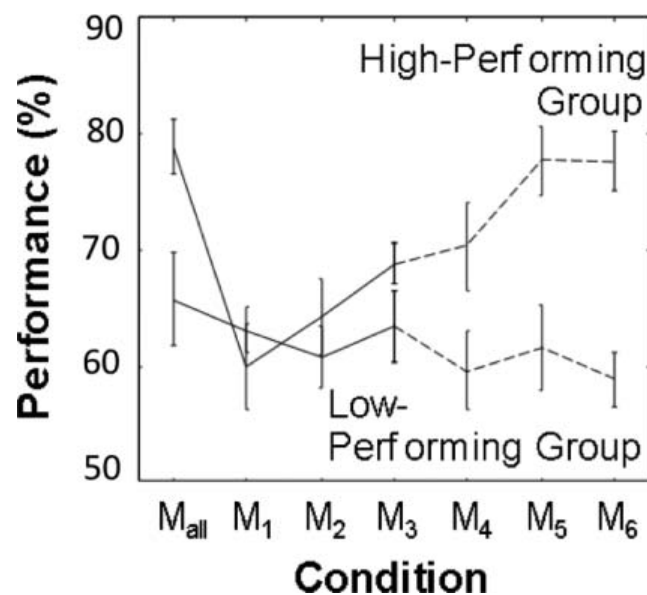

Figure 6. Percentages of correct judgments as a function of experimental condition for groups with high- and low-performing individuals. The dashed segments at the right indicate that conditions M_4 to M_6 were used to define the groups.

$\eta_\mathrm{p}^2 = .12$. The effect of group did not reach significance, $F(1, 24) = 2.79$, $p = .11$, $\eta_\mathrm{p}^2 = .10$. Post hoc tests indicated that, for the high-performing group, the performance in M_all was significantly higher than in the other conditions (ps $< .05$). Furthermore, for this group, performance in M_3 was significantly higher than in M_1 ($p < .05$). No significant differences were observed for the low-performing group.

Discussion

This study investigated the accuracy of anticipation on the basis of PLDs reconstructed with different numbers of PCA modes. The design of our experiment was inspired by Experiment 2 of Huys et al. (2008), but where Huys et al. (2008) addressed ground strokes in tennis, we used penalty kicks in football. The average anticipation accuracy for the unmodified PLDs was 72.3%. This relatively high percentage is in line with previous studies. It demonstrates that PLDs contain information for the perception of biological motion (Johansson, 1973) and, in particular, for anticipatory behavior in sports (Diaz et al., 2012; Higueras-Herbada et al., 2015; Huys et al., 2009; Huys et al., 2008).

The percentage of variance explained by the PCAs was high, reaching an average cumulative 97.4% with the first five modes and 98.7% with the first six modes. These results are similar to the ones reported by Huys et al. (2008), who found that the percentage explained by the first five modes was 96.2%. Likewise, Troje's (2002) pioneering study showed that more than 98% of the variance in walking patterns was explained with four PCA modes. These results confirm that biological motion contains redundancies and thereby highlight the usefulness of dimensionality reduction techniques such as PCAs.

The main pattern of results over our experimental conditions with and without PCA-based manipulations replicates the main pattern reported by Huys et al. (2008). We observed a drop in anticipation performance from the condition with the unmodified penalties to the condition with penalties that were reconstructed only on the basis of the first mode as well as an increase in performance with the successive inclusion of the higher modes. This overall pattern shows that a substantial part of the information that is used for the anticipation of penalties in football is contained in penalties that are reconstructed on the basis of few PCA modes.

A difference between our results and the ones concerning ground strokes in tennis is that performance appears to recover more quickly with the inclusion of modes in the case of the ground strokes. This difference is easily appreciated from a comparison of the overall shape of the curve in the right panel of our Figure 5 and the overall shape of Figure 7 of Huys et al. (2008). In the considered experiment of Huys et al. (2008), performance in the condition with the unmodified shots was significantly better than performance in the equivalents of our conditions M_1 and M_2 (indicated by Mode$_1$ and Mode$_{1-2}$ in Figure 7 of Huys et al., 2008). In our experiment, a significant difference in the average performance was observed also for M_4.

Another noteworthy result of our experiment is that we observed differences between separately analyzed high- and low-performing groups. Individuals in the perceptually skilled group anticipated better in the condition with the original penalties than in conditions with fewer PCA modes. For individuals in the perceptually less skilled group there were no significant differences among the conditions. This result may indicate that highly skilled individuals, in contrast to less skilled ones, are able to extract higher order invariants: Their

performance suffers in the conditions with fewer modes, where these invariants are not available. This interpretation is consistent with studies that show that gaze patterns tend to change with experience (Ward et al., 2002; Williams et al., 2002). The interpretation is also consistent with ecologically motivated approaches to learning, which attribute improvements with practice to changes in variable use (Jacobs & Michaels, 2007).

The previous remarks bring us to a weakness of many of the studies in the PCA-based body of research, including the present one. Although it is shown that information for perception is contained in actions that are reconstructed with relatively few modes, and it may even be shown which modes are the more relevant ones, it is not shown what the information is. To appreciate this point, one may note that typical ecological claims about the use of informational variables—such as the inertia tensor (Solomon & Turvey, 1988), optical acceleration (Michaels & Oudejans, 1992), or some fractional-order derivative (Jacobs, Vaz, & Michaels, 2012)—allow precise predictions about performance. In contrast, claiming that information for perception is contained in a few PCA modes does not. Our claim that six PCA modes are sufficient, for instance, does not allow us to predict whether a particular penalty will be perceived as being shot to the left or to the right.

To indicate why candidate variables from typical ecological research allow more precise predictions than the dimensionality reduction reported in the majority of PCA-based studies, we need to address a crucial aspect of the ecological notion of information. In the ecological view, information for perception is information *about* to-be-perceived properties (Michaels & Carello, 1981). To-be-perceived properties are therefore a necessary part of any ecological inquiry on the informational basis of perception. In contrast, PCAs search for dimensions that describe the global structure of the action independent of to-be-perceived properties. That is, the optimization performed by PCAs is unrelated to to-be-perceived properties and, therefore, to a large extent unrelated to the ecological notion of information. This implies that after having reduced the dimensionality, one still has to identify the information about to-be-perceived properties that is contained in the dimensionality-reduced action.

To identify the information in the dimensionality-reduced action, one may compare PCA results for actions with different values of the to-be-perceived property (Huys et al., 2008). Such attempts, however, have not always been successful (Bourne et al., 2011). To conclude this article, let us more speculatively indicate an alternative route for researchers who are interested in dimensionality reduction and information usage. We believe that such researchers may want to consider discriminant analyses instead of (or in addition to) PCAs. Rather than searching for dimensions that best describe the action as a whole, discriminant analyses search for dimensions that best distinguish categories (Xiang, Fan, & Lee, 2006; cf. Troje, 2002). If one takes these categories to be the to-be-perceived properties (e.g., the left vs. right direction), then the modes of the discriminant analyses are inherently related to the to-be-perceived properties. This may make the modes obtained with discriminant analyses better suited to the ecological notion of information than the modes obtained with PCAs.

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Information in Complex Biomechanical Actions: A Linear Discriminant Algorithm

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Point-light displays allow scientists to present kinematic information isolated from pictorial information. Principal component analyses (PCAs) can be used to obtain low-dimensional approximations of intrinsically high-dimensional point-light actions (Daffertshofer, Lamoth, Meijer, & Beek, 2004). Many point-light actions are well described with 4-6 dimensions. For example, with five dimensions one can describe more than 97% of the variance in tennis shots (Huys, Smeeton, Hodges, Beek, & Williams, 2008), football penalty kicks (Higueras-Herbada, Travieso, Ibáñez-Gijón, & Jacobs, 2017), and walking patterns (Troje, 2002).

Dimensionality-reduced point-light actions can be used as stimuli in psychophysical experiments. Observers may be asked to judge outcomes of the actions, such as the final direction of tennis shots or penalty kicks. Consistent with the finding that 4-6 dimensions describe much of the total variance of many actions, stimuli constructed on the basis of 4-6 dimensions lead to judgments that are not significantly different from stimuli that contain all variance (Higueras-Herbada et al., 2017; Huys et al., 2008).

The above-described psychophysical results demonstrate that a substantial part of the information that is used for the anticipation of the outcome of actions is contained in the dimensionality-reduced actions. But what is that information? Related to this question, several authors have analyzed the results of PCAs that were performed separately per action outcome. Such analyses have not always revealed clear differences. As an example of this, Bourne, Bennet, Hayes, and Williams (2011) claimed that "the dynamical structure underpinning the handball penalty shot does not differ greatly across locations (p. 40)".

In Higueras-Herbada et al. (2017) we have argued that PCAs are not perfectly suited to distinguish actions according to their outcomes, and hence that PCAs are not closely related to information about the outcomes. This is so because PCAs search for dimensions that best explain the overall variance in datasets. In contrast, linear discriminant analyses (LDAs) search for dimensions that best explain differences between subsets of the total dataset (Xiang, Fan, & Lee, 2006). LDAs might therefore be more closely related to the ecological notion of information than PCAs.

The present chapter describes a novel LDA algorithm. The algorithm was

applied to football penalties. The used penalties were registered by Lopes, Jacobs, Travieso, and Araújo (2014). These penalties were also used in a PCA-based psychophysical experiment reported in Higueras-Herbada et al. (2017).

Method

Our initial dataset consisted of 48 time-series: 3 Cartesian coordinates of 16 registered markers. Each time series contained 1000 data points: 100 data points per penalty for 10 registered penalties. The 100 data points per penalty were the resampled time series that were registered between the second last maximum height of the non-kicking foot and ball contact.

