The reality of practice: an action systems approach to serious gaming

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Introducing action systems

the units of action are themselves functional actions, and ... bodily displacements are a consequence of, not constituents of, actions

— Edward Reed (1988, p. 46)

1.1 Introduction

The aim of this thesis is to introduce an action systems approach to rehabilitation science. That is, this thesis aims to promote a perspective that gives action, or activity, primacy in thinking about motor learning issues in rehabilitation. Of course, changing the outlook of a field, or even just making room for a new perspective to be developed, requires much more work than any one thesis could hope to accomplish. This thesis should thus be read as merely preparing the ground. It does so by focusing on some of the empirical and perspectival issues the adoption of a novel approach raises.

As a case in point, this thesis will focus on the use of serious games for becoming dexterous at using a prosthetic hand. Serious games are video games that are fun to play but aim to provide skills useful in reality (Graafland, Schraagen, & Schijven, 2012). The first chapters of this thesis will empircally evaluate to what extent serious games for prosthesis use *are* in fact useful in reality. The fact that this thesis is the first attempt to provide such an evaluation is indicative for the need to allow novel perspectives in motor learning to inform research.

Highlighting the need to re-think the basic assumptions of serious gaming for motor learning, the thesis goes on to introduce a different theory of motor learning and apply that to serious gaming (Chapter 4). By doing so, it shows the merits of allowing for a different view on motor learning. After that, the thesis takes a theoretical turn and presents an experiment that shows how to conceptualize the process of motor learning from an action system perspective. Based on these findings, in Chapter 6 the perspectival change that the thesis seeks are explicated more fully. To prepare the ground, this introduction will present a brief historical overview of rehabilitation engineering and serious gaming and of the theory of action systems in human movement sciences. It will be argued that the adaption of serious games was never primarily motivated by theoretical developments. Historically, technological development and engineering solutions have taken the lead in informing rehabilitation science. The available technology for instance defines the requirements for succesful rehabilitation in a very concrete way—one is supposed to be able to control a cursor using surface EMG before re-learning to button up a shirt with a prosthesis (e.g. Smurr, Gulick, Yancosek, & Ganz, 2008). In less tengible ways moreover, technological development has transformed theories of motor learning to accommodate for these practical changes.

1.2 A history of rehabilitation engineering

Rehabilitation medicine is a comparitively young field. Although medicine grew to fruition in the 17th century, it was not until the 1930s and 1940s, when high numbers of wounded soldiers returned from the first and second world war, that rehabilitation medicine became an independent field of study (Dillingham, 2002, Kinney & DePompolo, 2013; see Krusen, Kottke, & Lehmann, 1941/1990). Having developed largely under the influence of a mechanistic worldview (Ahn, Tewari, Poon, & Phillips, 2006; Dijksterhuis, 1964; Feyerabend, 1975), rehabilitation medicine as a science consequently began the study of its subject-matter along these traditional lines. It build on knowledge that was acquired almost exclusively in mechanistic and reductive terms.

As rehabilitation science developed further, it did so to a large extent, within military institutions and funding bodies (see Dillingham, 2002; Kinney & DePompolo, 2013). As it did, it frequently crossed paths with mechanical engineering. Sharing a similar mechanistic background, a tight and reciprocal connection between rehabilitation science and engineering grew. Indeed, "rehabilitation engineering" has become a dominant approach within rehabilitation science. The approach has greatly increased our understanding of the workings of the physics of the body. As it did however, the field increasingly offered solutions to rehabilitation problems

that re-conceptualize its subject-matter for rehabilitation scientists as well as for practitioners and patients.

Consider the example of upper limb prostheses that will be pursued in this thesis. As the body is conceptualized in mechanistic terms—basically as a machine—the loss of an arm or a hand merely required substitution by a replacement part. First this was nothing more than a hook. But as the need for the replacement of body parts increased, and rehabilitation medicine took off, a (pneumatically) opening and closing grabber was invented around the first world war (see Childress, 1985). After the second world war there was an enormous development in upper limb prosthetics as engineers and rehabilitation physicians and prosthetists in the US army started to work closely together (Childress, 1985). By the 1960s prostheses were electrically powered and gained several degrees of freedom.

Upper limb prostheses continue to be in high demand and their development is still driven by progress in engineering (i.e. biomechanical and computer engineering). To this day, the field assumes that the artificial arm should resemble the mechanistic workings of the original arm as closely as possible. Thus, design still aims to simulate its many degrees of freedom (e.g. Gonzalez-Vargas, Dosen, Amsuess, Yu, & Farina, 2015) and its afferent and efferent pathways (Kuiken, Marasco, Lock, Harden, & Dewald, 2007), and engineering is making progress in doing so.

1.2.1 Getting beyond motor learning

This mechanistic conceptualization of the human hand also had a downside however. As a collateral, the role that motor learning theory got to play changed with this mechanistic starting point. As long as a patient still required long rehabilitation programs to learn to make dexterous use of the prosthesis, the prosthesis was not designed properly. Having to rely on motor learning theory became a design flaw, a sign of not having engineered the problem away yet. The ideal prosthesis would simulate the missing limb perfectly, and would diminish the contribution of motor learning to rehabilitation training to a minimum. In short, our need to rely on motor learning has come to be viewed, or rather has come to be treated, as an undesired consequence of the artificial hand not yet being similar enough—a problem to be solved not by opening up to perspectives on motor learning but a problem to be overcome by more engineering.

In sum, rehabilitation science was committed to improving a patient's functioning which it largely identified with the mechanistic means to do. It moreover extended these means by adopting engineering principles in parts of the rehabilitation field. Thus rehabilitation science has had very little reason to doubt the conceptual background by which it approaches motor learning issues (in fact, questioning this background is easily viewed as running counter to the needs of a patient—as anyone who has tried it will attest).

As will become clear however, with the adoption of the latest technologies a tension between the goal of improving a patient's daily life and the reductive means to do so becomes more palpable. In fact, in an effort to engineer the need to learn a skill away, in practice the need for motor learning only increased. With this increase, the need to have perspectives on, and theories of, motor learning available actually also becomes more pressing. To see this, let us return to the history of prosthesis use.

1.3 Re-conceptualizing motor control

As engineering took over and prostheses became increasingly more high tech, prostheses were not only electrically powered, it also became possible to open and close these mechanical hands using an electric signal generated by the patient's own remaining musculature. That is, the myoelectric current detectable at the surface of the skin that so far was merely a by-product of acting, could be now be used to enable such acting (see Chapter 2).

To accommodate this engineering achievement something extraordinary now happened to theories of motor learning. With this newly developed possibility of controlling a prosthesis using myoelectric currents, a theory of motor control was required that would provide a rationale for pursuing this possibility. In a two-step process, existing motor control theories (at least, what I will call, the "reductive" ones, see Chapter 6) were adopted to re-conceptualize the learning of a skill in engineering terms. First, the leaking electric current at the surface of the skin was considered a "signal" and was "output" of a muscle. This enabled a vocabulary that gave "myoelectric control" a natural place in mechanistic motor learning theory.

Second, because of this change, rather than delivering "output" to a joint to be put into motion, the activated muscle could now deliver this output to an external amplifier to put the prosthesis into motion. Apart from missing some feedback loops to the neural "control system," which is a mere practical problem, there seems to be no fundamental difference in the motor control process (see Figure 1 of Parker, Englehart, & Hudgins, 2006, for a particularly salient example). In an unintentional sleight of hand, the use of myoelectric signals was made perfectly continuous with any other action in daily life—it was reverse engineered into the motor learning theories available to rehabilitation science. By doing so, such motor learning theories helped to *justify* the solutions engineering offered rehabilitation medicine.

All the while, in order to replace the function of the hand, patients are thus getting taught to be dexterous at controlling the myoelectric current that they generated. The available motor learning theories supplied the rationale for doing so. Notice that in this way, the specific engineeringsolution of the sixties for replacing a missing limb slowly changed the nature of the learning process for rehabilitation at all levels of consideration. As we saw, for theorists it re-conceptualized the motor learning process to fit the use of a "myosignal."

For clinicians as well as for patients, the changes were even more substantial. For them the enineering solutions meant having to develop and undergo boring and repetitive myoelectric signal training: for example, learning to move a line or a dot on a screen to an arbitrary point by contracting a single muscle. For them, the more the artificial hand began to resemble a natural hand, the less the skills required to operate them seemed to resemble daily life.

1.3.1 Taking games seriously

This myoelectric signal training appeared at odds with the goal of improving daily functioning, and the engineering approach could have inspired critical views on motor learning to have a say. Instead however, the mechanistic approach started to inspire an engineering solution to the problem of a boring training regime that patients were required to undergo too: video gaming was adopted to ensure the training would remain enough of a challange and would remain fun enough to keep going.

Games, even video games, had been used as a training tool for over half a century. The earliest examples of such video games were created during the Cold War to prepare military personal and the first video games for learning skills outside the military developed alongside these projects (Djaouti, Alvarez, Jessel, & Rampnoux, 2011). But, as the possibilities of video gaming and e.g. virtual reality took off in the nineties, rehabilitation science also started to adopt these technologies (Holden, 2005; Lovely, Stocker, & Scott, 1990). In order to train the control of the myoelectric signal, video games, which I will call "myogames," could now be used (see Armiger & Vogelstein, 2008; Anderson & Bischof, 2012; Lovely et al., 1990; Oppenheim, Armiger, & Vogelstein, 2010).

The question of how a skill acquired in such a myogaming task would actually help to improve myoelectric prosthesis skills however became even more pressing. That is, the question became what motor learning principle might account for, or would even predict, that myogaming skills will transfer to prosthesis use (see Chapter 2–4 and 6). As will be detailed in Chapter 6, any theoretical justification seems to rely on a set of assumptions that is hardly challenged—in fact, it is the very set that got patients in this position in the first place.

This question of "transfer" between different tasks—from serious gaming to ADL—plays a comparatively minor role in research so far (see Chapter 6 for reasons for this). If the use of myogames for improving prosthesis use is defended at all, it is done so without any direct empirical evidence that training such artificial and remote tasks will be beneficial to learning to perform a prosthesis task. As a case in point, with the exception of Chapter 2 and 4 of this thesis, the basic assumption that such myogames *would in fact* benefit prosthesis skills has never been evaluated.

To sum up, as the mechanistic and reductive approach is applied to rehabilitation, it diverts issues of motor learning to issues of engineering, engineering aims to rid rehabilitation of the need for motor learning altogether. In the meantime however, doing so new mechanistic conceptions and further issues for motor learning arise. These issues even gain urgency as rehabilitation engeneering has amputees playing myogames in order to prepare them for the use of their artificial limb (Dawson, Carey, & Fahimi, 2011; Smurr et al., 2008).

The need to question the basic perspective that got rehabilitation science (patients, practitioners and theorists) in this position is thus bigger than ever (see Chapter 6). That is, the question that Edward Reed (1988) posed—of whether not only the "physical body," but also a learning patient should be understood in mechanistic terms—should be addressed. The time for bringing action system considerations to rehabilitation science is now.

1.4 The theory of action systems

Having outlined the path that led to the use of myogaming in prosthesis learning, in the remainder of this introduction the theory of action systems will be sketched as an alternative to motor control theories in rehabilitation science. This exposition will serve to highlight the fundamental difference in background assumptions that this theory has. The introduction will end with explaining the value that such a different background has brought, and continues to bring, to the field of human movement sciences.

Based on James Gibson's work on perception (J. J. Gibson, 1966, 1979), in the early eighties Edward Reed introduced the theory of action systems (Reed, 1982, 1988, 1996). Action systems are temporal structures organized to perform a certain task. Formally, an action system is formed by the adaptive coordination of the whole body as it aims to attain an environmental goal (cf. Bernstein, 1996; J. J. Gibson, 1979; K. M. Newell & Vaillancourt, 2001; Reed, 1996; Warren, 2006). In this thesis the terms "action system," and "skill" (and "ability") will be used interchangeably. That is, having a locomotory action system is equated with having locomotory skills or abilities. Having an action system at ones disposal then means one is reliably able to perform a certain "action", or "activity" and thus "attain a certain goal" or "achieve a certain task."

