A Design Space of Sports Interaction Technology

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ABSTRACT

With this monograph we introduce a new, systematic taxonomy of Sports Interaction Technology (Sports ITech) that defines a design space of existing and future work in this domain. We set the taxonomy in a context of our view on sport science and sports practice, target outcomes of sports and the underlying factors influencing them, and the role that sports technology plays to support sports science and practice. In that setting we systematically build and illustrate a taxonomy for the design space for Sports ITech as a sub-area of sports technologies, with specific attention for the adequate inclusion of knowledge from the sports

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sciences. We build on the basis of existing taxonomies and a vast body of literature from multiple domains of HCI, technology, sports science, and related work in Sports ITech, complemented with what we identified as obvious gaps in the literature. We finally share the conclusions after a discussion of the limitations of our work.

The contributions of this monograph are as follows. First, we offer a description of a design space, exemplified through existing work in a way suitable to support designers, technologists, and sports people with a design mindset to design, deploy, and adapt Sports ITech. Second, we see this as a call to action to bring HCI and the sports sciences closer together in the new field of Sports Interaction Technology, to set a shared agenda for future developments. Third, we offer this as the collation of a reading guide and wayfinding support in the literature from the many underlying disciplines of Sports Interaction Technology.

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1

Introduction

1.1 Background and Motivation

With this monograph we bring together a systematic taxonomy that defines a design space of Sports Interaction Technology (Sports ITech). This taxonomy, exemplified by existing work in the field, is meant to be used by designers of Sports ITech. It will help better highlight and position existing work. It will also provide input and inspiration for the design and deployment of such technology.

The articulation of this design space is an outcome of the Dutch ZonMw funded Smart Sports Exercises (SSE) project, which aimed to develop novel kinds of digital-physical training exercises in ambient intelligent environments. In those environments, body worn movement sensors and a pressure sensitive floor were used to measure athlete behaviour during sports activities. Displays, integrated in the floor, provided feedback or presented novel exercise forms and training games. The SSE project focused partly on developing and validating tools for sensing and modelling individual and group level volleyball behaviours (Salim *et al.*, 2020a; Beenhakker *et al.*, 2020). The project also concerned the design, validation, and embedding of novel digital-physical exercise forms in sports practice (Postma *et al.*, 2019, 2022c). Extensive analysis of the volleyball context was used to develop concepts and prototypes that were evaluated in a user-centred approach with trainers, innovation managers, industry professionals, and athletes. While doing so, we experienced a need to map the design space in order to more easily explain our work to stakeholders as well as to identify gaps and opportunities for further designs. This monograph presents the resulting framework that reaches beyond the specific volleyball use case of the SSE project into the larger field of Sports ITech. The SSE project was in that sense reminiscent of the choices that Sports ITech designers generally encounter. Not only do the specifics of the sport or the technology influence the design space, but also the frameworks that underpin the objectives of a design. Through this monograph we share the collective insights from literature in the field in the form of a taxonomy to benefit future Sports ITech designs.

1.2 Global Approach

We developed our taxonomy in several iterative steps. The initial insights were derived from a research through design approach (Stappers and Giaccardi, 2017), in which we built prototypes of Sports ITech and reflected on their purpose and value in a user-centred approach. We felt that there was room for an explicit articulation of a design space; therefore we surveyed existing literature and used our own artefacts to exemplify an initial sketch of the design space. We then gathered additional literature sources in order to: 1) articulate how we see the context of sports science, sports practice, and general sports technology in which Sports ITech is placed, and 2) articulate the design space of Sports ITech itself in a literature-grounded, cohesive and extensive taxonomy. Here we describe and exemplify the resulting design space through theory (i.e., existing frameworks) and practice (i.e., existing artefacts of Sports ITech). This makes it possible to highlight sparsely populated areas in the design space and to represent important positions in order to facilitate inspiration and inquiry into designing the right thing (cf. Frayling (1994, 2015) Stappers and Giaccardi (2017), Zimmerman *et al.* (2007), and Dalsgaard (2010) on research into/through/for design).

As is often the case with design space papers,[1] the framework and exemplifying examples are the result of design, design research, and followup research from a variety of researchers working on various types of interactions, contexts, and goals.

1.3 Sports Interaction Technology as Part of a Larger Context

Our Sports ITech taxonomy does not stand in a vacuum – it is articulated within our view on the larger context of sports practice and sports science on the one hand, and innovative developments of sports technology on the other hand. To capture the dynamic interplay between sports and technology, we developed the '21st Century SPORTS Framework' for **S**upporting in-**P**ractice **O**utcomes through **R**esearch & **T**echnology in Sports (see also Figure 1.1). Over the next couple of paragraphs we will use this framework to sketch in broad strokes this broader context of sports and (interactive) technology.

Within sports there are targeted outcomes: what people strive for in sports. The 21st Century SPORTS framework summarises these as performance, learning, and engagement. Underlying factors in a complex network of relations that may influence attainment of these outcomes are, for example, physiology, biomechanics, genetics, and nutrition – but there are many more possible factors (cf. Hristovski *et al.*, 2017; Williams and Kendall, 2007). In sports practice, athletes, coaches and trainers attempt to *maximise outcomes* based on insights about these underlying factors, their mutual relations, and their apparent relation to the outcomes. In sports science, scientists attempt to *obtain new and more detailed fundamental insights and models* regarding what are the underlying factors, and how they are related to each other and to the targeted outcomes.

Sports technology, finally, is a tool to support these endeavours. Technology supports athletes in achieving better sports practice; but it also supports scientists in generating new fundamental knowledge. In brief, the 21st Century SPORTS Framework distinguishes three types

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[1] E.g., Lakier *et al.* (2019), Müller *et al.* (2010), Kosmalla *et al.* (2017b), Mueller and Muirhead (2015), Ishii *et al.* (1999), Mueller *et al.* (2011), and Surale *et al.* (2019).

of Sports Technology, namely Physical Sports Technology, Sports Data Technology, and Sports Interaction Technology: (see Figure 1.1).

1. **Physical Sports Technology** is typically characterised by a strong focus on gear (e.g., the clap skate in speed skating (Ingen Schenau *et al.*, 1996)), materials (e.g., artificial turf in hockey and other sports (Fuss *et al.*, 2007)), the built environment (e.g., the physical organisation of children's playgrounds (Withagen and Caljouw, 2017)), and apparel (e.g., the shark-suit in swimming (Hutchinson, 2008)); often with a focus on increasing safety and/or performance.

2. **Sports Data Technology** focuses on data science. Typically, it aims to leverage (big) data to gain more insight into sports performance. Research generally targets measurement and analysis of sports data (e.g., Brefeld *et al.*, 2019) as well as dashboard and retrieval systems that help athlete and coach *make sense of the data* (Stein *et al.*, 2017). The insights acquired from these analyses contribute to a better scientific understanding of sports, as well as to better interventions in training programs and match strategies in sports practice.

3. **Sports Interaction Technology**, which is the focus of the remainder of this monograph, involves novel kinds of digital-physical exercise systems and aims to boost performance, engagement and learning through human machine interaction *that occurs with and around the 'acting body'*. That is, the user in Sports ITech is typically engaged in whole-body movement activities as part of, or related to the human machine interaction. Sports ITech shares characteristics with the general notion of exertion games (games that center on exertion and bodily effort both as purpose of the interaction as well as the main modality to control the interaction; Mueller *et al.*, 2016). However, in contrast with this, our definition of Sports ITech focuses more strongly on interactive training and competition. Although exertion plays an important role, it is not the end goal nor a necessity in itself but rather it is at the service

of sport-specific qualities and characteristics. This places different demands on the design of interactive applications.

Sports ITech typically involves HCI technology implemented with a sense-think-act cycle,[2] where the system senses input (e.g., sports relevant behaviour), decides upon appropriate responses in the context of the desired activity (e.g., a novel soccer training activity), and delivers these responses through displays, wearables, novel tangible interfaces, or smart environments. For example, in Football Lab (Jensen *et al.*, 2014a), a football area is surrounded by four "rebounders", smart goals enhanced with sensors that measure hit position, and lights and loudspeakers that provide feedback and game instructions, where the system responds in certain ways to player actions in order to encourage them to carry out soccer-related exercises.

In the remainder of this monograph we focus on Sports Interaction Technology and describe a taxonomy to systematically describe and analyse this field in terms of form and function of the technology.

1.4 Aim and Contribution

Building on a variety of our own Sports ITech design projects for climbing, cycling, rowing, running, skiing, and playing volleyball, we postulate that the development of a Sports ITech design space framework satisfies a latent need, both for HCI technologists and designers who enter the sports domain as application context, and for sports professionals who approach their work with a design mindset and want to incorporate interaction technology in their work. Students in these fields can benefit from a better understanding of Sports ITech, but also researchers, professionals, and policy makers may find benefit in this work.

In existing partial taxonomies, sports science and movement science are often underrepresented (e.g., Kajastila and Hämäläinen, 2015). As we will argue in a subsequent section, we see a need to integrate more

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[2] Note that the sense-think-act adage is purely a high-level descriptor of a typical HCI system's architecture and should thus not be taken to represent the way in which human athletes interact with the world.

fundamental knowledge from those disciplines into this subdomain of HCI, in line with the HCI tradition and history of embracing methods, knowledge, and techniques, and practitioners, from other fields of science (cf. Lazar *et al.*, 2017). After computer science and information science, ethnography, psychology, and design, the rise of sports HCI can be supported by more explicit inclusion of expertise from fields including sports science and human movement science.

With this monograph we aim to offer a threefold contribution. First, we contribute by more clearly framing and articulating a research domain, namely that of Sports ITech. This can help in identifying gaps, realising new opportunities, and grounding choices for design, research, and development in this still relatively young field. Second, this monograph embodies a call to arms for drawing more sports and movement scientists to the field of HCI in support of this subdomain. Third, thanks to the extensive multidisciplinary bibliography, this monograph aims to orient the reader exploring literature from the many disciplines underpinning Sports ITech (e.g., ‘motor learning’, ‘game design’, ‘pedagogy’ and ‘interaction design’).

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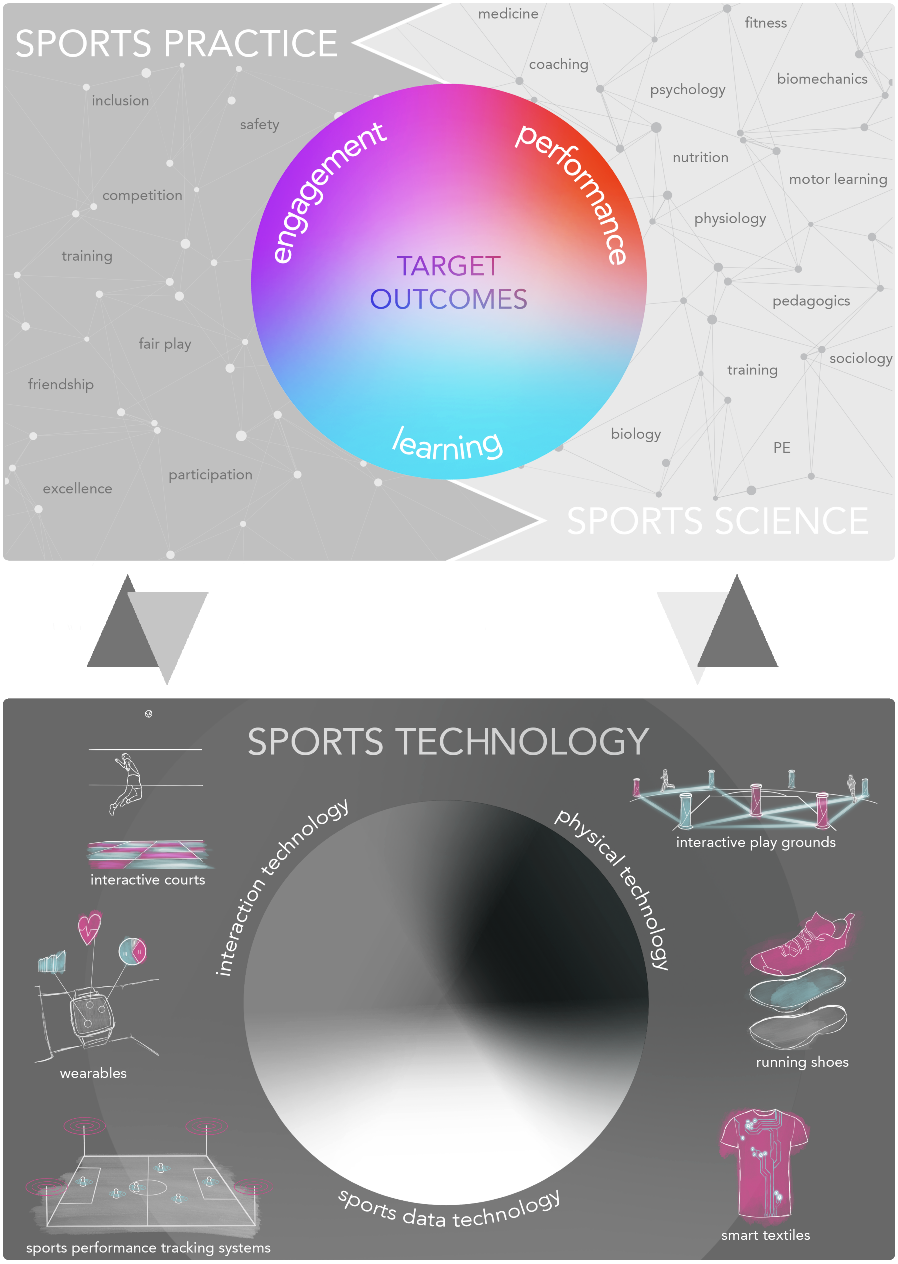

Figure 1.1: The 21st Century SPORTS Framework for **S**upporting in-**P**ractice **O**utcomes through **R**esearch & **T**echnology in Sports. The figure illustrates the interrelation between sports practice, sports science, and their intended outcomes, and the role of technology to support these, with the *sports science* aspect and the *sports technology* aspect further illustrated with exemplars.

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2

A Taxonomy for Sports Interaction Technology

In this section we introduce the top levels of our taxonomy of Sports ITech. With it, we aim to provide a design space for designers, scientists and practitioners to guide their efforts in designing and deploying new, meaningful and exciting interactive technologies for sports. The taxonomy also sketches the bigger picture of how sports and interaction technology are related through form and function. In later sections we elaborate on this by systematically discussing relevant literature on *human computer interaction* and *sports science*, adding detail to existing theoretical frameworks and putting them into context.

2.1 Approach

Reilly *et al.* (2009) proposed a 'General-purpose taxonomy of computer-augmented sports systems', which serves as a starting point for the current work. They provided an excellent road map to deal with the ever-growing complexity of the field of computer augmented sports as it existed at the time, more than a decade ago. Since then, technology has continued to evolve and so has the role of interaction technology in sports. We aim to expand on the taxonomy proposed by Reilly and colleagues and bring it up-to-date with recent developments – both in sports science and in Sports ITech. We do this by identifying and adding meaningful constructs and concepts to their general-purpose taxonomy.

We followed a strict methodology. Our first step was to consult an extensive body of literature on both sports science and computer science to identify meaningful classifications and distinctions that had not already been made by Reilly *et al.* (2009). Frevel *et al.* (2020) provide a slightly different outlook on the overarching forms and functions of what they call SportsTech, which we reconciled with the taxonomy of Reilly and colleagues. We also looked in more detail at specific subareas of the taxonomy. Fullerton (2014), for example, proposed a classification of “Player Interaction Patterns”, detailing the various ways in which players interact with each other and with the interactive system. These player interaction patterns were not part of the original taxonomic framework of Reilly et al. but seem to be very relevant when considering interactive systems for sports. Similarly, other classifications such as the “10 Lenses to design Sports-HCI” of Mueller and Young (2018) were added to Reilly’s taxonomy to tailor it specifically to Sports ITech. In adding dimensions to the taxonomy we did so because we thought they are meaningful for understanding how HCI and sports science relate, to form unique opportunities for the design of interactive systems.

The second step was to take a bottom-up approach, trying to fit existing Sports ITech systems into the taxonomy. If we were unable to classify a piece of research into the taxonomy, we added new branches and nodes. Areas that have been well explored in the Sports ITech literature therefore received relatively more attention, but we did not limit ourselves to the main branches only; also less well sampled areas of Sports ITech were incorporated. This bottom-up stage was an iterative process, additional literature was studied until no novel (sub)classifications emerged. Put differently, the process continued until the constructs were stable (Glaser and Strauss, 1967; Muller and Kogan, 2010; Charmaz, 2006).

In the third step we went to the sports science literature and added fundamental knowledge from the field that was deemed most relevant to the Sports ITech that we included, and we summarized that literature specifically in light of implications for existing and future Sports ITech. In this monograph we present the end product of this methodology.

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2.2 Overview of the Top Level Branches

As a prelude to the full taxonomy, we present a high-level overview of the top-level branches, as shown in Figure 2.1. The taxonomy starts with the distinction between *Form* (right-hand side) and *Function* (left-hand side). While function follows from form and vice versa, this relationship is not one-to-one. Systems that vary widely in form might still serve the same purpose, and vice versa.

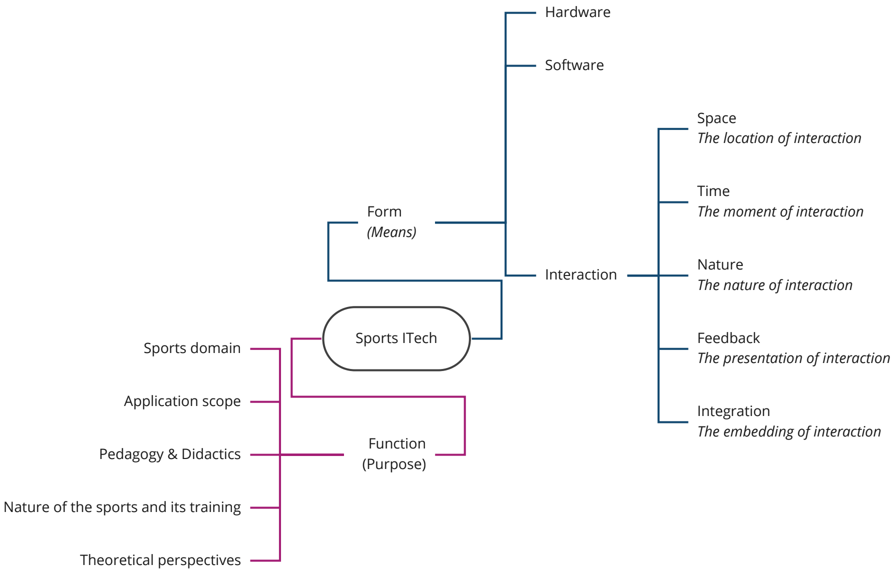

Figure 2.1: A high-level taxonomy of Sports Interaction Technology, elaborated from the taxonomy by Reilly *et al.* (2009)

Following Reilly *et al.* (2009), *Form* is further divided into hardware, software and interaction. Our work mainly focuses on the interaction; for an excellent starting point on the hardware and software of Sports ITech, please refer to their work. Reilly *et al.* (2009) focus their discussion of interaction mostly on feedback (i.e., *How, When and to Whom* information is presented). Adding insights from other literature, we started from the following primary division: the space and time in which the interaction takes place; the nature of the interaction and how it changes the sports activity itself; the augmented feedback that the athletes receive on their sports performance and results; and the integration of the interaction in practice in a training programme.

Function, on the left-hand side, is further subdivided into: sports domain; application scope; essence of the training experience; pedagogy and didactics; and the theoretical perspectives on motor control & motor learning that the athlete, trainer, or designer adheres to. While the first two are directly borrowed from Reilly *et al.* (2009), these constructs are given a (mostly) different interpretation in our taxonomy. The other branches are added from sports science.

In the next section, we start our discussion with *Form*, setting the stage for the more involved discussion of *Function* which then follows.

3

The Form of the Interaction

Interactivity is at the heart of the *Form* of Sports Interaction Technology. Interactive systems come in different shapes and sizes, ranging from simple visual displays (Ahtinen *et al.*, 2010; Fadde, 2006) to fully immersive mixed or virtual reality environments (Staurset and Prasolova-Førland, 2016; Bideau *et al.*, 2004; Kosmalla *et al.*, 2017b) and from artefacts (Fogtmann *et al.*, 2011; Izuta *et al.*, 2010) to interactive projection floors (Sato *et al.*, 2019; Moreno Celleri *et al.*, 2016). Also auditory systems have been extensively explored, with systems ranging from auditory feedback systems (Cesarini *et al.*, 2014; Hermann and Zehe, 2011; Schaffert *et al.*, 2009) to audio-games (Garcia and Almeida Neris, 2013; Urbanek *et al.*, 2019) and from musical guidance (e.g. Spotify Running) to audio-supported imaginary reality games (Baudisch *et al.*, 2014). Finally, haptic devices have also found their way to sports (Kosmalla *et al.*, 2016; Spelmezan, 2012; Erp *et al.*, 2006), but are less prevalent than their visual and auditory counterparts. A whole class of multimodal systems for feedback and interaction on its own is the use of virtual humans or embodied conversational agents, which can be used to guide and encourage users doing exercises, including modelling the desired behaviour (i.e., showing the proper execution) but also delivering motivational and other feedback (Chao *et al.*, 2004; Eyck *et al.*, 2006; Aghajan *et al.*, 2009).

All these systems obviously distinguish themselves in different aspects regarding the form that the interaction takes, as shown in Table 3.1. In this section we discuss the various ways in which interactivity is realised in Sports ITech and discuss how these relate to design choices that can be made for new systems. Throughout, the discussion is extensively illustrated with State of the Art examples.

Table 3.1: ‘Form’ taxonomy – The Forms that Sport ITech can take

THE FORM OF SPORTS ITECH
We describe the wide range of forms that Sports ITech can take through five lenses

Space
Where does the interaction take place, in relation to the sports activity?

Time
When does the interaction take place, in relation to the sports activity?

Game Nature
The nature of the interaction reshapes the sports activity

Feedback
Supportive information can be delivered in many forms

Integration
Sports ITech is used in sports practice in a larger setting of training and competition, raising questions of sequencing and planning of the activities with the Sports ITech

3.1 Space – The Location of Interaction

Regarding the Space of Interaction, not all Sports ITech is used ‘on the field’ where training or competition itself takes place. We make a distinction between *in-situ* and *ex-situ* systems, as shown in Table 3.2.

Sports ITech systems that are strictly used outside the training context are said to be ex-situ; systems that are strictly used in the

Table 3.2: First 'Form' subbranch – Space in which the interaction takes place

FORM – SPACE Where does the interaction take place, in relation to the sports activity?
In-situ *Interaction with the technology happens in the same space as the sports activity, e.g., on the field*
Ex-situ *Interaction with the technology happens in another space than the targeted sports activity, e.g., a rowing simulator for practicing towards rowing in a real boat on the water*

natural practice setting are said to be in-situ. For other systems, the distinction spans a spectrum over the level of similarity between the Sports ITech system on the one hand, and the practice context and performance context on the other hand, in terms of, for example, social situatedness, task-similarity and physical context. Ex-situ and in-situ systems each have their own unique advantages in advancing the training experience for trainers and athletes.

One distinct advantage of *ex-situ* systems is that they enable athletes and trainers to continue their training beyond the confines of the traditional training setting. This might be useful when traditional training is impractical or even impossible. For example, rowing simulators (Delden *et al.*, 2020; Rauter *et al.*, 2011; Ruffaldi and Filippeschi, 2013) allow rowers to pursue their training schedules when weather conditions would obstruct traditional training. Ex-situ systems not only allow athletes to continue training 'off the field', but may also focus on aspects that are difficult to train on the field. Perceptual-cognitive training regimens are often mentioned in this regard (Fadde, 2006) (however, see the work of Renshaw *et al.* (2019) for a critique with respect to *transfer effects* of such training regimens). Another potential advantage of ex-situ systems is that they can be designed to provide the learner with a safe environment for practice. This is especially relevant for extreme sports and sports that bear considerable risks (Lei *et al.*, 2018; Staurset and Prasolova-Førland, 2016; Kosmalla *et al.*, 2017b). Finally, another potential advantage of ex-situ systems is that they allow users to learn from past experiences by having them scrutinise or even relive (pre)recorded scenarios (Savelsbergh, 2017). Clearly, when situatedness is treated as a principled design dimension and not as an afterthought, it holds great potential.

In-situ systems, on the other hand, are used in the natural training (or performance) setting. In-situ systems are already part of the training regime of many. Consider for instance the use of sports watches (e.g. Garmin, Polar, Fitbit) and smartphone-applications (e.g. Strava, Runkeeper, Nike Training Club) in running, cycling, and fitness, or the Homecourt app that contributes to shot practice in basketball. One notable manifestation of in-situ interactive systems are (bio)feedback systems, in which athletes receive an immediate display of their performance to allow adaptation of their behaviour.[1] The single biggest advantage of in-situ systems is that the practice-context remains as close as possible to the performance-context, which is thought to promote learning and transfer (Brunswik, 1956). Kosmalla *et al.* (2017a) for example used full-sized, in-place projections of expert climbers (expert-modelling) on an interactive climbing wall where climbers are working, to guide them towards the use of proper climbing technique.[2]

The in-situ / ex-situ distinction is not a binary one, but rather a continuous dimension along which Sports ITech systems vary depending on the similarity between the practice-context and the performance-context. Take for example 'Slackliner', an interactive slackline training assistant that provides advice on the athlete's technique (Kosmalla *et al.*, 2018). With Slackliner, athletes can perform all the same actions, in much the same social and physical setting, as they can when using a traditional slackline setup. This makes it a mostly in-situ system. However, Slackliner is not easily implemented in an outdoors-setting, while slacklining *is* typically performed outdoors. As such, Slackliner breaks similarity in terms of physical context, so it is not entirely in-situ.

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[1] Hermann and Zehe (2011), Stienstra *et al.* (2011), Cesarini *et al.* (2014), Boyd and Godbout (2010), and Nylander *et al.* (2013).

[2] Some other exemplary in-situ Sports ITech systems include the work by: Altimira *et al.* (2016), Chi *et al.* (2004), Davis (2015), Kosmalla *et al.* (2016), Mueller and Muirhead (2015), Oliver and Flores-Mangas (2006), Trajkova and Cafaro (2018), and Turmo Vidal *et al.* (2019).

Given the spectrum of possibilities from ex-situ to in-situ, there are three additional things that we see in existing system designs. First, some systems show clear potential to be used in-situ, but are not yet applied as such. This classification provides a way to position existing systems along a continuum of in-situ/ex-situ, but can also be used to look at the *potential* of an ex-situ system to be used in-situ eventually, or vice versa. Second, some systems transcend the in-situ/ex-situ distinction; they can be either depending on how you use them in practice. One such system is TacTowers, which might just as well be used "on the field" as "off", a characteristic expressly praised by players and coaches (Fogtmann *et al.*, 2011, p.7). Another such system is presented by Daiber *et al.* (2013). With BouldAR, they presented a social platform for boulder training that could be used to define, document and share 'problems' (i.e. climbing routes). BouldAR can be used in-situ to define and create new and challenging problems *and* BouldAR can be used ex-situ to share these routes and discuss them after practice. Third, technology such as Virtual Reality allows one to (re)create any real world context for the user in a technological setting (e.g., Kosmalla *et al.*, 2017b; Tan *et al.*, 2015; Delden *et al.*, 2020; Kajastila and Hämäläinen, 2015; Holsti *et al.*, 2013).

Using this, there exists Sports ITech that augments an ex-situ system (e.g., running on a treadmill) with virtual environments that mimic the in-situ context, which in a way re-contextualises the experience and ideally combines the best characteristics of both ex-situ and in-situ technology. For example, the treadmill is an archetypal example of an ex-situ system. Whereas runners would normally advance through the world as they go, treadmill running does away with that experience and keeps runners almost stationary in space. Häkkilä *et al.* (2013) augmented a treadmill with a VR experience providing athletes the opportunity to 'navigate' their own city in 3D by running on the treadmill. Similarly, Kosmalla *et al.* (2017b) enrich the experience of bouldering by providing climbers with vistas of real mountain faces in VR, instilling them with a sense of true mountaineering.[3]

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[3] Although this will probably not deliver the full range of experience of mountaineering: see, for example, the work of North and Harasymchuk (2012).

In all its complexity and nuance, this in-situ/ex-situ distinction is exemplary for how our design space works. We describe a distinction that can be used to categorise examples of variations along a spectrum; this in turn facilitates communication, can trigger evolving existing systems towards either side, and can inform new directions for the design and deployment of Sports ITech.

3.2 Time – The Moment of Interaction

Choosing the right moment for users to engage in interaction is a powerful tool in the design of interactive training systems. Changing the moment of interaction can fundamentally change the nature of an exercise. Interactive training systems can be *prospective*, *conspective* or *retrospective* in nature (or a combination thereof), regarding when the user interacts with the system in relation to when the sports activity takes place, as shown in Table 3.3.