Before computing the LDA, a PCA was used to reduce the dimensionality from 48 to 6. With this PCA we obtained 6 dimensions, or PCA modes, and the projections of the original data on these modes. The PCA computed the 6 dimensions so that these explained as much variance of the total dataset as possible. See Daffertshofer et al. (2004) for more detail on the application of PCA to biological movement.

Within the 6-dimensional dataset obtained with the PCA, our LDA searched for new dimensions, the LDA modes. The LDA algorithm maximized the differences between the averaged projections for penalties to the left (first 500 data points of the time series) and right (last 500 data points). The optimization considered a time window between approximately .56 and .11 s before ball contact (i.e., between frames 60 and 90 of the resampled projections). Detecting information during this interval may permit goalkeepers a timely reaction.

Figure 1. Projections of first PCA and LDA modes averaged for left and right penalties.

Results and Discussion

Figure 1 shows the projections for the first PCA and LDA modes. For the PCA, these projections increased monotonically. This increase corresponds to the forward movement of the kicker, which constitutes a large part of the overall variance. The LDA captured the overall approach in its higher modes: the projections for the first mode were cyclic. In contrast to the PCA projections, the LDA projections for left and right penalties differed substantially between frames

60 and 90. We next analyze this difference for all modes.

The upper panel of Figure 2 shows the above-mentioned difference in the projections, which was optimized in the LDA, for all six PCA and LDA modes. The difference was large for the first LDA mode and lower for the higher modes. The decay over successive modes indicates the extent to which the LDA was successful in concentrating the left-right differences in the first modes. For the PCA, rather than decreasing over modes, the difference was maximal for Mode 3, followed by Modes 2 and 4.
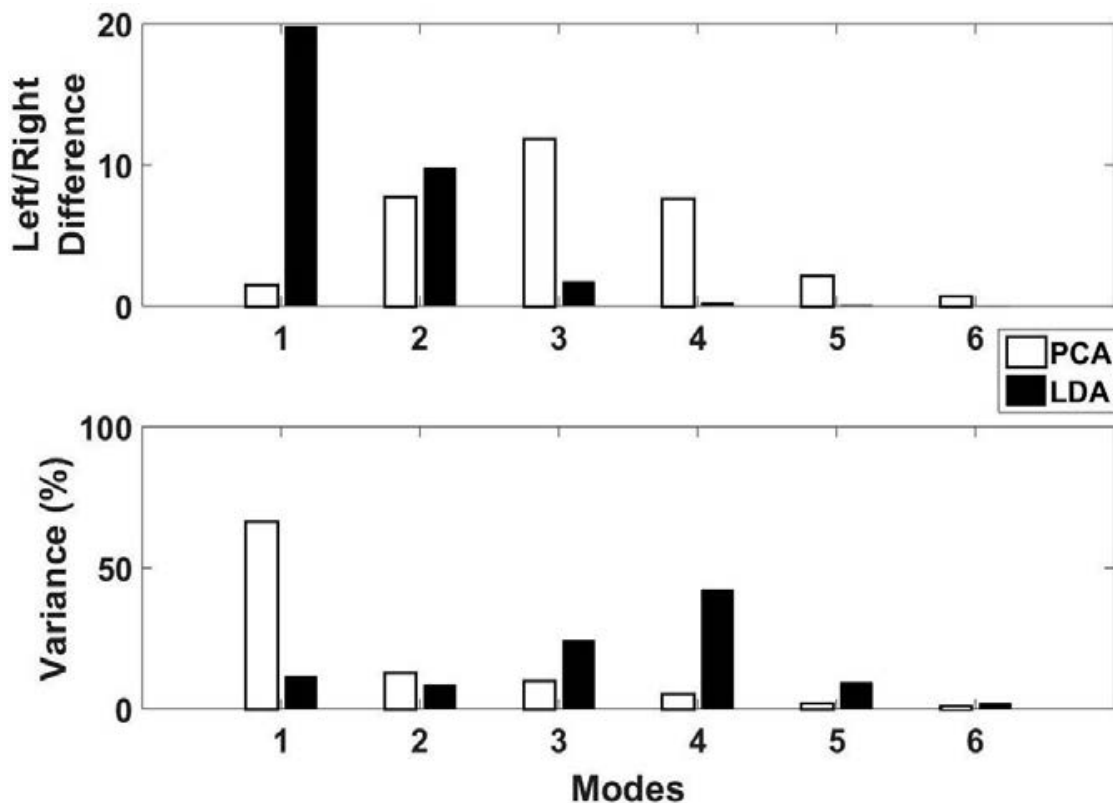
Figure 2. Upper panel: Mean differences between the projections of left and right penalties for PCA and LDA in the optimized interval. Lower panel: percentage of variance explained by PCA and LDA modes.

The lower panel of Figure 2 shows the variance explained by the different PCA and LDA modes. This quantity was optimized in the PCA. As expected, the first PCA mode explained much variance and the explained variance was lower for the higher PCA modes. For the LDA, Mode 4 explained most variance, followed by Mode 3 and Mode 1. The variance that was explained by the six modes together was high: 98.2%. As a consequence of our methodology, this percentage was identical for the PCA and LDA.

In short, differences between penalty kicks to the left and right are distributed over PCA modes. LDA-based reorganizations of the PCA-reduced subspace concentrate the differences in the first few modes. One may therefore hypothesize that the information that observers use to anticipate the action outcome is included in the first few LDA modes while it is distributed over most PCA modes. Psychophysical research is needed to test this hypothesis.

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The direct learning theory: a naturalistic approach to learning for the post-cognitivist era

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Abstract

In 2017, Di Paolo, Buhrmann, and Barandiarán proposed a list of criteria that post-cognitivist theories of learning should fulfill. In this article, we review the ecological theory of direct learning. We argue that this theory fulfills most of the criteria put forward by Di Paolo et al. and that its tools and concepts can be useful to other post-cognitivist theories of learning. Direct learning holds that improvements with practice are driven by information for learning that can be found in the dynamic organism-environment interaction. The theory formally describes information for learning as a vector field that spans a space with all the perception-action couplings that may be used to perform an action. Being located at a point of such a space means using a specific perception-action coupling. Changes in perception-action couplings due to learning can be represented as paths across the space, and can be explained with the vector field of information for learning. Previous research on direct learning considered actions that were best understood with single perception-action couplings. To conclude the article, and inspired by the criteria of Di Paolo et al., we discuss an extension of the theory to actions that are best understood with multiple perception-action couplings.

Post-cognitivist approaches to psychology are a heterogeneous group of theories brought together by their shared rejection of the central assumptions of cognitivism: the poverty of the stimulus doctrine, the representational basis of the mind, and the computer metaphor of the brain. Their origin can be traced back to the early days of cognitive psychology in the 1940s–1950s. Since then, post-cognitivist approaches have independently proliferated on their opposition to the hegemonic cognitivist framework. As a result, the theoretical landscape in psychology has been enriched with a variety of alternative theories of cognition (Calvo & Gomila, 2008).

The cognitivist approach claims that cognition is based on mental representations, that is, symbolic intermediates between the observer and the world. As a consequence, the digital computer is considered as the best model to understand the operations of the mind, and information theory as the best tool to analyze it. In this computational portrait of cognition, perception is

a process of enrichment and inference upon the ambiguous sensory stimulation to produce a representation of the most likely state of affairs of the world. Unsurprisingly, the mental operations that bring about veridical perception within the cognitivist explanation are abstract computations over abstract mental representations. Perception is considered, therefore, to be indirect. A practical consequence is that the focus of research in cognitivism is on perceptual errors that might reveal the cognitive processes underlying these errors.

Despite the particularities of the different post-cognitivist approaches, they share crucial commitments (Gonzalez-Grandón & Froese, 2018). The term "4E

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cognition" refers to embodied, embedded, enacted, and extended, as the expression of these commitments (Rowlands, 2010, p. 3). The 4E approach to cognition eschews the metaphor of the brain as a processor of information and considers that the agent-environment relation is central to understand cognition. Haugeland (1998) highlighted that the terms embodied and embedded emphasize that "mind, therefore, is not incidentally but intimately embodied and intimately embedded in its world" (p. 237). In addition, enaction emphasizes the importance of what the agent does to perceive meaning and extendedness implies that cognition spans beyond the body, including parts of the environment.

The original formulation of the 4E approach to cognition did not include the ecological theory of perception among its defining members (Gonzalez-Grandón & Froese, 2018; Haugeland, 1998; Kiverstein & Clark, 2009; Rowlands, 2010). However, the main commitments that characterize the 4E approach (the non-representationalism; the extended, embodied, and embedded nature of cognition; and the active role of the agent) are fundamental assumptions of ecological psychology since its inception in the middle of the 20th century (Gibson, 1979; Michaels & Carello, 1981). In addition, the ecological approach to perception has a record of more than 60 years of empirical research on perception across the different modalities, on the active role of the perceiver through the perception-action coupling and the analysis of exploratory actions, on motor control including anticipation, and on learning. In sum, we think that the naming of the approach would be equally appealing and more encompassing under the label "5E cognition," with the fifth E standing for ecological.

The absence of ecological psychology in the original 4Es maybe the related to the fact that the 4E notion itself emerged in close relation to philosophical questions. One of the main aims of this article is to help bridge the gap between disciplines to foster interdisciplinary cross-pollination. Ecological psychologists are, first and foremost, experimental psychologists. This primacy of experiments is responsible for our bias toward explanations grounded in real situations with ecological validity. We do appreciate the formal elegance of models, but if one aims to explain cognition as an activity of life, models should refer to actual experiments with real organisms or other situations with ecological validity. Said in other words, abstract models whose equations, symbols, and graphs do not refer to aspects of real actions of organisms in environments are less common and less appreciated in ecological psychology.