The important aspect these concepts share is that they all stress the task someone needs to perform. They thus pertain not only to the coordination of the body, but equally to the environment in which the coordination takes place—in fact, an action system is a relational notion that pertains to the "organism-environment system." For example, most of us learn to form a locomotor system which can be instantiated either by walking or crawling (Withagen & Michaels, 2002) or possibly even by using a wheelchair (Kunz, Creem-Regehr, & Thompson, 2013), or we use a manipulatory system for manipulating the environment, such as when grasping a cup. In each case, the action system can be determined by the environmental task it helps to achieve, while utilizing different anatomical and mechanical parts (which I will later call "body functions"): both walking and wheeling aim for achieving the same task, as do grabbing a cup by hand or with a upper limb prosthesis. Actions should thus be contrasted with "motion," "movement," "motor" or "body-functions" that all refer to displacement of a position of (a part of) the body over time.¹

If movements, and body functions, are not the elements of an action system, the question is what parts do constitute an action system—this will be dealt with in detail in Chapter 6. Briefly, as the opening quote suggests, rather than being built from sequences of muscular contractions or changes in joint angles, action systems are themselves constituted by smaller scale units of action that each have their own sub-task to perform (Reed, 1988).² For example, being able to dexterously brush one's teeth requires an organized structure of actions to perform it: it requires a "tooth-brushing action system." Nested within this action system are sequences

¹Note that this thesis sticks to the convention of using "motor" in the contraction "motor control" and "motor learning" and to "movement" in "(human) movement sciences." In these contexts, I will take them to be neutral terms.

²By convention, in this thesis the small scale "units of action" are sometimes referred to as "perception-action cycles" (see e.g. Warren, 2006), or "information-motor couplings" (Bootsma, 1998, and Chapter 5). Such terms are used to stress the fact that action systems always have a perceptual component. The organization of perceptionaction cycles together form an action systems for attaining a task.

of small scale actions, such as turning on the tap, spreading toothpaste on the brush, brushing, and spitting that have a definite function relative to the whole (Reed, Montgomery, Palmer, & Pittenger, 1995, see also Chapter 5). Some of these actions are more important than others but none are sufficient for skillfully toothbrushing by themselves. Importantly, every small scale action brings forth a meaningful (action relevant) change in the environment to further the completion of the overall task.

1.4.1 Learning as forming action systems

More precisely however, each unit of action—at any scale—can have two distinct *functions* in the environment (see J. J. Gibson, 1966; Reed, 1996). First, it can have a performatory function, aimed at changing aspects of the environment to achieve the goal of the task. For example, opening the toothpaste tube in order to brush one's teeth (Reed et al., 1995) or dropping a Tetris-block by holding down a key so as to be awarded points. Second, it can have an exploratory function in finding out what actions are afforded in the environment. For instance, when looking around to locate the toothbrush, or when rotating a Tetris block to see where it fits (Kirsh & Maglio, 1994). So, a unit of action can be either primarily for acting so as to attain the goal of the task (i.e. performatory) or for *perceiving* what specific actions the task's environment affords (i.e. exploratory). In fact, Reed's contention is that these roles determine in each case what role (neuro)physiological aspects play. For example, whether afferent and efferent neural pathways are contributing to perceiving or to acting (for details see Reed, 1982).

During learning a task, previously established exploratory action systems are used to find the best way to achieve the task. That is, during learning the best mode of relating perception and action is found. This process is scrutinized in Chapter 5. For now it will suffice to note that as an efficient organization of perceiving and acting is formed and units of actions nest to form a new functional unit, the action system is no longer exploring, but is acting to attain the goal of the task: it has become a performatory action system (sometimes at a new scale of organization; see Chapter 5).

Transfer and the process of differentiation

To get an action system properly adapted to the task at hand, there is an additional process in play. Through exploration the best mode of relating perception and action may be established, but this relation itself must be fine-tuned continuously (Bingham, Coats, & Mon-Williams, 2007; Jacobs & Michaels, 2007). This continuous adaptation of the perception– action relation is called "calibration" (see Bruggeman, Pick, & Rieser, 2005; Bruggeman & Warren, 2010; Rieser, Pick, Ashmead, & Garing, 1995). Formally in calibration, the system re-adapts its sensitivity to the information that is available to perform the task (see e.g. Jacobs & Michaels, 2007, and this thesis Chapter 3 and 4). For example, when having learned to walk with a certain optic flow speed, the transfer to crawling (the same locomotory action system) requires tuning the perception–action cycles to the optic flow (see Withagen & Michaels, 2002).

When considering motor learning as the formation of an action system, the processes of exploration and calibration are thus of pivotal importance for understanding "transfer"—that is of the effect that performing one task has on the subsequent performance of another task. Transfer of a rehabilitation task to activities in daily life (ADL) is enabled by the ability to explore for, and the (re-)calibration of, an action system across tasks (more on the notion of transfer, and some refinements in Chapters 3, 4 and 6).

Finally it should be noted that through exploring and calibrating, action systems develop that fit the specifics of the task. That is, as one becomes dexterous, perception–action cycles adapt. They come to depend more and more on highly specific possibilities to act that the task starts to offers. In fact, exploratory actions are aimed at finding out exactly how the current task *differs* from others, so as to use those particular differences to fine-tune performatory actions to the task. Learning is therefore often called a process of "differentiation" (J. J. Gibson & E. J. Gibson, 1955; Michaels & Carello, 1981).

This process of differentiation is a fundamental move away from traditional conception of motor learning, as it implies that a learner does not learn to perceive and "internalize" abstract similarity across tasks (forming e.g. an internal model in the process; cf., Zhao & Warren, 2015), but it implies one learns to perceive and make use of concrete differences as they matter to the organism in the environment. We learn to refine the environment further and further as we encounter it, and get more in touch with the world as we learn (see Chapter 5; for conceptual issues that this view solves see H. L. Dreyfus & S. E. Dreyfus, 1987 and the appendix).

1.4.2 The reception of the action systems approach

As this brief introduction makes clear, the theory of action systems relies on a set of assumptions unlike those of traditional theories of motor learning—including those found in rehabilitation science. Taking "actions" as the starting point of a theory and asserting that "movement" merely followed from these actions (e.g. Reed, 1988, p. 46) reverses many of the fundamental issues in motor learning. It changed how to phrase the question of control, how to conceptualize the process of learning, and what enables transfer. At the time that action system theory emerged, these re-conceptualizations of the study of motor learning were alien to large parts of the field of movement sciences.

Reed however explicated the theory when the conceptual apparatus of this field was still very much developing. Human movement sciences had only just emerged out of basic disciplines in medicine (such as of anatomy and [neuro]physiology), biology, philosophy and experimental psychology. In the late sixties and early seventies these disciplines started to cross paths as they thematized motor control issues.

As Reed so sharply distinguished movement from action, and shifted theoretical priority to the latter, he positioned his theory in opposition to the many dominant mechanistic theories that took movement as their starting point. In the emerging field of movement sciences the possibility of this contrast made quite a stirr and gave rise to a formative debate known as the "motor-action controversy" (see Meijer & Roth, 1988).

1.4.3 A formative debate

The motor–action controversy that pitted the "action" approach against traditional "motor" approaches sparked several related issues. For example, researchers noticed that they dealt very differently with concepts of mental representations (i.e. internal models), the role of the environmental and with the locus of motor control. Moreover, the scientific value assigned to laboratory tasks and "ecological" tasks of daily life differed on both sides of the aisle. Beek and Meijer (1988) argued that many of the distinctions however are not clear-cut, rather, they suggest, the controversy that the motor–action distinction created, originated in differences in the historical backgrounds of the different research practices.

As will be argued in Chapter 6, one important aspect in which these historical backgrounds differed was whether they required either a reductive or a non-reductive explanation of the phenomenon being studied. Briefly, taking a reductive stance on a subject matter means that we understand or explain the behavior of a system at one level by understanding the basic underlying components (and their relations) at a level below. By contrast, a non-reductive, or emergent, stance claims that the higher level has its own intrinsic dynamics that deserves attention in its own right (see Chapter 6).

Reed's theory of action systems originated in a relatively marginal practice that resisted reduction (see e.g. Heft, 2001; Reed, 1996; Tamboer, 1988). Reed inspired to give actions, or activity, independence from the movements that might accompany them and his theory was therefore a strong example of an emergent approach (see also the appendix). His theory thus had a background alien to, and largely incompatible with, the dominant mechanistic and reductive approach.

In human movement sciences the motor–action controversy was never resolved, and agreeing to disagree, many differences both within and between motor- and action-based theories can be found. As can the many practical, methodological and theoretical differences that the controversy brought to prominence. This however can be viewed as a good thing: "human movement sciences" remained a plural and the field kept several "points of comparison" (Feyerabend, 1975, p. 24). Through the debate, many fundamental issues were brought into prominence and helped to articulate and continue to re-articulate the subject matter of the field as a whole. Thus, offering different perspectives and a multitude of (opposing) theories the field has the diversity in tools and methods to critically evaluate its merits and refrain from going down a single narrowing path. This thesis is a plea for such plurality of mind, in human movement sciences and beyond.

1.5 Overview of this thesis

This thesis will start by critically evaluating the current generation of myogames. Although such myogames might seem artificial and far removed from rehabilitation practices, they are used every day in clinical situations in order to help patients to become dexterous in using a myoelectric prosthesis. However, as they are developed in a highly reductive milieu, there has been little emphasis on showing whether such training actually improves prosthesis use.

In Chapter 2, a simple myogame called "Breakout-EMG" is introduced, and it is shown how the ability to play this game is quickly learned. This motor learning however has no measurable consequence for the ability to use a prosthesis in a transfer-task. Crucially, it is shown that what is learned during the game is a highly task-specific modulation of the myoelectric signal. The experiment suggests that "myoelectric control" might not be a "body-function" existing independently of the task in which such control is shown.

Chapter 3, explores this idea further by studying a different myogame. It aims to determine to what extent the goal of the game and the specific muscles involved in generating the signal matter to goal attainment. The study systematically varies a myoelectric gaming task and looks for transfer to a standardized myogaming task. The results suggest that neither the goal, nor the anatomical aspects of a task is by itself sufficient to characterize the forming action system. Rather, by allowing either exploration or calibration, any similarity across tasks will allow the learner to achieve continuity across performances and thus increase the transfer effect. In Chapter 4, the results of Chapter 2 and 3 are applied to the learning of myoelectric prosthesis use through serious games. When using a myoelectric prosthesis, many aspects of performance change. Transfer from a myogame to a prosthesis task could therefore proof difficult. Based on the functional nature of action systems however, specific forms of augmented feedback might offer a way of increasing the continuity in function across tasks. In Chapter 4, an empirical experiment is presented in which several myogames are compared to a myogame that includes additional task-relevant feedback. It is shown that, in order to have myogaming skill transfer to prosthesis use the game needs to incorporate feedback that is relevant to the gaming task but also, crucially, to the prosthesis task it sets out to improve. Thus, the chapter delivers a successful proof-of-principle of applying an action systems perspective to rehabilitation problems.

In order to better understand the dynamics of perceiving and acting during the learning of an action system, in Chapter 5 a different empirical experiment is presented. Here participants create tools from unfamiliar materials while their eye movements are recorded. In the chapter, it is shown how an action system for creating tools forms over time, and how cycles of perceiving and acting (looking and manipulating) nest within one another to form functional unities at increasingly broad scales. Importantly, it shows the principle direction in which the development of an action system moves—as one learns, the system comes to rely more and more on the particulars of the task it aims to perform. Learning, that is, is considered as a process of increasingly relying on the specifics of the environment (this theme is further taken up in the appendix).

Against the background of the empirical results of these four chapters, in Chapter 6 the (meta-)theoretical underpinnings of the action systems approach are explicated. In an action systems approach, the function of any anatomical aspect (such as the eye movements in Chapter 5 or the generated EMG currents of Chapters 2–4) depends on the function of the action system it is involved in. Chapter 6 explicates exactly what this means for rehabilitation science and how this relates to the traditional view on motor learning. The chapter aims to make clear that paying attention to the task-specific and context sensitive constitution of action systems requires a fundamentally different view on motor learning. Crucially, it aims to show that adopting this view is far from easy, and that reductive

methods and theories easily drown out emergent initiatives. Chapter 6 ends by suggesting that a focus on transfer may be a useful tool to allow for emergent views to inform research practices within rehabiliation science. In should be stressed that the argument however is not to displace the traditional "reductionist" approach. The argument is rather to give "emergent" approaches, such as the action systems approach, the autonomy to independently inform rehabilitation research and practice.