Table 3.3: Second 'Form' subbranch – Time at which the interaction takes place

FORM – TIME When does the interaction take place, in relation to the sports activity?
Prospective *Interaction with the technology happens before the actual sports activity starts, e.g., a workout scheduling portal*
Conspective *Interaction with the technology happens alongside / as part of the targeted sports activity, e.g., giving direct augmented performance feedback during execution of the movement*
Retrospective *Interaction with the technology happens after the targeted sports activity has finished, e.g., dashboards for analysing past performance*

With *prospective systems*, athletes interact with the system *before* entering into the training activity or executing a certain exercise, for example with a tool that helps plan out a training schedule. An analog variant to this is a coach who explains game tactics on a whiteboard before the athletes go into the field to play the game, or who prescribes exercises to perform at home. Prospective systems allow the user to interact or get involved with the principal mechanics of an exercise before actively engaging in it. As a Sports ITech example, the ClimbVis system by Kosmalla *et al.* (2017a) included the option to assist a climber on an artificial climbing wall by (beforehand) projecting a life-size, in-place, shadow of an 'instructor' performing the desired movement for them to study. This is based on the concept of expert modelling, which can be a powerful means of learning (Edwards, 2010).

With *conspective systems*, the interaction with the user happens in real-time as the sports activity takes place. Conspection, meaning *observation with understanding*, thus allows for behaviour to be guided or steered as the exercise unfolds. Examples of such systems in sports are: pacing by following a virtual partner in cycling (Feltz *et al.*, 2020) or rowing (Hoffmann *et al.*, 2014), interactive projections making handball players decide their target once they jump (Jensen *et al.*, 2015b) or projecting visuals in front of a cyclist that indicate a to be covered distance within a certain time (Zhao *et al.*, 2019), and learning novices the motion sequence for archery (Geiger *et al.*, 2013). These examples focus on challenges, goals, leaderboards, and feelings of progress. Other examples of conspective systems are designed more for playfulness, discovery, and open ended play, for instance in a table-tennis table showing water ripples when a ball bounces on it (Ishii *et al.*, 1999), and other systems that create room for exploration and open-ended play (Valk *et al.*, 2013). Finally, (bio)feedback systems are also often conspective systems, providing immediate or slightly delayed feedback about performance, form and execution. For example, Anderson and Campbell (2015) describe providing real-time video feedback overlaid with an expert model while the athlete carries out the activity; others offer on-the-fly sonification of rowing movement (Effenberg *et al.*, 2016; Schaffert *et al.*, 2009); and a variety of commercial wearable systems present heart rate and GPS data to help the athlete learn about their own body's performance in real time, to keep intensity within certain training regimens, or to push harder (Tholander and Nylander, 2015).

Finally, with *retrospective* systems, users interact with the system after finishing the sports activity. The earlier mentioned ClimbVis system also allows *post hoc* reviewing of one's own past performances in relation to an experienced climber's performance, through an in-place projected third person view of a past performance of themselves (Kosmalla *et al.*, 2017a). Pijnappel and Mueller (2014) developed Copy-Paste Skate for skateboarders. After performing a skateboard trick, users could observe an abstracted version of their trick in the form of a light-display on the wall. Also, right after performing the trick, users could 'feel' their trick through haptic feedback in the floor and could 'hear' their trick through aural feedback rewound at half speed. This is a form of self-modelling, a technique shown to be effective in motor-learning (Hodges and Williams, 2012, pp.7–17). Other systems that provide the user with the chance to interact with past performances are in the form of dashboards for sports data retrieval (e.g., Perin *et al.*, 2018; Polk *et al.*, 2014; Shao *et al.*, 2016).

Some systems can even be either prospective, conspective or retrospective in nature, depending on their use. BouldAR (Daiber *et al.*, 2013) is an Augmented Reality application for bouldering that allows athletes to: study route problems before going to practice (prospective); define and document routes while practising (conspective); and share routes after finishing practice allowing for elaborate tech-mediated discussions (retrospective). With the electronic baton for relay racing by Davis (2015), runners are presented with relevant metrics about their performance in real time, while information is also stored for presentation and analysis later on. Modern sports watches can be observed to combine all three timings by providing help in setting out routes or training plans (prospective), present heart rate zones, cadence, power or speed as feedback during the exercise, possibly alongside route information (conspective), and aid reflection after the activity (retrospective)

One final remark about timing concerns not the moment of interaction in relation to the moment of the sports activity, but rather the frequency and timing with which information is provided to users during the execution of the sports activity, which is mainly an issue for conspective systems. This topic is discussed in more depth in Section 3.4 which is about delivery of feedback.

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3.3 Game Nature – How Interaction Shapes the Sports Activity

Sports ITech can focus on different spaces and times relative to the sports activity that it pertains to, but can also more fundamentally vary in how the nature of the sports activity is changed by what the interaction adds. Table 3.4 shows the five sub-dimensions (including sub-branches) in which we discuss this topic further.

Table 3.4: Third 'Form' subbranch – Nature of the interaction

FORM – GAME NATURE The nature of the interaction reshapes the sports activity
Exercise modification (Ishii *et al.*, 1999; Postma *et al.*, 2019) *Enhance existing sports activity, or introduce fully novel activities*
Behaviour steering (Delden *et al.*, 2017; Postma *et al.*, 2022b) *Steer the player with different levels of forcefulness and transparency*
(Multi)user-game relations Locatedness (Mueller *et al.*, 2007b) *Athletes are co-located, or geographically / temporally distributed* Player Interaction Patterns (Fullerton, 2014) *Athletes interact with each other and the game in various patterns*
Constraints on action (Newell, 1986; Newell and Jordan, 2007) Performer constraints *Interaction shaped by characteristics of the athlete, e.g. heart rate and body weight* Environment constraints *Interaction shaped by athlete-external factors, e.g. lighting and ground surface* Task constraints *Interaction determined by the design of the task, e.g. introducing new goals and rules of game*
Gamification, Playification, and Sportification (Deterding *et al.*, 2011; Nicholson, 2012) *Apply game mechanics, playful characteristics, or typical sports mechanisms to the interaction*

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3.3.1 Exercise modification

The first distinction in this branch concerns whether the sports activity itself remains the same, regardless of what the interaction adds. Ishii *et al.* (1999) distinguished between interactive systems that *augment* sports activities (keeping the core of the activity recognisably the same but extending it with more actions, decisions support, or instructions) and systems that *transform* them (leading to fundamentally new activities). We extend this with systems that *inform* about sports activities, leaving the activity alone but "merely" displaying information about it. This is summarized in Table 3.5.

Table 3.5: Subspace – Exercise modification

Form – Game Nature – Exercise modification	Enhance existing sports activity, or introduce fully novel activities (Ishii *et al.*, 1999; Postma *et al.*, 2019)
Inform	*Sports activity remains essentially unaltered but additional information is provided to the athlete while exercising*
Augment	*Sports activity is enhanced with extra interactive possibilities, but remains recognizably close to the original activity*
Transform	*A new, transformed sports activity is made available through the interaction technology*

With *inform* the sports activity itself is not directly changed, but sports data is used to present athletes with a factual representation of their performance such as heart rate, speed, or power expenditure, either in real-time or time-delayed. The measurement and analysis of data and the corresponding dashboard technology can be said to be a whole field on its own. This is discussed at more length elsewhere (Kokaram *et al.*, 2006; Perin *et al.*, 2018); existing literature covers architectures for such systems (Matejka *et al.*, 2014; Brunauer *et al.*, 2020; Renò *et al.*, 2017); hardware for measurement and tracking (e.g., Van der Kruk and Reijne, 2018; Fuss, 2008; Cust *et al.*, 2019; Düking *et al.*, 2018); tools for analysing and modelling sports data (e.g., Brefeld *et al.*, 2019); novel forms of visualising (Perin *et al.*, 2018; Polk *et al.*, 2014) and querying (Shao *et al.*, 2016) the data, or the decision making that builds upon this data (e.g. Vales-Alonso *et al.*, 2015, 2010; López-Matencio *et al.*, 2010) – although the latter is also often left to the coach or athlete. While it might be argued that dashboards and data-retrieval tools are only minimally interactive, they can still have a profound effect on the way athletes and trainers give substance to their training, be it because information can lead to sense making and decision making (Stein *et al.*, 2017), because it can lead to *motivation* making someone push harder, or because it changes the lived experience of the sport (Tholander and Nylander, 2015). Additionally, *inform* systems can also ask leading questions or steer the user's attention to certain specific aspects of the activity and the user's performance in a way that it contributes to scaffolding the user's reflection, which impacts learning and performance.

With *Augment*, interaction technology is used to augment the nature of a sports training exercise (Ishii *et al.*, 1999). Rather than just presenting information about the athletes' performance, augmentation can include instructions and advice, or changes to the parameters of the exercise. Yet, with *augment*, information is added to the exercise without abstracting away from its intended form, purpose or goal. Augmentation and augmented reality are gaining traction in the world of sports. For example, HomeCourt[4] uses an iPhone's camera-array and computer vision to augment home training experiences. The advantage of the *Augment* approach is that it uses what already works (the sports activity as it exists) and extends it with extra possibilities through technology. The challenge then, however, is to make sure that the technological enhancements add real value, given that the core sports activity remains recognisably the same.

With *Transform*, finally, technology is used to comprehensively transform the nature of a sports training exercise (Ishii *et al.*, 1999), meaning that interaction is introduced and implemented in a way that gives rise to a completely novel training experience. This experience

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[4] https://www.homecourt.ai/ Date accessed: 24 June 2022.

might in no way resemble traditional training experiences anymore. Transforming sports exercises allows for more flexibility in designing novel training exercises than augmentation, but is arguably also more difficult to implement as it abstracts further away from traditional exercises. This potentially leads to reduced transfer to actual training and match performance (Gray, 2019). Furthermore it carries the risk of inexpedient behaviour, that is, leading athletes to learn an incorrect form or technique because they adapt too much to the demands of the transformed task at the cost of focusing on the sports skills that should be addressed (Kajastila and Hämäläinen, 2015; Jensen *et al.*, 2015a; Halouani *et al.*, 2014). The climbing games of Kajastila and Hämäläinen (2015) are a good example of transformed training experiences. In one of their games, climbers had to evade projections of chain-saws, or were challenged to stay within a projected triangle while climbing around. This transformed the climbing experience, which usually focuses on the task to get to the top of the wall, into a set of evasion games.

3.3.2 Behaviour steering

Focusing on how the Sports ITech system targets the athlete, we can say that many systems aim to change the behaviour, perception, skills, or attitude of the athlete as they act in the sports activity. "Behaviour Steering" has been described by Delden *et al.* (2014) as an extension to the larger family of persuasive strategies, where the focus is on directly changing the behaviour of the user. The steered behaviour, in turn, could indirectly lead to changed (potentially, more permanent) perceptions, attitudes, skills, and social relations. Earlier work explored behaviour steering strategies of varying forcefulness ('require', 'insist', 'entice'; Delden *et al.* (2017)) and varying levels of transparency about the validity of presented information ('coaxing'; Postma *et al.* (2022b)).

Steering mechanics relate to mechanics of nudging (Thaler and Sunstein, 2008) and of persuasion (Fogg, 2002). Although fundamentally different in certain ways, all aim to elicit change, be it in behaviour or through attitude. Such mechanics can vary in a number of aspects. They can be momentaneous (changing someone's behaviour or attitude right now) or future directed (heightening the chance that someone will show desired behaviour at a future moment). The scope of the intended change can vary from minor (e.g., get someone to move a bit faster) to large (get someone to change their lives). The mechanics can be static, or dynamic and adaptive. They can be more direct in changing the ultimate outcome behaviour of interest (e.g., persuade someone to live a more active life) or more indirect via an intermediate factor (steer someone to pay more attention to their time spent sitting, in the hope that this will also change their attitude towards living actively). Furthermore, strategies to change someone's behaviour can be more, or less transparent about the goal; be more, or less forceful; and involve more, or less explicitly the active willingness of the person whose behaviour is changed, when the change occurs.

Behaviour steering roughly falls under the subarea of 'procedural persuasion' in the multidimensional model of persuasion as described by De la Hera Conde-Pumpido (2014). Their model describes three types of persuasive mechanics, among which 'narrative persuasion' and 'cinematic persuasion' are more focused on changing the heart and mind of the user first, and 'procedural persuasion' aims to change the behaviour itself as point of access. Based on the work of Stenros (2007), De la Hera Conde-Pumpido (2014) subsequently subdivides procedural persuasion strategies as relating to a game's: 1) grade rules (e.g. in-game measures, scores/possessions/lives), 2) goal rules (outcome related, victory/defeat), and 3) meta rules (modification of the rule system, as Frasca describes how one plays *with* rather than *within* the game). In Sports ITech, one can find quite some examples of procedural persuasion where the execution of the athlete's behaviour is directly influenced, leading to outcomes of engagement (e.g. having a form of balanced play might be beneficial for skilled players (Altimira *et al.*, 2016)), performance (e.g. improving motivation with a simulated partner to show higher effort (Feltz *et al.*, 2020)), and learning (e.g. learning an effective pacing strategy (Hoffmann *et al.*, 2014)).

Behaviour steering does not completely fall under the definitions of persuasive technology, however. As Tromp *et al.* (2011) describe, technology influences people by mechanisms that encourage or discourage; are strong or weak (forcefulness); and are hidden or apparent (transparency, which they call salience). In this spectrum of possibilities, behaviour steering differs from truly persuasive technology as it more explicitly includes possible aspects of forcefulness and non-transparency in its mechanisms. In the original definition of Persuasive Technology, Fogg (2002) explicitly ruled out any form of coercion and deception; the user is supposed to be willingly and transparently persuaded. Coercion and deception may be negative extremes, but more broadly any form of forcefulness and non-transparency have been considered suspect when used in persuasive technology – even though several researchers offered critique that in practice, many persuasive technologies include such mechanisms and we need new ways of looking at persuasive technology (Kampik *et al.*, 2018; Smids, 2012). This includes the terminology we use for these kinds of system. Delden *et al.* (2019) argue, based on a survey with 488 respondents, that different terms (e.g., steering, persuasion, or support) are perceived differently in relation to descriptors of real world interventions regarding perceived level of deception, coercion and manipulation, which may have many ramifications.

Aspects of forcefulness, non-transparency, and non-validity can be found in sports practice as well. Consider the golf-teacher who relies on physical guidance to teach a golf swing (forcefulness; Hodges and Campagnaro, 2012); the athletics coach who yells “you can do this” (validity); or the basketball youth coach who expressly designs for game balance in practice forms such that learners will experience a certain level of success (transparency; Koekoek *et al.*, 2014; Koekoek *et al.*, in press). These practice forms are uncontroversial and widely accepted in sports. As such, allowing a certain amount of forcefulness of steering and some lack of transparency in interventions in sports training seems fitting, given the nature of sports.

Also in Sports ITech, we see interventions that closely represent *steering* in which forcefulness and non-transparency can be recognised. ‘Hidden balancing’ provides a clear-cut example of non-transparency in Sports ITech systems (Gerling *et al.*, 2014). With hidden balancing techniques, player performance is covertly balanced between two differently skilled (or abled) players. When done properly, (hidden) balancing can promote fun, engagement and self-esteem (Altimira *et al.*, 2013, 2016; Gerling *et al.*, 2014; Graf *et al.*, 2019; Jensen and Grønbæk, 2016; Mueller *et al.*, 2012b; Delden *et al.*, 2014). Sports ITech systems can also exhibit ranging degrees of forcefulness, from gently enticing users to elicit certain behaviours (Delden *et al.*, 2017) to strictly enforcing a particular movement (Jezernik *et al.*, 2003). Although the mechanisms are not always explicitly hidden, users are generally not aware of the way (or even why) they are steered.

Based on the above literature, we further discuss behaviour steering based on three underlying dimensions (see Table 3.6).

Table 3.6: Subspace – Behaviour steering

Form – Game Nature – Behaviour Steering Steer the player's behaviour on different levels of forcefulness and transparency (Delden *et al.*, 2014; Delden *et al.*, 2017; Postma *et al.*, 2022b)
Forcefulness (Delden *et al.*, 2017) *Freedom to act within the game differently than the designer intended*
Transparency (e.g., Postma *et al.*, 2022b) *Possibility for athlete/player to know about the occurrence of steering, its intended target behaviour, and its purpose*
Validity (e.g., Hämäläinen *et al.*, 2005; Postma *et al.*, 2022b) *Information from the system on which the user decides to act may have varying levels of validity*

The first underlying dimension of behaviour steering is its *forcefulness*. Delden *et al.* (2017) explicitly investigated a range of levels of forcefulness in behaviour steering. Steering is forceful when there is little room for the player/athlete to act different from the target behaviour that was intended by the designer.

The second underlying dimension is the *transparency* of the system, which can be regarding the intended target behaviour, the very fact that steering occurs, and the purpose of the steering. This ranges from transparent to covert: in some systems, all information is actively available; in others, some information is under-emphasised or actively withheld. For example, Postma *et al.* (2022b) explored a form of covert behaviour steering.

The third underlying dimension is the *validity* of the information that the system offers. Based on available information on, among other things, target behaviour and performance, the user decides how to act. Information from the system on which the user decides to act may have varying levels of validity. Information about targeted behaviour or own behaviour may be represented truly, exaggerated or underplayed, or even distorted to some extent. For example, Hämäläinen *et al.* (2005) offered exaggerated feedback about own performance to athletes and Postma *et al.* (2022b) offered a misrepresentation of the athlete's capabilities, in both cases to steer the behaviour of the athlete.

In light of these three underlying dimensions, we discuss five steering strategies from literature in more detail.

A well-known way to steer behaviour in interactive applications is quite simply to *require* an agent to perform a certain action in order for the game to work as intended. Jensen *et al.* (2015b), for example, created an interactive installation to train perceptual decision making in handball in which players were required to jump off from a touch plate in order for the relevant targets to appear. This is a quite forceful way of steering the user towards performing the desired behaviour: without performing the required action, the game does not progress.

Another approach to steering behaviour, less forceful, is to *insist* (but not require) that players perform some action by providing them with game-outcome related rewards or conversely by handicapping players if a particular action is not performed (Delden *et al.*, 2014). In the comprehensive cycling exercise by Feltz *et al.* (2020), participants were insisted to at least keep up with their virtual partner by mentioning that their scores were dependent on the least distance travelled by the two of them, whereas true targeted main outcome was the mean watt produced. Similarly, LED lights used for pacing on a running track 'insist' that the athlete follows their speed and timing (Taylor *et al.*, 2021). The 'insist' mechanic is less forceful: the game still proceeds even if the target behaviour is not employed, but showing the desired behaviour leads to in-game meaningful advantages.

Thirdly, based on the concept of nudging, Delden *et al.* (2017) proposed a more subtle approach to influence player behaviour and performance in the form of *enticement*. With enticement, players are neither required nor insisted to perform a certain action, but are enticed to behave in a certain fashion by providing rewards that have intrinsic value to the player, but no value in terms of game-related outcomes. A typical example of enticement is to provide players with items that add to the appeal of their in-game avatar. In the cycling study by Feltz *et al.* (2020), this was nicely demonstrated with a red hue on the screen whenever the participant dropped in effort.

The fourth approach is *overt misrepresentation*: athletes are shown information that is to some extent invalid, to steer them to better performance, but they are aware of this (the system is transparent). For example, Hämäläinen *et al.* (2005) and Granqvist *et al.* (2018) both exaggerated the characteristics of the athlete in the game environment (avatar flexibility, jump height, etc) to steer their performance while contributing to a good experience.

The fifth and final approach was recently introduced by Postma *et al.* (2022b) under the term *coaxing*. Their aim was to trick players into showing changed behaviour by providing them with feedback that misrepresents their athletic performance through data (invalid information), without them being aware of that fact (non-transparent). Athletes were led to believe that their performance or athletic abilities are different from what they truly are.

The more subtle variants of these steering strategies require the use of somewhat indirect prompts to get the user to express the desired behaviour. So far, people have at least successfully steered movement behaviour using prompts in the visual domain (e.g., Delden *et al.*, 2017; Landry and Pares, 2014) (or more forceful instructions to follow a visual representation (Hoffmann *et al.*, 2014)), by haptic cues (e.g., Ruffaldi *et al.*, 2009) (which is closer to prompts than the rather literally forceful force-feedback of Rauter *et al.* (2011)), or providing feedback in the audio domain via sonification of movement parameters (e.g., Effenberg *et al.*, 2016). As mentioned by Delden *et al.* (2017), the indirect forms of steering might define a new in-activity goal in themselves, thus changing what the player strives for in the game as well.

In summary, by employing various approaches, a designer of sports interaction systems, together with stakeholders and players, can decide how powerful, controlling, covert, or forceful the steering elements are (Delden *et al.*, 2017; Postma *et al.*, 2022b).

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Interestingly, note that these mechanics can also occur without Sports ITech in events such as the Tour de France.[5] There are adaptive rules that *require* riders to finish within a certain time after the winner to not be disqualified. The sprinters are *insisted* to partake in intermediate sprints to gain points for a parallel goal, or finishing first on a last climb can lead to additional removal of seconds. Less prominent, even in such a professional race they make use of *enticing* racers with embellishments, via a judge-appointed "most attacking rider of the day" recognition, which is rewarded with wearing white numbers on a red background the day after.[6] And even *coaxing* (albeit unintentionally) may be recognized in a recent event[7] in which a competitor in an Olympic cycling event was convinced, based on the most recent information they had, that they were the frontrunner and then won, where in fact they were riding second place. This had influenced the resulting experience, the team's chosen tactics, and perhaps performance.

3.3.3 (Multi)user-game relations: Locatedness

The next branch of our taxonomy concerns facets of the interaction between multiple players. First of these, locatedness (not to be confused with *Space*, see Section 3.1) is about whether or not players are co-located while interacting with one another. If not co-located, players are said to be distributed, either in space, in time or in space *and* time (see Table 3.7).

By far the most Sports ITech systems provide co-located user-user interactions (e.g. Fogtmann *et al.*, 2011; Ludvigsen *et al.*, 2010; Rebane *et al.*, 2017; Ishii *et al.*, 1999; Graf *et al.*, 2019), probably not in small part because practising sports is typically a social and co-located endeavour itself. Still, many solitary sports activities remain, such as going for a jog. Some designers have used the concept of co-located play to transform a solitary experience into a social one (e.g., Häkkilä *et al.*, 2013; Park *et al.*, 2012; Ahtinen *et al.*, 2010), aiming to boost engagement, motivation, connectedness and performance.

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[5] https://letour.fr Date accessed: 24 June 2022.

[6] Although the additional small monetary compensation does not fit well with enticing as postulated by Delden *et al.* (2017).

[7] https://www.cyclingnews.com/news/olympics-van-vleuten%2Dcelebrates-but-mistakes-silver-for-gold/ Date accessed: 24 June 2022.

Table 3.7: Subspace – Locatedness and Distributed Play

Form – Game Nature – Locatedness and Distributed Play Athletes are co-located, or geographically / temporally distributed
Co-located *Multiple athletes carry out their sports activity together, at the same moment in the same place*
Over-a-Distance (Mueller *et al.*, 2007b) Geographically distributed *Athletes do their sports activity together at the same time, but are not in the same place, e.g., shadow boxing with an opponent who is in another city (Mueller* et al.*, 2008a)* Temporally distributed *Athletes interact with a "historic representation" of another athlete while doing their sports activity, e.g, running against the schedule of a past performance (WaveLight, https://www.wavelight-technologies.com)* Spatiotemporally distributed *Combination of the previous two types of "distributedness" (e.g. GhostPacer, 2020)*

Arguably, correspondence chess was among the first attempts to bridge the gap between geographically distributed players. It is rumoured that King Henry I and King Louis VI already engaged in this form of chess (Wall, 2007). Today, with the rise of technology, more and more people seek to bridge the gap in space and time to practice sports with others, e.g. following online fitness classes. Also interaction designers extensively looked into the potential of "sports over a distance", most notably Mueller and his team.[8]

With "sports over a distance", Mueller challenges Vossen's contention that "*locatedness* is essential to all sports" (Vossen, 2004, p.61), effectively untangling the confound of *physicality* and *locatedness* (see also Mueller *et al.*, 2008b, p.265). This 'networked approach' allows users to interact over time (GhostPacer, 2020; Strava Support, 2020; O'Hara, 2008; Go, 2020) and space (Mueller and Gibbs, 2007a; Mueller *et al.*,

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[8] Mueller and Gibbs (2007a, 2007b, 2006), Mueller *et al.* (2006, 2008a, 2009a, 2010a, 2007b, 2014, 2003a, 2003b, 2009c, 2009b, 2011).

2003a, 2006, 2008a, 2010a; Yao *et al.*, 2011; Nintendo, 2020; Beelen *et al.*, 2013). The co-located and distributed presence can furthermore be within teams, or across teams, or in a mixture of the two (Delden *et al.*, 2016a). Players can even be distributed in space *and* time.

Big fitness brands like Fitbit, Nike and Strava connect users by means of leaderboards and other social features. This type of interaction can have an effect on the way athletes shape and structure their exercises (Hafermalz *et al.*, 2016). Take Strava, an application for running and cycling that records among other things split times and (average) pace. Strava hosts leaderboards for specific segments, showing which Strava-users completed that segment fastest (e.g., “king of the hill”). When visiting popular segments one can see a runner or cyclist divide their efforts with regards to these predefined segments, so as to deliver the best possible performance on that specific segment. As such, Strava enables athletes that are both geographically and temporally distributed to interact with one another, continually shaping each other’s exercise practice.

Sports ITech that enables ‘temporally distributed sports’ is mostly geared towards racing past performances of peers, most notably in running. GhostPacer[9] for example makes use of light-weight AR-glasses to project a holographic opponent that mimics the pace of others on a certain route. WaveLight[10] is another such example. WaveLight is a professional pacing system that is being used in athletics (competitions) to support performance. The system consists of a series of LED-lights, mounted to the inner bend of an athletics track. The LED-lights can be programmed to a show the pace of past performances of others, e.g. personal bests or world records. Finally, Strava’s ‘king of the hill’ feature, in which runners compete for the best split-time on a certain segment of a route, is widely used (Hafermalz *et al.*, 2016). Still, ‘temporally distributed’ Sports ITech has only received little attention in research; here we identify an opportunity in the design space for future work.

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[9] https://ghostpacer.com Date accessed: 24 June 2022.

[10] https://www.wavelight-technologies.com Date accessed: 24 June 2022.

3.3.4 (Multi)user-game relations: Player Interaction Patterns

Besides locatedness, relations between players are also determined by team and opponent formats. Adapted from the seminal work of Avedon (1981) on invariant structural elements in games, Fullerton (2014) introduced seven 'Player Interaction Patterns' to characterise the (three-way) interaction of player with other players and the system (see Table 3.8).

Table 3.8: Subspace – Player Interaction Patterns

Form – Game Nature – Player Interaction Patterns	Athletes interact with each other and the game in various patterns (Fullerton, 2014)
Single Player vs Game	*Player has to beat the game on their own, e.g. climbing a rock face on your own*
Multiple Players vs Game	*Multiple players simultaneously attempt to individually beat the game, without interacting with each other, e.g. a shuttle run*
Player vs Player	*Two players pitted against each other, e.g. tennis*
Unilateral Competition	*Multiple players pitted against a single player, e.g. a game of tag*
Multilateral Competition	*Free-for-all: every player pitted against all others, e.g. Fortnite*
Cooperative Play	*Multiple players work together to beat the game, e.g. reaching the summit of Mt. Everest*
Team Competition	*Two or more teams of players compete whereby team members cooperate to win as a team, e.g. volleyball*

The first, and probably most familiar Player Interaction Pattern is termed 'single player vs. game'. In this mode, players interact only with the system and not with any additional players, e.g. "Whack a Bat" and "Spark Game" (Kajastila *et al.*, 2016); "Platform Jumping Game" (Holsti *et al.*, 2013); "Hanging off a Bar" (Mueller *et al.*, 2012a) and various other systems (Jensen *et al.*, 2015b; Hämäläinen *et al.*, 2005;

Sidharta and Cruz-Neira, 2005). The second is called 'multiple individual players vs. game' and captures the situation in which multiple players interact with the same system at the same time without interacting (directly) with one-another, like in a shuttle run test (Leger and Lambert, 1982). In the third mode, 'player vs. player', players directly interact with one another through the system, e.g. "One-on-One" (Fogtmann *et al.*, 2011); "Spots mode" (Ishii *et al.*, 1999); "Space Ball 1" (Izuta *et al.*, 2010) and various other systems (Altimira *et al.*, 2016; Mueller and Walmink, 2013, Mueller *et al.* 2006, 2008a). In the fourth mode, 'unilateral competition', multiple players are pitted against a single player, as for example in the traditional game of "Tag" (Konkel *et al.*, 2004; Delden *et al.*, 2014, 2016a). The fifth mode is much like the fourth, however in 'multilateral competition' all players are pitted against each other, more colloquially known as 'free for all' (Mueller and Gibbs, 2007a). 'Cooperative play' is the sixth mode, in which players cooperate to play the system, e.g. "Painting mode" and "Thunderstorm mode" (Ishii *et al.*, 1999); "Space Ball 2" (Izuta *et al.*, 2010) and various other systems (Ahtinen *et al.*, 2010; Takahashi *et al.*, 2018). And last but not least, with 'team competition' two or more teams (directly) compete against each other, e.g. "Imaginary Reality Basketball" (Baudisch *et al.*, 2014); "3v2" (Jensen *et al.*, 2014a) and various others (Nojima *et al.*, 2015; Rebane *et al.*, 2017). Here we have provided a condensed overview of the various Player Interaction Patterns, exemplified through existing Sports ITech systems. As Fullerton provides a very clear reading on the topic, the interested reader is further referred to their work (Fullerton, 2014, see also: Avedon, 1981).