Among the different perspectives included under the umbrella of 4E cognition, enactivism is the approach that has moved most from theoretical toy models to more tangible and applied psychological research. Noteworthy examples of experimental psychology performed from an enactive perspective can be found in

the field of sensory substitution (Auvray, Hanneton, & O'Regan, 2007; Bermejo, Di Paolo, Hüg, & Arias, 2015; Froese, McGann, Bigge, Spiers, & Seth, 2012; Lenay, Gapenne, Hanneton, Marque, & Genouëlle, 2003; Visell, 2008; cf. Díaz, Barrientos, Jacobs, & Travieso, 2012). As a consequence, we think that enactivism is the most appropriate member of the 4Es for an empirically informed dialogue with the ecological approach. The general relation between ecological psychology and enactivism has extensively been discussed in Fultot, Nie, and Carello (2016) and the associated open peer commentaries (cf. Mossio & Taraborelli, 2008).

The specific focus of this article is on learning. For the classic cognitive approach, theories of learning are often enrichment theories. Such theories may suppose, for example, that improvements with practice are to be found in the process of stimulus enrichment with inferences using previous knowledge. Under the 4E umbrella, interesting steps toward an account of learning have been made by Di Paolo, Buhrmann, and Barandiarán (2017; cf. Baggs, 2018, for an ecologically inspired review of this book). Di Paolo and colleagues indicate that sensorimotor learning is a crucial but neglected aspect of the sensorimotor approach. Among other things, they discuss general principles that a theory of learning should fulfill. To facilitate the interdisciplinary interaction among post-cognitivist approaches, we describe the ecological theory of direct learning (Jacobs & Michaels, 2007) and argue that this theory fulfills many of the requirements on learning theories that were identified by Di Paolo and collaborators.

Our article is organized as follows. The first section provides a brief introduction to ecological psychology and enactivism, discussing their theoretical relation. In the second section, we present criteria for theories of learning derived from Di Paolo et al. (2017). The third section reviews the direct learning theory and two exemplar studies that were performed under this theory. The fourth section discusses direct learning from the perspective of the criteria identified by Di Paolo and collaborators. Finally, the last section presents an extension of the theory of direct learning that aims to solve some issues for its application to a more general domain.

1. Ecological psychology and enactivism

James Gibson (1979) culminated his development of the theory of ecological psychology with the book "The ecological approach to visual perception." Gibson challenged, among other things, traditional conceptions about the object of perception and the appropriate level of analysis to study perception. During the first half of the 20th century, perceptual theories often defined the object of perception at the level of physical units, characterized by absolute measurements of distance,

volume, mass, or force. Gibson defined a new level of analysis, the ecological scale, which contains the organism-environment systems that psychology should be concerned about. A related departure of ecological psychology from classic theories is the use of the concept of information instead of the one of stimulus. The doctrine of stimulus poverty implies an elementaristic, passive, local, and instantaneous concept of the stimulus. For ecological psychology, in contrast, information is to be found in dynamic patterns of environmental energy. Any such pattern is a candidate informational variable that an organism can potentially use to control an intended action. Complex ambient energy patterns that extend over substantial time and space intervals are referred to as higher-order informational variables.

Some informational variables in environmental energy arrays are specific to properties of the environment that are relevant to the organism. Such informational variables and the specified ecological properties are bound by a one-to-one relation. This means that detecting the informational variable equals perceiving the ecological property. In this sense, the notion of information in the ecological theory is not akin to the correlational/probabilistic notion of information theory. The portrayal of perception as active information pickup is typically referred to as direct perception, because representational intermediates and mental processes are not necessary for perception to occur (Michaels & Carello, 1981). To reiterate this fundamental notion, the specificity between properties or processes of the organism-environment system and informational variables allows perception to be direct, that is, to be based on the detection of information (in the ecological sense).

Enactivism was proposed by Varela, Thomson, and Rosch (1991) as a general theory of cognition and psychological experience that considers cognition as the result of a dynamic organism-environment interaction. Nowadays, the enactive approach encompasses several flavors of the original formulation that share the principle of cognition as organism-environment interaction, but diverge on their preferred location along the organism-environment dipole, which is to say, on their respective emphasis on the organism or the environment (Barandiarán, 2017). The original formulation of enactivism defined cognitive systems as autonomous and operationally closed systems (Varela et al., 1991). This notion of autonomy was inherited from the theory of autopoietic systems (Maturana & Varela, 1987), a biological precursor of enactivism.

Autopoietic systems are the result of a self-sustaining closed network of interactions that constitute the identity of the system as a whole, that is, the autopoietic organization (Maturana & Varela, 1987). The behavior of autopoietic systems is not determined by natural forces, it is the product of the internal agenda of the autopoietic system. An autopoietic system takes advantage of natural causation to fulfill its internally defined goals. In this sense, autopoietic systems are considered autonomous: their interiors are complex enough to bring about a characteristic way of using energetic and material environmental perturbations while perpetuating their organization. In contraposition, the behavior of natural systems is passive-reactive against the laws of nature.

Foundational enactivism considers the nervous system as operationally closed and autonomous and hence focuses on neural dynamics in their explanation of behavior (Varela et al., 1991). The nervous system interfaces sensory and motor tissues to provide an adaptive coupling to the environment, but there is nothing of essential interest to be found outside of the closed network of neural interactions other than perturbations. In response to this solipsistic perspective of cognition, and to further reduce the appeal to representationalism, contemporary enactivism has evolved away from the strong internalism of the enactivism of Varela and colleagues (Barandiarán, 2017). This is clear, for example, in the emphasis of some contemporary enactivists on sensorimotor contingencies and on the dynamic role of the external environment that furnishes those contingencies (e.g. O'Regan & Noë, 2001).

Historically, the interaction between ecological psychology and enactivism has not been particularly fluent. Autopoietic enactivism has rejected direct perception since its initial proposal for two reasons. First, it is argued that direct perception overemphasizes the importance of the environment (Varela et al., 1991). Relatedly, the use of the word *information* in the ecological approach is considered by autopoietic enactivism as implying instructive interactions with the environment, thus breaking the principle of operational closure of the organism. Second, enactivism argues that the ecological approach is a form of a physicalism. Such claims remain common in the work of contemporary enactivists (e.g. Di Paolo et al., 2017, p. 81). The examples throughout this article will illustrate that these claims, rather than being faithful with the ecological tradition, highlight a problem of communication between (and understanding of) approaches with different philosophical backgrounds (cf. Baggs, 2018).

Nowadays, researchers can crudely be divided in three different positions regarding the relation between ecological psychology and enactivism (Fultot et al., 2016). The first position holds that the theoretical differences are irreconcilable. Cariani (2016), for example, argues that ecological psychologists defend a direct realism and claim that meaning is in the environment, whereas enactivists defend perspectivist ontologies and claim that meaning is in the head of the agent. A second position is that the theories complement each other at different levels of analysis. In this sense, Heras-Escribano (2016) proposes that the approaches can be reconciled in a shared research program in which

enactivism accounts for the subpersonal processes via neurodynamics, and ecological psychology explains the agential level through direct perception (cf. McGann, 2016). A third position holds that there are already bridges between the theories. Stapleton (2016), for example, points to research that joins the ecological concept of affordance and the process of sense-making from enactivism.

Despite the theoretical differences, many points of agreement become obvious if one considers the approaches in the context of specific perceptual-motor problems. Let us illustrate this with two examples. First, walking to a target, which is a rather simple action for humans and other animals. A variable that specifies the direction of motion in the temporal changes of the visual field, the optic flow, is the focus of expansion (Warren, Kay, Zosh, Duchon, & Sahuc, 2001). If we change our walking direction, we modify what is at the focus of expansion. If we move orthogonally with regard to the direction of a target, the target will not be at the focus of expansion. Walking to a target can be achieved by keeping the focus of expansion at the target. This means that the focus of expansion may used to control locomotion by correcting deviations from the intended direction.

This perceptually guided behavior can easily be incorporated in an enactive description. Visual expansions are the result of a sensorimotor loop that can be enacted (we can turn right and left and control the focus of expansion). Moreover, its detection does not specify the effect on the organism (it is not instructive) and, therefore, does not break the operational closure principle. In addition, an agent can use the mastery of this sensorimotor contingency. However, the focus of expansion is a higher-order variable at the ecological scale (it is contained in the time evolution of a substantial part of the optic array). Its behavior is lawful, and it is so because of the laws of optics. It is useful for the prospective control of locomotion and, at the same time, it requires the relative movement of the perceiver, which in the ecological approach is achieved through the perception-action coupling.

As a second example, consider the muscle-based perception through wielding (Turvey & Carello, 1995). Perceiving properties of objects by wielding is a daily activity, as when handling utensils. Individuals can perceive properties such as the length and width of hand-held objects or whether the objects are bent or not. To do so, inertial properties are explored. During wielding, forces and torques are applied, and spatial translations and rotations are obtained as a consequence. For linear movements, the mass of an object is the relation between the total force that is applied and the acceleration that is produced as a result. For rotational movements in three dimensions, a higher-order quantity captures the relation between the rotational forces (i.e. torques) and accelerations: the inertia tensor. The inertia tensor is a nine-dimensional quantity (i.e. a 3×3 matrix) that is based on the distribution of mass along the object (Solomon & Turvey, 1988). Despite its apparent complexity, the inertia tensor describes the relation between forces and movements. As such, the components of the inertia tensor can be detected through wielding, which is to say, by applying forces and observing their relation to the movements.