The appendix is a short theoretical chapter written in reaction to a particularly reductive theory of motor control. It is included because the issues it deals with are highly relevant to this thesis. However as the rather technical text is a comment on a particular paper and moreover brings assumptions to light that go beyond the claims needed for advancing this thesis it is added as an appendix only.

In the epilogue the topic of transfer is expanded on and the merits and limits of serious gaming from an action systems perspective are discussed. Based on the perspective promoted in this thesis the epilogue ends with a plea for acknowledging the diverse realities of practice.

Task-specific adaptations in myogaming

Van Dijk, L., Van der Sluis, C. K., Van Dijk, H. W. & Bongers, R. M. (preliminarily accepted). Learning an EMG controlled game: task-specific adaptations and transfer. *Plos ONE*.

Abstract

Video games that aim to improve myoelectric control (myogames) are gaining popularity and are often part of the rehabilitation process following an upper limb amputation. However, direct evidence for their effect on prosthetic skill is limited. This study aimed to determine whether and how myogaming improves EMG control and whether performance improvements transfer to a prosthesis-simulator task. Able-bodied right-handed participants (N=28) were randomly assigned to 1 of 2 groups. The intervention group was trained to control a video game (Breakout-EMG) using the myosignals of wrist flexors and extensors. Controls played a regular Mario computer game. Both groups trained 20 minutes a day for 4 consecutive days. Before and after training, two tests were conducted: one level of the Breakout-EMG game, and grasping objects with a prosthesis-simulator. Results showed a larger increase of in-game accuracy for the Breakout-EMG group than for controls. The Breakout-EMG group moreover showed increased adaptation of the EMG signal to the game. No differences were found in using a prosthesis-simulator. This study demonstrated that myogames lead to taskspecific myocontrol skills. Transfer to a prosthesis task is therefore far from easy. We discuss several implications for future myogame designs.

2.1 Introduction

Although video games that aim to improve myoelectric control are becoming an important part of the rehabilitation process following an upper limb amputation (Anderson & Bischof, 2012; Smurr et al., 2008), little is known about the benefits of training myoelectric control by video gaming (i.e. using a myogame). Many studies so far limit their research to the development of the myogame, and do not include an evaluation of training effects after using the game (Davoodi & Loeb, 2012; De la Rosa, Alonso, de la Rosa, & Abásolo, 2008). Studies that did include the training of the myogame often did not provide statistical support for apparent improvement in performance and, with the exception of one study (Ison & Artemiadis, 2014), none have used a control group (Armiger & Vogelstein, 2008; Lovely et al., 1990; Ma, Varley, Shark, & Richards, 2010; Oppenheim et al., 2010; Pistohl, Cipriani, Jackson, & Nazarpour, 2013; Terlaak, Bouwsema, van der Sluis, & Bongers, 2015). Most importantly, there is, to our knowledge, only one study that determined whether training effects will subsequently transfer to other myoelectric tasks, such as the use of a prosthesis (this thesis, Chapter 4). That study showed a task-specific learning effect that transferred only on a few highly task-specific outcome measures. The study thus raised the concern that the way myogames are currently adopted in clinical situations might not promote any transfer of skill. The current paper aims to evaluate this implication.

By focusing research on motivational aspects and playability rather than on explicitly designing for transfer to activities of daily living (ADL) (see e.g. Lovely et al., 1990; Oppenheim et al., 2010), myogame development has been able to proceed without paying much attention to aspects that could constrain transfer to actual prosthesis use. For example, studies often do not attempt to simulate the way the amplitude of the myosignal is related to the opening and closing of the prosthesis hand (Armiger & Vogelstein, 2008; Lovely et al., 1990). Other technical constraints of the prosthesis are also not taken into account (e.g. motor delays, EMG response curves)—nor can they be, as detailed technical specifications are often not supplied by prosthesis manufacturers. Finally, the consensus in motor learning literature is that training is task-specific—that is, in order to transfer a skill between tasks, the goal of these tasks should be as similar as possible (K. M. Newell, 1996; Reed, 1988; Schmidt, 1975; Woodworth & Thorndike, 1901). So far however, myogames deliberately deviate from real ADL tasks in order to remain entertaining and motivating (Anderson & Bischof, 2012; Armiger & Vogelstein, 2008; Davoodi & Loeb, 2012; Ison & Artemiadis, 2014; Lovely et al., 1990; Ma et al., 2010; Oppenheim et al., 2010; Pistohl et al., 2013; De la Rosa et al., 2008).

These concerns led Van Dijk et al. (Chapter 4) to create an experimental set-up that controlled both technical constraints and the amount of task similarity. After providing evidence that the used myogames were actually learned, the study showed to what extent the learning of these games affected the performance of a prosthesis task. The results showed that neither the technical similarity in EMG interfacing nor the goal of the gaming task will ensure transfer. Rather, only the training conditions in which very specific feedback was added to the game elicited transfer to the use of a prosthetic device. Crucially, this feedback was not only relevant to attaining the gaming task, but the feedback was also important to the prosthetics grasping task that the participants needed to perform to assess transfer.

Since the current generation of myogames typically has little similarity with the activities in daily life they set out to promote, the question therefore becomes to what extent the set-up currently adopted in serious gaming research will elicit transfer to a basic prosthesis task. The main aim of this study is to determine what learning and transfer effects can be expected from training with the current generation of myogames. We aimed to stay as close as possible to currently established practices: we developed a basic but motivational myogame that is comparable to those currently used in research, and we used a prosthesis task similar to the previous transfer study that reflects the basic settings and function used by patients in ADL (Chapter 4).

To reach our aim this study answers three questions. A prerequisite for showing transfer is showing learning during training. Therefore, the first question is whether our serious game that incorporates a myoelectric control interface can be learned. If the myogame is learned we expect an increase in accuracy of in-game performance after training in comparison to the sham training. Finding a learning effect, the second question is what change in the gaming task might account for this. Although Chapter 4 does not report on this issue, it suggests highly task-specific adaptations of the myosignal. We evaluate this prediction by looking into the relation between the myosignal and the goal of our game (i.e. intercepting a ball). The third and final question is whether learning effects of this myogame transfer to the actual use of a prosthesis during a grasping task. If so, we expect participants to get more skilled at using a myoelectrically controlled prosthesis. This skill improvement will be reflected in (a) the participants' ability to adapt the aperture of the grasping hand to the size of an object (Chapter 4). This adjustment has been found in experienced prosthesis users (Bouwsema, Van der Sluis, & Bongers, 2010b) and is also typical for grasping with an intact hand (Bootsma, Marteniuk, MacKenzie, & Zaal, 1994; Castiello, 2005; Meulenbroek, Rosenbaum, Jansen, Vaughan, & Vogt, 2001; Smeets & Brenner, 1999). Skill improvement will also be reflected in (b) the time that the myoelectric hand remains maximally opened: this is expected to be shorter in skilled prosthetic users (Bouwsema, Kyberd, Van der Sluis, & Bongers, 2012).

2.2 Methods

2.2.1 Participants

Twenty-eight able bodied adults participated (mean age 21.39 (SD 1.95) y); 21 men and 7 women. The participants played video games for 4.32 (SD 4.38) hours a week. All participants (1) were right handed, (2) had corrected to normal vision, (3) were free of any (history of) disorders of the arms or upper body, and (4) had no prior experience in the use of myoelectric devices. The study was approved by the local ethics committee (Ethics Committee for Human Movement Sciences, University of Groningen, the Netherlands) and a signed informed consent was obtained from all participants prior to the start of the experiment. Upon completion of the experiment all participants received a gift voucher.

2.2.2 Materials

In order to train the use of myoelectric control in a serious game, a customized version of the game "Breakout" was created (originally created by Atari Inc.). This game, called "Breakout-EMG" was run on a laptop computer. Two active socket 13E200 MyoBock electrodes (Otto Bock Healthcare products, Austria) were used. The electrodes used a bandwidth of 90-480 Hz and a notch filter at 50 Hz. After that the signal was rectified and low pass filtered (2nd-order). The amplification of the signal could be controlled linearly with a gain controller. These signals were fed into the laptop computer, via a NI-USB 6009 data acquisition device (National Instruments Corporation, USA) that sampled the signals at 125 Hz. Custom LabView software (National Instruments Corporation, USA) digitally filtered the signals (low pass filter, cutoff frequency 150 Hz). The game sampled these digitally filtered EMG signals at 50 Hz. To log all the gaming data for analyses, in a separate process the (x and y) positions of the elements of the game were written to a text file at 90 Hz.

As a sham training, a standard platform game called "Super Mario Bros" was run on a Nintendo Entertainment System (Nintendo Co. Ltd, Japan). This game was connected to a LCD-TV monitor.

To resemble a myoelectric upper-extremity prosthesis for a transradial amputation level as closely as possible, a myoelectric simulator was developed (Figure 2.1) (Chapter 4 Bouwsema, Van der Sluis, & Bongers, 2008, 2010a, 2012).

This simulator consisted of a myoelectric hand attached to an open cast in which the hand could be placed, and a splint that was adjustable in length and attached the simulator to the forearm with a Velcro sleeve. The myoelectric hand was a MyoHand VariPlus Speed (Otto Bock Healthcare products, Austria) with proportional speed (15–300mm/s) and grip force control (0-~100N).

During the myoelectric simulator task three wooden cylinders were grasped. These cylinders were 10 cm in height and were either 2 cm (small), 4 cm (medium) or 6 cm (large) in diameter. In order to measure the aperture of the myoelectric hand during the grasp, a goniometer (Cermet PC300



Fig. 2.1. Top view of the myoelectric simulator while grasping the medium cylinder. The goniometer is attached to the thumb and index finger.

potentiometer, Contelec, Switzerland) was attached to the thumb and index finger of the hand. The goniometer sampled the angle of the hand at 2000 Hz and sent this data to the laptop computer. Because of a technical problem the angular data on the trials grabbing the largest cylinder could not be established. Therefore, only the data on grabbing the small and medium cylinders are presented.

2.2.3 Design

Participants were randomly assigned to either the Breakout-EMG group (n = 16) or to the Control group (n = 12) as they signed up. The Breakout-EMG group trained the game "Breakout-EMG" (see Figure 2.2). Breakout-EMG was a videogame in which the objective was to intercept a bouncing ball so that it did not hit the ground. By bouncing the ball with the paddle, a wall of blocks could be hit. The overall objective of the game was to clear the screen of these blocks. The movement of the paddle to the left and right was controlled using the myoelectric signals from the flexor or extensor muscles of the wrist, respectively. The speed of the paddle was proportional to the amplitude of the EMG signals. During testing and training with Breakout-EMG the participants were free to hold their arm in any position they felt comfortable with as long as the electrodes were not perturbed (e.g. by hitting the table). The Control group trained in playing Super Mario Bros. In this game the objective was to control an avatar and safely guide him through a world by jumping platforms and avoid enemies.

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The game was played using a standard hand held Nintendo controller, which was held in the palms of both hands and typically operated using both thumbs (i.e. pressing down with the left thumb for moving the avatar left and right, and pressing down with the right thumb for jumping). The experiment was conducted in 5 days and consisted of 4 training sessions. On the first day a pretest was performed, after which 4 days of training followed. On the fifth day a posttest was performed. For practical reasons, participants were randomly assigned to either have the first training session after the pretest on day 1, or have their fourth training session prior to the posttest on day 5.



Fig. 2.2. Screenshot of Breakout-EMG showing an example of a terminal ball drop. The distance that the ball needed to move was calculated by determining the interval from the point at which the ball began to drop down towards the ground (*t0*) and the point at which the ball got to the height (y-position) of the paddle (*t1*). The required distance was the difference in position of the paddle at *t0* and the position of the ball at *t1*. The required distance was correlated to the observed net EMG signal (see text for details).