It can be seen that Sports ITech comes in different flavours, with especially the categories of "player vs game" and "player vs player" being well sampled. It might be that these categories are well represented because they fit the nature of sports well. Many sports are organised in a one-on-one fashion, like: fencing, boxing and tennis. Other player interaction patterns are less prevalent in Sports Interaction Technology, like "unilateral competition" and "multiple player vs game". These schemes are further removed from classical sport interaction patterns, which is not to say such schemes are completely absent sports. Conquering Mount Everest with a team of mountaineers and completing a mud run with friends are forms of “multiple player vs game”; Ultimate Tag, a fast-paced sports activity that much resembles the traditional game of tag, can be considered unilateral in competition.

Although not all Sports ITech is game-like enough to employ the Player Interaction Patterns in the design, the patterns that do occur in a specific sports domain greatly matter for how to go about designing Sports ITech for that domain. Some sports involve opponent strategies, others not; some involve team cooperation strategies and social interaction whereas others do not. A reflection on the Player Interaction Patterns contained in a sport may lead to inspiration as to what to design for. Player Interaction Patterns also offer an opportunity to deliberately vary upon the patterns beyond what is common in a certain sport, to create novel forms, *transforming* the sports activity as described in Section 3.3.1.

3.3.5 Constraints on Action – Impacting the agent / task / environment triad by manipulating one facet

This section concerns the question of what is manipulated in order to achieve the goal in Sports ITech: the player, the environment, or the task. We discuss this issue based on Newell’s Theory of Constraints (see Table 3.9), an authoritative framework for discussing this topic in the context of (motor) learning.

Newell’s Theory of Constraints (Newell, 1986; Newell and Jordan, 2007) is a conceptual framework often used in Physical Education and sports practice to promote (motor) learning and has been widely adopted.[11] The basic premise of Newell’s work is that movement skill acquisition occurs through the dynamic interplay of numerous constraints (Renshaw *et al.*, 2010). When focusing on the dynamic system of an athlete there are redundant degrees of freedom (Bernstein, 1967b) that trough constraining can result in certain behaviour. Muscle architecture, genetic make-up, heart rate, state-of-mind, ambient light, socio-cultural context, task goals and many other factors shape the emergence of behaviour and learning. The influence of constraints is easily illustrated

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[11] Chow *et al.* (2007, 2011), Correia *et al.* (2019), Davids *et al.* (2012a, 2013, 2015), Brymer and Renshaw (2010), Renshaw *et al.* (2010), and Seifert *et al.* (2017).

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Table 3.9: Subspace – Constraints on Action

Form – Game Nature – Constraints on Action Changes to agent, environment, or task, make a difference to how the sports activity unfolds in the interaction between these three facets (Newell, 1986; Newell and Jordan, 2007)
Performer constraints Structural *Structural, relatively time independent, aspects of the performer ("agent") shape the sports activity, e.g., body morphology* Functional *Functional, more dynamic and fleeting, aspects of the performer shape the sports activity, e.g., emotion or motivation*
Environment constraints *Environmental aspects, external to the agent, shape the sports activity, e.g., temperature or the built environment*
Task constraints Goals *The goal of the task shapes the sports activity* Rules *The "rules of the game" shape the sports activity*

by considering how body morphological characteristics result in distinct player specialisations within sports: e.g. the 'center' versus the 'point-guard' in basketball, and between sports: e.g. the gymnast versus the sumo-wrestler. Some constraining factors are relatively fixed and others offer the opportunity for modification. In Physical Education and sports practice, according to this theory, trainers and coaches are tasked with identifying and manipulating the relevant constraints to promote learning, of which motor skill acquisition is a relevant part.

Newell proposed that constraints could be classified in three main classes: *organismic constraints*; *environmental constraints* and *task-constraints*. Organismic constraints are those constraints that relate strictly to the organism's biological system, like body morphological characteristics and emotion. Organismic constraints, as postulated in Newell's work, hold resemblance to "The Moving Body"-lens from the

Exertion Framework by Mueller *et al.* (2011). Organismic constrains can be further divided into *structural constraints* and *functional constraints*. Structural constraints are relatively time independent constraints, like body mass and composition. Functional constraints are more fleeting and dynamic, like heart rate, lactate concentrations and motivation. Environmental constraints on the other hand are those constraints that are strictly external to the organism, like location, the built environment, social context and ambient light and temperature. Finally, task-constraints specifically pertain to the goal and the rules of the task being performed. Note that the distinction between environmental constraints and task constraints can be an ambiguous one.

In basketball for instance, the height of the rim is lower for kids than for adults; is rim height a task constraint or an environmental constraint? Arguably, changes in rim height cause a change in task; while at the same time the environmental layout changes. And what about ball size and weight – kids playing with a smaller, lighter ball? In his original formulation, Newell did not explicitly mention “implements and equipment” under task-constraints (Newell, 1986) though later on Newell did (Newell and Jordan, 2007). Pragmatically however, it might not matter that much. Knowing that the framework of constraints provides three dimensions along which the design of Sports ITech can be varied might prove prolific, regardless of which category the variation falls under.

In practice, Newell’s Theory of Constraints has been implemented in widely diverse ways without making use of interaction technology. Popular implementations include: Field size manipulation and small-sided games (environment) (Olthof *et al.*, 2015, 2018, 2019a, 2019b; Amani-Shalamzari *et al.*, 2019; Gabbett and Mulvey, 2008; Buszard *et al.*, 2016; Serra-Olivares *et al.*, 2015); scaling of equipment (environment) (Buszard *et al.*, 2016; Wright, 1967; Davids *et al.*, 2008); setting subgoals or changing the overall task-goal (task); introducing additional rules for play (task); influencing player motivation (organism); and influencing emotions (organism) (see also: Headrick *et al.*, 2015).

Many of these implementations are probably not unfamiliar to sports interaction designers. Field size manipulations (environment) have found their way in Sports ITech applications (Altimira *et al.*, 2016;

Postma *et al.*, 2019); virtual reality and augmented reality are being employed to present players with novel contexts (environment) (Kosmalla *et al.*, 2017b; Baudisch *et al.*, 2014); implements are introduced (environment) to allow novel training regimens (e.g. Fogtmann *et al.*, 2011; Jensen *et al.*, 2014a; Jensen *et al.*, 2015b; Andres *et al.*, 2018; Mueller and Muirhead, 2015; Nitta *et al.*, 2015; Chi *et al.*, 2004; Graaf *et al.*, 2009); community learning and sharing of acrobatic moves and locations are supported for Parkour (task) (Waern *et al.*, 2012); heart rate is being employed to shape behaviour (organism) (Ketcheson *et al.*, 2015; Mueller and Walmink, 2013; Mueller *et al.*, 2010b; Nenonen *et al.*, 2007; Walmink *et al.*, 2014; Stach *et al.*, 2009); player capacities and action possibilities are modified within interactive games (Delden *et al.*, 2014; Graf *et al.*, 2019) and player intentions (organism) are being influenced through steering techniques like enticement (Delden *et al.*, 2017); see also Section 3.3.2. Finally, interaction technology is also easily implemented to explicitly influence task goals (Fogtmann *et al.*, 2011; Kajastila *et al.*, 2016; Kajastila and Hämäläinen, 2014) (task). What ITech adds to the possibilities for manipulating constraints is especially its vast capacity to *dynamically* and *adaptively* vary constraints; e.g., without an interactive display built into the floor it would be hard to *dynamically* vary the field size throughout a volleyball match.

Again, the categories are overlapping. Some environmental manipulations (e.g., embellishments) may work or not depending on the psychology and personality of the person, which makes the manipulation "agent related environmental constraints". Finally, there are not many artefacts that can be rightfully listed under 'task constraints - rules' and 'performer constraints - structura (however, see: Petersen Matjeka *et al.*, 2021). Arguably this is because rule changes are easily implemented (e.g., telling players they *have* to pass the ball three times before scoring), posing little design challenge, while structural changes are very hard to implement (e.g. one's body-morphology is not easily altered). With structural organismic constraints, it is also the question whether (momentary) changes to such constraints are sensible from a standpoint of representative design (Brunswik, 1956).

All in all, thinking about the constraints addressed by a specific Sports ITech system not only offers a way to categorise systems; it also offers an invitation to explicitly consider what are the constraints that can conceivably be manipulated for a given sports related goal, and as such point to possible solutions in the form of novel interactions.

3.3.6 Gamification, Playification, and Sportification

ITech that is used for sports can be shaped and adapted in various ways in an attempt to make the experience of the user closer to the preferable state identified by the designer. From the perspective of game design, a recurring essential element is targeting, enabling, and facilitating such different experiences (Schell, 2008). Although a designer is not able to design the aimed for experience directly, the game design choices enable various experiences (Schell, 2008). One way to look at Sports ITech from a designer perspective is to enable a more play-like, game-like, or sports-like experience. As an example, Sports ITech designers can target users to go to their maximum effort in a virtual bike ride (Löchtefeld *et al.*, 2016), adapt their physical effort to another player in a social experience while jogging (Mueller *et al.*, 2010b), or making physical effort central while keeping the focus on playing a game by 'hanging off an excercise bar' (Mueller *et al.*, 2012a). While all revolve mainly around triggering player effort during a technology-mediated interaction resembling sports, the subsequent experiences are very different. In order to facilitate the design for these experiences we build on Deterding *et al.* (2011) using the terms playful design and gameful design. Furthermore, inspired by the play-game-sports continuum (Meier, 1981; Vossen, 2004) we add sportsful design (see Table 3.10).

When considering to make a design more gameful, this is strongly related to the well-known definition of gamification: *'the use of game design elements in non-game contexts'* (Deterding *et al.*, 2011, p.9). In the accompanying paper they also deliberately positioned the term gamification and the academia-preferred use of 'gameful design' as different from playful design. This follows Caillois well-known treatment of play on a spectrum between the free play-like 'paidia' and more structured game-like 'ludus' (Caillois, 1961; Deterding *et al.*, 2011). From this, gamification focuses on the ludus, whereas the PLayful EXperiences (PLEX) framework of Lucero *et al.* (2014) in addition

Table 3.10: Subspace – Gamification, Playification, and Sportification

Form – Game Nature: **Gamification, Playification, and Sportification** Apply game mechanics, playful characteristics, or typical sports mechanisms to interaction (Deterding *et al.*, 2011; Nicholson, 2012)
Gamification *Use of game design elements in non-game contexts to enhance interaction (Deterding* et al.*, 2011), e.g., points, badges, and leaderboards*
Playification *Use of playful design elements to enhance interaction (Nicholson, 2012; Márquez Segura* et al.*, 2016), e.g., incorporating humour, excitement by stimulating senses, or opportunities to nurture*
Sportification *Use of sports elements to enhance interaction, e.g., introducing referees, skill-related challenges, or bodily expression in a non-sports activity*

includes a focus on the playfulness (i.e. paida part of the spectrum). In a similar fashion *playification* is thus proposed (Nicholson, 2012), accordingly calling for a focus on playful behavior (Márquez Segura *et al.*, 2016). For instance, typically related to playification is triggering curiousity, incorporating humour, excitement by stimulating senses, or opportunities to nurture (Lucero and Arrasvuori, 2013), whereas the goal and rewards-oriented is related more to gamification (Nicholson, 2012; Márquez Segura *et al.*, 2016).

Building on this gradual distinction with generative power, we extend the playification-gamification dyad with the term *sportification* following Heere (2017) who introduced this term in a sports management context. With sportification referring to a practice of improving engagement by adding sports elements to non-sports contexts. Rather than to pinpoint overlap and borders of the concepts, or discussing definitions, there might be more merit in reiterating their suggested stereotypical features regarding the use of sportification. Such features can easily be integrated or emphasised for instance related to their suggestion of organisational structure and focus on physical prowess, including the use of judges, referees, bodily expression, uniforms, skill-related challenges, and scheduled matches. Although sportification has been introduced fairly recently one can already actively recognise it in practice and academia. In news and footage on (Finnish) hobby horse riding competitions, we recognise a sportification of the originally playful activity of walking, rotating, and jumping, with a hobby horse, in the form of adding seriousness with organised events including juries (Artemis Hobbyhorses, 2019). As another example, related work regarding physical rehabilitation explicitly mentioned the possible advantages of adding a referee to rehabilitation activities (Márquez Segura *et al.*, 2016).[12]

There are various forms and combinations related to a sports-related context resembling a priori more a game, play, or actual sport that arise after applying these three strategies of playfication, gamification, and sportification. There is playification of sports (e.g. adding hedonic-related effects such as water ripples (Ishii *et al.*, 1999)). There is sportification of games, which is very recognisable in eSports with large sums of prize money, huge audiences, and with big institutionalised organisations behind it. Although harder to find there are systems that might be seen as sportification of already sportful play experiences such as slacklining facilitated with technology to provide a skill acquisition-oriented routine (Kosmalla *et al.*, 2018). Of course there is also gamification of sports, for instance shooting a ball against a wall but competing over a distance combined by adding a virtual layer implying additional rules as in ‘Breakout for Two’ (Mueller *et al.*, 2003a).

So we might say, Sports ITech can help to create *sportful games* such as exertion games that are closely related to existing computer games (e.g. Hanging of a Bar (Mueller *et al.*, 2012a) and Kick Ass Kung-Fu performed on stage, adding room for spectacle (Hämäläinen *et al.*, 2005)). Sports ITech can also help to create *sportful play*, such as playful use of an e-bike (beyond commuting) which is responsive to posture (Andres *et al.*, 2018; Mueller *et al.*, 2018). There is Sports ITech to create *gameful*

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[12] Although this latter was done in a call towards playification over gamification, rather than the call for sportification that we recognise in it.

sports, although many sports are already competitive, rule bound, and outcome-oriented, other game aspects might be highlighted such as virtually facilitated challenges (Feltz *et al.*, 2020), adding targets or obstacles (Kajastila *et al.*, 2016), or simply adding points or transforming measures into scores (e.g. the commercial soccer wall Yalp Sutu can indicate the speed of impact). Sports ITech can also result in more *playful sports*, such as running together over a distance hearing a representation of the other's effort (Mueller *et al.*, 2007a), there is no direct goal or outcome but it opens a space of what to do and elements to enjoy.

Similar to the idea behind moving from 'augment' up to 'transform' (Ishii *et al.*, 1999), there are extreme cases where the *-ication* becomes the essence and takes over the original activity. Gamification of a sport can make it 'a game', in some modes of interactive climbing the sports is no longer the essence but the game becomes the core such as avoiding chainsaws while on a wall (Kajastila *et al.*, 2016). In a similar fashion the sportification of a game can turn it into a full-fledged sport with professionalisation, institutionalising, and prowess to name a few elements, as we mentioned eSports is often seen/treated as a sport (Postma *et al.*, 2022a) and now involving scholarships, trainers, tournaments and coaches. Playification of sport can turn it into play, for instance in *'I Seek the Nerves Under your Skin'*, running is turned into something we would call a play activity, constant acceleration of running is coupled to the playing of a poem, or fading of the poem when this not achieved (Marshall *et al.*, 2016). As the authors recognise this is hard to do and players decided for themselves on how to interpret the experience, whether to confirm to the challenge or rather see it as a open-ended play.

In all of these cases it is important to keep in mind that playful or gameful mindset are often essential in the decision of calling something a game or play (Deterding *et al.*, 2011; Schell, 2008; Stenros, 2015). In a similar fashion we should anticipate that a sportful mindset can play a role in the extent to which something is seen as a sport. Incorporating the right combination of the elements in the right extent is seen in relation to targeting the right experience for training, motivation, entertainment, 'performances' and many more sport-related elements.

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3.4 Feedback – Delivery of Supportive Information

Almost every type of interaction described in the earlier sections makes use of some kind of *feedback on the athlete's sports performance and results*. In this section we specifically address the *form and content* of the feedback (see Table 3.11). Which aspect of the athlete's performance and result is the feedback about, and with what timing and frequency is it delivered? In the "Function" section, we dive into more detail into what the feedback is supposed to achieve; here we focus on the general form of delivery.

This section is a nice example of how the division of Form and Function that we employ in this monograph can be an artificial one. When considering feedback and the timing, frequency, content and modality thereof, form and function are tightly intertwined. Different forms of feedback serve different purposes. Therefore this section will be slightly different in tone than most of the other sections. Here, we will discuss the different forms of feedback and their effectiveness and application to sports starting from textbook[13] distinctions in sports science (in which typically the term "augmented feedback" is used to denote the supportive information and its form of delivery), while still illustrating and elaborating the relevant concepts with existing work in Sports ITech. This information is crucial in the design of any Sports ITech employing feedback.

Feedback is closely related to the performance of actions by the athlete; it happens around episodes of sports activity. Figure 3.1 sketches the rough structure of the feedback cycle. Instructions / demonstrations can be considered 'up-front feedback'; one can furthermore get feedback while performing a movement episode; or afterwards after finishing a movement episode. Finally, feedback is often (though not always) followed by subsequent attempts at performing (better). Feedback provides information about the athlete's execution of the movement, about possible earlier reference executions by self or others, or about the differences between the current attempt and the desired execution

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[13] Edwards (2010), Magill and Anderson (2011), McMorris (2014), Schmidt *et al.* (2018), Schmidt and Lee (2014), Gollhofer *et al.* (2013), and Hodges and Williams (2012).

Table 3.11: Fourth 'Form' subbranch – Delivery of Augmented Feedback; based on textbook distinctions from sports science (Edwards, 2010; Magill and Anderson, 2011; McMorris, 2014; Schmidt and Lee, 2014; Schmidt *et al.*, 2018; Gollhofer *et al.*, 2013; Hodges and Williams, 2012). The last two (Function of and Need for augmented feedback) are typically mentioned in literature together with the other four, however in this monograph we discuss these two elsewhere under the 'Function' branch of our taxonomy.

FORM – FEEDBACK Supportive information can be delivered in many forms
Timing of the feedback *Feedback can be delivered with different timings in relation to the moment of movement*
Modality of the feedback *Feedback can be delivered in various modalities that each have their (dis)advantages*
Frequency of the feedback *Feedback may be delivered for each and every movement, or less frequently*
Content of the feedback *There is a wide range of considerations regarding the content of the information in the feedback*
Function of the feedback *The function of the feedback may be to inform, motivate, guide, attune, or reinforce. However, this topic is discussed in the 'Function' section*
Need for augmented feedback *The role of the feedback may vary in how necessary it is, or may even be a hindrance. This is also discussed as part of the 'Function' section*

of movement. Given this structure of the feedback cycle, Table 3.11 presents the distinctions typically made in the aforementioned text books regarding the form of delivery of feedback.

The term 'augmented feedback' in sports science is used to set external sources of feedback apart from internal, sensory sources of feedback. Sensory feedback is ever-present and provides information about the body (proprioceptive feedback) and the environment in which the body is situated (exteroceptive feedback). Together, these feedback

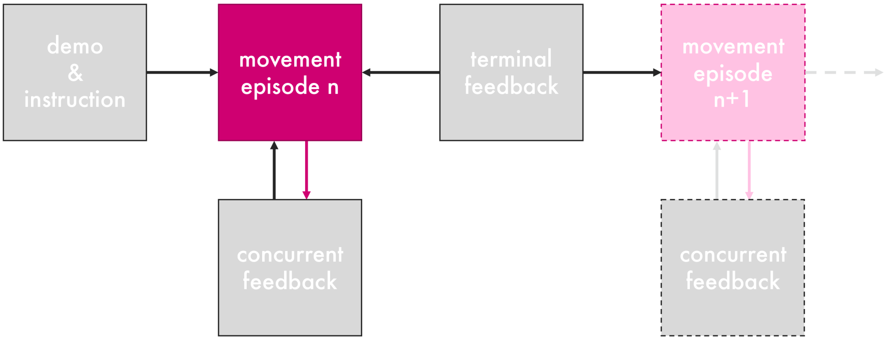

Figure 3.1: Structure of feedback cycle

sources inform the learner about the state of the agent-environment system. What in sports science is called "augmented feedback"[14] may be given by an external entity, such as a trainer, coach or interactive training system. It supports sensory feedback and might serve different purposes.

The effectiveness of augmented feedback is interdependent on timing; modality; frequency; and content. All dimensions should be carefully considered in designing augmented feedback; if designed improperly, augmented feedback might actually hamper motor learning and performance rather than promote it (Sigrist *et al.*, 2013). Furthermore, the use of feedback is strongly related to the sport it is a part of (including, among others, nominal and functional task complexity) and the purpose that it serves in the sports activity (e.g., learning versus performance). These latter two facets are discussed as part of the Function branch of our taxonomy in Section 4.3.1 (see also Section 1.3).

Before delving into the specifics of augmented feedback, it is important to note that "*Few research findings are universal and exceptions to general findings may appear and must be taken into account when searching for the most effective instructional practices.*" (Edwards, 2010). Furthermore, the effectiveness of feedback designs is often discussed in a comparative fashion. For example, knowledge of performance is

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[14] Not to be confused with the term augmentation as used in earlier sections to denote some property achieved by adding technology to sports activities.

often regarded as more effective than knowledge of results (see also Section 3.4.4). However, providing knowledge of results might still be more effective than providing no feedback at all. To belabour the point, one feedback design need not be *ineffective* because some other feedback design is *more* effective.

3.4.1 Timing of feedback

The first aspect to consider is the *timing* of the feedback in relation to the execution of the movement it pertains to (see Table 3.12).[15] When considering the timing of feedback, there are again three distinct moments in which feedback can be provided: before, during or after the execution of the movement – although in all cases, augmented feedback at least typically happens as part of the training exercise or sports activity, thus as part of *conspective* systems (cf. Section 3.2).

Feedback provided before a movement is typically in the form of demonstration or instruction. With demonstration, a learner is shown how to perform a movement prior to execution. There are multiple dimensions within the concept of demonstration that determine the effectiveness thereof. Demonstration can occur via different media, e.g. video-recording or live and in a demonstration learners can model experts or peers, each with their own distinct advantages (see also Section 4.3.3).

When feedback is not provided prior to the execution of a skill it can either happen during the execution (concurrent feedback) or after the execution of the movement (terminal feedback). In either case, the choice of the timing of the feedback requires a careful consideration of the *Functions* of feedback as described elsewhere; for example, whether terminal or concurrent feedback is most appropriate depends on the nominal task complexity (see Section 4.3.4), the functional task complexity, the modality and the purpose. Overall, terminal feedback is considered more effective and appropriate than concurrent feedback. The major argument against concurrent feedback is that it can create a dependency. That is, performers become dependent on the presence of concurrent feedback in the execution of the movement, which means

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[15] Note that this is distinct from the time of interaction as addressed in Section 3.2.

Table 3.12: Subspace – Timing of Feedback

Form – Feedback Delivery – Timing Feedback can be delivered with different timings in relation to the moment of the movement/sports activity		
Before the movement	Instruction	*The provision of detailed, often verbal, information about a movement or exercise, prior to its execution*
	Demonstration	*A visual illustration of a movement or exercise, typically provided by peers or experts*
During the movement	Concurrent feedback	*The provision of supporting information during movement execution*
	Guidance	*The (often physical) constraining of motor error, typically by an instructor, during movement execution*
After the movement	Immediate terminal feedback	*The provision of feedback immediately after movement execution*
	Delayed terminal feedback	*The time-delayed provision of feedback after movement execution, including: feedback-delay interval; post-feedback delay interval; and inter-response interval*

that when concurrent feedback is withheld performance degrades, according to the guidance-hypothesis (Salmoni *et al.*, 1984; Schmidt, 1991), although this may be different for different feedback modalities (Fujii *et al.*, 2016). Still, there are a number of distinct situations in which the use of concurrent feedback is preferable. First, while concurrent feedback has often been found to hamper motor learning, it has also been shown that concurrent feedback typically leads to performance gains in the skill acquisition phase. As such, concurrent feedback might be used when trainers / coaches / players wish to boost performance (but not learning *per se*). Also, learners typically benefit more from concurrent feedback when task complexity is high. Finally, the early stages of learning can benefit well from concurrent feedback.

Terminal feedback is typically preferable over concurrent feedback. Terminal feedback has been shown effective for both low and high task complexity (nominal and functional). Increments in performance during the skill acquisition phase are well preserved in retention tests. There are several additional considerations for terminal feedback. First, the timing between the end of a movement and providing feedback (feedback-delay interval). Second, the timing between providing feedback and the following movement (post-feedback delay interval). And finally, the time between two practice attempts (inter-response interval). Each of these have a role in the effectiveness of feedback. Overall some delay between execution and feedback seems beneficial for learning (not necessarily for performance). As a rule of thumb, both the feedback-delay interval and the post-feedback delay should be at least 5 seconds each. A practical consideration in this regard is the trade off between the desired feedback-delays and the total number of trials that can be performed within the time available.

3.4.2 Modality of feedback

Augmented feedback can be presented using different modalities (see Table 3.13). The most commonly used modalities are visual, auditory and haptic in nature, with the latter modality often being further divided into tactile (i.e., sense of touch) and kinesthetic (i.e., sense of bodily position and orientation). Also, multimodal feedback systems are on the rise. Different modalities have distinct advantages.

Visual feedback has been used, for example, to provide instructions (Kosmalla *et al.*, 2018; Anderson *et al.*, 2013) and embellishments (Hicks *et al.*, 2019; Delden *et al.*, 2017) as well as direct feedback on the athlete's performance (e.g., Fadde, 2006). Visual displays allow for the presentation of highly complex and multi-dimensional information. Still, this might not always be desirable. Sometimes designers explicitly design abstract visual displays that only capture the relevant biomechanical / biodynamical properties of a movement. Such abstract displays can range from simple one-dimensional representations, like the red laser dot used in rifling to indicate the future hit area, to more complex higher-dimensional representations of movement. Bonnette *et al.* (2019),

Table 3.13: Subspace – Modality of Feedback

Form – Feedback Delivery – Modality Feedback can be delivered in various modalities that each have their (dis)advantages
Visual feedback *Ranging from realistic representations to increasingly abstract mappings and visualisations*
Auditory feedback *Using the many properties of sounds, such as pitch, timbre, rhythm, spatialisation, etcetera*
Haptic feedback Tactile *Varying in density and placement of tactile feedback actuators and in the frequency, intensity, and patterning of the generated feedback stimuli* Kinesthetic *Feedback supporting/accentuating the self-perception of body position and orientation*
Multimodal feedback *Working across multiple modalities simultaneously can strengthen the effectiveness and impact of feedback*

for example, mapped a number of key biomechanical parameters of squatting to an abstract visual representation to improve squatting technique (in the context of an ACL injury risk reduction program).

Auditory feedback is another often used form of feedback. This can be in the form of "sound icons" such as an alarm bell when a threshold value is exceeded, or by directly mapping certain measurement values to sound parameters. Auditory feedback can mean that data is directly made audible (audification), as is the case with the frequency spectrum of an EMG. Auditory feedback can also mean that dimensions of a movement are translated through a mathematical function to dimensions of audio (sonification), as discussed by Sigrist *et al.* (2013). There are a number of dimensions available for creating such a mapping, allowing for higher-order data to be characterised by sound, i.e. loudness, pitch, timbre, timing, rhythm, localisation, reverberation, spatialisation, and mono (left vs right ear) versus stereo. Different sound dimensions have different qualities in relation to the movement characteristic to be translated. For instance, information about timing is best captured by rhythmic patterning of a pitch-mapped stream and information about key events is best communicated through changes in loudness (Sigrist *et al.*, 2013). Auditory feedback has been successfully applied both in the form of terminal feedback and in the form of concurrent augmented feedback. As compared to concurrent visual feedback, concurrent auditory feedback appears to create less of a dependency for the learner.