As indicated in the previous paragraph, wielding objects allows the detection of multiple candidate variables. Later in this article, we will need more precise definitions of three of those variables: mass (M), static moment (SM), and the first principal moment of inertia (I_1) (i.e., a main component of the inertia tensor). The following expressions of these variables indicate their close linkage

$$I_1 = \int \rho(s)\delta(s)^2 \mathrm{d}V \qquad (1)$$

$$SM = \int \rho(s)\delta(s)\mathrm{d}V \qquad (2)$$

and

$$M = \int \rho(s)\mathrm{d}V \qquad (3)$$

In these equations, $\rho(s)$ is the mass-density function of the wielded object, $\delta(s)$ the distance to a given axis of rotation, and V the volume of the wielded object over which $\rho(s)$ and $\delta(s)$ are integrated (Jacobs, Silva, & Calvo, 2009). The mass of an object can be detected through linear exploratory movements or by holding the object still against the effect of gravity. The static moment of an elongated object, such as a rod, can be detected by suspending it horizontally from a single grip and noting the rotational force that is generated. As mentioned above, active exploration with rotational movements allows the detection of the components of the inertia tensor, including the first principal moment.

The fundamental notions required to understand the muscle-based perception through wielding, typically studied from the ecological perspective, are laws that connect a motor component (the forces) to a sensory component (the resulting movements). Such notions can easily be accommodated in an enactive account. Consider, for example, the similarities between muscle-based perception and the enactive portrayal of the perception of softness through exploration of a sponge:

> Having the sensation of softness consists in being aware that one can exercise certain practical skills with respect to the sponge: one can, for example, press it, and it will yield under the pressure. The experience of softness of the sponge is characterized by a variety of such possible patterns of interaction with the sponge, and the laws that describe these sensorimotor interactions we call, following MacKay (1962), laws of sensorimotor contingency. (O'Regan, Myin, & Noë, 2005)

2. General principles for 4E-inspired theories of learning

The goal of this section is to explicitly formulate a list of requirements that should ideally apply to any theory of learning that falls under the umbrella of 4E cognition. Without aiming to be exhaustive, our hope would be to obtain a tentative list on which different contributors of the 4E approach may agree. We will first describe requirements that are implied by the 4E concept itself. Following those, we describe requirements that were selected from chapter 4 of Di Paolo et al. (2017)—which we believe to be the main attempt so far from the enactive approach to formalize a learning theory. A final requirement in our list is taken from the ecological approach. In subsequent sections of this article, we will use the obtained list of requirements to assess the contributions of the theory of direct learning.

The most obvious requirements are the ones implied by the name of the 4E approach. That is, a theory of learning from the approach should be consistent with the commitments to describe cognition, and hence learning, as an *embodied, embedded, enacted*, and *extended* process. Relatedly, a learning theory in the 4E approach should be *non-representational*. This means that learning cannot be portrayed as an improvement in syntactic operations or computations on symbolic representations. Less obviously, the processes that are responsible for the improvements with learning should not be based on such computations and representations either.

We next consider elaborations of and additions to these requirements that were formulated by Di Paolo et al. (2017). One of the requirements that these authors mention is that learning should *transform perception* rather than construct perception out of previous processes other than perception. In their words, "the starting point from which perception develops is always already a form of perception" (p. 79). With regard to their specific theory, they claim that the process "starts always from an existing sensorimotor organization" and that it "develops from there into novel forms, differentiated forms, forms that become extinct and replaced by others, and so on" (p. 79).

Another set of requirements on a learning theory mentioned by Di Paolo et al. (2017) is that such a theory should be *action-based* and *world-involving*. With regard to the action-based part, they state that "adaptations only occur in the context of active, personal effort in remastering the visual world" (p. 79). However, it is not the activity of the learner as such that is claimed to be important. Rather, it is the dynamic interaction of the learner with the world. Di Paolo formulates this world-involving part of their requirement by saying that learning "involves a relation to the dynamics of the world beyond the mere supply of sensory input" (p.

80). More passive learning situations would lack "a chance to engage the world and attune to a new form of coupling with it" (p. 80).

Di Paolo et al. (2017) also mention that a theory of learning requires *adaptive mechanisms*, which may be based on a *normative evaluation* that provides the agent with feedback to evaluate if his or her current state of functioning is appropriate in a concrete situation. Related to the requirements of adaptive mechanisms and normative evaluation, Di Paolo et al. wrote the following:

> an agent can also learn from the way she fails. *Directed learning* [emphasis added] could rely, for instance, on gradients in the normative evaluation … or on details of perturbations encountered in failed assimilation attempts. (p. 103)

As we will illustrate in subsequent sections, we believe that this quote—including the wording used to refer to the learning processes—is indicative of the relevance of the direct learning framework to parts of the approach to learning sketched by Di Paolo et al.

Another pair of requirements on theories of learning that we have selected from the chapter by Di Paolo et al. (2017) relate to the fact that *learning never ends*. In the words of Di Paolo et al., for learners "this requires that they never reach strictly stable equilibrium" and that they "must retain a residue of dynamic criticality without which they would simply be unchangeable automatisms" (p. 102). A related requirement is that learning processes are *open-ended*. According to Di Paolo et al., this implies that learning does not have an end point, meaning that novel and un-anticipated perception-action solutions can be arrived at through learning (pp. 78, 98).

This brings us to the final requirement of our list, which was anticipated in the introduction. Many theories in the 4E approach agree that the formal aspects of dynamic models can usefully be applied to the understanding of cognitive processes. The theory sketched by Di Paolo et al. (2017) and the direct learning framework are no exceptions. A final requirement for a theory of learning, inspired by common practice within the ecological approach, is that the dynamic models that are inspired by the theory and that aim to illustrate the theory should be formulated *at the ecological scale*, meaning that they should refer to tangible aspects of real-world actions. Let us consider two purposefully simplified models to illustrate this requirement.

First, let S refer to an organism-environment system that includes all possible perception-action couplings in which the organism can engage. Note that S can be high dimensional. Given that learning implies a change in the organism-environment system and its perception-action couplings, we can refer to learning as the derivative of S. Second, let O be an organism with two action

possibilities: it may be at rest or move at a constant speed. In this second case, learning may be portrayed as, say, a change in the rules, or probabilities, by which the organism chooses to move or not.

However simple these models are, they might have some virtues. With respect to the first model, one may argue that it is not wrong in the sense that all types of learning will eventually be some further specification of the model. With regard to the second model, one may argue (or demonstrate) that its behavior has some similarities with human behavior, and hence that the model exemplifies how the considered behavior may arise. Despite these arguments, however, the points, spaces, trajectories, vectors, gradients, and so on that illustrate such models do not refer to tangible aspects of real world actions. Hence, if one accepts the requirement that models are ideally formulated at the ecological scale, one should be suspicious about the contribution of such models to learning theories in the 4E approach.

Di Paolo et al. (2017) state that "several of these principles are already present in other approaches" (p. 103). We believe that the theory of direct learning, not mentioned in the chapter, is a good candidate in this regard. The next section provides a summary of the direct learning theory, including two examples of actions that have been used to elaborate the theory.

3. Direct learning

The direct learning theory has been developed under the principles of the ecological approach (Jacobs & Michaels, 2007; cf. Jacobs, 2001). With the theory, the authors aimed to respond to the criticism that the ecological approach, at that time, did not provide a sufficiently detailed understanding of learning (Michaels & Beek, 1995). The direct learning approach considers two levels of analysis: the one of perceiving and acting and the one of learning (aiming for a theory that is consistent as well with the level of analysis of ecological realism; Jacobs & Michaels, 2002). The processes that are implied by perceiving, acting, and learning are conceived as multiple continuous and concurrent processes that occur at different timescales. The main research strategy of the direct learning approach is to scrutinize the traditional ecological principles, which were developed to understand perceiving and acting, and to explore how these principles may be interpreted or modified to be applicable to processes at the longer time-scale of learning.

Crucial among those principles, and giving rise to the name direct learning, is the claim of the traditional ecological approach that perceiving and acting are direct or information-based rather than inferential processes. Analogously, direct learning claims that learning is information-based. As does the traditional ecological approach at the level of perceiving and acting, the direct learning approach considers the directness of learning as a methodological doctrine. This means that, rather than aiming to prove or disprove the claim, the approach takes the methodological doctrine as its starting point and asks what else must be true if the doctrine is true. This search has led to a sequence of concepts, ideas, and empirical studies that, we believe, are useful to many members of the 4E approach.

In the framework of direct learning, the level of learning includes at least three processes: the education of intention, the education of attention, and calibration. With regard to the first process, the education of intention, one should realize that many actions are possible in any given situation. If a ball approaches, one may be able to catch the ball, dive away to avoid the ball, or try to hit the ball. The intention of an agent determines which action he or she aims to perform. The *education of intention*, then, refers to the process by which agents improve in choosing which action they aim to perform (or what property they aim to perceive). Assuming an intention is indispensable in the direct learning approach, and in the ecological approach in general, because it allows one to evaluate the environment and the performance of the agent in terms of the goals of the agent. This is related to the normative evaluation often mentioned by proponents of the enactive approach (Di Paolo et al., 2017; Hutto, 2005). A more detailed consideration of intentions and changes therein and their place in the direct learning framework can be found in Arzamarski, Isenhower, Kay, Turvey, and Michaels (2010; cf. Shaw & Kinsella-Shaw, 1988).

To give an example of the need for the concept of intention in the direct learning theory, note that assuming a particular intention is indispensable to evaluate the usefulness of informational variables. Variables that specify the property that an agent intends to perceive or act upon are useful whereas variables that are unrelated to that property, even though they may specify other properties, are not. Empirical evidence shows that, with practice, individuals graduate from the use of less useful variables to the use of more useful variables (e.g. Jacobs, Runeson, & Michaels, 2001). This gradual process of convergence toward specifying information, even if the intention of the agent is assumed to remain constant, is known as the *education of attention* (Gibson, 1979). The third process at the level of learning that is considered in the direct learning framework is *calibration*. This process refers to changes in how the informational variable that is operative at a particular moment is carried into perception or action.