2.2.4 Procedure

Fitting the electrodes

Prior to playing Breakout-EMG, the electrodes were fitted by palpating for the most prominent muscle bellies of the extensors and flexors of the wrist during contraction. The electrodes were subsequently placed at those sites and held in place by a flexible wristband. The signals were filtered and sent to the game computer. In the game environment both signals were calibrated by determining the minimum and maximum value of each electrode independently and scaling each signal to a standard range before the game began. The signal was amplified so that reaching the maximum movement speed in the game required 20% of the maximum voluntary contraction (MVC) of the muscles. This was necessary to allow for comfortable game-play and prevented muscle fatigue during training.

For controlling the hand of the prosthesis simulator at the pre- and posttest, the sites for fitting the electrodes were similarly determined. The electrodes were subsequently placed by attaching the prosthesis simulator to the participant's arm. The sensitivity of the electrodes was adjusted to the upper threshold for each participant individually, so that the maximum EMG signal that could be sustained for 2 seconds of each participant corresponded to the maximum opening and closing speed of the myoelectric hand.

Pretest and posttest

The pretest was equal to the posttest and these tests were used to determine the improvement in skill in playing Breakout-EMG and in using the prosthesis simulator. To determine whether the myogame Breakout-EMG could be learned, during the pretest and the posttest, participants from both the Breakout-EMG group and from the Control group were asked to play one level of the game. This level (level 1) consisted of a screen with 45 blocks that needed to be hit by intercepting and bouncing a ball (see Figure 2.2). The level started when the experimenter pressed start and finished when the last block was hit. The participants did not receive specific instructions other than to play the game.

In order to find out whether any improvement of skill in Breakout-EMG transferred to using the prosthesis simulator, the change in performance during a simple grasping task was measured. In this task participants sat at a comfortable position in front of a table wearing the prosthesis simulator. Prior to the start of the task participants were instructed to maximally open and close the myoelectric hand to establish the minimum and maximum aperture for each participant. Starting with a closed myoelectric hand,

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they were then asked to grasp one of three wooden cylinders that were placed at 35 cm from the starting position of the myoelectric hand, lift the cylinder slightly, and then place it back at its original position. Each cylinder needed to be grasped five times. The order in which the cylinders were presented was randomized. The participants were instructed to be as accurately as possible in grasping, emphasizing not to focus on speed of performance but rather to focus on not dropping the cylinder while grasping.

Training sessions

In each session the Breakout-EMG group trained by playing Breakout-EMG for 20 minutes. To keep the participants challenged during training, the game consisted of three levels. These levels differed in the amount of blocks to be hit (increasing the difficulty of attaining a high accuracy—i.e. a perfect score). After completion of each level, the participants received feedback on their performance: on their accuracy in intercepting the ball, on the number of points scored (with each block hit points were added) and the duration of the level. After playing all three levels, the participants started again at level 1. There were no negative consequences to a bad performance. The game had no sound.

The Control group played Super Mario Bros for 20 minutes per session. The participants were instructed to only play the first four levels of the game (i.e. level 1-1 to 1-4) and then start over. To match Breakout-EMG training, this game was muted so that it too had no sound.

2.2.5 Data analysis

Using customized Matlab (The Mathworks Inc., USA) scripts, all dependent variables used to determine in-game performance were calculated from the output file provided by Breakout-EMG (all dependent variables are listed in Table 2.1). As playing Breakout-EMG proficiently required a high degree of accuracy in intercepting the ball, we looked at accuracy for in-game learning effects. The accuracy with which the ball was intercepted was determined as the number of balls intercepted divided by the total number of balls that dropped to the ground level.

Tab. 2.1. All dependent variables and their within subjects factors for the repeated measures ANOVA. The within subjects factor "Test" had two levels: the pretest and the posttest. The within subjects factor "Cylinder" had two levels: the small and the medium cylinder. The between subjects factor for all variables was "Group," which had two levels: the Breakout-EMG and the Control group. All combinations of interactions, both between the within subjects factors and between the within and between subjects factors, were also tested for effects (see text for details).

	Variable	Within subjects factor(s)	Between subjects factor
In-game performance	Accuracy	Test	Group
	EMG-ball coupling	Test	Group
Transfer to prosthesis	Maximum hand opening	Test and Cylinder	Group
	Standard deviation of the maximum hand opening	Test and Cylinder	Group
	Plateau phase	Test and Cylinder	Group

To look into specific adaptations of the EMG signal to the goal of the game, we defined the "EMG-ball coupling" as a measure of adaption. The strength of the EMG-ball coupling was determined by calculating the correlation between the distance the paddle needed to move and the observed net EMG signal during the terminal drop of the ball. We calculated the required distance (and direction) that the paddle needed to travel from the start to the end of each terminal ball drop (see Figure 2.2). The start of the terminal ball drop was defined as the point in time where the last change in direction of the ball occurred before reaching the height of the paddle. A change in direction less than 1 cm from the height of the paddle was disregarded, as this change hardly influenced the required position of the paddle to intercept. The net EMG signal was the integral of the difference between the calibrated EMG signal of the flexor and extensor muscle, over the duration of the drop of the ball. The net EMG signal thus had both a magnitude and a direction, which corresponded to the speed the EMG signals gave to the paddle.

Changes in the use of the myoelectric simulator were determined from the angular data from the goniometer using customized Matlab scripts. The angular data was filtered using a low pass filter (cutoff frequency 20 Hz). Subsequently, the start and end of the opening as well as of the closing of the myoelectric hand were determined from the data. If participants were better able to control the prosthesis simulator due to a more controlled use of EMG signal in the game, we expect participants to better adjust the hand opening to the size of the cylinder; requiring a smaller maximum hand opening (MHO) during the plateau phase as they

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learned to use the prosthesis (Chapter 4; Bouwsema et al., 2010a; Bootsma et al., 1994; Castiello, 2005; Meulenbroek et al., 2001; Smeets & Brenner, 1999). The plateau phase was defined as the time from the end of the opening of the hand to the start of the closing, and by definition contained the maximum hand opening. Based on previous research (Bouwsema et al., 2012), we also expect that increased prosthetic skills would show as a shorter plateau phase. As the goniometer was sometimes repositioned between participants and sessions, we normalized the angular data to a value between 0 and 1 based on the measured minimum and maximum value of each participant prior to analysis. The maximum hand aperture corresponds to a distance between the thumb and index finger of about 10 cm. So a change in aperture of 0.1 corresponds to ~1 cm in change in distance between thumb and index finger.

To determine learning effects, several repeated measures ANOVA's were conducted on accuracy and on the strength of the EMG–ball coupling, with test (pretest, posttest) as a within subjects factor and group (Breakout-EMG, Control) as a between subjects factor. To determine transfer, repeated measures ANOVA's were conducted on the maximum hand opening, on the duration of the plateau phase, and on the standard deviation of the maximum hand opening, with test (pretest, posttest) and cylinder (small, medium) as a within subjects factor and group (Breakout-EMG, Control) as a between subjects factor. A summary of all planned analyses can be found in Table 2.1.

Based on their skewness and on a Shapiro-Wilk test for normality, we checked the normality of the dependent variables. All variables were judged to be normally distributed, with the exception of the MHO and the SD-MHO. We therefore transformed the data on these variables using a square root transformation ($x_{trans} = \sqrt{(x_{max} + 1) + x}$). As a precautionary measure we repeated this procedure for the EMG-ball coupling. To check the effects of the distribution we then repeated our analyses of the MHO, the SD-MHO and the EMG-ball coupling on the pre- and posttest with these transformed data. None of the analyses on the transformed data differed from the analyses on the non-transformed data. We therefore present only the results on the non-transformed data here.
Effect sizes were calculated using generalized eta-squared ($\eta_{\rm G}^2$) (Bakeman, 2005; Olejnik & Algina, 2003). For the in-game learning effects, the Breakout-EMG group is expected to improve relative to controls. Therefore, follow up comparisons were done using one-tailed independent *t*-tests (with Bonferroni correction for multiple comparisons). All analyses used a significance level of $\alpha = .05$.

2.3 Results

2.3.1 In-game performance

The accuracy of the Breakout-EMG group across all sessions, and the accuracy of the Control group on the pre- and posttest can be found in Figure 2.3. The increase in accuracy appeared to have been greatest at the start of the training. The improvement in accuracy after all training sessions was compared to the Control group. Accuracy of both the Breakout-EMG group and the Control group improved from pretest to posttest.

Importantly, the increase in accuracy after all training sessions was significantly greater for the Breakout-EMG group. A repeated measures ANOVA revealed a strong main effect for Test ($F(1, 26) = 58.25, p < .001, \eta_G^2 = .55$), and a significant interaction effect Test x Group: $F(1, 26) = 21.39, p < .001, \eta_G^2 = .20$. A follow up analysis revealed this improvement was explained by a difference between groups on the posttest (t(26) = -3.42, p = .002).

To better understand the changes in performance of the game, we examined the goal specific adaptation of the EMG signal from pretest to posttest. For this we used the strength of the EMG–ball coupling. An example of the EMG–ball coupling on a typical pretest and posttest is shown in Figure 2.4. The effect of the training on the EMG–ball coupling can be found in Figure 2.5.



Fig. 2.3. Mean accuracy (and standard error of the mean) on both the pretest and the posttest of the Breakout-EMG group (black points with grey error bars) and of the Control group (white points with black error bars), as well as the accuracy on all sessions for the Breakout-EMG group only. Each point denotes one trial of playing level 1 of the game. During the training sessions, after completing level 1 the participants played a trial at level 2 and a trial at level 3 before having another trial playing level 1. The accuracy on levels 2 and 3 are not shown. The number of trials participants played during a session depended on the time participants required to complete each trial. Therefore, not all participants managed to play three trials at level 1. The data on the first trial of each session is based on all 16 participants. The data on the second trial of each session is based on 15-16 participants. The third trial of each session is based on the data of 11-14 participants. Note that the biggest improvement occurred from pretest to the first session. There was a significant test effect from pre- to posttest. However, the improvement in the Breakout-EMG group was significantly greater than Controls (see text for details).



Fig. 2.4. Representative example of the relation between the net EMG signal (x-axis) and the required distance (cm) to intercept the ball (y-axis) during a full trial of Breakout-EMG (Note that distance is actually expressed in units specific to the program used to design the game. However, on the monitor we used, these units are approximately equivalent to centimeters.). The net EMG signal has no unit of measurement but is the integral of the difference between the flexor and extensor EMG signal over the duration of the ball drop. Each point represents one interception attempt. To the left an example of a pretest, to the right an example of the posttest (of the Breakout-EMG group).



Fig. 2.5. Mean strength of the EMG–ball coupling (and standard error of the mean) on the pretest and the posttest for both groups. Both groups showed a significant test effect. However, the improvement in the Breakout-EMG group was significantly greater than Controls (see text for further details).

A repeated measures ANOVA on the strength of the EMG-ball coupling revealed a main effect for Test ($F(1, 26) = 10.09, p = .004, \eta_G^2 = .25$), and a significant interaction effect Test x Group: $F(1, 26) = 4.76, p = .038, \eta_G^2 = .12$. A follow up analysis revealed this improvement was due to a difference between groups on the posttest (t(14.46) = -2.42, p = .029).

2.3.2 Transfer to prosthesis use

A typical example of the aperture of the myoelectric over time is shown in Figure 2.6. Due to a technical problem one of the participants in the control group could not complete the pretest prosthesis task and was excluded from further analysis.

First, we looked at the maximum hand opening. The (normalized) maximum hand opening is shown in Table 2.2. Statistical analysis revealed a small significant effect for cylinder ($F(1,25) = 9.67, p < .001, \eta_G^2 = .05$). There was no significant main effect for Test, and there was no significant interaction effect Test x Group.

Adaptation of the hand aperture to the size of the cylinder could also be expected through a three-way interaction of Test x Group x Cylinder. That is, the difference in the hand aperture between cylinders is expected to



Fig. 2.6. Representative example of the hand aperture during the pretest (left figure) and posttest (right figure) during grasping a medium size cylinder. Both examples are from the same participant. This participant was assigned to the Breakout-EMG group, however the example is equally representative for the Control group. The time (s) is shown on the x-axis, the normalized aperture on the y-axis. A change in aperture of 0.1 corresponds to a change of ~1 cm in distance between thumb and index finger. The lines represent five trials of grasping a (medium) cylinder. The four round markers on each line represent (from left to right) the start of the opening, the end of the opening, the start of the closing and the end of the closing of the hand.

increase over time for the Breakout-EMG groups more than for the Controls. Analysis however revealed no significant three-way interaction effect.