Haptic feedback, just like auditory feedback, provides a range of dimensions that can be utilised to communicate information about movement characteristics, including: the number and placement of actuators, frequency, intensity, (relative) rhythmic patterning. So in combination, haptic displays allow for higher dimensional data to be communicated effectively. Haptic devices can take the form of biofeedback systems (Delden *et al.*, 2020; Ruffaldi *et al.*, 2009), providing feedback on posture and/or motor coordination, but have also been used to provide notifications (e.g. Fitbit - Surge, (Kosmalla *et al.*, 2016)) or to steer behaviour and provide more complex (tactical) information (Erp *et al.*, 2006; Förster *et al.*, 2009). While haptic feedback systems might well be used to provide feedback, little is still known about the mechanics thereof. It is not yet clear enough how haptic displays should be designed to provide effective feedback: Which haptic dimensions match well with which movement characteristics?

Kinesthetic augmented feedback serves to accentuate, support, or highlight the kinesthetic feel of a movement. It often involves the physical guidance of movement (Hodges and Campagnaro, 2012) through haptic guidance (Sigrist *et al.*, 2013). Kinesthetic augmented feedback can be more or less restrictive. The most restrictive form is 'position control', in which a user is guided through a movement by an external mechanism with little or no room to deviate from the intended trajectory (e.g. Lokomat, Hocoma AG, Volketswil, Switzerland). Less restrictive forms of kinesthetic augmented feedback (restrictive control) come in the form of apparatuses that guide users through a motion in much the same way as PE-teachers would do (Rauter *et al.*, 2011). Whereas strict position control keeps the user from making movement errors, restrictive control allows for some degree of error. Given that errors drive motor learning

(Sigrist *et al.*, 2013), 'restrictive control' is considered more effective than 'position control'.

With multimodal systems, more information can be communicated, while at the same time creating a more immersive experience. Multimodal systems have been explored in various combinations: audio-visual, audio-haptic; haptic-visual and audio-visual-haptic. Audio-visual systems have been shown effective by, for example, Jensen *et al.* (2014a); audio-haptic systems have been demonstrated by, for example, Großhauser and Hermann (2010); haptic-visual systems have been much implemented in commercial applications (e.g. Wii Sports) in which haptics add to the visual feedback that is presented and finally, a combination of all three has been successfully implemented (e.g. Pijnappel and Mueller, 2014; Ruffaldi and Filippeschi, 2013). The creation of multimodal feedback system is at this point in time both an art and a science. People can easily feel overwhelmed when too much information is presented to them using multiple channels. Also, the information being presented should be congruent, otherwise multimodality might in fact hurt performance and the sense of performance. Because of the immense degrees of freedom, within and between modalities and for tasks of ranging context, nominal task complexity, functional task complexity and purpose, a lot of work still has to be done to fully understand which systems work well under which circumstances.

Finally, beyond the visual, the auditory, and the haptic, interaction can in theory take place through all the sensory modalities that the human perceptual system is rich. However, some sensory modalities seem more suited to facilitate interaction (e.g. vision) than others (e.g. smell). That is not to say that smell, taste, temperature or even pain have no role in interaction at all. Some of these sensations might contribute to rich and persuasive experiences. Indeed, pain has often been implicated to be at the heart of many sports experiences (Nylander and Tholander, 2014; Mueller and Young, 2018; Tholander and Nylander, 2015). For obvious reasons, little work has been done to explore the role of pain in Sports Interaction Technology, however for some notable exceptions, see the work of Laso (2007).

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3.4.3 Frequency of feedback

Another aspect directly influencing the effectiveness of augmented feedback is the frequency with which it is provided. Generally, offering feedback for each and every practice attempt is most effective when functional task complexity is high (the task is difficult for this particular athlete). Put simply, novices are benefited by frequent feedback. When functional task complexity decreases, e.g. because of learning effects, the frequency with which augmented feedback is provided should decrease as well. For this, a number of 'feedback reduction schemes' can be employed (see Table 3.14).

Table 3.14: Subspace – Frequency of Feedback

Form – Feedback Delivery – Frequency Feedback may be delivered for each and every movement, or less frequently
Fading feedback *Straightforwardly decrease the proportion of practice attempts for which feedback is provided*
Bandwidth feedback *Only give feedback if error exceeds a certain bandwidth*
Self selection feedback *Offer feedback upon athlete's request only*
Summary feedback *Provide a summary of the athlete's performance after a larger number of attempts*
Average feedback *Summary feedback that only reports on general tendencies, not on specific trials*

The most straight-forward method to reduce the relative feedback frequency is to apply a feedback fading schedule. With such a schedule, learners receive frequent feedback in early practice stages and as skill improves over time, the feedback frequency is adjusted accordingly. Another way to reduce the relative frequency of feedback is to provide bandwidth feedback. With this, trainers only provide feedback when the learner displays errors that supersede a predefined acceptable bandwidth of errors. With increasing proficiency, the bandwidth of acceptable performance is narrowed, until performance is at some desired level. A third form of feedback fading is in the form of self-selection. In this form, learners request themselves whenever they wish to receive feedback. This type of feedback has been associated with high levels of motivation on the learner's part, which makes it a powerful technique. A fourth schedule, that lends itself particularly well for the use of technology, is summary feedback. With this, the trainer or coach observes a number of trials and provides a summary of the learner's performance. Summaries are easily provided using dashboards, graphs and statistics. Finally, average feedback, a form of summary feedback, can be provided. With this, learners receive an estimate of the *average* performance (error) only. It differs from summary feedback in the sense that learners are not provided with insights in trial-to-trial variations but are provided with feedback on general tendencies in their behaviour instead.

Which kind of feedback scheme is appropriate at what time is dependent on skill level, the task at hand and the dynamics of the learning process. For more information on schedules for fading feedback, please refer to the sports science literature on this topic (e.g. Sigrist *et al.*, 2013; Edwards, 2010).

3.4.4 Content of feedback

In previous sections, we discussed the various ways in which augmented feedback could be presented to the learner. We discussed the modalities involved and the timing issues related to delivering effective feedback. In this section, we will look at the nature of the information that is conveyed. Obviously, this starts with the *subject* of the feedback. This can be anything, for example: regarding the shape, speed, or strength of the movement; the technical execution; the success in achieving a goal with the movement; and so on. However, there are also more abstract dimensions in which the content of the feedback may vary, as summarised in Table 3.15.

First, feedback can be about the outcome of an action (Knowledge of Results, KR) or about the behaviour that led to that particular

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Table 3.15: Subspace – Content of Feedback

Form – Feedback Delivery – Content	The content of the feedback can vary along a number of dimensions
Type of feedback information	*Provide insight on the outcome of the action (Knowledge of Result) or about the behaviour that led to that particular outcome (Knowledge of Performance)*
Precision of feedback information	*Feedback content can be qualitative or quantitative; it can concern single errors, or multiple errors in one go*
Error correction response	*Feedback can be Descriptive (what happened) or Prescriptive (what should have happened)*
Focus of feedback	*Feedback can focus on what went right, or on what went wrong*
Focus of Attention	*Feedback can direct the athlete's attention inward, towards the movement, or outward, away from the movement to the context and the effect*
Validity of feedback	*Feedback can be correct or (intentionally or unintentionally) erroneous*

outcome (Knowledge of Performance, KP). KR is mostly about 'what' (correct or incorrect) while KP is more about 'why' (what caused the (in)correct action). Knowledge of Results can be particularly useful when the outcome of an action is not directly available to the learner (e.g. archery, riflery, diving) or when it is available but learners are not yet able to adequately evaluate what should be considered a good result (e.g. dance, ballet, gymnastics). Knowledge of Performance, on the other hand, explicitly helps learners to identify which movement characteristics lead to errors in performance and has typically more richness to it. In practice, teachers, trainers and coaches predominantly provide learners with Knowledge of Performance. This practice is supported by theory, as Knowledge of Performance is generally thought to be more effective than Knowledge of Results, especially in early stages of learning (Sigrist *et al.*, 2013).

Another distinction typically made is about the precision of feedback. With 'precision' referring both to the content of the feedback (quantitative or qualitative) and the amount of feedback (single-error response or multi-error response). Qualitative feedback statements, such as "good" or "go faster", provide the learner with a general sense of the adaptation that is needed to correct movement. Quantitative feedback on the other hand, adds precision and also provides the learner with an estimate of the magnitude needed to correct movement. Quantitative statements can range from: "a little more to the right" to "bend your head an additional 12.5 degrees along the sagittal plane". Which degree of precision is desirable depends on the individual skill level and the nature of the task. Feedback that is too precise has been shown to degrade motor learning. Conversely, imprecise feedback might hamper motor learning, too. It is generally contended that quantitative feedback is more effective than qualitative feedback in terms of performance and learning. Though, qualitative feedback can be used to boost motivation, in turn creating a positive environment for learning. Furthermore, qualitative feedback might provide experts with enough information to correct their behaviour of their own accord.

Feedback precision also relates to the number of different instructions that are provided in one go. Learners might make multiple movement errors while performing a certain action. Again, the level of precision is dictated by the skill-level of the individual and the nature of the task: "feedback should be provided with as much precision as a learner can meaningfully interpret" (Edwards, 2010, p.458).

Third, the error-correction response can be descriptive or prescriptive in nature. Descriptive feedback is factual in nature in that is describes to the learner what happened. Prescriptive feedback adds what *should* have happened. Overall, prescriptive feedback is thought to be superior to descriptive feedback in facilitating motor learning and performance. This is especially true for athletes in early stages of learning, where they might display difficulty in autonomously correcting their behaviour based on descriptive feedback alone. However, in the setting of Interaction Technology, note that prescriptive feedback is harder to automate.

Another classical distinction is about whether to provide feedback on what went right or on what went wrong. This distinction is sometimes also referred to as providing positive or negative feedback. Which approach is best suited depends on the intentions of the trainer/coach. Error-information is an important factor in motor learning, even to the point that motor learning is hampered if not enough errors occur in motor performance (Sigrist *et al.*, 2013).[16] Positive feedback, on the other hand, serves well to motivate people, with motivation serving as a facilitator for motor learning (although it has also been argued that motivation can also have a *direct* effect on motor learning (Schmidt and Lee, 2014)).

Yet another dimension in the content of augmented feedback is "focus of attention". When feedback is provided such that it directs the attention of the learner towards the movement itself, feedback is considered to facilitate an 'internal focus of attention'. Alternatively, when feedback is provided such that it directs the attention away of the movement itself, towards the effect of it, feedback is considered to promote an 'external focus of attention'. To illustrate the difference consider a basketball player practicing a free-throw. The coach might provide feedback with an internal focus of attention by saying: "really stretch your elbow on release". Alternatively, the coach might provide feedback with an external focus of attention by saying: "aim for the backside of the hoop". The prior example focusing the learners attention on body movements; the latter example focusing the learners attention on the intended movement effect. While it has been convincingly shown that feedback of the latter type is more beneficial to motor learning (Wulf and Prinz, 2001), both in terms of efficiency and effectiveness (Wulf, 2013), it is still very common for PE-teachers, trainers and coaches to direct athletes' focus of attention inward (Porter *et al.*, 2010). Various reasons for this have been put forward. Designing training regimens is still very much considered a craft, rather than a science, putting a premium on intuition and tradition (Porter *et al.*, 2010; Williams and Hodges, 2005). Also, for motor learning theory to make its way to practice typically takes some time (Porter *et al.*, 2010). Nevertheless, when designing feedback for interactive sports technology, it is advisable to provision feedback that prompts an external focus of attention.

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[16] An interesting parallel can be found in various types of machine learning, where negative rewards and negative examples can help explore the model space more effectively and efficiently.

The final dimension is about the validity of feedback. Validity in this context refers to whether or not the provisioned feedback is correct. Throughout literature, the importance of providing correct feedback is stressed. Motor learning and performance might be adversely impacted by inconsistent, incorrect and/or inappropriate feedback. As such, the provision of erroneous feedback is mainly discussed as something to avoid. However, as errors are thought to drive motor learning and skill acquisition, its potential might be more explicitly exploited. 'Error Augmentation' (AE), a novel concept in rehabilitation, is suggested to do just that (Israely and Carmeli, 2016). The idea with Error Augmentation is that errors are enhanced, either mechanically (Givon-Mayo *et al.*, 2014) or visually (Wei *et al.*, 2005), to promote motor learning. The premise here is that large errors contribute more to the process of motor learning than small errors. While the results of Error Augmentation on motor learning are still equivocal (Israely and Carmeli, 2016), it *does* show that the concept of erroneous feedback might be further explored to promote motor learning.

Another way in which the provision of erroneous feedback might be fruitfully applied is to impact *performance* rather than *learning*. In a recent study, the authors of this work performed an experiment in which volleyball players were misinformed about their ability to successfully intercept a serve (Postma *et al.*, 2022b). To one group of players, their abilities were overstated while to the other group abilities were understated. Although the results did not significantly impact performance, a trend could be observed in the data: participants whose abilities were understated outperformed their counterparts. What this potentially shows is that athletes' performance might be impacted by the information they receive about their own abilities. A final note on the validity of feedback pertains to its use in fundamental research. In motor learning research, experiments revolving around the provision of erroneous feedback have uncovered fundamental principles underlying motor learning (e.g. Krakauer, 2009, 2000).

3.5 Integration – Embedding ITech Activities in Training Schedules

Finally, the Form of a Sports ITech system extends beyond 'just the thing itself' as discussed so far. Equally important is the design of how the system is to be embedded in practice: the exercise and training routines / programmes that it is a part of. This is also a design consideration: design of Sports ITech, or indeed any kind of HCI, involves as much the design of the *activities* rather than only the technological artefact itself (Márquez Segura, 2016). Besides designing the activities *with the Sports ITech*, one also needs to see design in light of the relation of those activities with other, complementary, activities in training and competition, and the temporal sequencing of the various activities. In this section we address this topic guided by textbook distinctions[17] from sports and exercise sciences (see Table 3.16). These distinctions provide crucial information in the design of Sports ITech since these questions of integration also directly impact design choices.

Broadly construed, training schemes are designed using the following six concepts: distribution of practice, scheduling of practice, variability of practice, skill partitioning, mental practice and augmented feedback. The latter theme is typically discussed separately because of its extensive nature, and indeed we already covered this in the previous section. Here we follow this conventional subdivision and will focus on the other five concepts, starting with 'distribution of practice'.

3.5.1 Distribution of practice

Distribution of practice concerns the spacing of practice, both *between* and *within* practice sessions. Distributed practice, compared to massed practice, is generally seen as preferable in terms of learning efficiency. That is to say: (motor) learning is best served by shorter sessions distributed over longer periods of time. This is the case both for between-session distributions as for within-session distributions, though for the latter the effects are less pronounced and arguably more ambiguous.

While distributed practice is typically preferred over massed practice, at least in terms of learning, there are two pragmatical constraints when designing interactive training regimens: time constraints and physical/physiological constraints. In sports, practice time is often

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[17] Edwards (2010), Magill and Anderson (2011), McMorris (2014), Schmidt and Lee (2014), Schmidt *et al.* (2018), Williams and Hodges (2004), Gollhofer *et al.* (2013), and Hodges and Williams (2012).

Table 3.16: Fifth 'Form' subbranch – Integration of the interaction technology in sports practice.

FORM – INTEGRATION AND DEPLOYMENT Sports ITech is used in sports practice in a larger setting of training and competition, raising questions of sequencing and planning of the activities with the Sports ITech
Distribution of practice *Shorter or longer episodes of activity, grouped together or spread over time within and across practice sessions*
Scheduling of practice *Group activities for one separate skill together, or alternate between different skills over time, mixing the practice for various skills*
Variability of practice *Keep practice conditions for one skill constant for a longer time, or practice each skill in a broad variety of ways in ranging contexts*
Skill partitioning *Practice complex motor behaviour in whole, or practice its constituent parts in isolation*
Mental practice *Practice only 'in movement', or also rehearse motor skills in a mental practice without carrying out the movement*

limited; it is not always possible to provide athletes with an optimally distributed practice schedule. As such, it might be more appropriate to mass practice to a certain extent, reducing the time athletes spent idle. When done properly, this might help athletes master a certain skill over a shorter period of time, albeit at the cost of efficiency. Besides time, training load is also a factor to be reckoned with. Athletes are (physically) limited in the amounts of training they can handle within a unit of time. Although fatigue is not thought to hinder learning (McMorris, 2014), it might still be a relevant factor to account for. For example, athletes might get fatigued, keeping them from performing the to-be-learned skill at all. This might for instance be the case in sports that rely on strength, such as bouldering, climbing and weightlifting. Also, performance under extreme duress might lead to injury (Thomas *et al.*, 2010; Chappell *et al.*, 2005) and illness (Jones *et al.*, 2017). Finally, performance decrements due to fatigue might be demotivating to athletes, thus hampering learning in that way.

3.5.2 Scheduling of practice (sequencing)

'Scheduling of practice' is a term from literature that pertains to the sequence in which different skills within a session are trained. Skills can be trained in blocked order (i.e. AAA-BBB-CCC), random order (ACC-ACB-BBA) or in some hybrid order (ABC-ABC-ABC) (Edwards, 2010). Typically in motor skill acquisition, learning is best served by presenting athletes with a training schedule in which distinct skills are presented in random order. That is to say, retention and transfer effects are greatest for random practice. Acquisition performance (i.e. performance increments in practice) however, is greatest in blocked practice. This effect forms a potential caveat for designers and practitioners: One might be inclined to think that the greatest improvements in *learning* are seen under blocked practice conditions because acquisition performance increases fastest under that condition. However, this fast increase in acquisition performance must not be confused with learning *per sé*. That being said, depending on the goal in mind; designers and practitioners might opt for blocked practice for short term benefits and for random practice for long term benefits. Naturally, the issue of blocked, hybrid and random practice is much more nuanced than that (e.g. Edwards, 2010; McMorris, 2014; Schmidt and Lee, 2014).

3.5.3 Variability of practice

Variability of practice is about the variety of ways in which a particular skill is practised during training. Constant practice, as the name implies, holds that a skill is practised consistently in the same fashion and under the same conditions (as is required by the performance context), whereas variable practice holds that a skill is practised in a broad variety of ways in ranging contexts. Generally, the choice for either constant or variable practice is motivated by the 'specificity of practice' principle. This principle holds that the level of transfer between the practice context and the performance context is determined by the similarity between the two. If the task or skill is to be performed in a stereotypical way and under constant circumstances (e.g. a free kick in soccer), constant practice is typically advocated. If the task or skill is to be performed in various ways under ranging circumstances, variable practice is typically advocated. Though, it should be remarked that the adage of 'constant practice for closed skills' (skills executed in a stereotypical manner under stable circumstances) is challenged in literature. It is being suggested that varied practice might actually also be more beneficial to the learning of closed skills than constant practice (Shea and Kohl, 1990), however this remains a topic for debate.

3.5.4 Skill partitioning

Skill partitioning is a practice typically invoked to facilitate the learning of complex motor behaviours. By segmenting or simplifying a complex movement, athletes are allowed to gradually master the intended skill. Some motor skills are difficult to master because they consist of a great number of component parts (e.g. dance routines). Such skills are said to be high in *task complexity*. Other motor skills are difficult to master because a high level of (spatial / temporal) organisation exists between its component parts (e.g. rowing). Such skills are said to be high in *task organisation*. When deciding whether to implement 'part practice' in training to facilitate the learning of complex motor skills, task complexity and task organisation should both be taken into account. 'Whole practice' is advised for behaviours with low task complexity and high task organisation, while 'part practice' is advised for high complexity and low organisation (Fontana *et al.*, 2009; Naylor and Briggs, 1963; Magill and Anderson, 2011).

By having athletes involved in 'part-practice', complex motor movements can be more effectively mastered. Part practice can be done in one of three ways, that is: segmentation, simplification and fractionalisation (Wightman and Lintern, 1985). Segmentation, as the name implies, segments complex movements into smaller units, e.g. in learning dance routines, different elements of a dance can be practised in part and later in whole. With simplification, the aim is to preserve ecological validity while simplifying the task demands, for example: volleyball players could practice smashing the ball first *without* blockers and later *with* blockers. Alternatively, volleyball players could practice smashing the ball first with *tossed* balls and later with *setted* balls. Finally, fractionalisation aims to temporally untangle complex motor movements, training movements in isolation that would otherwise be performed simultaneously. In javelin throwing for example, the approach and the throw are normally tightly temporally intertwined; with fractionalisation, the throw and the approach could be practised in isolation. Though it should be noted that practitioners should tread carefully when applying fractionalisation; removing the inherent temporal relationship between nested components of a motor skill might lead to inexpedient behaviour.

Skill partitioning aims to guide athletes gradually to performing complex motor movements in whole. A meaningful intermediate stage, bridging part-practice with whole-practice is *temporalisation*.[18] With temporalisation, movements are practised at a fraction of the intended speed. In basketball, the footwork for a lay-up can be effectively practised at lower speeds. The same holds for mastering various Martial Arts fighting forms and techniques. Temporalisation allows athletes to execute a movement in whole, while retaining much of the ecological validity of the movement. Through temporalisation, movement speeds can be gradually increased until the athlete is able to perform the action at the desired speed. In our experience of rowing, soccer, skiing, basketball and fencing practice it is common to resort to temporalisation. 'Keepie Uppie' (i.e. keeping up a soccer ball) can for instance be practised using a balloon, rather than an official soccer ball to slow down the act of keeping the ball in the air. It should be noticed, that not all movements are eligible for temporalisation. Movements that require momentum, dynamic balance or are explicitly driven by gravity (e.g. diving) typically lend themselves less well for temporalisation. Moreover, extemporalisation (i.e. increasing the speed of movement) was recently applied in the context of speed skating. In 2020, the World Championships speed skating were held at the Utah Olympic Oval in Salt Lake City - which boasts a notoriously fast track because of its high altitude (low air pressure equals higher speeds). To prepare for the attainment of such higher speeds, relevant in the context of cornering,

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[18] Term coined by the authors of this work.

Dutch speed skaters trained with large fans that gave them a boost in speed.[19]

3.5.5 Mental practice

With mental practice, athletes cognitively rehearse skills or routines without overt physical movements. Mental practice has proven to be effective when used *in addition* to physical training. Using mental practice as a substitute for physical training is typically considered counterproductive (Hird *et al.*, 1991). As such, mental practice is best used whenever physical training is difficult. Besides motor learning and skill acquisition, mental practice can serve a range of other purposes that are considered beneficial, such as: enhancing motivation, improving concentration, controlling emotional responses and building confidence (Weinberg, Gould, *et al.*, 1999). Two key determinants of effective imagery are the vividness of the mental experience and the level of control over the mental experience; both factors can be trained.

Within mental practice two forms of imagery can be discerned. With *internal imagery*, skills are rehearsed from a first person perspective. It emphasises the (kinesthetic) feel of the movement, its situatedness and the senses. With *external imagery* on the other hand, skills are rehearsed from a third person perspective: athletes picture themselves as others would view them while performing a skill. External imagery empathises the form of movements. As such, it is contended that external imagery benefits skill learning when *form* is important, whereas internal imagery benefits skill learning when *sensory information* is critical. These contentions however are not unambiguously backed by literature and need further investigation.

All in all, these different aspects of the integration of interaction in practice are an important design constraint. When designing Sports ITech, the choices made regarding integration in practice determine a large part of the form of design of activities and exercises around the Sports ITech artefact, and as such can also influence all other aspects of the Form of Sports Interaction Technology.

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[19] https://www.staff.universiteitleiden.nl/news/2020/02/will-wind-turbines-take-the-long-track-speed-skaters-to-gold Date accessed: 24 June 2022.

4

The Function of the Interaction

So far, we addressed the *Form* of various Sports Interaction Technologies. The *Functions* of Sports ITech are equally important to ground design choices and opportunities: what is the sports context, practically and theoretically, in which the technology has to operate, and what is the purpose of the technology, what aims are addressed through it? This second part of our taxonomy is concerned with this perspective.

The *Function* side of our taxonomy as shown in Table 4.1 consists of five main branches. The first branch deals with *sports domains* and how different sports domains may influence and inspire the design of different interaction technologies. The second branch is about the *application scope* of Sports Interaction Technology. Sports ITech can be applied in a great many ways, ranging from entertainment to research; and from physical education to officiating; we discuss related work in Sports ITech in these various application scopes. Naturally, Sports ITech holds great potential for improving training and practice; helping athletes to perfect performance, boost engagement and accelerate learning. As such, the third branch concerns *training experience*. What is practice and training about (nature)? And what are athletes training for (outcome)? To optimally deliver on the training experience, salient aspects of the

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didactics and pedagogics associated with training and coaching will be discussed in the fourth Function branch. Finally, we discuss in the fifth branch the underlying *theoretical perspectives of motor learning* and how these influence the design and implementation of Sports ITech.

Table 4.1: 'Function' taxonomy – The Function of the Sport ITech in the context of sports performance and training

THE FUNCTION OF SPORTS ITECH	The functions of Sports ITech are to a large extent determined by the practical and theoretical background of the sports context in which it serves
Sports Domain	*Sports domains can be classified on their phenomenological (dis)similarities or on their underlying dimensions*
Application Scope	*The various stakeholders of Sports ITech participate in distinct application scopes that can be sources of inspiration for novel Sports ITech*
Nature of the Sport and its Training	*The nature of the sport and its training determines the Sports ITech design in many ways*
Pedagogy, Learning, and Didactics	*Both sports training and Physical Education have a large basis in theory of pedagogy, learning, and didactics, understanding of which can enrich the design of Sports ITech*
Philosophical Accounts of skill acquisition and motor learning	*The theoretical perspectives on motor learning that trainers or athletes subscribe to, explicitly or implicitly, strongly influences what one considers to be the right kind learning situation (and thus, what Sports ITech one designs)*

Obviously, in this part we will draw heavily upon literature in sports science and pedagogy. We will however, where possible, illustrate the taxonomy with examples of existing Sports ITech to make more tangible the different ways in which this knowledge can be used as grounding for design decisions.

4.1 Sports Domain

Not every sports domain is the same; as we already saw in the Form sections of the taxonomy, some sports activities may fit better certain types of interaction technology. In order to work towards a description of different sports domains, we first look at possible definitions of sports. When is a game considered a sport?

Sports and games

An intuitive classification to distinguish sports from non-sports is to follow the *International Olympic Committee* in their decision to classify sports as being ‘Olympic’ or not. For many, the classification by the IOC will feel intuitive. Sports like athletics, basketball, and judo are Olympic, while sports like ballet, yoga, and various motor sports are not. Yet, the intuitive notion of ‘Olympic’ sports is not strictly informed by theoretical and philosophical considerations of what is considered a sport. There are other factors which co-determine the inclusion of a sport in the Olympic Programme. Popularity of the sport (in the hosting country), costs, ethics, and relevance to younger generations are also decisive factors that co-determine whether or not a sport is to be included in the Olympic Program. This means that sports are sometimes dropped or included anew. While probably being recognised as proper sports by millions, baseball and softball were dropped from the Olympic Programme in 2008, only to be included anew in the Olympics of Tokyo.

Several philosophical accounts exist that define sports in relation to games and play. To understand how sports relate to game and play, we start with a widely influential definition on games (and sports) as provided by Suits and Hurka (1978, p.41):

> To play a game is to attempt to achieve a specific state of affairs [prelusory goal], using only means permitted by rules [lusory means], where the rules prohibit use of more efficient in favour of less efficient means [constitutive rules], and where the rules are accepted just because they make possible such activity [lusory attitude].

It can readily be seen that many of the statements in Suits' definition are directly applicable to sports, yet not uniquely characterise sports. Suits' definition fits checkers just as well as it fits volleyball. Building on Suits' influential account on games, Vossen (2004) proposed three additional distinctions that could be used in conjunction with Suits' definition to arrive at a more fine-grained taxonomy of games – one from which a definition from sports naturally follows.

The first distinction they make is that of *competitive versus noncompetitive* games. In short: competitive games involve *opponents*, whereas noncompetitive games do not. The second distinction concerns *opponent relations* within games, with *interactive* games explicitly involving aspects of offence and defence and non-interactive games[1] involving no such aspects (a notion that is critiqued by Jensen *et al.* (2013)). Finally, Vossen's third and final distinction concerns physicality, contrasting *physical* games with *nonphysical* games. This last one is particularly interesting in the context of sports (Vossen, 2004, p.61):

> Essentially, goal attainment is made impossible within all sports except by means of varying degrees of motor competency. In all games that are not sports the physicality of the participants is not a necessary means of prelusory goal accomplishment in that it is accessible via alternative means. In other words, locatedness is essential to all sports whereas it is not required of games that are not sports.