To provide a more formal interpretation of these learning processes, needed to outline subsequent aspects of the theory, let us consider the following equation

$$F = f(I) \tag{4}$$

in which *I* is the informational variable that is used at a particular moment, *F* refers to a particular action parameter (e.g. a force exerted by the action system; when studying perception, *F* is substituted for a perceptual parameter, *P*), and *f* is the single-valued function that describes how information is carried into perception or action. The equation describes how an action system functions at a particular moment. An intention determines that the system acts the way it does, and therefore sets up the equation as a whole. Even with a constant intention, however, the equation that best describes the functioning of a system changes with practice. In line with our previous description, the education of attention corresponds to changes in the informational variable *I* and calibration to changes in the single-valued function *f*.

Equation (4) is essentially the same as the traditional ecological concept of *control law* (Warren, 2006), which has frequently been used to formalize aspects of the ecological approach at the level of perceiving and acting. Changes in the equation over time, formalized by the temporal derivatives of *f* and *I*, provide a foot into the door of the direct learning theory. To describe further aspects of the theory, we need to advance from the disembodied description of equation (4), without reference to a particular action, to action-related and thereby falsifiable interpretations of the concepts that are implied by the equation. To do so, we have selected two empirical studies on direct learning that we consider particularly relevant to members of the 4E approach.

3.1. Learning as continuous movement through a space: the pole-balancing example

Jacobs, Vaz, and Michaels (2012) analyzed learning using a cart-pole task (Figure 1). The task of participants was to keep the unstable pole on the cart balanced for 30 s. Performing this action requires practice: participants needed between 22 and more than 150 trials to maintain the pole balanced for three consecutive trials. Participants control the force, *F(t)*, that they apply to the cart. In line with the ecological approach, and the concept of control law, Jacobs et al. assumed that the applied force is a function of information detected a short time interval before exerting the force. What information was used? And, what function related that information to the applied force?

To answer these questions, Jacobs et al. (2012) used a version of equation (4) that is applicable to this particular action

$$F(t) = k\theta^{(\alpha)}(t - d) \tag{5}$$

In this equation, $\theta^{(\alpha)}$ is the fractional derivative[1] of order α of the angle of the pole (see Figure 1), *d* is the perceptual-motor delay, and *k* is a constant. The
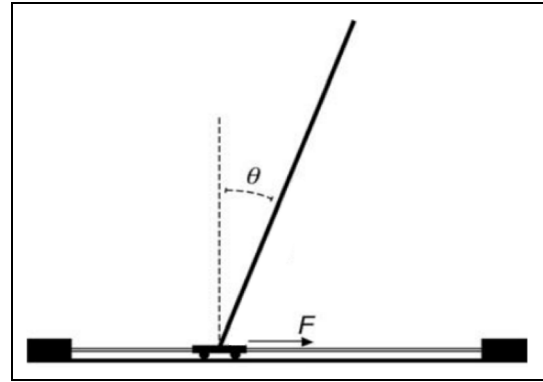

Figure 1. The cart-pole system. Participants moved the cart with their dominant hand along a steel rod with the aim to keep the pole balanced.
Adapted with permission from Jacobs et al. (2012). Copyright by American Psychological Association.
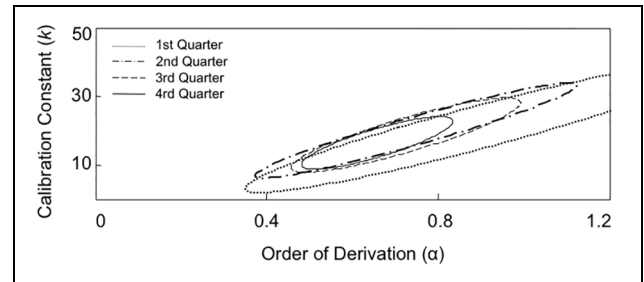

Figure 2. Information-calibration space used to study cart-pole balancing. The ellipses indicate the location of the group of participants in the space for each quarter of trials during the experiment.
Adapted with permission from Jacobs et al. (2012). Copyright by American Psychological Association.

quantity $\theta^{(\alpha)}$ is the informational variable used in to control the action (*I* in equation (4)), α is a parameter that changes with changes in the education of attention, and *k* is a constant that changes with changes in calibration. Both the education of attention and calibration were formalized in ways that were considered as simple as possible to capture the relevant phenomena: both changes were portrayed as single-dimensional. Moreover, the calibration function *f* in equation (4) was as simple as a multiplication by a constant. Note that, together with the equations of motion of the physical system, equation (5) allows one to predict the performance of the agent-environment system as a whole.

We are now in the position to introduce another important aspect of the direct learning approach: learning processes are portrayed as continuous trajectories through a space. Most studies in the direct learning framework considered *information spaces*. Jacobs et al. (2012) instead used a combined *information-calibration space* (Figure 2). The coordinate axes of this space are

the parameters that indicate the education of attention and calibration of an individual at a particular moment, which is to say, the parameters α and k in equation (5). If one registers the movements of an individual that performs the action, one can determine the parameters α and k that best fit the performance, and hence localize the individual at a point in the space. A substantial number of empirical studies on direct learning show that learning, when analyzed this way, can be described as a process of convergence toward the more useful regions in such spaces (e.g. Michaels, Arzamarski, Isenhower, & Jacobs, 2008; cf. Abney & Wagman, 2015; Huet et al., 2011; Michaels & Romaniak-Gross, 2012).

For the pole-balancing task, this convergence toward the more useful regions in the space is illustrated in Figure 2 by the ellipses that summarize the empirically determined locations of the whole group of participants, at different phases of the experiment. Whereas the ellipse that indicates the initial performance (first quarter) is large, showing that individuals were widely distributed over the space, and the ellipse indicating performance later in the experiment (fourth quarter) is small, showing that individuals by then had converged toward a more limited region in the space. Jacobs et al. (2012) further showed that the region on which individuals converged is indeed the most useful region. That is, an agent-cart-pole system remains well balanced if one uses the αs and ks from this region and simulates the performance of the system using the forces computed with equation (5) together with the appropriate equations of motion.

So far, we have introduced the education of intention, the education of attention, and calibration, and we have seen how, in the context of particular actions, the latter two processes can be empirically tracked and analyzed as trajectories through information and information-calibration spaces. The claim that learning processes are information-based can now intuitively be understood as the claim that patterns in the dynamic agent-environment interaction that emerges while an agent is localized at a particular point in the space push the agent through the space. In the pole-balancing example, information for learning may be found, for example, in the particular ways that the pole remains balanced or falls down over multiple trails. We next provide more tangible illustrations of how the informational basis of the learning can be defined and analyzed.

3.2. Information for learning: a dynamic touch example

In the previous sections, we have introduced the central claim of the direct learning approach: learning processes are driven by information that emerges from the agent-environment interaction over some time. Whereas the previous section provided an example of how one may analyze and observe the changes due to learning, the present section concerns a study that provides a tangible example of information for learning: the muscle-based mass-perception study by Jacobs et al. (2009). Participants in that study were asked to freely wield unseen objects (called tensor objects) with their right hand and to judge the mass of those objects as compared with a reference object in their left hand. Instead of equation (4), we now use the equation

$$J = f(I) \qquad (6)$$

in which J is the mass judgment made on a particular trial and I the informational basis of that judgment, which is to be detected from the object through wielding.

For our current purpose, it is sufficient to analyze the education of attention. This means that we need an information space that allows us to track changes in the informational basis of performance (i.e. changes in I). The equation used by Jacobs et al. (2009) to describe that information space was

$$I(x,y) = yI_3 + (1 - y) \int \rho(s)\delta(s)^x dV \qquad (7)$$

It is crucial to understand that, in this equation, I is an informational variable that can be detected from the object through wielding and that the informational variable depends on two parameters: x and y. For a description of the general shape of the equation, and a motivation for using this one, we refer the reader to Jacobs et al. We provide the full equation here to emphasize that the direct learning theory has been worked out at the level of measurable quantities. Let us further mention, for completeness, that I_3 is the third principal moment of inertia and that the remaining terms are the same as in equations (1) to (3).

With an informational variable, I, that depends on two parameters, x and y, we have obtained a two-dimensional information space. If x and y are both zero, the equation matches the one for mass (equation (1)). If $x = 1$ and $y = 0$, the equation matches the one for static moment (equation (2)). Other values of x and y correspond to other detectable informational variables. Jacobs et al. (2009) used this information space to track the information usage with learning of individuals in different experiments and conditions. The upper panel of Figure 3 presents the results for the pretest and posttest for a group of participants who received feedback based on mass. The lower panel presents analogous results for individuals who received feedback based on static moment. Consistent with the results from other studies in the direct learning paradigm, the figure shows that learning goes together with convergence toward the more useful informational variables.
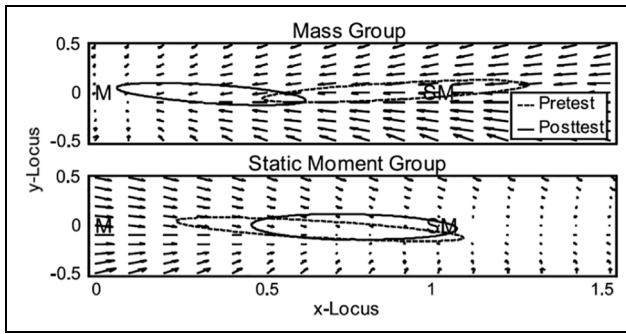
Figure 3. Ellipses that indicate the location of individuals in the information space defined by equation (7), for groups of individuals with feedback on mass (upper panel) and static moment (lower panel), in the pretest (dashed outline) and posttest (continuous outline). The vector fields correspond to the information for learning defined in equations (8) and (9). Adapted with permission from Jacobs et al. (2009). Copyright by Taylor & Francis Group, LLC.
M: locus corresponding to mass; SM: locus corresponding to static moment.