The duration of the plateau phase can also be seen in Table 2.2. Analysis revealed a small significant effect for cylinder ($F(1,25) = 6.74, p = .016, \eta_G^2 = .04$). There was no significant main effect for Test, nor were there any significant interaction effects.

The standard deviation of the normalized maximum hand opening is also shown in Table 2.2. As one of the participants in the control group had only one correct grasp of the small cylinder during the pretest, the standard deviation in MHO could not be established in this case. We excluded this participant from analysis. Analysis revealed a significant effect for cylinder $(F(1,24) = 9.52, p < .001, \eta_G^2 = .14)$. There were no other significant effects. **Tab. 2.2.** Mean (and standard error of the mean in brackets) of the normalized maximum hand opening (MHO) (0-1; 0 being closed and 1 being fully opened), as well as of the standard deviation of the normalized maximum hand opening (SD-MHO), and of the duration of the plateau phase (s) for the small and the medium cylinder for both groups on the pretest and the posttest.

		Pretest	Posttest
MHO, small	Breakout-EMG	0.95 (0.03)	0.96 (0.02)
	Control	0.87 (0.05)	0.91 (0.05)
MHO, medium	Breakout-EMG	0.98 (0.01)	0.99 (0.01)
	Control	0.97 (0.01)	0.94 (0.05)
SD-MHO, small	Breakout-EMG	0.04 (0.02)	0.04 (0.01)
	Control	0.06 (0.03)	0.07 (0.03)
SD-MHO, medium	Breakout-EMG	0.02 (0.01)	0.01 (0.01)
	Control	0.03 (0.02)	0.02 (0.01)
Plateau-phase, small	Breakout-EMG	1.71 (0.18)	1.81 (0.28)
	Control	1.74 (0.16)	1.51 (0.13)
Plateau-phase, medium	Breakout-EMG	1.67 (0.18)	1.49 (0.16)
	Control	1.69 (0.14)	1.35 (0.13)

2.4 Discussion

In this study we tested whether a simple myogame that conforms to the specifications of the current generation of myogames (i) can be learned, and if so (ii) what changes in the myosignal may account for such in-game learning. Finally, we tested (iii) whether in-game improvement would transfer to a prosthesis task conforming to the settings typically used in clinical practice. Our results showed that performance on playing the Breakout-EMG game improved significantly in comparison to controls. Moreover, we showed that the increase in in-game performance was associated with an increase in the EMG–ball coupling. When compared to the control group however, we found no indications of transfer of this skill to a prosthesis task. That is, the participants learned to adjust the EMG signal they generated specifically to the requirements of the gaming task.

The main aim of this study was to determine what learning and transfer effects can be expected from training with the current generation of myogames. Therefore we aimed to maximize our chances of finding transfer. To do so, we chose a "sham" control group to control for testing-effects, for the amount of training, and for motivational aspects such as novelty effects or the effect of being part of an experiment (a Hawthorne effect). We did not choose a comparable myoelectric interface with comparable muscular involvement for the controls. With respect to transfer, this meant that all positive effects of training the game on prosthesis use should have shown up in the post test performance. Thus, in our opinion, the current set-up maximized chances of finding transfer to our prosthesis-task. Consequently however, if we had found transfer, we would not have been able to pin-point its likely origin. Combining the current results with previous transfer effects (Chapter 4) however, creating more subtle control conditions will be an interesting next step in order to tease out how different aspects of a game can influence transfer.

As a step in improving the design of myogames for prosthesis use, the current study aimed to provide an evaluation of current practices: it stayed close to both the settings and designs of myogaming research and to settings clinically used in prosthesis fitting. We thus designed a basic game much like those currently used, a game that was fun to play and easy to control by myosignals. We trained participants to play this game using the same muscles as they had to use for handling a prosthesis simulator. The EMG signals were furthermore proportionally related to the speed of the end-effector, just as in a prosthesis task. Thus we followed the same logic as earlier studies using myogames (Lovely et al., 1990; Ma et al., 2010), but extended this to include a transfer test. If improvement in prosthetic control was, for example, based on isolating muscular activity, the repetitive generation of EMG signals or on re-calibrating the acquired EMG control to a new range (cf. Liu, Mosier, Mussa-Ivaldi, Casadio, & Scheidt, 2011), we should have found transfer to our prosthesis task. Our results however, corroborate earlier findings (Chapter 4) and imply that creating a game that transfers effectively to ADL, may not be that easy.

In the end, myogame training should make the transfer to starting to practice with an actual prosthesis easier. It might therefore have its biggest role early in the rehabilitation process (i.e., in the pre prosthetic phase), when for example neural plasticity is high but wound healing prohibits the use of a prosthetic device (see Smurr et al., 2008; Terlaak et al., 2015). To facilitate transfer, our study points to several design features that deserve scrutiny in future myogame development. First, Breakout-EMG required less activation to play than did the myoelectric hand (i.e. 20% MVC, which is ~80% "comfortable contraction," see Anderson & Bischof, 2012, Terlaak et al., 2015). In as far as the calibration to MVC is reported, this is a common design choice that is aimed at preventing

fatigue during training (Anderson & Bischof, 2012; Ma et al., 2010; Pistohl et al., 2013; Radhakrishnan, Baker, & Jackson, 2008). In accordance with clinical practice (Ortiz-Catalan, Håkansson, & Brånemark, 2014), the myoelectric hand was however calibrated so that the maximum opening speed required the MVC sustainable for 2 seconds. Although it was recently shown that aligning the EMG intensity required for in-game performance with actual prosthesis use is insufficient for allowing transfer (Chapter 4), this does not preclude the possibility that it could create favorable conditions for transfer to occur. Thus it seems that future myogames should aim to determine the effects of these settings.

Second, as any myoelectric prosthesis, our prosthesis simulator had a time delay between generating the myosignal and the change in aperture. Such a delay was not present in the game as this would have made our game unplayable. As our grasping task was self-paced, timing the EMG signal was much less critical than in Breakout-EMG. It has been shown in a controlled pre-posttest design that simulating this delay is not sufficient to allow for transfer (Chapter 4). Nonetheless, it may still be beneficial to accommodate for a delay parameter in a future game design. To do so however, we need better estimates of the movement characteristics of currently available prostheses in relation to the generated EMG signals. To our knowledge, such estimates are not currently available. Future research should aim to establish these estimates and determine their exact effects on transfer.

An interesting aspect of our current study is our finding on in-game learning. This may help to guide ideas to improve myogaming for prosthesis use. The development of a strengthened coupling between the generated EMG signal and the game implies that during the game a very task-specific adaptation of the myosignal occurred; participants coupled their EMG directly to the required distance to make the paddle move in order to intercept the ball. This may indicate that when learning a myoelectric skill, it is not the myosignal that is being controlled as such, nor is control limited to the relation between the signal and the movement of the end-effector. What is being controlled might be the myosignal relative to goal-relevant information in the task (see also e.g. Chaper 6 Bootsma, 1998; Reed, 1988; Warren, 2006). Our in-game learning effects thus add to the previous effect study (Chapter 4) by suggesting that transfer is enabled in so far as the myosignal can be coordinated to the similar goal-relevant information across tasks.

An important limitation of our current set-up was our use of able bodied participants controlling a prosthesis simulator. So far, myogame research has not shown much empirical evidence for their benefit (see e.g. Anderson & Bischof, 2012, Armiger & Vogelstein, 2008, Davoodi & Loeb, 2012, Lovely et al., 1990, Ma et al., 2010, Oppenheim et al., 2010, Pistohl et al., 2013, De la Rosa et al., 2008, but see Chapter 4). The current designs therefore do not yet warrant testing for motor learning effects on patient groups. Simulators have been used before to approximate prosthesis use and it appeared that kinematic performances is comparable to performances with real upper limb prostheses (Bouwsema et al., 2012). The advantage of using these methods is that the small population of persons with upper limb amputations will not be bothered with research that does not lead to clinically useful results. Generalization to clinical populations that are already using myogames should however be handled with caution especially since myogames might also be used for rehabilitation goals other than motor learning. It should also be noted that we cannot rule out that our training period was too short for transfer to occur. Although previous research that used the same amount of training was successful in this respect (Chapter 4), and although we did find in-game learning effects, transfer of this particular game might require more extensive training time.

2.5 Conclusions

Although myogames are becoming an integral part of rehabilitation, designing a game that actually transfers to ADL is far from trivial. The marked improvement in myogame performance does not transfer to a prosthesis task. We have thus shown the need to explicitly design myogames for transfer to daily life and hope to have put some new design considerations on the map. By providing an evaluation of the transfer effect of the current generation of myogames, this study can provide a starting point for developing myogames that successfully transfer to activities of daily life.

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The anatomy of action systems

3

Van Dijk, L., Heerschop, A., Van der Sluis, C. K. & Bongers, R. M. (submitted). The anatomy of action systems: task differentiation when learning an EMG controlled game.

Abstract

This study aims to determine to what extent the task for an action system in its initial development relies on functional and anatomical components. Fifty-two able-bodied participants were randomly assigned to one of three experimental groups or to a control group. As a pre- and posttest all groups performed a computer game with the same goal and using the same musculature. One experimental group also trained to perform this test, while the other two experimental groups learned to perform a game that differed either in its goal or in the musculature used. The observed change in accuracy indicated that retaining the goal of the task or the musculature used equally increased transfer performance relative to controls. Conversely, changing either the goal or the musculature equally decreased transfer relative to training the test. These results suggest that in the initial development of an action system, the task to which the system pertains is not specified solely by either the goal of the task or the anatomical structures involved. It is suggested that functional specificity and anatomical dependence might equally be outcomes of continuously differentiating activity.

3.1 Introduction

When learning to perform a task, not only the means to achieve the goal of the task need to be learned, but the goal itself also refines as the action becomes more dexterous. For instance, when learning to play tennis, we at first only have a general idea of how to hit the ball. Over learning however, we learn to discern the many ways a ball can approach, and develop different strokes to accommodate for this. Moreover, we learn to return the ball strategically, for example steering the opponent to the right of the court, and thus the goal of the stroke changes as well. In other words, during learning a reciprocal differentiation of both action and goal results in changes in the details of what constitutes the task over time. Within the theory of action systems (Reed, 1982, 1988, 1996), this reciprocal differentiation of both action and goal during learning has received comparatively little attention. Rather, the focus has been on fully-differentiated systems.

According to Edward Reed's theory of action systems, when acting, the human body is organized in a goal-directed way in order to attain a task (Reed, 1982; see also Bernstein, 1996, J. J. Gibson, 1979, Reed, 1996, K. M. Newell & Vaillancourt, 2001, Warren, 2006). The coordinated system that is reliably formed as a task is performed, called an "action system," is characterized as being *functional*—that is, as being adapted to attain a certain goal in the environment. By looking at the effect that performing one task has on the performance of a subsequent, different, task (i.e. a transfer-effect), research has shown that fully differentiated action systems are task-specific: they are strongly dependent on the availability of task-relevant information for their formation, but largely independent of the anatomical components taken up (see Bruggeman & Warren, 2010; Rieser et al., 1995; Withagen & Michaels, 2002). Critically however, the findings of anatomical independence assume that the task for the action system has been fully established.

Consequently, the theory of action systems, that takes the functional organization of action as its starting point has come to be taken to be at odds with studies that show the importance of anatomical components for action (e.g. Durgin, Fox, & Kim, 2003; see also Bingham, Pan, & Mon-Williams, 2014 and Chapter 6 of this thesis). By taking the learning

of action systems into account, this chapter aims to show that such an opposition is not implied. In particular, in this chapter we aim to look at the early learning of an action system in order to determine what constitutes the task for an action system in its early development. To make a start on this, we will first introduce the processes of calibration and exploration to show how in these processes both functional and anatomical aspects are always implicated while forming of an action system.

3.1.1 Two processes for learning

A primary process in getting an action system to be functionally specific to a task is the process of "calibration." This process maps the action system to the perceptual information necessary to perform a specific task (see Rieser et al., 1995; De Vries, Withagen, & Zaal, 2015; Withagen & Michaels, 2005). In a seminal study for example, Rieser et al. (1995) showed that as long as information for forward movement (optic flow) is available to calibrate to, an action system for locomotion can be set up irrespective of the anatomy involved. In a transfer task, the specific mapping of locomotion to optic flow during walking influenced locomotion during side-stepping, but not to throwing or turning in place (see also Bruggeman & Warren, 2010; Withagen & Michaels, 2002). Calibration to perceptual information is thus independent of the anatomical components used, but instead relies on the availability of task-relevant information, such as the optic flow that specifies moving forward.