With these three additions to Suits' framework, Vossen defines sports as *physical* games that are: noncompetitive and noninteractive (e.g. hopscotch); competitive and noninteractive (e.g. 100-meter sprint); or competitive and interactive (e.g. basketball). Vossen's delineation of sports has been influential within Sports ITech. Their model spurred further inquiry into the nature of games and sports (e.g. Mueller *et al.*, 2008b; Fogtmann, 2011; Jensen *et al.*, 2013) and has served as a lens for design (e.g. Mueller *et al.*, 2010a; Fogtmann, 2011). In the next section

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[1] Note that in Vossen's account 'interactivity' is used to refer to the nature of sports (i.e. involving offence and defence) as such the term carries a different meaning in Vossen's account than in typical HCI-literature.

we will discuss further distinctions that distinguish various sports from one another.[2]

Sports and sports domains

In literature, there is no clear-cut definition on how various sports relate to form a sports domain. Yet, colloquially, people tend to group together certain activities when talking about sports, e.g. “I really like playing ball sports” or “I always find martial arts intriguing to watch”. Indeed, different sports might be grouped along different dimensions. Common classifications revolve around, e.g. skills (Gentile, 2000); physiology (Mitchell *et al.*, 2005); hedonic qualities (Mueller and Young, 2018) or the way (opponent) players interact with one another (Fullerton, 2014; Avedon, 1981; Jensen *et al.*, 2013; Skultety, 2011; Fogtmann *et al.*, 2011).

Different classifications provide different lenses for designing Sports ITech. For our own taxonomy, more globally aiming to distinguish sports domains, we start from a phenomenological account (Livingston and Forbes, 2016; Livingston *et al.*, 2020) that intuitively classifies the various sub-domains that might be discerned within sports. We will then examine how well essentialist taxonomies (describing more fundamentally the underlying dimensions that determine the distinction between certain sports) fit this phenomenological classification. We focus on existing taxonomies that look at ‘competition formats’ or ‘opponent formats’, as such taxonomies have proven prolific in the context of sports (interaction) technology design.[3]

Building on the work of Stefani (1999), Livingston *et al.* (2020) constructed a concise, yet comprehensive, taxonomy that classifies sports in one of eight domains (see Table 4.2). Their taxonomy classifies sports using a two-level hierarchical system. At the first level, sports are subdi-

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[2] Alternatively, as also recognised by Vossen, the relationship between play, games, and sports can also be considered a continuum in which *sports* evolve from *play* through increasing levels of regulation, achievement orientation, habituation and institutionalisation (Vossen, 2004; Meier, 1981).

[3] Vossen (e.g. 2004), Stefani (1999), Skultety (2011), Mueller *et al.* (2008b), Fogtmann *et al.* (2011), Fogtmann (2011), Mueller *et al.* (2011), and Fullerton (2014).

vided in 'combat', 'independent' and 'object' sports. Thereby, Livingston and colleagues echo Stefani (1999) who contended that sports could be classified as: *"combat sports where each competitor tries to control the opponent (e.g., boxing and fencing), object sports where each competitor tries to control an object in direct competition with the opponent (e.g., soccer and chess) and independent sports where each competitor is unimpeded by the opponent."* At the second level, Livingston and colleagues depart from Stefani's taxonomy and provide additional subclassifications for 'independent' and 'object' sports. With independent sports further subdivided in 'aim/projectiles', 'aesthetic' and 'racing/lifting' and object sports in 'net/court', 'invasion', 'fielding' and 'target'. In their view, 'combat' sports need no further subclassification (Livingston *et al.*, 2020). Table 4.2 shows for each subclassification the type of sports that are associated with it. It can be seen that there is a high level of consistency among the sports listed per sub-domain – on a phenomenological level, but fitting well with the kind of design choices one makes when developing Sports ITech.

However, there are other ways of looking at the distinction of different sports domains. Skultety (2011) for example draws a distinction between two modes of assessment i.e. 'standardised' and 'vis-à-vis'. In a standardised mode of assessment, the quality of behaviour is measured against a preset standard (e.g. gymnastics). In vis-à-vis, the quality of behaviour is measured relative to the standard that is set by the opponent (e.g. pole-vaulting). This distinction by Skultety separates Livington's 'aesthetic' sports (i.e. standardised) from other sports.

Further, many taxonomies, just like the one of Livingston and colleagues, include a distinction that set apart 'independent sports' from other sports (e.g. Skultety, 2011; Jensen *et al.*, 2013; Fullerton, 2014; Stefani, 1999), with independent sports being characterised by "minimal to no oppositional interaction with competitors" (Livingston *et al.*, 2020, p.62). To capture this characteristic, different essentialist dimensions have been proposed. Skultety (2011), for example, proposed that a fruitful distinction would be between 'encumbered' and 'unencumbered' sports. With unencumbered sports, athletes are unable to directly influence one another's behaviour (Mueller *et al.*, 2008b). The 'independent sports' category of Livingston *et al.* (2020) aligns directly with this distinction.

Table 4.2: First ‘Function’ subbranch – Sports domains from a phenomenological perspective

FUNCTION – SPORTS DOMAINS PHENOMENOLOGICAL Sports domains can be classified on their phenomenological (dis)similarities (Livingston *et al.*, 2020)		
Combat		*Athletes are pitted directly against each other, often in close proximity, aiming for control of the opponent (e.g., boxing, taekwondo)*
Independent	Aim/Projectiles	*Focus is on distance and/or accuracy with which an object is propelled towards a (general) target (e.g. shooting, javelin throwing). There is no active interference from other athletes*
	Aesthetic	*Focus is on the aesthetic and skilful execution of complex actions by the athlete (e.g., diving, figure skating)*
	Racing/Lifting	*Focus is on the speed or strength with which certain actions are executed (e.g., cycling, weight lifting)*
Object	Net/Court	*Individuals or teams try to gain control over an object in an uncontested competition space (e.g. squash, volleyball)*
	Invasion	*Individuals or teams try to gain control over an object in a contested competition space. Opponents play in opposite directions (e.g. soccer, basketball)*
	Fielding	*Individuals or teams try to gain control over an object in an uncontested competition space. Opponents alternate in offence and defence (e.g. baseball, cricket)*
	Target	*Individuals or teams take turns in propelling objects towards a contested playing space to gain positional or strategic advantage (e.g., boccia, curling)*

Jensen *et al.* (2013), however, critiqued this distinction because it limits the definition of 'influence'. That is to say, athletes in a 100-meter sprint (classified as unencumbered) are not allowed to (physically) influence the performance of others. However, even in the 100-meter sprint, offensive and defensive behaviour can be distinguished. To overcome this, Jensen proposed an additional distinction, to go along with the encumbered-unencumbered distinction, i.e. 'concurrent' versus 'subsequent'. In subsequent sports, athletes take turns competing (e.g. diving, ski jumping, hammer throwing, weightlifting). In concurrent sports, athletes compete simultaneously (e.g. ice hockey, squash, karate, lacrosse, and the 100-meter sprint). Taken together, Jensen arrives at four distinct opponent formats: concurrent-unencumbered; subsequent-unencumbered; concurrent-encumbered and subsequent-encumbered. While very helpful in the design of interactive exercises, Jensen's taxonomy (as well as others) falls prey to the same critique that was voiced against Skultety: In Jensen's taxonomy, clearly distinct opponent formats still fall under the same category.

To see why this is the case, consider that combat sports; net/court sports; invasion sports and fielding sports all fall under the same classification, i.e. concurrent-encumbered sports. This is counter-intuitive. In combat sports athletes are in close proximity, quite literally fighting a 1-on-1 battle for victory. While in net and court sports, like volleyball, players are organised in teams and separated by a net. Which is again different from invasion sports, where players are *also* organised in teams, but now share the same space. Finally, in fielding sports, athletes are organised in teams *and* share the same space, but differently so than in invasion games. In fielding sports, like cricket and baseball, playing space is not contested like in American Football and rugby, instead players are running their rounds in a more or less structured way, allowing for less direct contact between players of different teams. Clearly, the way in which the playing area is set up, either physically or formally co-determines the relevant interactions that are possible within a certain sport (cf. Livingston *et al.*, 2020). Put differently, the formal and physical setup of the space of interaction is determinative for the level of kinesthetic empathy that is allowed for (Fogtmann, 2011, 2007; Fogtmann *et al.*, 2011; Ludvigsen *et al.*, 2010). Such distinctions matter for our designs. Also they open new perspectives. For example, Strava may originally be designed as application that is recording personal data. But by adding friends that are competitive it also opens the perspective of competition in an unencumbered, subsequent activity.

None of the taxonomies discussed above (Skultety, 2011; Mueller *et al.*, 2008b; Jensen *et al.*, 2013) align perfectly with the phenomenological account of Livingston *et al.* (2020). With each of the taxonomies, clearly distinct oppositional formats end up together (e.g. soccer and boxing). Based on the findings from the previous section, we summarise the most salient essentialist dimensions that have been proposed in the classification of sports into domains in Table 4.3. (For further reading, please refer to: Vossen, 2004; Jensen *et al.*, 2013; Mueller *et al.*, 2008b; Skultety, 2011; Livingston *et al.*, 2020.

Table 4.3: First 'Function' subbranch – Sports domains approached from an essentialist dimensions

FUNCTION – SPORTS DOMAINS Sports domains can be classified on the basis of various essentialist dimensions
Competitive format *The opponent can hinder or influence performance (encumbered) or not (unencumbered) (Vossen, 2004; Skultety, 2011; Mueller* et al.*, 2008b; Jensen* et al.*, 2013)*
Assessment mode *Quality of behaviour is measured against a preset standard (standardised) or against a standard set by the opponent (vis-à-vis) (Skultety, 2011)*
Temporality *Athletes compete at the same time (concurrent) or not (subsequent) (Jensen* et al.*, 2013)*

Different sports domains are characterised by interactions, purposes and mindsets that are unique to that particular domain (Skultety, 2011; Fogtmann, 2011). Being aware of these inherent and unique differences allows for more effective and experience-tailored design of Sports Interaction Technology; different sports domains present athletes with different challenges.

4.2 Application Scope

Athletes are central users of Sports ITech, but obviously, there are many more stakeholders. Other classes of users may play a role in Sports ITech focusing on the athlete, and there may be other applications focusing exclusively on some of the non-athlete stakeholders. Taking one or another specific stakeholder as central user for Sports ITech provides us with different *application scopes*. For example, the Physical Education teacher is obviously involved in school sports applications; referees play a central role in Sports ITech for officiating; and dashboards for player health statistics have a large role for scouts and medical staff.

The taxonomy of Frevel *et al.* (2020), for example, is built around the three groups of stakeholders athlete, consumer, and management. Reilly *et al.* (2009) distinguish training, safety, refereeing, and entertainment, which implies additional stakeholders to those first three. Other authors mention, for example, broadcasting as field for innovative sports technology, which adds media and audience (Schlegel and Hill, 2020), or focus on the stadium experience in which the fan audience has a central place (Schlegel and Hill, 2020; Shields and Rein, 2020).

Classes of stakeholders can again be subdivided with greater granularity, expressing insights about the type of user as well as the type of applications they might be involved in.

Taking the various literature that we read into account we came to a fairly pragmatic subdivision of possible stakeholders and the application scopes in which they play a central role. This leads to a discussion of Sports ITech for a number of mostly distinct application goals (see Table 4.4): (1) audience entertainment; (2) sports as leisure or entertainment for the athlete; (3) officiating; (4) physical education; (5) assessment; (6) management, recruitment, and sponsorships; and (7) last but certainly not least, training and competition. Viewing sports through the lens of these stakeholders and application scopes offers a near inexhaustible supply of inspiration for distinct novel Sports ITech concepts.

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Table 4.4: Second 'Function' subbranch – Application scope

FUNCTION – APPLICATION SCOPE	The various stakeholders of Sports ITech participate in distinct application scopes
Audience entertainment	*Enhance audience entertainment, either during spectating, or by pursuing audience engagement between events*
Athlete's leisure	*Improve the experience and engagement of the athlete who does sports for leisure or hobby*
Officiating	*Support officials in sports in carrying out their tasks*
Physical education	*Support teachers and children in development of physical literacy*
Assessment	*Support assessment of performance (snapshot view), learning (over time), and transfer (long term view)*
Sports management	*Support team management, scouting, marketing, and sponsorship management – less directly concerned with changing the nature of the sports activity itself*
Training	*Support training practice of athletes and trainers*

4.2.1 Audience Entertainment

One of the major classes of applications of (interaction) technology in sports is in *entertainment*. While sports are already known for their engaging nature, Sports Interaction Technology allows *more* people to enjoy sports qualitatively *better*. This not only applies to people practising sports, but also applies to people watching sports.

Regarding where the audience can be found, people watch sports in a stadium, or remotely from home or any other place. Furthermore they do so at different times: in real-time as the event takes place, or retrospectively through recordings and other media. Not every person in the audience is there for the same reasons: Giulianotti (2002) describes the football audience as subdivided in supporters, followers, fans, and flaneurs; and some visitors of a stadium might even simply go to the match for the opportunity for socialising that it offers. Furthermore, one can find research on exploiting machine learning strategies for sports betting, which is yet another take on the audience member (Hubáček *et al.*, 2019).

Shields and Rein (2020) discuss the challenge of attracting audience crowds to stadiums in the future, including the role of technology in making stadium experiences *frictionless*. Schlegel and Hill (2020) focus their discussion of the future smart stadium on perspectives on audience engagement throughout the season and around a match. A possible way to engage the audience more might be to augment existing sports through the use of Augmented Reality (e.g. a hololens), providing additional information about players while watching a game (Azuma *et al.*, 2019). The meaning of audience interaction extends beyond “watching a game in a stadium”, though. Consider for instance how the FIFA game allows a gamer to user their favourite real-life players in their virtual team. Or consider how ‘match prediction’ apps, like scorito,[4] spur engagement and entertainment to prospective spectators prior to major sporting events like the FIFA World Cup. More generally, also consider how radio and television have popularised sports spectacles, like the Olympics, or how Twitch and other platforms offer forms of game streaming for (e-)sports, including direct audience feedback (e.g., Hilvert-Bruce *et al.*, 2018). Or how in stadium sports, multi vantage-point, high-speed cameras provide unprecedented detail to our viewing experience, during the match or indeed afterwards in review.

Modern systems like HawkEye even go beyond the mere replay (in slow motion) of events by adding a level of analysis on top. Indeed, computer vision has found its way to sports and entertainment. SecondSpectrum for instance employs machine learning and computer vision to visually augment sport games, with appealing visuals and statistics live on television. Besides that, SecondSpectrum offers users an exhaustively labelled database of events, plays and games which can easily be

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[4] https://www.scorito.com Date accessed: 24 June 2022.

searched; see also the work of Johansen *et al.* (2009) on this. While radio and television offer limited interactivity, novel interactive concepts are being developed to engage spectators with the sports. With WeApplaud for example, fans who are watching a soccer game from home are invited to share the stadium atmosphere by clapping (Centieiro *et al.*, 2012). WeApplaud encourages fans at home to participate in the applause happening at the game itself, awarding points for joining free clapping, synchronised clapping (e.g. slow clap) and clapping synchronised with stadium chants.

Finally, the audience can take a more active role in interaction with the athlete. In cycling, athletes are helped by the audience offering them water, or even briefly pushing them along for an extra boost. In Formula-E this has been turned into a fundamental Sports ITech concept: with the FanBoost, audience members can vote for their favourite driver to give them (literally) extra power for the race (Finn, 2020).

4.2.2 Sports as leisure, hobby, or engaging entertainment activity for athletes

Naturally, sports ITech can also be used to add a layer of entertainment to the way *players* experience sports. As we will address later, entertainment and engagement are a major target outcome of sports – both for the performance oriented athlete, and for people for whom sports is mostly a leisure activity. Sports ITech can for instance be used to balance games for increased engagement;[5] augment sports;[6] transform sports[7] and enable athletes distanced in time and/or space to exercise with one another to improve the social experience.[8] Thereby, ITech might be used to add to the hedonic qualities inherent to sports (Mueller and Young, 2018). Taking it one step further, the hedonic quality can be the main or even only motivating factor for doing the sports activity, and one can explicitly design for this as seen for example

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[5] Altimira *et al.* (2016, 2013); Gerling *et al.*, 2014; Graf *et al.*, 2019; Jensen and Grønbæk, 2016; Mueller *et al.*, 2012b; Nojima *et al.*, 2015; Stach *et al.*, 2009).

[6] Delden *et al.* (e.g. 2020), Karoff *et al.* (2012), Hämäläinen (2004), Jensen *et al.* (2015b), and Pijnappel and Mueller (2014).

[7] Ludvigsen *et al.* (e.g. 2010), Ishii *et al.* (1999), and Mueller and Walmink (2013).

[8] Mueller *et al.* (2007a, 2003a, 2008a).

in work on entertaining exertion interfaces (Mueller *et al.*, 2003b) or e-sports (Martončik, 2015).

4.2.3 Officiating

Officiating can almost be considered a sport in its own right. Umpires, referees and officials are tasked to make ongoing, real-time and challenging calls that may have a determinate impact on the course of a game. It is their role to make sure that sports games follow their intended course and that justice is being done (Collins, 2019, 2010). With (recent) advances in sensor technology, digital image processing and (ubiquitous) computing, technological officiating aids gain an ever-growing presence in sports. And with good reason. Electronic timing systems, like starting block detection and photo-finish video cameras, provide unprecedented temporal accuracy in adjudicating false starts and close finishes, respectively. Multi-angle, ultra high-speed cameras provide Video Assistant Referees (VARs) with an exceptional view of the game. The well-known HawkEye system is used for example to settle disputes about ‘leg-before-wicket’ in cricket and ball placement in tennis. Less well known are the SensorHogu system for refereeing martial arts (Chi *et al.*, 2004), and the halfpipe competition scoring system by Harding *et al.* (2008) that detects the objective execution of tricks to leave the jury free to focus on the subjective aspects of execution. Such advanced systems can be used to overcome judgement errors in officiating, arising for example from limited perceptual accuracy or bias (Kolbinger and Lames, 2017).

Yet, technological officiating aids are not a panacea. Not infrequently are novel technologies met with criticisms, both from athletes, spectators and scientists. While these criticisms are ranging, there are a couple of recurring themes. First, technological officiating aids have the potential to harm the ‘epistemological privilege’ of officials (Collins, 2010; Collins, 2019); see also the work by Livingston *et al.* (2020) on this. In the pre-technological era, sports officials were bestowed with natural authority. With their (extensive) training and experience, and their often superior view, umpires were considered the most suitable people to reliably judge the situation on the field. However, (high definition, high speed, multi-angle) replays put the audience on par with the officials, at least in terms of viewing position, which has exposed mistakes on part of the referee. These mistakes have been, and often are, well-publicised leading to referees losing authority. (In soccer such events have fuelled the introduction of the VAR, the Video Assisted Referee (Collins, 2019)).

Second, officiating technology has sparked controversy for changing the nature of a sport (e.g. Kolbinger and Lames, 2017; Borysiuk, 2005; Cho *et al.*, 2020; Moenig, 2017). The case of Taekwondo presents a nice illustration of this. In the early days of (Olympic) Taekwondo, performance was assessed by a set of three judges that adjudicated whether or not an attack was effective. For an attack to be effective, the kick should land within the scoring area; make a distinctive contact sound and have a clear visual impact on the opponent (Cho *et al.*, 2020). Per round, each judge would keep track of the score and would award a point to the fighter that had dominated that particular round. Ultimately, the fighter that earns the most points wins the fight. This scoring process, however, was often the focus of controversy and criticism (Moenig *et al.*, 2012). Many found it to be nontransparent and subjective. This fuelled the introduction of the Protector and Scoring System (PSS), which is a wireless electronic scoring device that is integrated within the protective padding (hogu) of the fighters (cf. Chi *et al.*, 2004). The sensors within the padding are activated when hit with enough power. In essence, an elegant solution to overcome the difficulties in scoring.

The scoring system, however, sparked controversy in itself for changing the nature of the sport, e.g. *"the introduction of the PSS came with a significant cost: the near destruction of the intricate, artful, technical sparring/kicking style and system that had evolved over the decades prior to its implementation"* (Moenig, 2017). While this sentiment might be strongly worded (see, e.g., Salmon, 2019), the fact of the matter remains that the introduction of the PSS caused a shift in fighting style. Fighters adopted a fighting style that was more focused on setting off the PSS sensors, rather than delivering 'artful' blows to the opponent. PSS-enabled fights show an over reliance on stationary kicks with the front leg (Moenig, 2017), a proportionally different use of offensive techniques (Cho *et al.*, 2020) and show taller fighters to have an advantage over shorter ones (Moenig, 2017). In Taekwondo, the tension between transparent and objective scoring on the one hand and honouring the spirit of the game on the other hand is tangible. The World Taekwondo Federation is involved in a continued effort to reconcile the two through rule changes and technical improvements. And with their latest improvements, they may be getting close (Salmon, 2019). Besides Taekwondo, similar phenomena have for example been observed in fencing, with the introduction of electronic scoring (Borysiuk, 2005) and in tennis, with the introduction of HawkEye (Kolbinger and Lames, 2017). With HawkEye came the addition of a new strategic element to the game, that is: when best to challenge a line call? When designing interaction technology for officiating in sports, its effect on the nature of the game should be carefully studied.

Besides the impact that Sports Interaction Technology might have on the authority of referees and on the nature of the sport, there are a number of additional sensitivities that should be taken into consideration when designing (interactive) officiating aids for sports. First, the fluency, or rhythm, of the game should be considered in the implementation and design of officiating technology (Collins, 2019; Livingston *et al.*, 2020). The flow of the game should be honoured as much as possible, simply because there is inherent value to flow (Csikzentmihalyi, 1997), but also because interruptions might lead to disadvantageous side-effects, such as an increased risk of injury (Svantesson, 2014). It should be noted that the preservation of flow is just as much a design-sensitivity as it is an implementation-sensitivity. Currently in tennis, HawkEye is implemented such that players each receive two ‘challenges’ per set to adjudicate line-calls with. If a challenge is ‘won’, the player retains the same number of challenges. Implementing HawkEye this way ensures that not every line-call is reviewed and that the flow of the game is much maintained.

A second design sensitivity in developing officiating technology is cost. Specifically, the consideration whether the financial investment is worth the over-turn rate (i.e. the number of calls that are (rightfully) corrected through the use of technology (Kolbinger *et al.*, 2014; Kolbinger and Lames, 2017; Livingston *et al.*, 2020; MacMahon *et al.*, 2014)). Third, technology is not infallible either. For one because technology might distort (officials’) perception and qualitative appraisal of rapid unfolding events, e.g. by the use of slow-motion replay (Vannatta, 2011; Kolbinger and Lames, 2017; MacMahon *et al.*, 2014). For another because technology is only accurate to a certain extent (Kolbinger and Lames, 2017; Collins, 2010; Collins, 2019; MacMahon *et al.*, 2014; Livingston *et al.*, 2020; Dyer, 2015). These and other aspects of officiating technology should be taken into consideration when designing Sports ITech for officiating purposes.

4.2.4 Physical Education

A major area of opportunity for applying Sports ITech is Physical Education. Existing work can be found from various perspectives. Some work focuses on digital teaching resources, platforms for planning out lesson series, monitoring and setting personalised student goals, and other perspectives on digital teaching resources (Souza *et al.*, 2020; Borse and Gokhale, 2019). Other tools are developed to support teachers in their monitoring and evaluation process, such as VideoTag (Koekoek *et al.*, 2018). Finally, there are tools that support teachers in PE in doing the teaching as such (novel apps and equipment). This is also found on the market in the form of companies such as Embedded Fitness[9] who offer hardware plus activities designed with the hardware. In a way, most technologies discussed in this monograph fit that purpose, but proper application then depends on embedding the technology in the proper pedagogical context and on the creativity with which the teacher does so. The pedagogy and didactics that is a necessary component in such Sports ITech is discussed in more detail in Section 4.4.

4.2.5 Assessment

Refereeing, scouting, training, Physical Education: in sports there is often a need to assess the quality of movement of athletes, for varying purpose. In this section we look at a specialised application scope of Sports ITech, namely technology that supports assessment. This can be either by automating part of the assessment process itself, in measurement, modelling, and presentation of feedback on (quality of) movement,

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[9] https://embeddedfitness.com Date accessed: 24 June 2022.

or by offering digital-physical setups that facilitate eliciting diagnostically relevant situations in which the athlete is triggered somehow to relevant behaviours that are then subjected to either automated or human assessment.

Systems that support measurement of some given interpretation of 'skill' have been argued to be helpful in making assessments more objective, as well as to be helpful towards, for example, automatically providing the athlete with adaptive training advice (Ahmadi *et al.*, 2009), coaching and teaching (Preuschl *et al.*, 2010), match rating (Minka *et al.*, 2018; Elo, 1978; Colley, 2002; Govan *et al.*, 2008; Massey, 1997), and refereeing (Harding *et al.*, 2008).

This is a challenging task. One can measure 'quality of movement' as a kind of assessment input to training advice, instructions, and other goals, but (a) it is important to have a good model in sports terms of what is 'good' execution; (b) this model needs to be operationalised into a computational interpretation of 'good execution' that is measurable, yet does justice to the nuances of the underlying concept of 'good execution' in sports terms; (c) it is a separate challenge to make evident how the measurements should then be translated to decisions and actions, and (d) how to present these in the form of helpful feedback. How these systems are employed by specific categories of users in a certain application is addressed elsewhere; here we focus on the assessment technology itself.

To start with, what constitutes 'skill level', whether it is a unidimensional or multidimensional construct, and whether it is assessed on a spectrum or as a small number of discrete skill levels (e.g., amateur – semi professional – elite), differs between papers. Furthermore, many papers in the domain of automated skill assessment focuses on the automated measurement and do not address the use of the resulting assessments in great depth. Wang *et al.* (2018), for example, assess the skill level of an athlete based on data recordings from volleyball spikes. They distinguish three discrete skill levels (elite, sub-elite and amateur players) from the quality of the executed spike actions. This work provides insights in what are relevant motion features that distinguishes amateur players from elite players, and as such a possible operationalisation of what could be considered "good" execution of the spike. However, the authors do not yet address how distinguishing the three skill levels should be turned into fitting assessment feedback. Ghasemzadeh *et al.* (2009), looking at ideal wrist rotation trajectories in a golf swing, suggest that a fitting assessment feedback to the athlete could be to simply represent the diagnostic values (i.e., wrist rotation over time) plus an ideal reference line; the assumption is that this would allow the athlete to improve their performance, although the authors do not evaluate this aspect.

Stienstra *et al.* (2011) in fact showed that performance increments can readily be achieved by providing an athlete *just* with feedback on movement (through sonification) without reference to a representation of an ideal movement. The idea behind this is that inter-modal convergence allows athletes to relate anomalies in speed-skating technique to anomalies in the presented sound-scape (see also Cesarini *et al.*, 2014). Ahmadi *et al.* (2009) go one step further in their analysis of automated skill assessment on tennis serve actions: they have a more precise and detailed concept of what is “good” execution of an action (in this case: tennis serves), a richer operationalisation in terms of measurement values, and a more grounded model of the path to improvement that follows from the outcome of their automated skill assessment. Their starting point is to show that skill level in tennis serve actions, as a spectrum from amateur to elite players, correlates to a progressive development in the relation between certain parameters such as wrist flexion and shoulder rotation. They suggest that further development of a player’s skill could be taken as specific improvement goal along that ‘line of improvement’ in the relation between those parameters, a goal can be pursued and monitored using automated measurement and feature based feedback: their ‘line of improvement’ can really be taken as a *path* towards improvement.

As next development, it still remains to be seen how exactly this development should be pursued from a pedagogical perspective because simply saying “feature A in your serve should be closer to value B” is not necessarily helpful enough to actually achieve that desired development (cf. Section 3.4.4, regarding the content of augmented feedback). Brunauer et al. aim to use expert knowledge on what feedback to give when measured features of an athlete’s sports movement exceeds hand crafted thresholds, and aim to turn such expert knowledge into rule based feedback systems – although their work so far mostly focuses on the detection and classification (Neuwirth *et al.*, 2020) and the architectural requirements for the pipeline system from sensors to feedback (Brunauer *et al.*, 2020). Harding *et al.* (2008), on the other hand, focus on strengthening and clarifying the role of the human referee next to the technological system. They put sensors on snowboards, and discuss how a mixture of automated assessment and expert based judging might be used to referee half pipe competition.

Regarding creating diagnostically relevant situations, Sports ITech lends itself well towards supporting assessment and diagnostics thanks to its capacity to create specific situations and scenarios that are adapted to the users interacting with the system (Poppe *et al.*, 2014). Weichenberger *et al.* (2015) for example, developed a fencing robot for assessment of fencer's performance, which helps by creating a diagnostic setting that, thanks to the technology, is controlled yet ecologically valid. This leads to being able to assess aspects of the athlete in a controlled way that could not be done so well without the tech – regardless of whether the assessment is subsequently done by an automated system, or by a human assessor. Faure *et al.* (2020) survey the use of virtual reality to create diagnostically relevant situations that are hard to create in a controlled way while on a real sports field.