For the relation between direct learning and other 4E theories, it is relevant to note that the informational variables represented by points in information spaces are actively picked up rather than detected in a passive manner. For muscle-based perception this is obvious: participants actively wield the to-be-perceived objects. Furthermore, and related to the traditional ecological claim that perceiving and acting are inseparable processes, the exploration that participants perform to detect the inertial informational variables depends on which variables they detect. To demonstrate this, Michaels and Isenhower (2011b; cf. Michaels & Isenhower, 2011a) determined the positions of participants who performed a muscle-based perception task in an information space and analyzed the way in which they wielded. Indeed, being localized at a certain point in the space went together with certain ways to explore (cf. Arzamarski et al., 2010). The continuous changes in what information is detected that are captured by the convergence in information spaces, therefore, should be hypothesized to go together with continuous changes in the exploratory movements that underlie the information detection.

Apart from this short aside on exploratory movements, being able to empirically track the learning of individuals as trajectories through a space allows us to proceed to a next step in the theory of direct learning: explaining the learning itself as an information-based process. As well-known from the theory of differential equations, trajectories through a space are specified by the temporal derivatives of the coordinates of the space at each point in the space. Those temporal derivatives define a vector field on the space. Along with the ellipses that describe the movements through the space

with practice, Figure 3 gives vector fields that would predict such movements.

Now consider an individual who is localized at a particular point in the space, performing the wielding and making his or her judgments as determined by the information that is represented by that point in the space (in interaction with the world, or in this case the object that he or she happens to encounter). Such an individual would be predicted to move along the space according to the vector at his or her locus. The remaining question in the direct learning framework is: what informational pattern, detectable over multiple trials from the relation between the judgments, the resulting feedback, and other information detectable through the wielding, would specify the vector that indicates the observed movement at that locus? In the direct learning framework, a detectable informational quantity that specifies the movement through the space for all loci in the space and for all experimental conditions qualifies as *information for learning*.

The information for learning proposed by Jacobs et al. (2009) is described by the following equations

$$x'(t) = -k_1 covariance\{E, SM/M\} \qquad (8)$$

and

$$y'(t) = -k_2 covariance\{E, I_3\} \qquad (9)$$

In these equations, k_1 and k_2 are constants, E is the error as indicated by the feedback, and the other variables are as defined earlier in this article. Together, the temporal derivatives on the left hand side of the equations specify a vector in the space, as they should. Jacobs et al. showed that the vectors specified by the detectable quantities on the right hand side correspond reasonably well to the observed movements through the space. In fact, those vectors are the ones plotted in our Figure 3. With this example of detectable information for learning, we have completed our description of the central claims of the direct learning theory.

Obviously, it is possible to accept or use some of the tools of the direct learning framework without accepting the entire theory. For example, our portrayal so far argued that learning trajectories are based on vectors, which means that learning is based on detected informational quantities that are as many dimensional as the space that is used to describe the learning. Even from within the framework of direct learning, however, we have tentatively explored the alternative view that learning may be based on single-dimensional potential functions on the space (Jacobs, Ibáñez-Gijón, Díaz, & Travieso, 2011). Figure 4 illustrates this type of analysis for the information space defined in equation (7). The surface in the upper panel shows a detectable measure of the maximum level of performance that can be achieved by individuals who use the different loci in the space. The empirically measured probability density
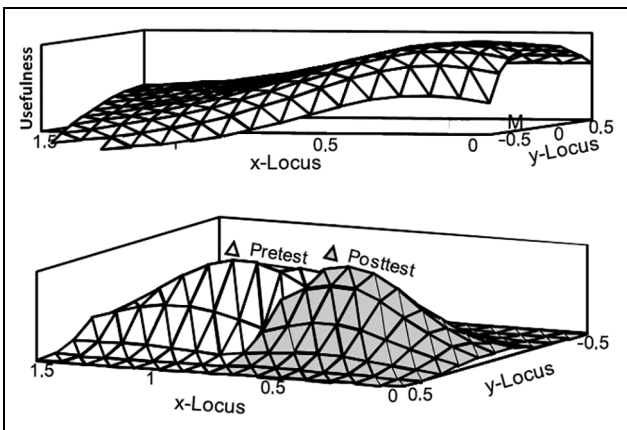
Figure 4. Upper panel: Usefulness function for the information space indicated by equation (7) for a mass-estimation task (the *fast* condition of Experiment 2 of Jacobs et al., 2009). More useful variables are indicated by a higher surface. Lower panel: distributions functions that indicate the locations of the group of individuals before and after practice.
Adapted with permission from Jacobs et al. (2009). Copyright by Taylor & Francis Group, LLC.

functions shown in the lower panel of the figure indicate that, with practice, individuals move from the less useful to the more useful regions in the space. We cannot rule out that movements through information spaces are causally linked to usefulness functions rather than to vectors that represent information for learning.

One should note that learning based on information that is as many dimensional as the space in which learning takes place, and that specifies a direction, is the more elegant formulation of the direct learning theory. This is so because it takes most advantage of the different time scales of perception and action and of learning. If learning is slow, the processes of perceiving and acting can generate the learning vectors without noteworthy changes in the locus of the learner, and in the extreme, the information for learning can be generated with the learner being located at a single point in the space. If the information for learning is a single-dimensional usefulness function, however, this function needs to be sampled from several nearby loci in the space to determine a direction of change. This sampling process necessarily mixes movements in the space, which are supposed to be slow, with the perceiving and acting that generates the information about the usefulness, which are supposed to be fast. However this may be, if one assumes that the information vector field is the gradient of a usefulness function, parts of the theory may be illustrated with usefulness functions as well as with information vectors, without bothering about which of the two is causally related to the learning. As such, we will make use of usefulness functions in the remaining part of this article. Note that this part of the direct learning theory shows similarities to the

suggestion concerning *directed learning* by Di Paolo et al. (2017) that was quoted in the previous section.

Summarizing the main tenets of the direct learning theory, then, it is claimed that perceiving and acting are fast information-based processes that cause a dynamic interaction of the agent and its environment. In this interaction, the way that the agent perceives and acts at a particular moment has observable consequences. Information that drives the slower learning processes is claimed to be present in the rich higher-order structure over time of these observable consequences.

4. Direct learning and enactivist principles for a theory of learning

As stated above, the aim of this article is to put forward the theory of direct learning as an empirically supported framework for post-cognitivist approaches to learning. In this section, we assess to what extent the direct learning theory fulfills the requirements that were derived from the analysis of Di Paolo et al. (2017).

The first set of requirements for such a theory is that it must comply with the basic commitments that characterize the 4E approach, that is, it should portray learning as an embodied, embedded, enacted, and extended process. We added to this general list an explicit commitment to non-representationalism and the need to formulate research questions at the ecological scale (that is, referred to aspects of real-world actions). Direct learning was developed within the ecological approach. In this sense, it assumes the basic tenets of the ecological approach, in particular: the directness of psychological processes that follows from a non-representational stance; the active nature of perception-action that parallels the enactive requirement; and the assumption that the ecological scale is the proper level of analysis for psychological phenomena, which incorporates embeddedness, embodiment, and extendedness at the root of the approach.

The first requirement derived from the analysis of Di Paolo et al. (2017) is that learning should transform perception, rather than to construct perception out of pre-existing non-perceptual processes. As explained in the previous section, the direct learning theory proposes information and calibration spaces and vector fields of information for learning to account for the changes in perception-action couplings. Every point in such spaces stands for a specific perception-action coupling. In other words, being at a certain point of an information-calibration space means using a specific informational variable, with a specific calibration, to control an action. As such, being at a certain point generates a specific interaction with the environment, which, in turn, contains information that allows the agent to modify its behavior at longer time scales. This information in the loci-specific interaction with the

environment can be formalized as a vector that indicates the direction and magnitude of change for a specific perception-action coupling. In sum, direct learning attempts to establish the laws by which perceiving and acting are transformed.

The next requirements are two intimately related notions: learning should be action-based and world-involving. This means that the actions of the learner or the mere sensory input that follows an action are not important per se. The relevance of action for learning only appears in relation to the dynamic interaction between the learner and the world. Note that this is what information for learning attempts to describe: how the dynamics of the current perception-action coupling constrain the evolution of the coupling itself. A clear example of world-involvedness can be found in Jacobs et al. (2012), who included the physical equations of motion of the cart-pole system as an essential part of their portrayal of learning (see their equations (1) and (2)).

Di Paolo et al. (2017) also highlighted that a post-cognitivist theory of learning requires adaptive mechanisms to determine the change of the current perception-action engagement. These adaptive mechanisms are assumed to be based on a source of normative evaluation that furnishes the agent with feedback to evaluate the appropriateness of its current state of functioning. One should observe that postulating such mechanisms may imply the risk to reintroduce traditional representational thinking in theories, because it may seem to require a traditional representational/inferential agent (or homunculus) that is responsible for the adaptive processes (i.e. for the mastery of sensorimotor contingencies; Noë & Noë, 2004). Warnings against reintroducing traditional representational thinking in this way can be found in Jacobs and Michaels (2007, p. 330; cf. Hutto, 2005, p. 392). As we have shown, however, the direct learning approach holds that processes such as normative evaluation and behavioral adaptation themselves can be accounted for at the ecological scale without appealing to representations or inferences. This, in fact, is why direct learning received this name: the adaptation due to learning is hypothesized to be information-based, which is to say, specified in the current agent-environment interaction.