Nonetheless, some studies have shown that the anatomical components taken up in the system can influence task performance (e.g. Durgin et al., 2003; Bingham et al., 2014). This has prompted Bingham et al. (2014) to refine the relationship between task-function and anatomical aspects in an important way. The study created a different discrepancy for each arm between the haptic and visual feedback for the location of an object to be reached (Bingham et al., 2014). While the visual feedback remained the same for each arm, haptically the object was either moved forward or backward—requiring the relation between perception and action to be re-calibrated for each arm independently.

In a transfer test, Bingham et al. (2014) showed that the resulting perception–action relationship did not transfer between arms. The study thus showed that to keep an action system adapted to its environment, if both limbs require a different perception-action relation, then they are functionally distinguished. In other words, discerning anatomical aspects can be the outcome of a functional process. Therefore, Bingham et al. (2014) proposed the "mapping theory of calibration." They proposed that when adaptation to a task requires one limb to be mapped (i.e. calibrated) differently to the available information than the other limb, the two limbs get functionally differentiated based on the available feedback—in effect differentiating into two different tasks and thus into two separate action systems. In short, the task can come to include anatomical terms. As the process of calibration keeps an action system adapted to perform a certain task, it in turn too allows anatomical constraints to emerge as functionally relevant to task performance.

So anatomical aspects can emerge as task-relevant distinctions. However, the converse was also recently shown: task-relevant distinctions emerge on the basis of anatomical constraints. De Vries et al. (2015) showed that in an unfamiliar task in which the length of a stick needed to be estimated using either hands or feet the "education of attention," that is the moving towards the most useful perceptual information (De Vries et al., 2015; Jacobs & Michaels, 2007), was partly constrained by the anatomy used. Crucially, the results of their experiment suggested that this was so because the ability to distinguish perceptual information with either hands or feet differed. In other words, the ability to explore for more useful information was constrained by the anatomical components taken up during performance (De Vries et al., 2015). Some anatomical aspects, it seemed, could not (yet) generate the appropriate type of information for acting. This implies that when the goal of the task is still unclear and the learning process is dominated by exploration for, rather than calibration to, information, the task might be partly distinguished by the anatomical components used.

Taken together, these studies suggest that, in principle, the theory of action systems covers the possibility of accounting for anatomical dependence. Although action systems are defined relative to a task and often end up as largely independent of their specific anatomical components, the task itself might be differentiated by the learner based, in part, on the anatomical constraints it faces when learning to perform it (e.g. Bingham et al., 2014; De Vries et al., 2015). Consequently, during the learning of a task, the anatomical independence that comes to characterize a mature action system may be viewed as the outcome of a process of increasing adaptation and refinement of the task. In this process the action system changes along with the task that requires its development. To make a start in tracing these changes the current study aims to determine to what extent the task for an action system in its initial development relies on environmental and anatomical components.

3.1.2 Study overview

To determine this in an experimental set-up, two conditions needed to be met. First, it required the development of a completely novel action system. That is, the task to be performed needs to be highly goal-directed yet novel to the participants. Second, the task should require a completely novel use of an anatomical part of the body. In other words, the participants should not be able to rely on previous experience in using their body in some way to perform the task. We devised an experiment that required participants to perform a computer game that was highly goal-directed and required modulating the electromyographical (EMG) signals of their arm muscles to perform. As a computer game, the task was highly goal-directed yet novel. Moreover, EMG-current is typically a by-product of performing a task and is usually not a component part necessary to form a functioning action system. It thus introduces a new anatomical component to the task. Note however that learning to make use of such EMG current in a goal-directed way is not without application. For example, in rehabilitation, assistive technologies such as myoelectric prostheses require the development of action systems that embody these currents (see Bouwsema et al., 2010a; Pistohl et al., 2013; Smurr et al., 2008).

As previous studies showed, exploration and calibration both help to differentiate activity as it is developing. Therefore, we do not expect a task for an emerging action system to be either fully defined relative to its goal or by the anatomy used. Rather, our main question in this study is to what extent the task for an action system in its initial development relies on environmental and anatomical components. We will answer this question by changing either the goal of the computer game or changing the musculature used to generate the EMG signals after a training period. If the task for the emerging action system is predominately anatomically defined, then transfer (i.e. the effect that the learning of one task has on the performance of a different task) occurs even if the goal of the task is changed across performances but the musculature is kept the same. If an emerging action system is predominately goal-directed we expect that if the musculature used is changed, but the goal of the task is retained, then transfer will still occur.

To test these predictions, we used a pre-posttest design. We had three experimental groups and a control group. As a pre- and posttest all groups performed a computer game in which the goal was to catch falling objects. In the test all groups used EMG of wrist muscles to control the game. As a training, the experimental groups had to perform a different game or used different musculature. First a group of participants learned to play the game with the same settings as during the testing condition. Since in the game objects needed to be caught with a grabber that was controlled with wrist muscles, we call this condition "Catching-Wrist." Second, we had a group that learned to play a computer game in which the goal of the game was to intercept falling objects (i.e. a different training game)- but the muscles used to control the game were the same ("Intercept-Wrist"). Third, we had a group that, like the Catching-Wrist group had the goal of catching objects, but used their upper arm muscles to do so ("Catching-Arm"). Fourth, we had a sham control group ("SHAM") that played an unrelated video game.

When comparing the change in pre-to-posttest performance groups, we expected that: (i) if the task for an emerging action system is in part anatomically defined, then changing the goal but retaining the musculature used should enable transfer. Hence, we expect that the Intercept-Wrist group will then show significant improvement over the SHAM-group from pre- to posttesting. Conversely, changing the musculature while retaining the goal should then reduce transfer. Hence, we expect that the Catching-Arm group will show significantly less transfer compared to the Catching-Wrist-group.

(ii) if the task for an emerging action system is in part defined by the goal in the environment, then changing the musculature but retaining the goal should enable transfer. Hence in that case we expect the Catching-Arm group to show significant improvement over the SHAM-group from pre- to posttesting. Conversely, changing the goal while retaining the musculature should then reduce transfer. Hence, we expect that the Intercept-Wrist group will show significantly less transfer compared to the Catching-Wristgroup.

3.2 Methods

3.2.1 Participants

Fifty-two able bodied adults participated (mean age 21.90 (SD 3.27) y); 13 men and 39 women. The participants (1) were all right handed, (2) had normal or corrected to normal vision, (3) were free of any (history of) disorders of the arms or upper body, and (4) had no prior experience in the use of myoelectric devices. The study was approved by the local ethics committee and an informed consent was obtained from all participants prior to the start of the experiment. Upon completion of the experiment all participants received a gift voucher.

3.2.2 Materials

Two myogames were used—a Catching game and an Intercepting game and both ran on a laptop computer. Two pairs of self-adhesive electrodes were connected to a desktop computer via a Porti-5 data acquisition device (TMS International, The Netherlands) that sampled the data at 500 Hz. Custom LabView software (National Instruments Corporation, USA) digitally rectified and filtered the signals (high pass filter, cutoff frequency 10 Hz; low pass filter, cutoff frequency 20 Hz) and fed the EMG signals from the electrodes to the laptop via UDP at 125 Hz. The games resampled the EMG signal at 50 Hz and logged all changes on the screen during play to a text file.

The SHAM control group trained a platform game called "Super Mario Bros," which was run on a Nintendo Entertainment System (Nintendo Co. Ltd, Japan). This game was connected to a standard 32 cm (CRT) TV monitor.

3.2.3 Myogames

Catching game

In the Catching game the objective was to catch falling objects with a grabber so that the objects did not hit the ground. A screenshot of the game is shown in Figure 3.1. The falling objects had different shapes, each having a different color (light blue, blue and red). The objects were given a random size (that never exceeded the maximum aperture of the grabber). The objects that needed to be caught fell straight down from a "barrel" at the upper center of the screen. The grabber used to catch the objects remained stationary at the bottom center of the screen. In order to catch the falling objects, the closing and opening movement of the grabber (i.e. its aperture) was controlled using two myoelectric signals. The speed of the change in aperture of the grabber was proportional to the amplitude of the EMG signals. To make sure that the game required accurate use of the EMG signal, two constraints were imposed on goal attainment. First, the aperture of the grabber needed to be adapted to the size of the falling objects. If the aperture exceeded the diameter of the falling object more than 1.7 times, the grabber started to vibrate and gave off "sparks" (shown in Figure 3.1). Subsequently exceeding the diameter of the object by more than 2.3 times would cause the grabber to force closing rapidly. Second, the three shapes and colors of the falling objects represented their fragility (light, medium, strong). In this game the speed of closing the grabber therefore needed to be adapted to the fragility of the object. If the virtual force exerted on the object reflected by the closing speed of the grabber exceeded the object's threshold, the object would break.

Intercepting game

The objective of the Intercepting game was to intercept falling objects with a grabber so that the objects did not hit the ground. The game was identical to the Catching game group except (i) the aperture of the grabber was fixed throughout the game, (ii) the objects could not break, and (iii) the objects that needed to be caught fell downwards from a "barrel" at the upper center of the screen in any random direction (Figure 3.2). In this



Fig. 3.1. Screenshot of the Catching game. The opening and closing of the grabber at the bottom of the screen was controlled using two myosignals (of the wrist muscles or of the upper arm muscles). The goal of the game was to catch falling objects with a grabber so that the objects did not hit the ground (see text for details).

game not the aperture of the grabber, but the grabber's movements to the left and right were controlled using the myoelectric signals. To make sure that the game required a high accuracy in using the myosignals the grabber had large vertical edges (see Figure 3.2). This ensured that the objects could only be intercepted by timing the positioning of the grabber carefully. If the object made contact with the grabber's edges, the object would bounce away and the goal of intercepting it would not be obtained. The displacement speed of the grabber was proportional to the amplitude of the EMG signals.

SHAM game

The SHAM group, training in playing Super Mario Bros, had to control an avatar and safely guide the avatar through a world by jumping platforms and avoid enemies. The game was played using a standard hand held Nintendo controller, no control of a myosignal was implemented.



Fig. 3.2. Screenshot of the Intercepting game. The speed of the grabber at the bottom of the screen to the left and right was controlled using the myosignals (of the wrist muscles). The goal of the game was to intercept falling objects with the grabber so that the objects did not hit the ground (see text for details).

3.2.4 Design

The experiment was conducted over the course of 4 days and consisted of a pretest, 3 training sessions and a posttest. All groups performed the preand posttest, which consisted of playing one level of the Catching game using the EMG of the wrist muscles to control the game. On the first day the pretest was performed, which was followed by the first training session. On the second and third day the remaining two training sessions were conducted. On the fourth day the participants only performed the posttest. Participants were randomly assigned to either the Catching-Wrist-group (n = 13), the Intercept-Wrist-group (n = 13), the Catching-Arm-group (n =13) or to the SHAM group (n = 13).

3.2.5 Experimental groups

Catching-Wrist group

The Catching-Wrist group practiced playing the Catching game. They used the myosignals from the flexor and extensor muscles of the wrist. The signal from the flexor muscles acted to close the grabber and the signal from the extensor muscles acted to open the grabber.

Intercept-Wrist group

The Intercept-Wrist group was identical to the Catching-Wrist group in all respects but one: in this group the Intercepting game rather than the Catching game was practiced. The goal of this game was to intercept falling objects. Activation of the flexor muscles moved the cursor leftward whereas activation of the extensors moved the cursor rightward.

Catching-Arm group

The Catching-Arm group differed from the Catching-Wrist group only with respect to the musculature used to play the game. In the Catching-Arm group the game was not practiced using the wrist muscles, but by using the muscles of the upper arm. The signal from the lower part of the biceps muscle acted to close the grabber and the signal from the lateral head of the triceps muscles acted to open the grabber.

SHAM group

The SHAM group practiced playing Super Mario Bros. The game was played using a standard Nintendo controller held in the palm of the hand and required no myosignal use.