In this section, we mostly talked about assessment in the form of *qualitative skill assessment*. Meaning that we reviewed interactive systems that are concerned with providing a qualitative assessment of how well a movement or skill is executed. Besides qualitative skill assessment, much research has been done to also *quantitatively* assess skill. Most prominently in the form of sports ranking systems (Minka *et al.*, 2018; Elo, 1978; Colley, 2002; Govan *et al.*, 2008; Massey, 1997). Such systems are famously being used to rank players and to organise fair matches. That is to say, to optimise the competitive balance between players or teams. Interestingly, competitive balance can not only be estimated at the level of the individual (e.g Minka *et al.*, 2018), but also at the level of the game or sport itself to estimate the relative contributions of luck and skill to the overall outcome of the game (Zimbalist, 2002; Koning, 2009; Douglas, 2018; Mauboussin, 2012).

As mentioned before, automated technology to support assessment is not a neutral technology. It does not just simplify things: it changes the nature of the assessment, in whatever context and purpose, and as such changes the nature of the game. Although we do not address this in depth, this is an important topic to reflect on when making automated assessment support systems; in Section 5 we will briefly address ethics and the desirability of Sports ITech innovations.

4.2.6 Sports management

When it comes to Sports Interaction Technology athletes, coaches and trainers are not the only group of people that reap its benefits. The sponsors, management, and scouting teams have started to integrate interaction technology in their programs and use it to conduct their business.

Radicchi describes sports sponsorship as "*An agreement by which an individual or a company (the sponsor) invests in a sports entity (athlete, team, league or event) (the sponsee) by providing funds, goods, services or know-how. The aim of the sponsor is to exploit sports passion, excitement and emotions to reinforce its image, create visibility and increase brand loyalty*" (Radicchi, 2014).

Companies leverage the popularity of sports to promote their brand and invest a significant share of their marketing budget to build associations between their brand and the sports team. Nike, whose brand image revolves around *"authentic athletic performance"*, for instance signs top-level athletes to promote their brand (Lane Keller, 1999), including Michael Jordan, Christiano Ronaldo, and Eliud Kipchoge. Moving with the trend (and due to its ease of use) sponsors have started integrating interactive technology with their workflow to strategically place their signage around a sports team and develop their identity. The technology used by companies to attract their audience range from in-person augmentation and online augmentation.

The presence of interaction technology in the field of sponsorship is not very prevalent. Sponsors generally use data and innovative sensor-based technology to achieve their objectives. One of such innovative technologies researched by companies includes eye-tracking. Companies take advantage of the emotional experiences of audiences (when they are engrossed in the sport). The research into the above topics investigates the effect on how the audience reacts to certain brand stimuli in cluttered environments and the effect on their emotional perception of certain branding. Breuer and Rumpf (2012) have assessed the impact of eye-tracking to provide valuable insights into the effective sponsor message communication strategies. In one of their studies, they found using the brand placement strategy is wiser in a moderate level of surrounding intensity (excitement for the sport). Based on their analysis and information gathered using data and innovative technology like eye tracking sponsors can make use of interactive technology that used augmented reality and connect with their audiences. An interactive application developed by Stragraph in collaboration with Social Media Soccer and Skylab Studios is a good example of how sponsors can use augmented reality to improve their outreach. One application created by them allowed football fans to interact with Italy's flag in augmented reality. Fans could click on one of the stars above the flag letting them view the highlights of the world cup finals. Another application allowed fans to learn about their favourite team by letting them interact with a giant video wall. Fans could click on the logos of their favourite team and discover their team's most viral videos on the social network. Sponsors can make use of such applications to carefully communicate their brand's image and at the same interact with various audience (Sawan *et al.*, 2020).

Sports Interaction Technology can also help in managing a team. Managing a team does not only mean ensuring the athlete's daily activities are taken care of and running smoothly but compiling the necessary data etc. it also means working on the team dynamics and ensuring the athletes are engaged. A lot of sports-oriented products focus on individual or team performance monitoring or to prevent injuries. Only a few go beyond the training realms and focus on team building and dynamics. Bogers *et al.* (2017) explores the use of intelligently connected light jerseys to augment the engagement skills of high school basketball students with varying skill levels. The prototype developed by this team did not impede the playing experience of the student as they were not forced to act on the various stimuli emitted by the jersey.

As such this did not require the PE teachers to change their way of organising PE classes. Their study showed that students that most of the time side-lined got a lot more chance to engage in the sport. Interactive devices of this calibre can also help managers to improve team dynamics and at the same time conduct a guided training session (Bogers *et al.*, 2017). Apart from improving the team and player morale, trainers that manage elite level players make use of dashboards like FirstBeat[10] and Dotcomsport[11] by continuously monitoring player's physiological parameters, mental well-being and other relevant parameters. Interactive dashboards and data collected will help trainers, coaches, and other supporting staff to understand when certain players get tired/stressed out and help them easily manage their team.

Finally, Sports ITech has much facilitated scouting. The growth in sports technology and data science has helped scouts use sophisticated and innovative tools to monitor athletes without leaving their offices. These tools make it possible for them to make informative decisions before and during the scouting season. One such tool called Wyscout is used by football/soccer scouts, agents, coaches, players, and journalists alike. Various filters and parameters can be set on the interactive platform to retrieve the data, statistics, and video of the player. In the old days, team managers and coaches relied on the experienced scouts who went around to see multiple games from the grandstand or sidelines. There have been occasions where talented players would have been rejected by these scouts due to emotional reasons or intuition-based feelings. At times the performance of an athlete in a match may be hindered by an environmental factor or personal reasons, and the scouts should not use these small incidents to determine the potential of athletes and miss out on future talents.

Quantitative-backed recruitment rather than intuition will help companies/teams find and produce highly skilled athletes. Such an analysis would constitute collecting on-field data during practice and games of their efficiency in performing a task and analysing them to evaluate

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[10] https://www.firstbeat.com/en/professional-sports/team-solutions/ Date accessed: 24 June 2022.

[11] https://dotcomsport.nl/us/ Date accessed: 24 June 2022.

their value in the team/sports of choosing (Suryadia, 2020). Scisports[12] offers such a data-driven approach to support football organisations in their recruitment and scouting practices. Virtual reality also proves to be an effective tool to conduct scouting in an easy risk-free environment. VR technology provides scouts the possibility to obtain data in a much simpler and effective way without even having to leave the confines of their office space. Huang *et al.* (2015) developed an interactive virtual system called SIDEKIQ that helps football players improve their skills and provide coaches an interactive tool to easily assess the players. The system in turn can also be used by scouts to filter or select players that match their profile.

4.2.7 Training

Last, but certainly not least, one of the most prominent application domains for interaction technology in sports is the *training domain*. Partially because of the importance of training for performance and partially because of the immense variation that can be found in training regimens. There is more literature on sports training than any one human can read; bookcases full of books have been written just on basketball. Some written from a focal perspective, e.g. on tactics, drills or physiology, others from a holistic perspective. Sport skills can be delineated as being physical, technical, tactical or perceptual-cognitive and are ranging in task complexity. Some sport specific skills are hard to perform because they require immaculate timing (e.g. batting in baseball); others are hard to perform because they require immense strength (e.g. weightlifting). To complicate matters even further, no two athletes are alike. Athletes range in their motor abilities, aspirations and mindsets. All of these (and many more) dimensions interact to present trainers, coaches and designers of Sports ITech limitless opportunities to provide support to athletes in their training. Indeed, the dimensionality within the training domain is so great that we discuss the many applications of Sports ITech for training in its own right in Section 4.3. Here we mainly aim to set the stage stating: 1) that designing an effective training regimen is both a science and an art, and 2) that no taxonomy can do justice to the

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[12] https://www.scisports.com/ Date accessed: 24 June 2022.

many subtleties and distinctions that are present in sports (training). In the next section we take a functionalist approach and aim to provide the reader with some meaningful dimensions that could be taken into consideration when designing Sports ITech to support training.

4.3 Nature of the Sport and its Training

The next branch of our taxonomy concerns the nature of sports and its training (see Table 4.5). We first look at the outcomes pursued through training and the skill domains addressed. Then we discuss how feedback can play various roles / serve different functions in training. Next, we look at how these aspects are influenced by task complexity and the temporal structural aspects of sports. Finally, we discuss the separation between the sports training and the Sports ITech that supports it, in the form of the distinction between closed and open designs of Sports ITech.

4.3.1 Outcome of the Training

Millions of people actively participate in sports on a regular basis (Hulteen *et al.*, 2017). Each individual has their own unique training habits (Ogles and Masters, 2000), aspirations, and motives (Clancy *et al.*, 2016; Vlachopoulos *et al.*, 2000), ranging from enjoyment to mastery. Interestingly, young athletes often explicitly mention that learning a new skill or bettering existing skills is a driving factor to participate in sports (Kondrič *et al.*, 2013; Stern *et al.*, 1990; Passer, 1981; Sit and Lindner, 2005). Sports participation motives are ranging; dynamic and highly individual. Which is not to say that peers don't have a marked influence on the way individuals live and experience sports, on the contrary (Koekoek and Knoppers, 2015). In this section, we will follow the performance-engagement-learning distinction from the 21^{st} century SPORTS framework (see also Section 1.3) to characterise the main target outcomes in sports.

Probably the most intuitive and prominent target outcome in sport is *performance*. Performance speaks to the imagination: the world watched in awe when Usain Bolt set an all time record of 9.58 seconds

Table 4.5: Third 'Function' subbranch – Nature of the sport and its training

FUNCTION – SPORTS TRAINING The nature of the sport and its training determines the Sports ITech design in many ways
Outcome of the training *Roughly speaking, training targets performance, learning, and engagement*
Skill domains addressed *commonly divided in physical, technical, tactical, and perceptual-cognitive*
Functions of feedback *Feedback can be motivational or target the actual skill; in the latter case, it can be essential, facilitative, inessential, or a hindrance*
Task complexity (Sigrist *et al.*, 2013) Nominal (Gentile, 1972; Gentile, 2000) *Difficulty of task determined by environmental demands and action requirements* Functional *Difficulty of task determined by athlete's skills and characteristics*
Temporal structural aspects Micro *Phases of play to be taken into account in design* Macro *Unfolding demands posed by the rhythm of the sports season*
Freedom in functionality *Difference between closed designs (targeting one specific task and purpose) and open designs (can be adapted to many tasks and purposes)*

on the 100-meter sprint; when Epke Zonderland performed a wold's first triple flight element in a High Bar routine or when Eliud Kipchoge broke the magical 2-hour barrier in a marathon. Performance is more than breaking records, performance is displaying extreme prowess, e.g. as FC Barcelona has done over the past decade. Performance is in essence comparing. This means that it is either social comparing (i.e., better than the rest) or intrinsic comparing (i.e, better than before), Sports ITech provides numerous ways of charting and promoting these

The version of record is available at: http://dx.doi.org/10.1561/1100000087

performances. Well-known examples of Sports ITech that speak to the performance dimension are commercial wearables, like smart watches, heart rate monitors and cadence meters. More experimental systems expand on this in the form of biofeedback; informing the user about (the quality) of movement (Cesarini *et al.*, 2014; Boyd and Godbout, 2010; Stienstra *et al.*, 2011; Ruffaldi and Filippeschi, 2013).

Beyond (bio)feedback systems and wearables, Sports ITech has been involved with sports performance analysis systems[13] and interactive sports installations (Jensen *et al.*, 2015a; 2014a; 2015b; Kosmalla *et al.*, 2017b). Using interactive installations, relevant sports situations can be hyper-sampled; meaning that athletes are enabled to practice relevant skills on-demand. Consider for instance Football Lab (Jensen *et al.*, 2014a). Athletes practising their passing technique using this interactive installation get presented more opportunities for passing in 5 minutes than a professional in a whole 90-minute football match. While hyper-sampling is not unique to Sports ITech (a volleyball player can practice her serve many times in a row without the use of technology), Sports ITech profoundly increases the opportunities for hyper-sampling. Finally, Sports ITech has been employed in a more holistic manner to also target for example the social support structure of athletes (Woźniak *et al.*, 2015) or allowing athletes to train with (superior) virtual partners, either software-generated (Feltz *et al.*, 2020) or virtual representations of (geographically distributed) athletes (e.g. Mueller *et al.*, 2010b), however see also Zwift.[14]

Another major theme in sports (ITech) is that of engagement. Motives for playing sports can be wide ranging (Clancy *et al.*, 2016; Vlachopoulos *et al.*, 2000), but often include sociality (Nylander *et al.*, 2014; Woźniak *et al.*, 2015, Mueller *et al.*, 2003a, 2006, 2007b, 2011, 2008a, 2010a); inclusion (Gerling *et al.*, 2014, 2016; Hahn *et al.*, 2011) and fun (IJsselsteijn *et al.*, 2004). However also other hedonic qualities (Mueller and Young, 2018) like aesthetics (Pijnappel and Mueller, 2014), beauty (Mueller and Young, 2018) and pain (Tholander and Nylander, 2015) can play a marked role in the felt engagement of athletes with

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[13] https://inmotio.eu Date accessed: 24 June 2022.

[14] https://zwift.com Date accessed: 24 June 2022.

their sport. Engagement is a broad and multifaceted construct and is supported by Sports ITech as such. Skill balancing plays a major role in this regard. Many endeavours have been undertaken to lower the skill differential between players to promote meaningful competition (Altimira *et al.*, 2016; Gerling *et al.*, 2014; Mueller *et al.*, 2012b; Jensen and Grønbæk, 2016), implicitly leaning on the contention that balanced game-play promotes engagement, motor learning (Koekoek *et al.*, 2014) and sociality. Another major theme in Sports ITech and engagement is in 'spicing up' repetitive and tedious training regimens. The thought behind this aspiration is that training is more effective if athletes are well motivated, albeit externally. Examples of Sports ITech that add a layer of entertainment to training can for instance be found in many places (Kajastila and Hämäläinen, 2014; Kajastila *et al.*, 2016; Kosmalla *et al.*, 2017b; Jensen *et al.*, 2015b; Daiber *et al.*, 2013; Postma *et al.*, 2019). In the work of Kajastila *et al.* (2016) for example, climbers can practice their boulder skills while evading virtual chainsaws, solving interactive puzzles or by whacking virtual bats. All in all the engagement dimension offers ample opportunity for meaningful design of ITech for sports.

Finally, motor learning, is possibly best characterised as the lesser-known little brother of performance. Had Usain Bolt not learned how to leave the blocks quickly (something he notoriously struggled with), he would not have shattered the world record; had Epke Zonderland not learned how to perform a single flight element, he would not have been able to perform a triple one; and had Eliud Kipchoge not learned how to optimise his running economy, he would never have broken the 2-hour barrier. Skill acquisition and motor learning are fundamental to performance and arguably to engagement as well (see also, e.g., Kondrič *et al.*, 2013; Stern *et al.*, 1990; Passer, 1981; Sit and Lindner, 2005). So how can Sports ITech serve motor learning? Sports Interaction Technology can make intangible, elusive aspects of motor behaviour tangible. Making tactical (offensive / defensive) principles tangible is an excellent example of this. In volleyball for example, players find it typically hard to develop *formation awareness*, i.e. the ability to know *where* to position oneself and *why*. Using an interactive LED-floor, Postma *et al.* (2019) addressed this issue by designing a number of visualisations that functioned as 'discussion facilitators'. Visualising field coverage in various ways, trainers were able to visualise the positioning mistakes of their players and discuss with them suitable solutions.

Another approach to promote motor learning is to enrich the (augmented) feedback that athletes receive, either from their own body (e.g., through sonification, haptification or visualisation of relevant performance characteristics, Anderson *et al.*, 2013; Baudry *et al.*, 2006; Hermann and Zehe, 2011; Kosmalla *et al.*, 2018; Ruffaldi and Filippeschi, 2013; Cesarini *et al.*, 2014; Delden *et al.*, 2020; Pijnappel and Mueller, 2014), or from the trainer/coach (Erp *et al.*, 2006). Biofeedback systems prove a potent means to promote motor learning (Sigrist *et al.*, 2013). Finally, on a smaller scale, the field of Sports Interaction Technology is actively exploring also how to work with other concepts central to motor learning, e.g. stimulating an external focus of attention (Turmo Vidal *et al.*, 2019); fostering kinesthetic literacy (Sheridan and Mueller, 2010) and providing knowledge of performance (Delden *et al.*, 2020) rather than just knowledge of results (as is the case in many ergometers, wearables and smart watches). Motor learning offers a vibrant application scope for Sports ITech but needs to be designed and implemented carefully to be effective, see also Section 3.4 and Section 3.5.

4.3.2 Skill domains

The next topic that we will consider in the context of training (outcomes) is about skill domains: What skills are needed to produce the desired outcomes? Naturally, the answer to this question is highly dependent on the sports in question, the individual and the situation (see also Section 4.3.5). Still, there are a number of relevant distinctions to make in this regard when designing interactive systems for sports. We will not go into the nuts and bolts of all the skill domains, rather, with this section we aim to provide insight into the different dimensions that are associated with ability and skill. Below we will discuss the *physical domain*, the *technical domain*, the *tactical domain* and the *perceptual-cognitive domain*. It should be noted that this quaternity is by no means an objective or factual representation of skill domains. Many more taxonomies have been proposed that delineate skills differently (e.g.

Gentile, 2000; Fleishman, 1975; Edwards, 2010). In fact, following the specificity principle of Henry (1958), it might even be argued that skills share too little resemblance to even speak of a skill domain. Nevertheless, we feel that the delineation of skill in physical, technical, tactical and perceptual-cognitive components is both pragmatic and prolific in the context of the design of Sports ITech.

Physical domain

ATP-PCr / Glycolytic / Aerobic: All movements requires energy. However, dissimilar movements impose different demands on the system. Marathon running requires a constant and prolonged supply of energy, whereas a 50-meter dash requires a short, immediate burst of energy. Different metabolic pathways exist that serve ranging forms of exertion.[15] The primary distinction to be made in this regard is between the *anaerobic system* and the *aerobic system*. As the name implies, the anaerobic system is able to produce energy without the use of oxygen, whereas the aerobic system needs oxygen to deliver the required energy. The anaerobic system delivers energy via the breakdown of phosphocreatine (ATP-PCr system) and via the degradation (glycolysis) of glucose or glycogen.[16] The ATP-PCr system functions to meet the energy demand right at the onset of exercise or during very short bursts of activity (i.e. shorter than 5 seconds) (Smith and Hill, 1991). The ATP-PCr system can provide energy just as fast as it is used, however the biological compounds needed for this bio-energetic system to operate are only available in limited supply and are only synthesised when the athlete is in rest (Powers *et al.*, 2007).

The glycolytic system, on the other hand, takes approximately five to ten seconds (Gastin, 2001) to reach its maximal potential. The glycolytic system is the primary supplier of energy for the first 30 to 60 seconds of activity. Glycogen stores are much greater than phosphocreatine stores which allows the glycolytic system to provide energy for up to a couple of hours. Though, it should be noted that the relative contribution of

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[15] Farrell *et al.* (2011), Hoffman (2014), Kenney *et al.* (2015), Porcari *et al.* (2015), McArdle *et al.* (2006), and Powers *et al.* (2007).

[16] i.e. glucose stored in the liver and in muscle tissue.

the glycolytic system decreases over time. As exercise duration increases (up until the limits of human performance), the aerobic system becomes the dominant energy supplier. It is important to know how these bio-energetic systems contribute differently to dissimilar sports, because each of these systems require different forms of training to improve. The required energy for playing tennis, for example, is provided for 70% by the ATP-PCr system; for 20% by the glycolytic system and for 10% by the aerobic system; for wrestling these percentages are 45%, 55% and 0% respectively; while for the 1500-meter sprint these numbers are 5%, 35% and 60%. A comprehensible list of how these various bio-energetic systems contribute differently to various sports is given by Powers *et al.* (2007, p.451).

Power: A different, albeit related, dimension of physical ability or skill is *power*. Power is the product of *force* and *velocity.* From this definition, it can readily be inferred that the expression of power ranges between activities and between athletes. From slow and strong (e.g. deadlifting) to fast and explosive (e.g. sprinting). In this force-velocity relationship, strength and speed are inversely related (not linearly so). When the shortening velocity of a muscle goes up, the maximum force that can be produced goes down. Power-output (*not force*) is greatest at around 30% of the maximal shortening velocity of the muscle (Hoffman, 2014).[17] This power-velocity relationship not only holds at the level of individual muscles, but also at the macro-dynamic scale of e.g. sprinting[18] (Samozino *et al.*, 2016; Rabita *et al.*, 2015; Cross *et al.*, 2017). To train muscular strength, power or endurance, the specificity of training principle (Henry, 1958) can be followed (see below). Muscular strength can be promoted through *load training*, in which athletes train with (near-)maximal load with minimal repetitions (e.g. 1-5). Power can be increased through *power training*, which stresses the velocity at which force is produced. Power can be trained such that an athlete can produce a great amount of power *once* (e.g. *power clean* in weight-lifting) or such that athletes can produce (a lesser amount of) power *multiple times*

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[17] See also the work by Knuttgen and Kraemer (1987)

[18] For sprinting, peak-power output tends to trend towards 40%-50% of maximal shortening velocity.

(e.g. *blocking* in volleyball). Power of the latter kind is also associated with *agility*. Depending on the application, athletes should train with (near-)maximal loads at the maximal attainable speed with minimal repetitions (e.g. 1-2) for applications like the power-clean, while they should train with sub-maximal loads at maximal velocity with multiple repetitions (e.g. 5-10) for applications like blocking. Finally, muscular endurance can be promoted through *volume training*, in which athletes train with lighter loads but with greater numbers of repetition (e.g. 10-20). To stay true to the scope of this monograph, this section only provides a very short run-down of power and strength. For more in-depth information, the reader is referred to other literature (e.g. Porcari *et al.*, 2015; Hoffman, 2014; Kenney *et al.*, 2015).

Flexibility: Flexibility is about the range of motion that an athlete has in particular joints. Traditionally, two forms of flexibility are discerned: *Static flexibility*, which is about the absolute range of motion that an athlete is able to display for particular joints and *dynamic flexibility*, which is about the velocity with which the range of motion can be utilised (Fleishman, 1975; Schmidt and Wrisberg, 2008). As such, static flexibility is a relevant characteristic in sports as yoga, while dynamic flexibility is more relevant for gymnasts and figure skaters, but for instance also for pitchers in baseball. Stretching (both static and dynamic) may help athletes to improve their range of motion (Hoffman, 2014). Flexibility is joint (and muscle) specific, which means that stretching regimens should specifically target those joints / muscles for which an increased range of motion is desired.

Economy of movement: The concept of movement economy is most relevant for steady-pace aerobic performance. Movement economy is about the rate of oxygenation or the energy expenditure that is needed to perform work (McArdle *et al.*, 2010). Small increments in movement economy can lead to significant gains in the long run. Yet, movement economy is an elusive trait to train. In part, movement economy is related to technique: In running, biomechanical factors such as vertical oscillation, arm swing, leg stiffness and stride length were found to be associated with running economy (Moore, 2016). However, the identification of these factors has not yet resulted in consensus on how running economy can be (reliably) improved through technique (Moore, 2016; McArdle *et al.*, 2010; Eriksson *et al.*, 2011). Notwithstanding, Eriksson *et al.* (2011) showed that running economy of elite runners could be improved through concurrent auditory and visual feedback, highlighting the potential that interaction technology might have in this area.

Another way to improve on running economy is through (long-term) physiological training. Elite athletes have been shown to improve their movement economy by 8% (McArdle *et al.*, 2010) to 15% (Moore, 2016) over the course of 7 and 9 years respectively, which is a long time. Besides internal biomechanical factors, there are also external factors that influence movement economy. Maybe the most (in)famous example in this regard stems from the *Nike AlphaFly* and *VaporFly* running shoes (Hoogkamer *et al.*, 2018; Hoogkamer *et al.*, 2019). These meticulously designed running shoes have been shown to reduce the energetic cost of running by approximately 4%, in part due to superior energy storage and return qualities of the (mid)sole of the shoe (Hoogkamer *et al.*, 2019). Eliud Kipchoge, wearing the (a prototypical version of the) VaporFly's, even managed to break the 2-hour barrier in marathon running. Although there were numerous other (technological) aids that made this possible, the VaporFly definitely contributed towards that performance (Senefeld *et al.*, 2021; Dyer, 2020; Muniz-Pardos *et al.*, 2021).

Training principles: To effectively design Sports ITech to fit a specific sports context, a number of key training principles need to be upheld. The first is *the principle of specificity* (Henry, 1958), which holds that the training context should be representative of the performance context in order to maximise the effects of training (in essence similar to the thesis of Brunswik (1956). Put simply, to train for the 100-meter sprint, the athlete should practice sprinting. To train for marathon swimming, the athlete should practice endurance swimming. This principle not only applies to the bio-energetics involved, but also to muscle physiology, muscle coordination patterns, muscle contraction speeds (Powers *et al.*, 2007) and perception (Brunswik, 1956). The second principle central to training design is that of *reversibility*: training effects will diminish and ultimately disappear if training is halted. When time is the limiting factor, an athlete might follow a maintenance training program. Such a program is intended to mitigate the effects of reversibility (thus maintaining training effects) with a minimal amount of training.

The final principle discussed here is *the principle of overload*, which hold that the system must be overloaded in order for training effects to occur. Overloading can be achieved by increasing the duration, the intensity or the frequency of exercise (e.g. Powers *et al.*, 2007; McArdle *et al.*, 2010; Porcari *et al.*, 2015). The principle of overload should be applied with care. Too little stress on the system yields little or no training-effects while too much stress on the system (physically, physiologically or psychologically (Weinberg, Gould, *et al.*, 1999)) will prove ineffective and potentially even harmful. To avoid over-training, a rule of thumb is the 10-percent rule, which states that training load should be increased by no more than 10% per week (Powers *et al.*, 2007).

From theory to practice: Sports ITech for training in the physical domain: To put theory to practice; the specificity principle dictates that the anaerobic - ATP-PCr system can be trained using high-intensity interval training with work intervals lasting maximally 5-10 seconds. The anaerobic - glycogenetic system can also be trained using high-intensity interval training, however for the glycogenetic system the work intervals should last minimally 10 to maximally 60 seconds. Finally, the aerobic system can be trained using moderate / high intensity continuous training; long slow distance training or interval training. This latter triad provides a nice exemplification of how a designer of training programs can play with intensity (moderate / high intensity continuous training); duration (long slow distance training) or frequency (interval training) to increase the workload of the athlete. It should be noted that we only painted the picture of training physiology in broad strokes. The specific design of training regimens is highly dependent on, among other things, the individual characteristics of the athlete, the sport discipline and the overarching training goals. It goes beyond the scope of this monograph to get to the nuts and bolts of training design (work to rest ratio, number of sets and repetitions, etc); the interested reader is referred to additional literature[19] for in-depth information.

The question then arises: how to use the above insights as input for deliberate design decisions? The "Hanging Off a Bar" ExerGame-project by Mueller *et al.* (2012a) offers an interesting interactive platform that could readily be used in strength training. By adapting the game, inspired by the above basic principles of training in the physical domain, exercises can be made that deliberately focus the game on specific training types such as interval training, endurance training, power training, etcetera. In the interactive installation, players are hanging freely off a bar above a virtual projected river. Every once in a while, a virtual raft floats down the river, which gives the player time to take a breather. The objective of the game is to maximise the time spent hanging off the bar. This installation offers a number of interesting features that can be directly coupled to key principles of strength training. The time-interval between two rafts drifting by represents the *work-interval* while the time that can be spent on the rafts represents the *rest-interval*. Being able to play around with the work-to-rest ratio readily covers one of the principal dimensions in the design of strength training. At current, workload can only be influenced by altering the work-to-rest ratio, however the system might be extended to also vary the intensity of training. Participants could for instance be enticed to pull up their knees or perform a pull up by adding elements to the (physical) setup of the installation. This would increase the intensity of the exercise. This work from Mueller illustrates how *intensity*, *duration* and *frequency* can function as a lens in the design of Sports ITech.

Technical domain

In the previous sections, we discussed the physical dimension of skill and ability in sports, touching upon bio-energetics, power, flexibility and movement economy. In this section, we will be discussing the *technical dimension* of skill. Just what *is* technique? In answering this question, we follow the definition of Gløersen *et al.* (2018): *"Technique [] is*

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[19] Farrell *et al.* (2011), Hoffman (2014), Kenney *et al.* (2015), Porcari *et al.* (2015), McArdle *et al.* (2006), and Powers *et al.* (2007).

the individual, multi-segmental motion pattern employed by individual athletes in standard situations of their sport. The individual technique of an athlete emerges as a specific coordinative pattern after extensive practice." Clearly, technique is a major contributor to motor competence, a concept closely associated with *physical literacy* (Whitehead, 2010). So how should this principal dimension be trained? And equally relevant in the current context, how can interactive technology add to that? The answer to this question is highly individual, context-specific and not to mention equivocal. The number of individual techniques that may be defined within the context of sports is without limit. Even within certain sports, like gymnastics, the techniques are numerous. And while attempts have been made to group skills (Fleishman, 1975; Gentile, 2000), it is today's contention that transfer is maximal when the practice context resembles the performance context as much as possible, following the specificity of training principle (Henry, 1958; Brunswik, 1956).