The final set of requirements for a theory of learning identified by Di Paolo et al. (2017) are that learning never ends and must be open-ended. In line with these requirements, and with the Gibsonian view that perception itself is extended in time, Jacobs et al. claim that their theory "does not consider learning a process that has a beginning and an end. Learning does not start or stop" (p. 249). Illustrating this view, Michaels et al. (2008) designed a two-stage learning experiment. The structure of the feedback was changed from the first to the second stage of the experiment so as to modify the usefulness function and the information vectors. At

each stage, a movement through the information space was observed that was compatible with the feedback, even though during the first stage near optimal performance was reached. Hence, the claim that learning never ends has always been present in the direct learning theory.

Open-endedness is accommodated to a certain degree. Depending on the particular learning environment, or on the feedback given in an experiment, different loci in information spaces are the more useful ones. It has been demonstrated empirically that learners converge toward those loci that are the most useful ones in their particular task environment, and hence that learning does not have a fixed end point (Huet et al., 2011; Jacobs et al., 2009; Michaels et al., 2008). For Di Paolo et al. (2017), however, open-endedness seems to go further. They claim that "the learning and refinement of perception and action skills in some cases, if not unbounded, seems to have no obvious predictable bounds" (p. 101), and that learning is seen as "the combinatorial construction of new patterns of sensorimotor coordination in a potentially ever-growing space of possibilities" (p. 104). They further argue that such open-endedness and lack of predictability requires some degree of randomness. In contrast to this requirement, the direct learning framework implies bounds on learning in the sense that learning cannot extend beyond the considered information and calibration spaces. Likewise, the direct learning framework, in its current state, does not provide an explicit and empirically demonstrated formulation of how randomness affects learning processes.

To summarize, we believe that the theory of direct learning fulfills the large majority of the criteria that post-cognitivist theories should fulfill. Our main claim in this article, therefore, is that the theory would be useful to members of the 4E approach as a starting point for further theorizing about learning. With regard to the criterion of open-endedness, it is fair to say that the direct learning theory encompasses fewer phenomena than the approach to learning that was sketched by Di Paolo et al. (2017). An important advantage that is related to having a less-encompassing theory, however, is that the direct learning theory has been formulated more precisely and has been developed in a much closer relation to empirical research with ecologically valid tasks.

Finally, to demonstrate with an example that direct learning can be used as the starting point for further theorizing, we conclude this article with a speculative extension of the theory. Even though the theory presented so far is less in need of a representational homunculus that controls or supervises the learning than the to-be-presented extension, and better supported empirically, a few aspects related to open-endedness and randomness may be more easily incorporated in the extension. With this, we aim to illustrate

that extensions of the theory may be yet better suited to the criteria derived from the chapter by Di Paolo et al. (2017).

5. Direct learning and multiple perception-action couplings

Previous research on direct learning has addressed how experience with a particular task modifies and maintains a single perception-action coupling, or control law. Consider the example of displacing the hand with regard to the body with the aim to intercept an approaching object. Control laws that may be operative in this action have been studied extensively (e.g. Bootsma, Fayt, Zaal, & Laurent, 1997). To apply the direct learning framework, one would need to analyze the behavior of learners with an information-calibration space, a vector field that represents information for learning, and a usefulness function (cf. Jacobs & Michaels, 2006). Given that a single perception-action coupling is addressed, one would need one of each. For example, one would need only a single information-calibration space, independently of how many dimensions that space may have.

Some actions, however, are best described with several perception-action couplings (e.g. Van Hof, van der Kamp, & Savelsbergh, 2006; cf. Lee, Young, Reddish, Lough, & Clayton, 1983, p. 343). Consider a hypothetical catching action in which the catcher separately controls three action components: (a) the timing of the initiation of the catch, (b) the displacement of the hand toward the ball, and (c) the timing of the grasp component of the catch. Three control laws may be used to describe this action.[2] If so, to study learning, one may also use three information-calibration spaces, usefulness functions, and quantities that serve as information for learning. The question that would be raised, we believe, is to what extent the learning of the different perception-action couplings would be independent. Said more precisely, the organism-environment interaction may only generate useful and detectable information for learning for one action component if the other action components are performed at least reasonably successfully.

Consider Figure 5. Imagine that the horizontal axis is an information space for the timing of the initiation of the catch. The continuous curve is a hypothetical usefulness function, such as the maximum percentage of correct catches that may be achieved on the basis of the informational variables that are represented in the space. If the other action components would not be controlled in a sufficiently close to optimal way, one could not catch 100% of the to-be-caught balls, not even if one initiates the catches on the basis of the most optimal informational variable. This is illustrated by the dashed usefulness function in Figure 5. In light of

Figure 5. Hypothetical usefulness functions associated with an information space for one component of a multi-component action. The solid line stands for a situation in which the other components of the action are performed in a way that is sufficiently close to optimal. The dotted line stands for a situation in which this is not the case.
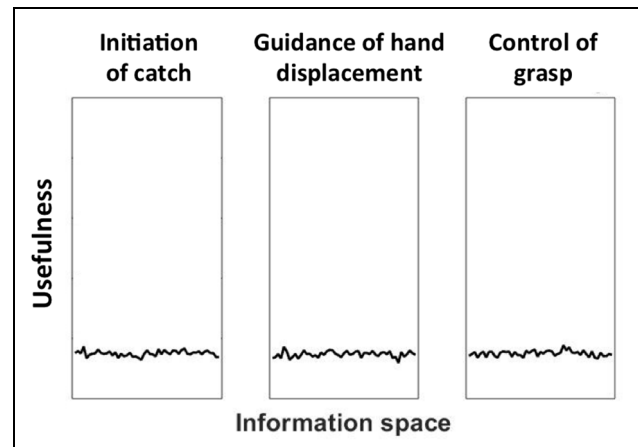
Figure 6. Flat usefulness functions that correspond to the components of a hypothetical catching action in which all components are performed in a way that is far from optimal.

the direct learning theory, one should imagine that the lower usefulness function goes together with an information field with shorter and less precise information vectors.

The previous argument implies that a relatively successful control of the hand displacement and of the timing of the grasp may be necessary to guarantee the existence of information for learning for the initiation of the catch. Likewise, a to-some-extent successful initiation of the catch may be necessary to guarantee the information for learning for the other components. Imagine, then, a particular observer that performs each action component on the basis of an informational variable with a very low usefulness. The three usefulness functions related to such a situation might be as the

approximately flat curves in Figure 6. To explain the left panel: even if the observer initiates the catch on the basis of a reasonably good variable, he or she will still catch only a few random balls as long as the control of the other components is insufficient. The question becomes: how can a learner get out of such a situation? If, as we have sketched, the overall situation is poor in information for learning, the answer to this question may require more than the direct learning theory as we have described it in earlier sections.

Given that the situation in Figure 6 is poor in information for learning, it invites some random behavior into the theory (and hence some individual differences in learning trajectories; cf. Withagen & Van Wermeskerken, 2009). By trying out different informational variables (i.e. loci) at the initial stages of the learning process, the learner might create a situation in which some slight peaks start to emerge in one of the usefulness functions. These slight peaks may form the beginning of a more deterministic learning process that increases the peaks also in the other usefulness functions. The slowly increasing optimality of the different action components will then guarantee the existence of information for learning for the respective components, which, in turn, allows direct learning. If a certain level of performance is achieved, the different action components may flexibly keep each other in shape, achieving a system that is robust to a wide range of perturbations.

One may speculate that situations such as the one described in Figure 6, in which the percentages of correctly performed actions are very low and some random behavior seems to be required, are more characteristic for infant learning (e.g. Van der Kamp, Oudejans, & Savelsbergh, 2003; cf. Kayed & van der Meer, 2007) than for the learning patterns shown by adults. Even for adults, however, some actions may initially be so cognitive/inferential, of such an exploratory nature, and/or so much based on instructions that one might question the usefulness of the direct learning theory on itself for such actions (cf. Runeson, Juslin, & Olsson, 2000). One could think, for example, about learning to swim a particular stroke, which is even unlikely to occur only on the basis of practice. The theoretical sketch provided in this concluding section may therefore increase the scope of the theory also for adults.

Declaration of Conflicting Interests

Funding

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Notes

1. Jacobs et al. (2012) reviewed the definition of fractional derivatives and discussed advantages of using that concept. To understand the following discussion, it is sufficient to know that $\theta^{(\alpha)}$ is a detectable informational variable that depends on the parameter α.
2. We use this suggestion only as a convenient way to illustrate the theoretical point that we want to make in this section. With the example, we do not aim to take side in the debate about how the initiation of catches, and the other action components, are actually controlled (cf. Bootsma et al., 1997, p. 1287).