3.2.6 Procedure

Fitting of the electrodes

Prior to playing one of the myogames, the electrodes were fitted by palpating for the most prominent muscle bellies of either the extensors and flexors of the wrist (for the Catching-Wrist and Intercept-Wrist) or the upper arm's biceps or triceps muscle (Catching-Arm group) during contraction. The self-adhesive electrodes were subsequently placed at those sites. To ensure proper placement throughout the experiment, the location of the electrodes was marked with a pen. The signals were digitally processed and sent to the game computer. In the game environment both signals were calibrated by determining the minimum and maximum value of each electrode independently and scaling each signal to a standard range before the game began. The signal was scaled and amplified so that the minimum and maximum speed of the grabber conformed to 5% and 25%. The fitting procedure was repeated each day for each individual participant before training started.

Pretest and posttest

The pretest was equal to the posttest. Participants were asked to play the first level of the Catching game, using the flexor and extensor muscles of the wrist. In this single testing level (level 1) 25 objects fell down and needed to be caught by controlling the grabber. The level started when the experimenter pressed start and finished when the last object was caught or had fallen down. The participants received verbal instructions explaining the goal of the game—i.e. to try to catch the objects before they hit the ground – and how to control the grabber.

Training sessions

In each session all myogaming groups trained by playing their game for 20 minutes. Each game consisted of three levels that only differed (1) in the amount of objects to be caught before advancing to the next level and (2) in the speed with which the objects fell down. At higher levels, more objects needed to be caught and the objects fell at greater speeds. The participants received concurrent feedback during their performance: they could for example monitor the number of objects that needed to be caught to advance to the next level, the current number of objects caught or missed and the number of objects that still remained. They also received feedback on the number of points scored (with each object caught). Upon finishing a level, a summary of these results was presented and, depending on the number of objects caught, the player would then either advance to the next level or play the same level again. After playing all three levels, the participants started again at level 1. The games had no sound.

The SHAM group played Super Mario Bros for 20 minutes per session. The participants only played the first four levels of the game (i.e. level 1-1 to 1-4) and then started over. The game was muted so that it had no sound.

3.2.7 Data analysis

All dependent variables used to determine in-game performance were calculated from the output file provided by the myogames using customized Matlab (The Mathworks Inc., USA) scripts. As playing the games proficiently required a high degree of accuracy in catching the objects, we looked primarily at accuracy to assess in-game learning effects. The accuracy was determined as the number of objects caught divided by the total number of objects that dropped from the "barrel."

In order to scrutinize on performance, we explored several other aspects of performance. Accuracy is primarily determined by three aspects: (1) making sure not to open the grabber too widely as this would cause it to force-close and miss the object. Therefore, we looked at the participant's ability to adjust the size of the grabber's aperture to the size of the falling objects. We calculated this relative maximum aperture (RMA) as the maximum aperture of the grabber per trial divided by the width of the falling object. Note that the RMA has an upper limit of 2.3, as opening the grabber further would result in forced closing. (2) Making sure not to close the grabber too far when catching as this would cause the objects to break. We therefore determined the mean peak EMG opening and closing signal from the 25 catching trials during the pretest and posttest. (3) Making sure to close the grabber at the right moment, otherwise the falling objects would either bounce off the grabber or fall through. Therefore, we looked at the timing of the catch. We calculated the distance of the falling object to the grabber at the moment that the peak EMG closing signal was generated for all trials in the pre- and posttest and analyzed their mean value and their variability (standard deviation) within the testing trial.

To determine changes in performance during learning, a repeated measures ANOVA was performed on the accuracy with Session (session 1, 2 and 3) as within subjects factor and Group (Catching-Wrist, Catching-Arm, Intercept-Wrist) as between subjects factor. Post hoc comparisons of the in-game performance were corrected for multiple comparisons using a Bonferroni correction.

In order to determine transfer effects, the change in performance was calculated from pretest to posttest and this change was compared across groups. Before this comparison, we first performed a univariate ANOVA to check for initial differences between groups in pretest performance. If this test would yield any differences between groups, the pretest value would be added to the subsequent analysis as a covariate—there were however no pretest differences in any of the dependent variables. Transfer effects for each of the above defined outcome measures was then determined by conducting an ANOVA on the change in performance with Group (Catching-Wrist, Catching-Arm, Intercept-Wrist, SHAM) as a between subjects factor. Effect sizes were calculated using generalized eta-squared ($\eta_{\rm G}^2$) (Bakeman, 2005; Olejnik & Algina, 2003).

Based on the change in accuracy, we set up specific hypotheses for each dependent variable beforehand. To test the first of our main hypothesis of whether the task was constituted by the anatomy involved, in a planned contrast on the change in accuracy (i) the Intercept-Wrist group was compared to the SHAM group and (ii) the Catching-Wrist was compared to the Catching-Arm. Likewise, to test the second main hypothesis of whether the task was constituted by the goal of the task (i) the Catching-Arm group was compared to the SHAM group and (ii) the Catching-Wrist was compared to the Intercept-Wrist.

Any improvement in accuracy may in part be the result of scaling the grabber's aperture to the size of the object. From our earlier experience with this task (see Chapter 4) we know that novices in the test task open the grabber too far, leading to low accuracy scores. Therefore we expected (i) the relative maximum aperture (RMA) of the Catching-Wrist group to have decreased from pre- to posttest significantly more than the SHAM group. As adjusting the aperture of the grabber cannot be learned in the Intercepting game it was expected (ii) that the RMA for the Intercept-Wrist group would decrease significantly less than the Catching-Wrist group, while (iii) the Catching-Arm group is expected to decrease its RMA more than the SHAM group.

As generating large bursts of activation could result in either opening the grabber too widely or in breaking the object that needed to be caught, we expected a decrease in peak EMG signal both for opening and closing the grabber from pretest to posttest. We expected (i) the Catching-Wrist group to have decreased its peak EMG signals from pre- to posttest significantly more than the SHAM group. Furthermore, it was expected (ii) that the Intercept-Wrist group would improve significantly over the SHAM group, and (iii) the Catching-Arm group would improve significantly over the SHAM group.

With respect to both the timing of the grasp and the variability in timing of the grasp, we expect the same patterns of results as in the RMA: (i) we expected that the Catching-Wrist group would improve performance significantly over the SHAM group. As the Intercept-Wrist-group would to be unable to learn about the appropriate timing because the task-dynamics were unavailable in their training game (intercepting), we therefore, (ii) expected the Intercept-Wrist group to be significantly worse than the Catching-Wrist group. As the Catching-Arm group equally had experience in timing the grasp, (iii) we expected the Catching-Arm group to significantly improve over the SHAM group.

All these hypotheses were tested with planned comparisons (contrasts) in the ANOVA. For our two main hypotheses concerning the change in accuracy, we used two ANOVA's with a different set of planned comparisons each. This meant that we had a total of four comparisons for the change in accuracy. For each of the two sets of hypotheses we therefore used a significance level of $\alpha = .025$. All other analyses used a significance level of $\alpha = .05$.

3.3 Results and discussion

3.3.1 Training performance

The in-game accuracy of all experimental groups across all sessions, and the accuracy of the SHAM group on the pre- and posttest is shown in Figure 3.3.



Fig. 3.3. Mean accuracy (and standard error of the mean) on the pretest and posttest for all groups and on the three training sessions for all experimental groups. Each point denotes the mean accuracy per trial (a trial consisted of 25 catches). To characterize the learning process across sessions the mean accuracy on the first trial playing level 1 (circles) and the last trial playing level 1 (triangles) for each 20 minute session are shown.

Visual inspection of the data shows that all groups increase their performance across sessions. A repeated-measures ANOVA was performed on the accuracy of the first trial of each training session with Session as within subjects factor and Group as between subjects factor. The analysis revealed a main effect for Session ($F(2,72) = 44.41, p < .001, \eta_G^2 = .46$) and for Group ($F(2,36) = 19.92, p < .001, \eta_G^2 = .53$). There was no significant interaction effect. A post hoc analysis revealed that the Intercept-Wrist group was more accurate than both the Catching-Wrist group (p = .003) and was more accurate than the Catching-Arm group (p < .001) in playing their respective myogame. Moreover, the Catching-Arm group that used the muscles, was more accurate than the Catching-Arm group that used the muscles of the upper arm (p = .029). These results suggest that the Catching-Arm game was the hardest task to learn, while the Interception-Wrist game was comparatively easy to learn.

3.3.2 Transfer performance

Accuracy

To test our main hypotheses we compared the change in accuracy of all the different groups from pretest to posttest. An ANOVA on the level of accuracy at the pretest (see Figure 3.3) with Group as a between subjects factor revealed no Group effects. The pre-to-posttest difference is depicted in Figure 3.4. The accuracy in the Catching-Wrist group has increased the most while the SHAM group showed no improvement. The two other groups appear to show an increase in performance in between the Catching-Wrist and the SHAM group.



Fig. 3.4. Mean difference in accuracy (and standard error of the mean) from pretest to posttest for all groups. The Catching-Wrist group improved most while the SHAM group showed no improvement. The Catching-Arm and Intercept-Wrist groups both showed improvement in between the other two groups.

To see whether these differences hold statistically we looked into the change in performance from pretest to posttest using an ANOVA on the pre-to-posttest difference in accuracy, with Group as between subjects factor. The general analysis showed a main effect of Group ($F(3, 48) = 13.31, p < .001, \eta_G^2 = .45$). Following this analysis our main hypotheses were tested using planned contrasts comparing the group effects. Our first set of hypotheses tested whether the task was in part constituted by the anatomy involved. Our planned contrast showed that the Intercept-Wrist group improved significantly compared to the SHAM group (p = .009). Moreover, it showed that Catching-Wrist improved significantly compared to the results indicate that transfer occurred if the anatomy was retained.

Our second set of hypotheses tested to what extent the task was constituted by the goal of the task. Our planned contrast showed that the Catching-Arm group improved significantly compared to the SHAM group (p = .012). Moreover, it showed that the Catching-Wrist improved significantly compared to the Intercept-Wrist group (p = .001). Both these results indicate that transfer also occurred if the goal of the task was retained.

Relative maximum aperture

The pre- to posttest differences in the relative maximum aperture (RMA) are shown in Figure 3.5.



Fig. 3.5. Mean difference in relative maximum aperture (and standard error of the mean) from pretest to posttest for all groups. There are no significant differences in performance between groups.

An ANOVA on the pretest value showed no significant differences between groups (grand mean RMA was 1.57 ± 0.04). We therefore conducted an ANOVA on the pre-to-posttest differences with Group as between subjects factor. The change in RMA from pretest to posttest can be seen in Figure 3.5. There was no significant overall Group effect. Only the first prespecified contrast was significant—that is, only the Catching-Wrist group differed significantly from the SHAM group (p = .015).

Peak EMG signal

The differences in peak opening and closing EMG signals are shown in Figure 3.6A and 3.6B respectively. As ANOVA's on the pretest peak opening EMG and on the pretest closing EMG revealed no differences between groups in initially generated peak EMG (grand mean opening signal, 0.720.05, closing signal, 0.610.03), we compared the pre-to-posttest difference with Group as between subjects factor. There were no significant effects for Group either for the peak opening EMG or for the peak closing EMG. Planned contrast also showed no significant differences.



Fig. 3.6. (A) Mean difference in peak opening signal (and standard error of the mean) from pretest to posttest for all groups. (B) Mean difference in peak closing signal (and standard error of the mean) from pretest to posttest for all groups.

Timing of the grasp

To examine to what extent the timing of the catch determined the improvement in accuracy we analyzed the distance of the falling object to the grabber at the moment of the peak closing EMG signal (henceforth "start of the grasp"). The grabber was located at position 0 (the objects started at position 3.8). An ANOVA on the start of the grasp on the pretest revealed no significant differences between groups (grand mean 0.82 ± 0.09). The mean difference in the start of the grasp from pretest to posttest is represented in Figure 3.7A. An ANOVA on the pre-to-posttest difference showed there was no significant Group effect. None of the planned contrasts revealed a significant difference between groups.



Fig. 3.7. (A) Mean difference in distance of the object to the grabber at the moment of peak closing signal (and standard error of the mean) from pre- to post test for all groups. The Catching-Wrist group improved its timing significantly over the other groups. (B) Mean difference in standard deviation of the distance of the object to the grabber at the moment of peak closing signal (and standard error of the mean) from pre- to post test. Although the absolute timing of the grasp appeared not to have been critical (the object is catchable along a large trajectory) improvement in accuracy (Figure 3.4) is closely matched by a decrease in variability of the timing of the catch (see text for details).