Moreover, the number of key performance variables (e.g. biomechanical, perceptual, physiological) that are related to the technical execution of a skill are typically high. Only in the, seemingly simple, act of running a myriad of modifiable biomechanical factors can be identified that relate to running technique (Moore, 2016). The identification of which takes considerable scientific scrutiny (Gløersen *et al.*, 2018; Lees, 2002) and is not without controversy (Moore, 2016). The complex interactions between the key performance metrics that underlie technique are often not well understood. And to complicate matters even further, individual variation between athletes (e.g. in body morphology, physiology, psychology) renders it difficult to translate scientific findings to the individual case. This point is nicely illustrated by Cavanagh and Williams (1982), who showed that the effects of alterations to stride length in runners (in terms of oxygen uptake) is highly individual. As such, the individual should always be central in technique analysis. Once relevant key performance metrics have been identified, there is the issue of *how* a meaningful change in technique can be realised. This issue is not trivial either. There are numerous considerations with regards to feedback design (Section 3.4) and the embedding of skill-practice into training (Section 3.5). Furthermore, there are pedagogical and didactic principles to uphold to facilitate the quest for meaningful change (Section 4.4). Finally, there are fundamentally different views on motor learning and skill acquisition that inform the nature and design of a training (Section 4.5); representationalists, for instance, strive for ideal movement whereas dynamicists strive for adequate action. While *ideal* and *adequate* will often coincide, this difference in focus (amongst other things) leads to a fundamentally different design of training regimens.

When designing Sports ITech for training in the technical domain, it is important to combine the strengths of technology with the strengths of the human trainer. Interaction Technology is particularly good for creating systematically varied, controlled situations in which the athlete has to use certain techniques in a certain way. Technology is also good for automatically measuring objective characteristics of the athlete's execution of the technique. The human trainer, on the other hand, is much better at *interpreting* these measurements, and turning them into decisions regarding the athlete's need for being offered this or that next technical training situation. In the ideal combination, the technology becomes a tool in the hands of the trainer, who remains responsible for goal setting, choosing the best training setting, and parametrising the exercises for a particular athlete.

Tactical domain

Potentially as involved and elusive as the technical dimension of skill, is the *tactical* dimension. Much of the same considerations that hold for the technical domain, also hold for the tactical domain: 1) Tactical behaviour is sport specific, 2) Many forms of tactical behaviour can be discerned within a sport, 3) Many key performance variables can be related to a single tactical situation, 4) Much variation exists between seemingly similar tactical situations, 5) Much variation exists between players and teams, and 6) There are a myriad of ways in which players can be instructed to achieve a meaningful (and lasting) change in tactical behaviour. This virtually limitless space of possibilities provides much opportunity to the interaction designer. The key is to strike a meaningful balance between specificity and generality. That is to say: How can interaction technology be designed such that the idiosyncrasies of sport, context, player and situation can be upheld without losing general applicability?

One striking example comes from Fogtmann and colleagues who developed *TacTowers*, an interactive training installation, that is designed to aid handball players in training their "micro-tactical skills" (Fogtmann *et al.*, 2011; Ludvigsen *et al.*, 2010). The installation incites representative game-like situations that requires players to rely on their micro-tactical skills (e.g. anticipation and decision making) to win. As such, TacTowers shapes a rich learning environment (Walinga and Koekoek, tbd) that allows for the hyper-sampling of relevant game-like situations (cf. Jensen *et al.*, 2014a). An ex-situ, screen-based alternative to TacTowers is *IntelliGym* (see: Savelsbergh, 2017). With IntelliGym, soccer and hockey players can relive, or experience anew, tactical situations from behind a computer screen using a digital training-interface that presents them with meaningful tactical scenarios.[20] Finally, another form in which tactical behaviour can be improved is to help trainers effectively communicate the, often intangible, principles of tactical performance to their players.

In recent work, we explored this approach in the form of *discussion facilitators*: data-driven, situated visualisations that help trainers and players evaluate on-field tactical situations (see also the work by Postma *et al.*, 2019). Similar to technical training, Sports ITech systems for tactical training often concern setting up game settings in which meaningful situations can be tried out, varied systematically, and reviewed and commented upon. Again, the technology is good at creating such settings; the trainer is good at knowing which learning situations a team needs to be exposed to, or how to interpret (and turn into decisions) the performance that they show in the tactical "problems" that were set up. Tactical situations emerge by manipulating the right combinations of constraints (task, environment, agents); learning happens by choosing the right conditions and setting up the right problems to which the athletes should be exposed.

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[20] https://www.intelligym.com Date accessed: 24 June 2022.

Perceptual-cognitive domain

Finally we will discuss a skill domain that has received considerable traction over the past decade(s), which is *perceptual-cognitive training*. With perceptual-cognitive training, both the perceptual as the cognitive aspects of performance are recognised as skills or abilities that can be trained and improved. In part, this contention can be traced back to the finding that expert athletes display different gaze-behaviour in sports than do novice players and are generally more accurate at predicting the outcome of a movement (based on limited information); (see also the work by Dicks *et al.*, 2015). When considering the design perceptual-cognitive training systems for sports, two (orthogonal) dimensions stand out along which such systems typically vary. *Task specificity* concerns the extent to which a training system targets a specific skill, with skill-specific systems on one end and integrative systems on the other (Postma *et al.*, 2019). *Training context* concerns the extent to which an interactive system can be applied within the natural context of training, with on the one extreme, systems that are primarily used *off the field* (ex-situ) (Farrow, 2013) and on the other extreme, systems that are primarily used *on the field* (in-situ). With examples abound, we highlight a number of systems that nicely typify the four quadrants, i.e. ex-situ – skill specific (Fadde, 2006), ex-situ – integrative (Savelsbergh, 2017), in-situ – skill specific (Kosmalla *et al.*, 2017a; Jensen *et al.*, 2015b; Sato *et al.*, 2019) and in-situ – integrative (Jensen *et al.*, 2014a; Fogtmann *et al.*, 2011).

Another classification, distinguishing between perceptual-cognitive training techniques, is that of Gray (2019). In a recent review, Gray discerns between five forms of perceptual-cognitive training, i.e. *"(i) training using non sport-specific stimuli; (ii) training using sports-specific stimuli to improve anticipation and decision-making; (iii) training designed to restrict visual information during real play; (iv) training designed to improve gaze behaviour; and (v) training using sports virtual environments."* Gray shows that these various forms vary widely in effectiveness, generalised perceptual-cognitive training systems (i) even show no evidence of transfer. This finding is supported by recent work of Renshaw *et al.* (2019). Finally, a special case of perceptual-cognitive, or psychomotor, skill is *kinesthetic empathy*, defined by Fogtmann as *"the empathic part of humans' innate bodily intelligence"* (Fogtmann *et al.*, 2011; Fogtmann, 2007). Kinesthetic empathy relates to qualities such as anticipation, deception and decision-making and is strongest when two athletes are placed facing each other (Fogtmann *et al.*, 2011).

4.3.3 Feedback functions

How can Sports ITech, specifically feedback, be tailored to support these different target outcomes in sports? In Section 3.4, we already discussed the many shapes and forms in which augmented feedback can be provided. Here we will talk about the different functions that augmented feedback can have to support performance, engagement and motor learning. In doing so we follow the textbook distinctions that are made to delineate the functions of augmented feedback in sports.[21]

Augmented feedback can be *essential* to motor learning, i.e. athletes are unable to learn without feedback about their performance. This is for instance the case when task-intrinsic feedback provides insufficient information, for example about the outcome of the movement. For novices in competitive diving, for instance, it might be hard to know how much 'splash' they caused when hitting the surface of the water. In such cases, augmented feedback might be essential to learning (and arguably one of the few examples in which providing *knowledge of results* is powerful). Second, augmented feedback can *facilitate* motor learning, i.e. athletes are able to learn particular skills without feedback, but their learning curve is steepened by providing augmented feedback. This is for instance the case with novice runners trying to improve their running technique. Third, augmented feedback can be *inessential* to motor learning, i.e. athletes are able to learn a skill just as well *with* as *without* augmented feedback. There is no classic case to decorate this statement with; if feedback is redundant to motor learning, the augmented feedback is probably ill designed (e.g. feedback is overly specific or not specific enough; too little or too much feedback is provided; or the provided feedback is quite simply erroneous). It is important to be alert to the

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[21] Schmidt and Lee (e.g. 2014), McMorris (2014), Magill and Anderson (2011), Hodges and Williams (2012), Gollhofer *et al.* (2013), and Edwards (2010).

effectiveness of augmented feedback. It is easy to brush off ineffective feedback as 'no harm, no foul'. However, it should be taken into consideration that the provision of augmented feedback can create dependency in learning (Salmoni *et al.*, 1984; Schmidt, 1991). If this is the case with redundant feedback, it can over time become counterproductive. Fourth, augmented feedback can *hinder* motor learning, i.e. athletes learn a particular skill better or faster *without* augmented feedback. Feedback that hinders motor learning points to serious flaws in the structuring or design of augmented feedback. Augmented feedback can be an hindrance when feedback is erroneous, inappropriate or untimely.

4.3.4 Task Complexity

Sports Interaction Technology can greatly contribute to (motor) learning, engagement and performance in sports. However, for it to be optimally effective, *task complexity* should be explicitly addressed. Csikszentmihalyi and colleagues, for example, showed that skills and challenges (in sports and everyday life) should be optimally balanced to arrive at a state of flow, which is associated with high levels of intrinsic motivation (Csikzentmihalyi, 1997; Jackson and Csikszentmihalyi, 1999). Similarly, to chart an optimal learning path for (novice) athletes, task complexity should be carefully weighted against skill level. Task difficulty (or task complexity) can be divided in nominal task complexity and functional task complexity (Sigrist *et al.*, 2013; Guadagnoli and Lee, 2004).

Nominal task complexity

Nominal task complexity refers to the difficulty of a certain task *regardless of the athlete performing the task*. Shooting a free throw in basketball for example has a lower nominal task difficulty than shooting a three-pointer. Similarly, performing a single somersault has a lower nominal task complexity than performing a double one. Knowing the progression of nominal task complexity in a training domain helps one to design deliberately for specific and relevant variations of difficulty levels. At a more abstract level, one could say that nominal task complexity is the relative scaling of skills (within a certain skill domain or sport). A very nice exemplification of the concept of nominal task complexity can be found in judging aesthetic sports like diving, figure skating and gymnastics. In gymnastics for example, athletes are scored on the *complexity* and *execution* of their routine: A flawless performance of an easy routine might earn less points than an imperfect execution of a difficult routine.

Gentile developed a general purpose taxonomy to classify the nominal task complexity of skills using a two-dimensional system, comprising 16 skill categories (Gentile, 1972, 1987). Figure 4.1 displays Gentile's seminal classification of skills. Gentile considered task complexity to stem from the inter-relationship between activity and environment. The demands placed on the athlete by the environment are aptly referred to as *environmental demands* and are comprised of *regulatory conditions* (either in motion or not) and of *inter-trial variability* (either present or absent). The demands placed on the athlete by the nature of the activity are referred to as *action requirements* and are comprised of *body transport* (requiring a change in location or not) and of *object manipulation* (requiring an object to be manipulated or not). The crossing of these four binary qualities leads to the definition of 16 distinct skill categories that range in difficulty (see also the work by Adams (1999) and Wüest *et al.* (2014)). This allows the designer to gradually vary the difficulty of exercise programmes in a grounded and well chosen route by systematically varying in the various facets of Gentile's taxonomy.

Regulatory conditions are those conditions that influence, shape or determine the way a skill *can be* or *is to be* performed. Regulatory conditions in a penalty kick in soccer for example are the distance of the ball to the goal; the position and movement of the keeper; stadium lighting; weather conditions and the quality of the grass. The principal distinction to be made within this category, according to Gentile, is whether the relevant regulatory conditions are in motion or not. Gentile posited that tasks performed in the context of dynamic regulatory conditions are generally more difficult to perform than tasks performed in a more stationary context. Throwing a ball to a stationary teammate in rugby for example is more easy to do than throwing it to a moving teammate. Gentile further classified skills by the presence or absence of inter-trial variability; with skills that require an athlete to deal with inter-trial variability to be more difficult. Hitting a baseball from a

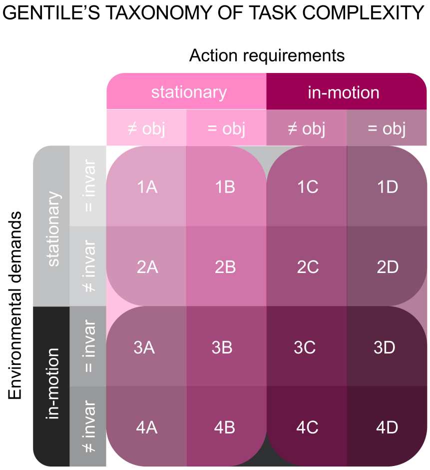

Figure 4.1: Gentile's taxonomy of task complexity

batting tee for example is more easy to do than hitting a ball that has been thrown by the pitcher (even if the pitcher is not actively trying to outperform the batter).

The two principal distinctions made within the action-requirements dimension are whether or not the athlete has to move (body transport) or whether or not the athlete has to manipulate an object (object manipulation). Tasks that require an athlete to change position are considered to be more difficult than tasks that can be performed on the spot. (Notice that, in Gentile's view, it is about a change of location and not about movement per sé). For example, performing a stationary serve in volleyball is considered less difficult than a jump-serve. Finally, tasks that require an athlete to manipulate an object are considered more difficult than tasks where this is not the case.

Functional task complexity

Up to this point, we mainly discussed task complexity in the form of *nominal* task complexity. We now turn to discuss *functional* task complexity; colloquially known as skill level. Functional task complexity is the nominal task complexity relative to the skill level of the athlete. Put into concrete terms: functional task complexity is low for an expert athlete performing a task with low-level nominal task complexity. Conversely; functional task complexity might be high for a novice performing that very same task (Sigrist *et al.*, 2013; Guadagnoli and Lee, 2004). Whereas nominal task complexity remains invariant, functional task complexity might change over the course of time; for instance due to the effects of motor learning.

Functional task complexity and skill level have a very pronounced role in sports. Most, if not all, sports have a league system, separating novices from experts and everything in between. Soccer in the Netherlands for example is classified in ten different tiers, from the premier division (first tier) to the “fifth class” (tenth tier). Teams that are of comparable skill level are pitted against one another. Through promotion and relegation, players and teams can move up or down the pyramid. Some very elaborate systems exist to manage, rate and record the skill level of athletes (e.g. tennis, gymnastics and figure-skating).

Functional task complexity then is relevant to the designer of Sports ITech when explicitly targeting for example the distinction between novices and experts. It is not enough to know that “experts can do more difficult exercises”; models of functional task complexity explain how exactly this difficulty can vary.

4.3.5 Temporal structural aspects

There are a number of temporal-structural aspects to training that influence the design of Sports Interaction Technology and the effectiveness thereof. Training regimens are specifically designed and tailored by trainers to fit the needs of their athletes, which typically change over time (Postma *et al.*, 2019). A typical sports season lasts part of a year, has a beginning and end, and often consists of a series of phases with their own demands and characteristics. Pre-season training looks differently from off-season training, which again looks differently from in-season training. From a conditioning standpoint, pre-season training is focused on getting in shape, while off-season training is geared towards maintenance and recovery. Though also on smaller timescales, the needs and wishes of trainers, coaches and athletes vary. Players and coaches typically coordinate their training efforts in relation to tournaments and game schedules. Game preparation and practice is for example oftentimes tailored to specific opponents. Finally, on even shorter time scales, athletes get tired over the course of a training. It is up to the trainer to be sensitive to how the needs of athletes evolve over different time scales, and it is up to the interaction designer to facilitate and empower trainers to (hyper) tune their training regimens to the perceived needs of their athletes.

4.3.6 Freedom in Functionality of Sports ITech

Sports ITech, just like all man-made tools, influence the way humans interact with their environment. Running shoes offer joggers the possibility to run for extended periods of time over unforgiving and harsh terrain and surfboards offer surfers the possibility to ride big waves. Some of these (interactive) tools have a *closed design*, meaning that they are designed to have a singular purpose. The clap-skate is an excellent example of this (Ingen Schenau *et al.*, 1996). Other (technological) innovations on the other hand have a more *open design*, meaning that the tool serves a general purpose (cf. Withagen and Caljouw, 2017). Zwift is an excellent example of such an open design.[22] Zwift is a digital-physical training platform that allows users from all over the world to run or cycle together in a shared online environment. With Zwift, users can follow structured workouts, race others and explore virtual worlds. As such, this piece of digital-physical sports technology serves a number of different goals. Put simply, whereas all athletes would use the clap skate for its unique contribution to power output, athletes will use Zwift for ranging reasons. The closed and open design distinction is not a dichotomous one. All forms of (sports interaction) technology can be fit somewhere on the continuum of closed to open design.

While designed to serve a singular purpose, specialised Sports Interaction Technology might develop a broader application over time. This might for instance happen when such technology is embedded into greater system architectures. *Heart rate monitors* for example have been subjected to such assimilation. Mueller *et al.* (2012b) for example have used heart rate monitors to balance exertion experiences. Specifically,

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[22] www.zwift.com Date accessed: 24 June 2022.

with "Jogging over a Distance", they allowed geographically distributed joggers with different fitness levels to 'run together'. Normally, with different fitness levels, joggers run at different speeds or at different heart rates, making it either impossible to socialise or impossible to run at the desired speed. "Running over a Distance" solves this by connecting users with spatialised audio. When both joggers run at their desired heart rate, the audio is spatialised such that they appear to be running *side-by-side*. When either one of the joggers is running with a higher or lower-than-desired hear rate, the audio is spatialised such that they appear to be running *ahead* or *behind*, respectively. This use of heart rate monitors is seen to go beyond the intended use of simply measuring heart rate (also see Stach *et al.*, 2009). At a more basic level, the same could be argued for the use of Inertial Measurement Units, of which an ever-broadening application in sports is seen: e.g. automatic route detection in climbing (Kosmalla *et al.*, 2015); automatic action recognition in volleyball (Salim *et al.*, 2020b); group interaction modelling in volleyball (Beenhakker *et al.*, 2020); automatic video tagging (Salim *et al.*, 2019) and for trajectory changing motion balls (TAMA) (Ohta *et al.*, 2014). This process of *assimilation* or *recontextualisation* can also be employed as a deliberate design strategy, in which specialised equipment is given a different purpose by placing it in a greater system architecture or by using it in a different context.

Whereas closed function designs have a singular purpose, open function designs potentially serve a myriad of purposes. A (generic) ball is a classic case of open function design; it is used in ranging forms of play and sports. Open function designs in Sports Interaction Technology are quite common. They come in different shapes and sizes, ranging from interactive installations (Postma *et al.*, 2019; Jensen *et al.*, 2014b; Jensen *et al.*, 2015b; Delden *et al.*, 2020; Kajastila *et al.*, 2016; Graf *et al.*, 2019) and intelligent artefacts (Fogtmann *et al.*, 2011; Nitta *et al.*, 2015) to wearables (Kosmalla *et al.*, 2015; Erp *et al.*, 2006) and networked environments (Mueller *et al.*, 2003a; Mueller and Gibbs, 2007a; Mueller *et al.*, 2008a; Yao *et al.*, 2011). Open function designs present designers with different challenges and opportunities than closed function designs. Closed function designs fulfil a singular purpose perfectly, open function designs are a 'jack of all trades'.[23] The challenge for the latter is to offer the user (athlete and trainer alike) a comprehensive 'suite-of-games' (i.e. a coherent set of applications) for training (Delden *et al.*, 2016b). The key to the development of a suite of games is to carefully examine (the nature of) a sport discipline and deconstruct it into meaningful principal components.

With TacTowers, Fogtmann, Ludvigsen and Grønbæk set an example of how a suite of games can be designed around a meaningful sport specific dimension (Fogtmann *et al.*, 2011; Ludvigsen *et al.*, 2010). With their system, micro-tactical skills in handball players could be trained with the use of four distinct smart sport exercises i.e. 'Blocker', 'One-on-One', 'Lights-ON' and 'Extinguish'.

Note that 'openness' is not a fixed trait when it comes to Sports Interaction Technology. Through use, closed designs can become more 'open', however closed designs can also become more 'open' when new applications are developed for systems that currently only feature a single function. Put differently, the mere fact that only one application might have been designed for a platform that has in potential many uses, does not render the system 'closed' by default. So when considering the 'openness' of Sports Interaction Technology, it is always meaningful to look at the possibilities of the system to tap uncharted potential.

4.4 Pedagogy, Learning and Didactics

Pedagogy and didactics are part and parcel of sports practice, most notably in the context of motor learning and Physical Education (PE). How should PE-teachers, trainers and coaches alike effectively structure rich learning environments for their learners? And what role has interactive technology to play in this? In this section, we will discuss a number of concepts central to pedagogy and didactics as applied to sports and Physical Education (see Table 4.6). We focus on concepts that are specifically relevant to designers and deployers of Sports ITech, either because they are already applied to many Sports ITech systems,

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[23] *Jack of all trades, master of none; though oftentimes better than a master of one.*

or because we feel that Sports ITech is particularly suitable to address that aspect of pedagogy and didactics.

Table 4.6: Fourth 'Function' subbranch – Pedagogy, learning, and didactics

FUNCTION – PEDAGOGY	Both sports training and Physical Education have a large basis in theory of pedagogy, learning, and didactics, understanding of which can enrich the design of Sports ITech
Model-based practice	*"A blueprint which describes certain procedures for organizing content, task structures and the sequencing of learning activities" in Physical Education (Hastie and Casey, 2014)*
Modelling	*Motor learning through imitation of the self or others (peers or experts)*
Learning phases	*Prototypical stages in motor learning*
Assessment	*The quantification and qualification of motor competence*
Perceptions of the body	*The implicit or explicit appreciation of the physical self, often in relation to others*
Informal curriculum	*Implicit learning occurring through informal interactions between peers*

4.4.1 Model-based practices

A models-based practice can be defined as a "mechanism or pedagogical approach [that]... aligns outcomes with students, needs, and the teaching/instructional style" (Casey, 2016, p.55). Models-based practices such as *Teaching Games for Understanding* (TGfU, Bunker and Thorpe, 1986), *Sport Education* (Siedentop *et al.*, 2019), and *Student Designed Games* (Hastie, 2010) centralise PE student learning processes and provide "a blueprint which describes certain procedures for organising content, task structures and the sequencing of learning activities" (Hastie and Casey, 2014). Within these student centred pedagogical models the use of interaction technology becomes increasingly valuable (Kok and Kamp, 2018). These models emphasise hybridisation of self regulated learning processes, stimulation of collaboration with others, and developing meaningful experiences in student knowledge and understanding (Casey *et al.*, 2017).

One example of interaction technology within a game based approach, such as Teaching Games for Understanding, stimulating student learning is *digital video tagging* (Koekoek *et al.*, 2018). Digital video tagging facilitates teachers and coaches in the use of video images during physical education lessons and sport practices. During game play in small sided games, player behaviour can be video recorded while key events are tagged in real time. This tagging with the use of a tablet or mobile device can be executed by both teachers/coaches and players. The tagged videos are immediately available for game play analysis in between games or matches. Within TGfU approaches, questioning is one of the key pedagogical features in which tactical thinking processes of players are stimulated (Harvey *et al.*, 2016). For instance, a *debates of ideas* setting in which players exchange meanings through assigned discussions. In particular the use of video images in a debate of ideas session with players can support teachers when implementing TGfU principles (Harvey and Gittins, 2014; Koekoek *et al.*, 2019).

Several studies have paid attention to the use of digital technology with respect to a models based practice such as Sport Education (André, 2018; Koekoek and Van Hilvoorde, 2018). Sport Education curriculum models encourage teachers to focus on the development of children's competence, literacy and enthusiasm. Therefore lesson units are designed to work in sport seasons (in PE contexts) in which children learn one specific sport. Features of these units consist of player affiliation to teams/groups, formal competitions, culminating events at the end of season, keeping records, and festivities (Siedentop *et al.*, 2019). Interaction technology can play an important role with respect to these aspects in the enrichment of student learning processes. For instance, André (2018) presented several examples in a Sport Education season when using social media such as wikis and Facebook. Sinelnikov (2012) has explored the use of iPad's in a Sport Education season unit. In particular the focus was on team roles, student responsibilities, and student-iPad

The version of record is available at: http://dx.doi.org/10.1561/1100000087

interactions. The knowledge from this scholarly work also resulted in an overview of several technological developments that inform Sport Education and the way these can support teachers and students working in a sport season (Koekoek and Van Hilvoorde, 2018).

It is important to note that many model-based practices are firmly rooted in pedagogy and motor learning theory. As such, dissimilar approaches might be informed by dissimilar theoretical principles. For example, the principles that underlie teacher-centred approaches (e.g. Operant Model for Skill Acquisition (Siedentop and Rushall, 1972)) are fundamentally different from the principles that underlie learner-centred approaches (e.g. Sports Education (Siedentop, 1994)), see also Bessa *et al.* (2021). For interactive technology to serve its purpose in a PE setting, designers of sports ITech should be aware of the theoretical inclinations of their users and design their work accordingly. Contrasting the work of Jensen *et al.* (2015b) and Fogtmann *et al.* (2011), we can recognise a drill-based approach for *The Bouncer* (Jensen *et al.*, 2015b) and a game-based approach for *TacTowers* (Fogtmann *et al.*, 2011). Each distinctly different, but each receiving praise from their respective audiences.

4.4.2 Modelling

Modelling is a practice in which the learner observes and imitates motor behaviour in order to improve their motor competence. Modelling is frequently applied in the context of motor learning and skill acquisition. Take for instance the volleyball trainer that demonstrates what the perfect serve looks like, see also Section 3.4.1. Interactive technologies are perfectly suited to support modelling practices and have been successfully implemented to do so in the past (e.g. Pijnappel and Mueller, 2014; Kosmalla *et al.*, 2017a). In this section, we reflect on the relevant facets of modelling for the design of Sports ITech.

Video plays a significant role in physical education interaction technology. Consequently, there is information available about how modelling benefits learners. When providing feedback or feedforward two models can be distinguished about the question ‘who?’ (Ste-Marie *et al.*, 2012). Self-modelling (Zhang and Hongxin, 2018; Ste-Marie *et al.*, 2012) in which a student is provided with a video of themselves and other-modelling in which models are someone else (Weiss *et al.*, 1998). The latter addresses the multiple issues about for example what kind of skill level (Ste-Marie *et al.*, 2012; Walinga *et al.*, 2018), social learning theory (Bandura and McClelland, 1977), and inclusiveness (Doodewaard *et al.*, 2018). This section is restricted to the models that are related to skill level. When a model other than self is used, Ste-Marie *et al.* (2012) examined the difference between coping models and mastery models. A coping model closely resembles the students current skill capacities, as opposed to a mastery model that shows an expert example of the movement activities. Both models have shown to be effective in enhancing skill levels, however, the coping model has been related to the increase of self efficacy amongst students (Weiss *et al.*, 1998; Ste-Marie *et al.*, 2012). A result that is of interest to the physical education scholars because of physical literacy objectives (Whitehead, 2010).

The self as a model option is connected to the self regulation model of Zimmerman (2000) in which self reflection is stimulated. Experimental studies that compared external regulated feedback and self regulated feedback found positive effects on motivation, self efficacy and skill acquisition (Carter *et al.*, 2014; Chiviacowsky and Wulf, 2005). For example, Zimmerman and Kitsantas (1996) found that a self recording significantly influenced the performance of dart throwing compared to performance with just verbal feedback. Kok and Kamp (2018) suggested that the self regulation processes that are used with video-feedback are relatively timing and frequency orientated. According to them, there are wider opportunities to use video feedback for self regulation purposes by involving children in more content driven choices.

Teachers who use models in the context of education should be aware of the hidden message a video could give to the learners. For example, videos that aim to give examples of future learning objectives in sports and PE need to be carefully aligned with expected learning processes. Students might get motivated if future learning objectives appear unattainable. The learner will in this case not perceive the task as doable, resulting in lower self efficacy. Matching models within a bandwidth of doable tasks helps students grow within their zone of proximal development (Vygotsky (translated and edited by) Michael Cole, 1978).

4.4.3 Learning phases

Pedagogy is a wide concept used within the context of physical education and sports that includes multiple elements of teaching (see also paragraph on models based practices). The use of technology forces the teacher to answer the practical-pedagogical questions when, why, who, where and what? Walinga *et al.* (2018) suggested that these questions should be answered with at least the inclusion of analysis of the student's actual learning phase. Based on various models about stages of learning in motor skill acquisition (Bernstein, 1967a; Dreyfus and Dreyfus, 1980; Fitts and Posner, 1967; Newell, 1986; Schmidt *et al.*, 2018). Walinga *et al.* (2018) proposed the learning circle model to be indicative for digital interventions that are tailored to the students' learning phase. Based on the previous mentioned models regarding stages of learning, interaction technology use in the three phases of the learning circle (i.e., managing, stabilising, exploring) should support the process of respectively structuring to manage, informing to stabilise, and inspiring to explore. Pedagogy and the development of digital tools can be directed to this analysis by providing only the information that fits the objectives of the current stage of the student learning phase.