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Appendix B

Summary of Information Extracted From Studies in Review

Study	Number of Participants (Expertise: 1 = Low, 2 = Medium, 3 = High)	Sport [a] (Training: F = On Field; L = In Lab.)	Transfer Studied / Observed	Retention Studied / Observed (Days After Posttest)	Number of Trials of Training	Training Duration in Days	Training Duration in Min.	Type of Measures (Variable: DT = Decision Time; ER = Explicit Rule Formation; GR = Gaze Registration; MT = Movement Time)	Experimental Groups and Other Information [b]
Christina et al. (1990)	1 (2)	F (L)	No	No		28	400	Joystick (DT)	Experimental (I+): video
Williams (1993)	10 (1)	F (L)	No	No	48	1	90	Pen-Paper	Highlighting important data (I+)
Singer et al. (1994)	34 (1)	T (LF)	Yes / No	No	66	21	45	Oral (DT)	Mental (E+): explicit cues Physical (I-): movements Control (+)
McMorris & Hauxwell (1997)	30 (2)	F (L)	No	No	250 / 500 [c]	1		Pen-Paper	Exp1 (E+): 250 trials; exp2 (E+): 500 Both Occlusion, explicit cues
Farrow et al. (1998)	24 (1)	T (L)	No	No	160	28	120	Movement (DT)	Exp (E-): explicit, occlusion Placebo (-): pro videos Control (-)
Abernethy et al. (1999)	30 (1)	Sq (L)	No	No		28	80	Mouse	Exp (E+): video, explicit cues, occlusion, motor practice. Placebo (-): reading, motor practice. Contol (-): pshysical training
Moreno et al. (2002)	6 (2)	T (L)	No	No	270	28		Movement (DT, MT)	Exp (E+): video, explicit cues
Farrow & Abernethy (2002)	32 (2)	T (L)	Yes / Yes (Partially)	Yes / No (32)	600	28	240	Movement, Oral (ER)	Implicit (I+): second task Explicit (E-): explicit cues Both occlusion Placebo (-): videos of tennis Control (-): play tennis
Williams et al. (2002)	32 (1)	T (LF)	Yes / No	No		1	45	Movement (DT)	Explicit (E+): lab & field Guided discovery (I+): implicit cues Placebo (-): technical video Control (-)

Study	Sample N (groups)	Sport (Level)						Response (measure)	Intervention
Williams et al. (2003)	24 (2)	Hoc (L)	Yes / No (Only in DT)	No	40	1	45	Movement (DT)	Exp (E-): explicit cues + occlusion Control (-): Placebo (-): instructional video
Williams et al. (2004)	24 (2)	T (F)				1	20	Movement (DT)	Action (E-): court, explicit cues Perception (E-): court, explicit cues Technical (E-): biomechanics, practice
Poulter et al. (2005)	48 (1)	F (L)	No	No	96	7		Oral (ER, GR)	Explicit (E+): explicit cues Implicit (I-): secondary task Placebo (+): pro match Control (-)
Smeeton et al. (2005)	33 (2)	T (L)	Yes / No (Only in DT)	No	80	28	80	Movement (DT, ER)	Explicit instruction (E-): explicit cues Guided discovery (I-): relationships Discovery group (I-): questions For all: occlusion ball contact, full trial Control (-)
Hagemann et al. (2006)	63 (1) 20 (3) 21 (2)	Bad (L)	No	Yes / Yes (7)	200	7	45	Mouse	Attention (I+): implicit cues Video (I+): only videos Control (-)
Hagemann & Memmert (2006)	48 (1)	Bad (L)	No	Yes / Yes (7)	360	84	120	Mouse	Lab (E+): videos, explicit / implicit cues Field based (E+): field, explicit cues Placebo: videos worse quality
Caserta et al. (2007)	27 (2)	T (LF)				5	200	Movement (DT)	Perceptual-cognitive (E+): situational awareness, anticipation Technique-footwork (I-): technique Control (-): normal train
Gabbett et al. (2007)	40 (2)	Soft (L)	Yes / Yes	Yes / Yes (28)	360	28	120	Movement (DT)	Video (I+): occlusion, implicit cues. Placebo (-): arrows Control (-)
Gorman & Farrow (2009)	39 (2)	Bas (L)	Yes / No	Yes / No (14)	360	28	120	Mouse (ER)	Explicit (E-): explicit cues, occlusion Implicit (I-): secondary task Placebo (+): training with nonsport instruments Control (+)
Votsis et al. (2009)	80 (1)	Bad (LF)	No	Yes / Yes (14)	360	28	720	Movement (DT, ER)	Implicit cues (I+) explicit cues (E+) Control (-) Placebo (+): see matches

Study								Device	Conditions
Memmert et al. (2009) Experiment 1	60 (1)	Bad (L)	No	Yes / Yes (7)	360	1	120	Mouse	Random (I+): videos in random order Easy-to-hard (I+): videos easy to hard Control (-)
Experiment 2	60 (1)	Bad (L)	No	Yes / Yes (7)	360	1	120	Mouse	Random (I+): videos in random order Blocked perceptual training depth (I+) Blocked perceptual training lateral (I+)
Experiment 3	40 (1)	Bad (L)	No	Yes / Yes (7)	360	1	120	Mouse	100 % Feedback (I+) 66% Feedback (I+)
Savelsbergh et al. (2010)	30 (2)	F (L)	No	No	120	6	80	Joystick (DT, GR)	Perceptual training (I+): implicit cues Training (I+): videos Control (+)
Hopwood et al. (2011)	12 (3)	Cric (LF)	Yes / Yes	No	360	42	180	Movement (DT)	Perceptual training (I+): video, field Control (-): only field
Lola et al. (2012)	60 (1)	V (L)	No	Yes / Yes (14)	240	28	840	Keyboard (DT)	Explicit (E+): explicit cues, physical Implicit (I+): secondary task, physical sequential (E+): implicit, explicit control (-)
Abernethy et al. (2012)	60 (1)	Hand (L)	No	Yes / Yes (140)	336	2		Keyboard (DT, ER, Stress)	Explicit (E+): explicit cues (if-then) Verbal cueing (I+): general instruction Color cueing (I-): implicit cues Implicit learning (I-): secondary task Placebo (-): view matches Control (-)
Smeeton, Hibbert, et al. (2013)	34 (2)	C (L)	No	No	80			Keyboard (DT, ER)	Imagery no replay + explicit cues (E+) Video replay, explicit cues (E+) Outcome KR no replay, explicit cues (E+) Control (-)
Ryu et al. (2013)	28 (1)	F (L)	No	Yes / Yes (1)	448	7	280	Keyboard (DT)	Guided (I+): implicit cues Unguided (I+) Control (-)
Smeeton, Huys, & Jacobs (2013) Experiment 1	30 (1)	T (L)	No	No	240	1	114	Keyboard	Reliable (I+): dynamic differences in all body regions Unreliable (I-): half of the trials no dynamic differences Control
Experiment 2	22 (1)	T (L)	No	No	240	1	114	Keyboard	End effector (I+): only info in the end-effector Body (I+): no info in the end-effector

Study	Age (N)	Code						Mode	Description
Experiment 3	38 (1)	T (L)	No	No	240	1	114	Keyboard	End effector (I+): all but end-effector occluded Body (I-): end-effector occluded
Milazzo et al. (2014)	18 (3)	K (L)	No	No	180	42	48	Movement (DT, ER)	No feedback (I+): video no cues Placebo (-): videos of fights Control (-): normal training
Murgia et al. (2014)	38 (3)	F (L)	No	No	768	56		Keyboard	Exp: (I+) perceptual training DVD Placebo (-): DVD and advise to use Control (-)
Schorer et al. (2015) Experiment 1	19 (2)	V (L)	No	No	144	14		Keyboard	Exp (I+): occlusion: (spatial/temporal) Control (-)
Experiment 2	32 (2)	V (L)	No	No	144	14		Keyboard	Control (-) Attacker occluded (-) Occluded setter (-)
Tzetzis & Lola (2015)	60 (1)	V (LF)	No	Yes / Yes (7)	240	28	840	Keyboard, Movement (DT, ER)	Explicit (E+): explicit cues Implicit (I+): secondary task Analogy (I+): metaphor Control (-): see video
Nimmerichter et al. (2015)	34 (2)	F (L)	No	No	448	42	84	Pen-Paper (DT)	Training (I+): occlusion Control (-): normal train
Klostermann et al. (2015)	55 (1)	V (L)	No	Yes / Yes (7)	144	1	60	Oral (GR)	Functional cueing (I+) Dysfunctional cueing (I+) control videos no cues (+)
Milazzo et al. (2016)	18 (3)	K (LF)	Yes / No	No	360	21	96	Oral, Movement (ER, GR)	Implicit (I+): video Motor training (I-): Control (-): only normal training
Alder et al. (2016)	30 (3)	Bad (L)	Yes / Yes	No	72	1	90	Oral, Movement (GR)	High anxiety + explicit cues (E+) Low anxiety + explicit cues (E+) Control (-)
Alsharji & Wade (2016)	42 (3)	Hand (L)	No	No	784	7	140	Movement	Exp (I+): occlusion deception Control (-): Placebo (-): placebo video
Ryu et al. (2016)	50 (1)	Bas (L)	No	Yes / Yes (14)	144	3	120	Keyboard (DT, GR)	Moving window occlusion (I+) Moving mask occlusion (I+) Full vision (I+) Control (-): see videos

Study								Response	Conditions
Broadbent, Ford, et al. (2017)	21 (2)	Bas (L)	Yes / No	No	72	1	45	Movement (DT)	Sequential (I+) / Non sequential (I+)
Broadbent, Causer, et al. (2017) **Experiment 1**	24 (1)	T (L)	No	No	108	1		Oral	Blocked (I-) / Random (I+)
Experiment 2	56 (1)	T (L)	No	No	108	1		Oral	Blocked (I+) / Random (I-) / Bs stroop (I-) / rstroop (I-)
Dicks et al. (2017)	18 (1)	F (LF)		No	80	1		Movement	One-player training (I-): / Three-player training (I+):
Ryu et al. (2018)	36 (2)	Bad (L)	No	Yes / Yes	360	3	120	Keyboard (DT, GR, Deception)	low-SF: occlusion (I+) / high-SF: occlusion (I+) / Control training (I-)
Hüsdünker et al. (2018)	10 (3)	Bad (L)	No	No	330	28		Movement (EEG)	Intervention: stroboscopic training (I+) / Control: same without stroboscopic (I-)

[a] Bad = Badminton; Bas = Basketball; C = Cricket; F = Football; Hand = Handball; Hoc = Hockey; K = Karate; Soft = Softball; Sq = Squash; T = Tennis; V = Volleyball.

[b] I = Implicit; E = Explicit; + = Significant improvement observed; - = No significant improvement observed.

[c] This experiment included two experimental groups with 250 and 500 trials, respectively.

Table B.1 Summary of Information from Studies in the Review

Table B.1: Summary of Information Extracted From Studies in Review