Importantly, the amount of information that is presented to the learner through interactive technologies should be fitting to their learning stage. In the first phase of learning, the learners orientation is towards preventing failure and achieving first success. Providing too much and overly detailed information in the first stage of learning may result in overloading the learner, hindering performance on the given task. Presumably only global information is relevant at this point to support the learner in solving the basic challenges of the task, regardless of whether this is through video-feedback, augmented reality, animation, etc. In short: "*feedback should be provided with as much precision as a learner can meaningfully interpret*" (Edwards, 2010).

4.4.4 Assessment

Interaction technology can generate several benefits in the use of assessment tools for different pedagogical purposes. By doing the assessment automatically, as shown in an earlier section, or by supporting the teacher in other ways. According to the position statement of the AIESEP network (AIESEP, 2020), use of digital technology should undergo serious consideration by physical educators when starting an implementation of assessment within the educational practice. For instance, digital technology must be aligned with learning outcomes, pedagogy and assessment tasks. This means that the role of the teacher in using digital technology for assessment is also important. Teachers must have sufficient digital skills in which they can critically choose the right assessment tools. AIESEP warns explicitly for the power and influence of innovative digital technologies that may dictate PE teachers what and how they assess, in particular when ignoring critical examination and reflection. This also includes that teachers are obligated to ensure protection of data and the privacy of children.

The study of Rossum and Morley (2018) demonstrates how teachers can be involved in the development process in order to manage and reduce the possible risks that are pointed by the AIESEP position statement. These researchers developed a digital user-friendly movement assessment application. Therefore they described the nature of the process in the development of the tool together with teachers. Especially they explained the way they encounter experts' and users' dilemmas and how these are overcome. With a critical perspective on the realities of using digital technology they showed how a safe tool can be developed in order to assess children's movement competences. For further information, see additional literature (e.g., Van Rossum *et al.*, 2021; Morley *et al.*, 2019).

4.4.5 Perceptions of the body

The explicit and implicit body-messages that PE teachers and coaches communicate through the use of digital technologies can influence the way learners perceive and value their own bodies and abilities. In a recent study by Doodewaard *et al.* (2018) it was found that ability, gender, and ethnicity were not equally represented in PE instructional videos. Causing for a skewed norm in what is deemed to be desirable and normal (in terms of body image). Such (implicit) messages may provoke social inequalities in PE, causing for the privileging and marginalisation of certain students (Doodewaard *et al.*, 2018). See also the work of Van Amsterdam (2013) and Van Amsterdam *et al.* (2015).

When designing interactive technologies for PE, body-positivity should be the norm. Instructional videos, demonstrations, and other interactive technologies should paint a diverse and inclusive picture. Not just for the sake of being diverse, but for learners to be able to identify themselves with the examples, allowing them to adopt the content as suitable for their own situation.

4.4.6 Informal curriculum

Sports is a social endeavour. Today, tracking ones exercise might just be as important as exercising itself.[24] The 'quantified self' seems to be just as much about the metrics that quantify an exercise as it is about the ability to share those metrics with the world. Fitness apps like Strava, Runkeeper, and Nike Run Club provide users with a plethora of means to support this sharing need. Runkeeper captures this sentiment in their slogan: "Let's run together". Through leaderboards, social networks, and real-time location sharing, users can fulfil their need to informally share their performance and engagement with their sport. Besides a measured sense of performance (Tholander and Nylander, 2015), these apps fuel a lived and social sense of performance. This creates an 'informal curriculum' that goes beyond the (quantified) sports activity itself.

To many, the informal social engagement with sport is just as important as the engagement with the sport itself. In terms of Ryan and Deci's Self-Determination Theory (Ryan and Deci, 2000), social sports platforms have the potential to promote a sense of relatedness in (recreational) athletes. This social layer adds a dynamic and reciprocal relation to the practice of sports. On the one hand, people are enabled to share their sporting experiences, on the other hand people shape their sporting experiences to fit the social dynamics of a particular platform (Hafermalz *et al.*, 2016). TicToc is exemplary of this. TicToc users design and shape their dance routines to fit the nature of the platform.

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[24] https://www.vice.com/en/article/53dzv5/if-you-didnt-quantify-a-run-did-it-even-happen Date accessed: 24 June 2022.

Only the best dance routines are posted. Through the comments-section, Original Posters (OP's) are encouraged or discouraged to further pursue their efforts. In the context of Physical Education (PE), such informal undercurrents can be fuelled by digital technology too. A PE-teacher might show a video recording of a classmate for functional movement analysis, while all the learners are seeing are the clothes that the person in the video is wearing. Sports Interaction Technology inadvertently impacts social processes related to sports and exercise, social processes that are crucial in the context of motor learning, physical education, and physical literacy.

The exploration of student perceptions with respect to what they think about their learning processes in physical education lessons can be a valuable source of information for the implementation of interaction technology. For example, digital observation tools can be used to explore student perceptions of formal situations (i.e., debate sessions within TGfU contexts) in the way they judge tactical situations in basketball and what they might have learned (Koekoek *et al.*, 2019). Koekoek (2020) explored what perceptions of social interactions mean for perceived learning processes of students. The results of this study indicated that informal task-related interactions create an informal curriculum that is based on the fear of being mocked, on gender categorisations, and on wanting to have fun. Especially, the ambiguity in these social constructions of learning tasks in PE lessons (e.g. working together, assigned group work, debates/discussions) shaped the informal and formal curriculum in which they were situated.

The research by Koekoek (2020) emphasises the role of peers in movement activities especially together with the use of interaction technology. Critical reflection by teachers of the technology used in the learning situation is necessary in order to understand what learners meanings are with regard to collaboration with others, thoughts about working together in specific work group compositions, and also expectations of learning outcomes for themselves and those of others. Implementation of interaction technologies should be considered in perspective of these informal and formal dynamics that may occur and influence teaching goals when children come together in PE classes. For more information

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about student learning and interactions see also the work of Barker *et al.* (2017).

For designers, the main takeaway is that Sports ITech is never neutral with respect to social undercurrents and the informal curriculum in sports. Social sports platforms as well as technological training interventions impact the informal curriculum for better or worse. A TicToc-user that received a toxic comment on one of her dance performances might shy away from posting ever again. A high-school student might not feel represented by the skilful, able-bodied model from the PE instruction videos - harming her body positivity (Doodewaard *et al.*, 2018). And a (recreational) athlete might stop running just because he is always last in the leaderboard with his friends. Sports ITech must be designed with the informal curriculum in mind, promoting relatedness (Koekoek and Knoppers, 2015), competence (Koekoek *et al.*, 2014), and autonomy (Duivenvoorden *et al.*, 2021) in sports (Ryan and Deci, 2000).

The informal curriculum, and all other facets of the pedagogical and didactic context in previous sections, form important background to take into account when designing Sports ITech for educational purposes specifically.

4.5 Philosophical Accounts of Skill Acquisition and Motor Learning

With or without technology, it is important to create rich learning environments in which athletes have the opportunities, action possibilities, and motivation to learn (Tolentino *et al.*, 2009). It makes a great difference, though, what exactly one would consider the right kind of rich learning situation. Fundamental theories on learning in sports are important there. Our work should be consistent with instruction theory, pedagogy and motor learning theory[25] and general exercise and training principles (Brink *et al.*, 2010; Dijkhuis *et al.*, 2017; Borghuis *et al.*, 2008), including various approaches to motor learning discussed below.

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[25] Jacobs and Michaels (2007), Jacobs *et al.* (2012), Vilar *et al.* (2012), Stolz and Pill (2014), Travassos *et al.* (2012), Seifert *et al.* (2017), Davids *et al.* (2012b, 2012a, 2013, 2015), Headrick *et al.* (2015), Serra-Olivares *et al.* (2015), Brymer and Renshaw (2010), Renshaw *et al.* (2009, 2019, 2010, 2016), Correia *et al.* (2019), Chow *et al.* (2007, 2011), Carvalho *et al.* (2013), Araújo *et al.* (2006, 2016).

That is to say, the possibilities for designing digital-physical training exercises are bounded by philosophical principles and considerations.

To complicate matters even further, some scientific fields are characterised by a state of paradigmatic pluralism, meaning that multiple contrasting theories coexist and proliferate more or less independent of one another. Each with their own set of assumptions, predictions and research programs. This paradigmatic pluralism is especially pronounced within the cognitive sciences, to which the fields of motor learning and pedagogy belong. Grosso modo, two distinct theoretical perspectives can be discerned, with on the one hand representationalist theories (Fitts and Posner, 1967; Schmidt, 2003) and on the other hand dynamicist theories (Gibson, 2014; Bernstein, 1967b). Representationalism and dynamicism span a theoretical continuum, also encompassing grass-roots approaches (Bunker and Thorpe, 1982) and hybrid theories (Srinivasan *et al.*, 1982; Rao and Ballard, 1999) in between.

Later in this section we will discuss that it might matter a lot to which of these theories designers as well as their audience subscribe; a trainer's stance will influence what they give you in interviews and design reflections, and the starting point of the designer will (strongly) influence how one interprets and translates what one hears from participants. First, however, we discuss several salient theories and paradigms of learning in sports, summarized in Table 4.7, to provide some background to this.

4.5.1 Representational theories of motor learning

Representational theories of motor learning follow a mostly cognitivist paradigm. Cognitivists subscribe to the notion that perception is indirect, that our perception of the world is incomplete and needs to be mended and mediated by mental models and processes (Fodor, 1975; Wolpert, 1997). A nice instantiation of this intuition can be found in the (sense-making of) retinal image: How does the visual-perceptual system reconstruct 3D-space from a 2D image? These and other questions are archetypal for cognitivistic research. The cognitivist agenda is thus to understand how incomplete information about the world can be complemented and mentally processed such that our perception of the world

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Table 4.7: Fifth 'Function' subbranch – Theoretical perspectives on motor learning

FUNCTION – THEORETICAL PERSPECTIVES ON MOTOR LEARNING The theoretical perspectives on motor learning that trainer or athlete subscribe to, explicitly or implicitly, strongly influences what one considers the right kind of rich learning situation (and thus, what Sports ITech one designs)
Representationalist approaches *Theories of mind that describe perception and action as an indirect, mediated, and cognitive process*
Dynamicist approaches *Theories of mind that describe perception and action as a direct, emergent, and dynamic process*
Hybrid approaches *Theories of mind that seek to bridge the divide between representationalist and dynamicist approaches, either theoretically or pragmatically (grass-roots approaches)*

is whole, allowing for adequate behaviour. Against this background, representational theories of motor learning use a computer metaphor to learning. A plan/schema/program is first processed and then executed. Representationalists explain performance and control by referring to internal (brain) processes such as motor programs that determine movement (Schmidt, 1975; Fitts and Posner, 1967; Adams, 1971). Learning, in this paradigm, is acquiring these processes and/or forming motor programs. Because the programs prescribe the movements, learning is directed at providing the learner with explicit rules describing the performance that are to be internalised. In other words, these theories take a modular approach to motor learning. Motor skills can be subdivided into smaller bits. These bits can be trained individually. Separate motor learning blocks can be later assembled into greater actions. Training focuses on reducing the error between perception and action. Since mental models and processes are needed in order to process information to act adequately upon the world, the focus is to hone these models. The more accurate the mental model, the better the performance.

4.5.2 Anti-Representational theories of motor learning

Anti-Representational theories of motor learning, on the other hand, follow a more ecological approach (Bernstein, 1967b; Newell, 1985). Ecologists subscribe to the notion that perception is direct and that the world is perceived in terms of action possibilities, or affordances. The concept of affordances was originally put forward by Gibson (2014). A popular definition of his concept reads: *"The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill"*. From this definition, it is important to note that the concept of affordances is relational. Affordances capture the relation between (behaviourally relevant) properties of the agent's action system and (behaviourally relevant) properties of the environment (Warren, 1984). As a shorthand definition one could say that affordances are *possibilities for action*. The ecological agenda is thus to understand how the agent and the environment relate to each other in order to allow for direct perception of action possibilities: e.g. What information specifies whether it is still possible to brake a car to a safe stop? (Fajen, 2007) And what information specifies whether it is still possible to catch a baseball? (Postma *et al.*, 2018)

Against this background, a dynamicist approach to motor learning places more emphasis on the perception action couplings that are available in the environment for learning. They describe control in terms of the relationship between learner and environment (e.g., attunement, picking up better information). Learning can be seen as education of attention to the invariants that will appropriately motivate and/or constrain activity. In this setting, motor skill learning is about: *education of intention*, i.e. what action should be performed; *education of attention*, i.e. learning to attend to the information that is relevant in guiding behaviour; and *calibration*, i.e. a process that transforms the metric in which information is detected, establishing a mapping from information to movement (Jacobs and Michaels, 2007). As such, learning should take place in an appropriate environment and activity context fitting the domain of motor learning. The difference between the representational and anti-representational paradigms of motor learning can be seen in the respective approaches of "practicing for 10.000 hours" (deliberate practice) and "serious learning in play" (deliberate play) (Ericsson *et al.*, 1993; Baker and Côté, 2006).

When one follows an ecological, or anti-representational, approach to motor learning, it makes a lot of sense to approach training as a play activity (Côté *et al.*, 2007; Koekoek *et al.*, 2014, 2018; Walinga *et al.*, 2018) in rich learning environments that are constrained to improve learning (Davids *et al.*, 2008). A game based approach such as Teaching Games for Understanding can be used in the context of physical education and sport (Bunker and Thorpe, 1982; Harvey and Jarrett, 2014). Such an approach facilitates learning through meaningful movement in games. It advocates a learner-centred orientation with an emphasis on exploratory learning within modified "gamelike" situations. A nonlinear pedagogical approach can enhance this learning (Chow *et al.*, 2007). Nonlinear pedagogy emphasises the importance of learners exploring the solutions to problems by themselves, rather than coaches prescribing exactly what and how they must learn. This enhances intrinsic motivation and results of meaningful improvements in tactical skills. Tan *et al.* (2012) have stressed that a nonlinear pedagogy may be appropriate framework that supports the use of four main pedagogical principles within the TGfU model (i.e., sampling, representation,[26] exaggeration, tactical complexity).

If coaches and teachers apply these key principles and centralise decision making in the learning processes, then techniques that are performed by players are supportive to solving a problem that the environment offers (Griffin and Patton, 2005). This may be a more ecological approach to learning than more technique centred approaches (in the latter, regardless of the environmental purpose, techniques are seen as skills that are best practised in isolation). Measures as game involvement (Mitchell *et al.*, 2006) do not focus on the ideal techniques but rather the outcome of the action is important, notwithstanding the fact that skills of course do play an important role.

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[26] Here 'representation' refers to representative task design and not to perception.

4.5.3 Implications for design

Depending on which of these theoretical paradigms one subscribes to, one might design new digital-physical training exercises entirely different. For example, from the ecological dynamics perspective it makes little sense to have an athlete perform a thousand identical repetitions while this would make perfect sense from a representational perspective. The paradigmatic inclinations of the interaction designer shape what Sports ITech is developed while the (implicit) paradigmatic inclinations of the trainer/coach determine what sports exercises will be employed — even when in both paradigms researchers have been able to report successful impact from their training programmes on sports performance.

From a representational perspective, interaction technology might focus on repeated (drill) practice of a single movement, measuring the execution in detail and giving precise feedback on the desired perfect execution of that single movement. From an ecological perspective, repeated exposure to certain actions might still be desirable but would be embedded in a varying and varied context representative of the game (Brunswik, 1956). Interaction technology might then tend towards building game like interactive spaces that offer a rich and varied learning environment, and work on exercise series in which certain patterns in the environment are manipulated to elicit that action in many forms and contexts throughout the game.

4.5.4 Principal differences of facets to design for

These observations have possible implications for how we approach our design work in sports. We argue that it is important to take into account possible learning paradigms that could underlie our systems, but also to elicit information from the trainer and athlete's stance in these paradigms and take that on board both while interpreting the gathered information and while designing interventions. Below is a list of principal differences that characterise the distinctions between the two paradigmatic approaches. These distinctions can be taken as guidelines for the design of Sports ITech.

Elementary vs Holistic

Representationalists contend that perception is *indirect*, they assert that the world can only be perceived as a whole through active cognitive inference. Perception of the world is incomplete, inaccurate and elementary and can only be experienced as a whole through mental models that actively process and reconstruct the perceptual stimuli that reach our senses. Putting it overly simplistic, one could say that light intensity, colour and texture are registered first and that only through active inference that particular combination of elements is perceived as being e.g. a basketball. The representationalist approach to skill acquisition follows suit: Motor skills can be trained by mastering the individual components that underlie it. Following this line of reasoning, a spike in volleyball can be mastered by deconstructing the movement into its elementary, or modular (Renshaw *et al.*, 2019), parts (e.g. the run-up, the jump, and the spike). Dynamicist on the other hand contend that perception is *direct*. That means that no mental models and operations are needed to act adequately. Rather, all the relevant information is readily available in the environment. This means that the practice context should be representative of the performance context as much as possible so as to retain the highly context-specific information that specifies the perception-action relationship (Brunswik, 1956). Following this line of reasoning, a spike in volleyball can best be trained by designing a situated, contextualised and realistic spike-task, involving as much relevant characteristics of the performance context as possible (e.g. blockers, defenders and unpredictable passes).

Ideal movement vs Adequate action

Representationalist strive for *ideal movements*, meaning that underneath all the variability that athletes display in their motor behaviour, some ideal form exist that should be perfected. The pursuit for an ideal movement becomes manifest in biofeedback systems that provide feedback to the athlete by comparing their current performance to a golden standard. Dynamicist on the other hand strive for *adequate actions*, meaning that the outcome of an action is more important than the movement that produced it. The thought behind this is that variability in movement might be functional in dealing with ever-changing circumstances. Ideally in running, athletes strive to maintain an optimal cadence of about 180 strides per minute, however variability in cadence might be functional in dealing with changes in running surface. In the case of volleyball, an 'imperfect' spike might still be an adequate action if it results in a score.

Isolated vs Situated

Representationalists contend that elements of a skill can effectively be trained in isolation, meaning that specific mistakes in the execution of a movement can be targeted and trained separately (segmentation). From a representationalist point of view, the hand placement in a volleyball block can be trained in a 'dry run', that is without other players and even without a ball. Dynamicists contend that skills are best practised in whole, ideally in a realistic context. Dynamicist would prefer *simplification* over *segmentation* (see Section 3.5.4). With simplification, hand placement in a volleyball block can be trained by having a player block a ball that is hit by the trainer from a fixed position. This lowers the task complexity, while retaining much of the information that is in the original task.

Prescribe movement solutions vs Explore movement solutions

Representationalists typically value verbal instructions as a means to help athletes find the ideal movement (explicit learning). Verbal feedback can be given prior, during or after the execution of a skill. The aim with such feedback is to highlight errors and discuss or prescribe the solution to such errors. Dynamicists on the other hand see more value in athletes exploring the space of possibilities (implicit learning). The idea behind this exploration is that athletes need to experience themselves which movements lead to adequate actions and which perceptual information is associated with it. This is not something that a trainer or coach can (easily) explain.

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Variation for generalisation vs Variation for discrimination

Representationalists, just as dynamicists, value variation in training exercises. However, both do so for different reasons. Representationalists invoke variability in their training schemes to allow athletes to become more generalistic. The aim is to present athletes with systematically sampled variations so that their mental models are able to cope with ranging circumstances. This is done by varying along the principal dimensions (or elements) of an exercise. Dynamicists invoke variability in their training schemes to allow athletes to become more discriminate in the situations they encounter. The aim is to present athletes with situations that are meaningfully different. Variations in training exercises are meaningful when they allow athletes to actively explore novel movement solutions.

Hierarchical vs Nested

Representationalists assert that perception and action are hierarchical processes, meaning that manifest player behaviour is the result of numerous (cognitive) processes that underlie it. For instance, from a representationalist point of view, *reaction time* can be taken to underlie adequate behaviour in sports. In Formula 1 racing for example, reaction time is often trained by simple reaction time tasks. The idea is that by improving on the (underlying) quality of reaction time, drivers are also better able to respond to sudden changes on the track. From a dynamicist point of view, response time cannot be separated from the situation in which a swift response is needed. Indeed, every situation is unique and carries unique perceptual information to inform an adequate response. As such, response time is not seen as an underlying quality that determines performance, but rather the result of the perceptual information that is present in the ever-unique, dynamic and nested agent-environment system.

4.5.5 Hybrid theories and pragmatic approaches

It should be noted that not all theories on motor learning can be strictly placed either under the representationalistic flag or under the dynamicist flag. Besides these two grand theories, grass-roots theories exist that sprung from practice, incorporating elements of each side guided by pragmatism (i.e. what works well in practice). Teaching Games for Understanding (Bunker and Thorpe, 1982) is such a grass-roots, or hybrid approach, that lends elements from both the representationalist and the dynamicist side. Another hybrid theory, albeit not a grass-roots one, is the theory of predictive processing. Both dynamicists as representationalists have tried to embed predictive processing theory into their theoretical framework. It should be noted however that predictive processing is still relatively young and has consequently had little influence on the practice of motor learning and skill acquisition, therefore we will refrain from providing an extensive overview here. The interested reader is referred to additional literature on this topic (e.g. Wiese and Metzinger, 2017).

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5

Limitations of our Work

In this section we address three types of limitations to the work reported in this monograph. First, *coverage of papers, research fields, and existing taxonomies* is obviously not 100%; there are always trade-offs in what to include and what to leave out. Second, the *organisation of our taxonomy* could have ended up being different when looking at the field from other perspectives. Third, we addressed many forms of Sports ITech, but only for a few categories did we comment on the *desirability of the innovations*; ethics, values in sports, and other perspectives could shed interesting light on that topic as well. In this section we address the limitations of our work through these themes.

5.1 Coverage of Literature

Regarding coverage of the literature, several things can be said. First, methodologically we did not do a formalized structured systematic literature review, although we did search systematically across the various domains by snowball sampling combined with starting from our own experience in the various fields. The breadth and depth of the field that we surveyed is of immense scope and we drew from several disparate domains; we therefore felt it would not be feasible nor relevant or helpful to go through a formalised systematic review method. The papers that we included are, despite our careful attempts to be as complete as possible, almost certain to reflect some of our own biases and blind spots. We believe our coverage of the field of Sports ITech as a whole did not suffer unduly from this limitation; however we cannot guarantee that our sampling of papers has been complete. In addition, a work like this is never complete and needs to be updated regularly as well as kept open for critique and alternative or complementary perspectives. On the other hand, by setting out the global structure of our taxonomy, we do deliver a good starting point for more focused papers addressing one subbranch in more depth, for papers adding new subbranches, or for papers addressing unique and interesting combinations of subbranches.

Second, we did not only exclude papers, but we also excluded whole fields of research, making deliberate choices in how to address the field of Sports ITech. We left out discussion of fields such as persuasive technology, educational technology, and sports psychology. These are all highly relevant, but we thought we could give a more focused contribution by the selection that we made. As such, these are topics that could still be addressed in future work by us or by others – how these fields relate to, and can contribute to developments in Sports ITech. Furthermore, we expressly excluded fields that are concerned with, what we considered, secondary benefits of sports, e.g. ‘healthy ageing’ and ‘exercise as medicine’.

Third, we made specific choices in which existing taxonomies we did, or did not, incorporate fully into our taxonomy. Some of our choices are elaborated as part of the taxonomy sections. Other existing taxonomies may not have been included 1:1 in building our design space, but can easily be framed as combinations of parts of our taxonomy, such as the work by Mueller *et al.* (2008b), or have been used in combination with other partial taxonomies to derive our own view on a certain branch such as the work by Jensen *et al.* (2013). Other papers may not be reflected exactly in the structure of our taxonomy, but have been formational in developing our view on Sports ITech by clearly articulating a neighbouring field, such as Exertion Interfaces (Mueller *et al.*, 2016). Finally, there are typologies that have not been included because they provide a completely different perspective on innovation and Sports ITech, such as typologies of *design methods* for movement based interaction (e.g., Andersen *et al.*, 2020), or more on a meta level, a typology of *innovation processes* in sports such as the one by Tjønndal (2017) that distinguishes social innovation, technological innovation, commercial innovation, community-based innovation and organisational innovation.

5.2 Choices in Taxonomy Organisation

Regarding the structure and organisation of our taxonomy, it is important to acknowledge that it grew out of a first-person research perspective, meaning that our own context influenced which nodes are emphasised or left out. Furthermore, in some cases nodes were not detailed further into subnodes or leaves as it was unclear how to proceed on these: in sports science, as mentioned elsewhere in this monograph, there is sometimes an underlying fundamental disagreement in a particular subdiscipline as to what would be the right subnodes. This leaves room to future interesting research directions.

Sometimes there are multiple ways to make decisions on categorisation. For example, "training" can be categorised using 1) Scope, 2) Skill domain and, 3) Skill complexity. But also on other attributes, e.g. 1) Age, 2) Expertise, 3) Phases of play, 4) Player specialisation, 5) Seasonal aspects, 6) Audience, and 7) Ableness. Both categorisations capture "training" on a different level, with one not necessarily being better than the other. Our choice in such cases grew from what we thought would be both adequately representative as well as helpful in looking at possibilities for design and research of Sports ITech. As such, our taxonomy is not *only* a decomposition of the structural elements (see the work of Avedon, 1981) of Sports ITech, but also a phenomenological taxonomy, distinguishing between aspects that we find to be salient between and among ITech systems.

Finally, from the taxonomy presented in this monograph, it is not always made explicit in what way individual subbranches / dimensions relate to one another. This need not be problematic, in the sense that it allows prospective users to relate any number of dimensions in any way they seem fit. However, this comes at the cost of relations that have already been investigated in literature. For example, Ishii *et al.* (1999) related “augment and transform” with “competition and collaboration”. This particular relationship provided them with a wealth of design possibilities and relevant insights. At current, these readily investigated relations between dimensions are not explicitly (visually) represented by the taxonomic structure. However, such relationships do exist and have sometimes already been investigated (e.g. Jensen and Mueller, 2014; Mueller *et al.*, 2011). Perhaps equally important, many relationships have not yet been investigated. This taxonomy might facilitate the selection of combinations of relevant dimensions for further scrutiny.

5.3 Desirability of Innovations

Finally, it is important to emphasise that our monograph does not address the desirability of innovations that may follow from applying our taxonomy to design and research of sports innovations. From an ethical and value-based perspective the taxonomy might be easily misused. “Should we want this?” is an essential question. Consider, for example, so-called “mechanical doping”, but also technology that diminishes the experience of the sport, essential elements of the sport, or introduces unfair advantages based on cost, access, and availability. The question of desirability of interventions should be asked in light of the core values that traditional sports and augmented sports embody. Are novel Sports ITech innovations supportive of values such as friendship, solidarity, and fair play - as mentioned in the Olympic Charter (International Olympic Committee, 2020). And what about meritocracy, competition, and inclusivity? (Postma *et al.*, 2022a) And how might potential value-tensions be resolved? (Friedman and Hendry, 2019). The question of the desirability of interventions calls for future work a) regarding specific innovations, and b) regarding possibly more generalised views on what constitutes a desirable innovation of sports (see, e.g., Dyer, 2015; Miah, 2006) including perspectives on inclusion in sports (Wolbring and Tynedal, 2013). In that context, there is a variety of wicked problems well-known to the HCI community that are also relevant for the sports perspective such as diversity, inequalities, and inclusiveness.

However, what complicates the matter further is that certain innovations that are not necessarily great for the competitive aspect of the sport might still be good for its spillover into our daily lives, their applications in health care and rehabilitation, or in other domains. For example, the Formula-E racing developments are not just for winning competitions, but also serve as a test bed for development of consumer electric vehicles. As such, ethical debates on the desirability of innovation in Sports ITech should also not prevent us from researching technology that can be a beneficial contribution in other ways.

6

Conclusion

In this monograph we presented a taxonomy that frames a design space for Sports Interaction Technology. First we a showed more general view on sports science and practice as targeting certain outcomes and influenced through certain underlying factors, and sports technology as a field ranging across physical technology, data technology and interaction technology, to support sports science and practice. The main body of the monograph was dedicated to developing a taxonomy and design space for Sports ITech based on literature and related work from many sources. We gave suggestions as to how the taxonomy can be used in practice for varied combinations of design and research, and reflected on the limitations regarding choices that we made in presenting the taxonomy and design space. The monograph contributes not only a framework for understanding and designing Sports ITech, but also an overview that may help people identify interesting and fruitful gaps and opportunities that can lead to future novel developments in Sports ITech, and a call to action for more intensive collaboration between researchers, designers, and practitioners from the various fields that underlie Sports ITech. We hope that thereby our work contributes to an acceleration of innovation in this field.

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