However, depending on the size (length) of the object, the maximum aperture of the grabber and the magnitude of the peak closing EMG signal, the absolute distance of the object to the grabber may not be critical for the participant to catch the object. Indeed, judging from the standard error in Figure 3.7A, there is considerable variability between participants in absolute timing of the start of the grasp. Within a participant, the variability in timing the grasp may however still stabilize and thus help to improve performance. To characterize improvement in the timing of the catch, we therefore decided to look at the within-subject variability in timing the closing signal by calculating the standard deviation of the start of the grasp across all 25 trials of the pretest and posttest for each participant.

Variability in timing the closing signal

An ANOVA on the mean standard deviation of the start of the grasp revealed no significant differences between groups (grand mean 1.29 ± 0.06). The difference in mean standard deviation of the start of the grasp from pretest to posttest can be found in Figure 3.7B. An ANOVA on the preto-posttest differences in variability in timing the start of the grasp with Group as between subjects factor revealed a significant effect for Group $(F(3,52) = 8.46, p < .001, \eta_G^2 = .35)$. As expected, the first planned contrast showed the Catching-Wrist decreased the variability in timing the grasp significantly over the SHAM group (p < .001). The second expectation was also confirmed: the Intercept-Wrist-group was significantly more variable than the Catching-Wrist group (p < .001). The third planned comparison showed that the Catching-Arm group did not differ significantly from the SHAM group.

3.4 General discussion

In this study we set out to determine to what extent the task for an action system in its initial development relies on environmental and anatomical components. Our main finding on the accuracy of performance indicates that retaining either the environmental goal of the task or the musculature used will equally increase performance relative to training a control task. However, in comparison to training the test, changing either the goal or the musculature will also equally decrease performance. These findings indicate that in the initial development of an action system, the task to which the system pertains is not specified solely by either the goal of the task or the anatomical structures involved. It is both the goal of the task as well as the anatomical structures involved that contribute to the initial formation of an action system for a task. This suggests that the anatomical independence that comes to characterize a fully formed action system for that task is the outcome of a learning process—as is any anatomical specificity that is required (see Bingham et al., 2014).

By scrutinizing on measures of performance at the level of the actions within a trial, we hoped to be able to find indications of either exploration of information or of the calibration to information during the learning process. Looking at defining characteristics of the catching behavior in the test task, we were unable to find much systematic changes across learning. Neither the peak EMG signals generated nor the timing of the closing of the grabber appeared to reflect changes in performance between groups. The relative maximum opening and the variability of the timing tended to change in the same direction as our main accuracy measure, but these trends too failed to reach significance. It seems that, in our task, the overall accuracy was the best characterization of task performance. This might not be surprising, because the objective, in terms of the instructions given to the participants, was to try and catch or intercept as many of the objects as possible. Therefore, it seems reasonable to assume that the action system forms at this level of performance.

An object for future study might be to try and flesh out the role of the processes of calibration and exploration during learning. This might require scrutinizing on the behavior within single participants. That is, recent evidence has shown that during learning there are large individual differences in the information used (Dicks, Davids, & Button, 2010; Withagen & Van Wermeskerken, 2009). Moreover, in several learning studies it has been shown that the learning towards the use of information differs between individuals (Jacobs & Michaels, 2007; Golenia, Schoemaker, Mouton, & Bongers, 2014; Vegter, Lamoth, de Groot, Veeger, & van der Woude, 2014). In our study it might therefore be that participants were at different stages of their learning, and thus of information used, when entering the posttest. This might have resulted in variability of performance, and could have clouded systematic differences between groups on the posttest. Although we have explored for changes in behavior within participants, our analyses so far were not successful.

What might be the reason that we had not found clear indications of how task goal and anatomy interacted? Our results suggest that the anatomical independence that comes to characterize a mature action system can be viewed as the outcome of a process of increasing differentiation of the task. As detailed in the introduction, in this process of both calibration (e.g. Bingham et al., 2014) and exploration (e.g. De Vries et al., 2015), the action system changes along with the task to which it pertains. By focusing on the reciprocal differentiation of both action and goal during the learning of a task, there is no principled reason for not accounting for anatomical constraints within an action systems perspective. The theory of action systems is thus rich enough to deal equally well with functional as well as anatomical specificity. In the context of learning and differentiation (J. J. Gibson & E. J. Gibson, 1955) the action systems approach can thus gain much wider application.

One of the fields in which the action systems approach might contribute is that of motor recovery. Even though two of our experimental groups used a completely different set of muscles or the game consisted of a different kind of action, both improved significantly over controls in their ability to play the Catching-Wrist game. Both are innovative findings for motor recovery. For example, although seldom tested, in literature on EMG control the necessity of using similar musculature is often assumed (see Dawson et al., 2011, Dupont & Morin, 1994; but see Romkema, Bongers, & Van Der Sluis, 2013). Our finding of task-specific transfer might thus be helpful in developing novel training programs for learning to use an EMG signal to handle prostheses and other EMG controlled assistive devices (see Bouwsema et al., 2010a). Moreover, our finding of transfer in the absence of task-similarity is one of the first to provide empirical support for using muscle-specific EMG training in rehabilitation (e.g. Pistohl et al., 2013; Smurr et al., 2008; Terlaak et al., 2015). Combining these results with a differentiation account of learning, our current study suggests such a role primarily in the initial stage of learning (see also Chapter 4 and 6).

An important collateral of the action system approach is that it takes action to be the basic component and views anatomy as a derived classification (Reed, 1988; see Chapter 6). That is, in this view, it is only in the context of acting that anatomical properties can be distinguished as relevant. This fits for example with the interpretation that Bingham et al. (2014) gave of their results when they suggested that the "relevant anatomical properties must be incorporated into the functional dynamics of calibration" (p. 68). That is, what counts as relevant anatomy, is determined in learning to adapt to the task. We add to this the converse idea, that equally, what counts as the goal of the task is, in part, differentiated by the anatomy available (see De Vries et al., 2015). Over learning both anatomical and environmental aspects form in the context of the task that is differentiating as the participant acts.

Taking this point one step further, this interpretation can also have an important consequence for our understanding of transfer. In our study we used transfer, i.e. the effect of past performance of one task on the subsequent performance of another task, to establish a prior similarity between tasks. For example, finding transfer from the Catching-Wrist to the Catching-Arm group is then interpreted as showing that the tasks in both cases already share a similarity in goals, and therefore transfer occurred.

Against the background of the foregoing discussion, this interpretation can be questioned. Just as anatomical and functional relevance can be understood as two emerging aspects of learning a task, more generally, finding transfer between performances can also be taken to show that the participant was able to *achieve* similarity across performances in acting. In other words, when learning a skill, one does not need to learn about prior anatomical or goal-relevant similarities of the environment; one merely needs to become selectively receptive to the changing possibilities for action (Michaels & Carello, 1981; Reed, 1996; Rietveld & Kiverstein, 2014). Transfer, in such a view, is not a measure of covert similarity of tasks but of achieved continuity in acting.

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Task-oriented gaming for transfer to prosthesis use

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Abstract

The aim of this study is to establish the effect of task-oriented video gaming on using a myoelectric prosthesis in a basic activity of daily life (ADL). Fortyone able-bodied right-handed participants were randomly assigned to 1 of 4 groups. In three of these groups the participants trained to control a video game using the myosignals of the flexors and extensors of the wrist: in the Adaptive Catching group participants needed to catch falling objects by opening and closing a grabber and received ADL-relevant feedback during performance. The Free Catching group used the same game, but without augmented feedback. The Interceptive Catching group trained a game where the goal was to intercept a falling object by moving a grabber to the left and right. They received no additional feedback. The control group played a regular Mario computer game. All groups trained 20 minutes a day for 4 consecutive days. Two tests were conducted before and after training: one level of the training game was performed, and participants grasped objects with a prosthesis-simulator. Results showed all groups improved their game performance over controls. In the prosthesissimulator task, after training the Adaptive Catching group outperformed the other groups in their ability to adjust the hand aperture to the size of the objects and the degree of compression of compressible objects. This study is the first to demonstrate transfer effects from a serious game to a myoelectric prosthesis task. The specificity of the learning effects suggests that research into serious gaming will benefit from placing ADL-specific constraints on game development.

4.1 Introduction

Using a myoelectric prosthesis in daily life requires remarkable skills. As any skill, it requires effort and prolonged practice to achieve any level of dexterity. Lack of appropriate practice1 and limited incorporation of the prosthesis into activities in daily life (ADL) (Biddiss & Chau, 2007a, 2007b), contribute to the high rejection rates for using a myoelectric prosthesis (>20%) (Biddiss & Chau, 2007b). Serious games, i.e. games that are fun to play while supplying patients with skills useful in daily life (Graafland et al., 2012), may offer a way to improve prosthetic skills: they can provide a fun task with incremental levels of difficulty so that patients remain motivated and prolong their training (Rahmani & Boren, 2012), they can be individualized by allowing remote guidance by a therapist or physician (Holden, 2005) and they can incorporate augmented feedback in order to optimize learning (Van Diest, Lamoth, Stegenga, Verkerke, & Postema, 2013).

Research in motor control however, shows that skill learning is highly task specific (Censor, Sagi, & Cohen, 2012; K. M. Newell, 1996; Reed, 1988; Rieser et al., 1995). That is, the goal of the training task needs to resemble the goal of the task in daily life (ADL) in order for transfer to occur (Rieser et al., 1995). Serious games with a myoelectric interface (henceforth "myogames") that have been developed so far have not focused on this issue. Prioritizing playability and fun, their tasks involve e.g. hitting notes on a guitar (Armiger & Vogelstein, 2008), shooting balloons (Ma et al., 2010) or space ships (Anderson & Bischof, 2012). Although these studies make important technological contributions, their value to prosthetic skill learning remains unclear, as the focus has not been on transfer to a myoelectric prosthesis task. In Chapter 2 we did test for transfer to a prosthesis task following a four-day training period playing a myogame (a version of the "Breakout" game). Although the study showed task-specific in-game learning effects, it was unable to elicit transfer effects. The reason for this lack of transfer was hypothesized to be the difference between the task in the myogame and an actual grasping task.

Myogames should thus not prioritize playability and fun over task similarity. Rather, the task specificity of learning implies that the myogame needs to approximate the goal of a prosthesis task as closely as possible. In a basic grasping task, where the goal is to pick up an object, skilled prosthetic users show several task-specific adaptations. First, they scale the size of the aperture of the prosthesis hand to the size of the object (Bouwsema et al., 2010b). This finding is also typical for grasping with natural hands (Bootsma et al., 1994; Castiello, 2005). Second, when the object that needs to be grasped is fragile, research suggests experienced users are better able to adjust their prosthesis hand so that the object does not break (Bouwsema, Van der Sluis, & Bongers, 2014). Simulating a grasping task so that the goal requires these adaptation should therefore improve transfer to a basic grasping task.

However, while myogames should not sacrifice task similarity for entertainment, simply simulating a grasping task in virtual reality would risk sacrificing a games' motivational benefits for task-similarity. Despite this apparent contradiction, serious games may still offer a unique way to learn task-specific adaptations: by providing ADL-relevant feedback. This feedback should make information available in the game that also aids goal attainment when using a prosthesis in ADL. Crucially, this augmented feedback needs to be delivered in such a way that it matters to goal attainment in the game itself (K. M. Newell, 1991; Wulf, 2013). In a myogame to improve grasping skills, this means making the effect of scaling the virtual hand to the size of the virtual objects more salient and making the effect of carefully grasping fragile objects rewarding.

Based on these considerations, we developed a game that simulates a grasping task to the extent that it allowed us to augment ADL-relevant information in a game-relevant way. We created a catching game that is played with a myoelectric interface to simulate the basics of a prosthetic grasping task. The game incorporated the proportional relation between EMG-amplitude and end-effector typically found in a myoelectric prosthesis. We then created three versions of this game, in the first version (called "Adaptive Catching") we augmented the ADL-relevant information with additional feedback that mattered to attaining the goal of the game. In the second version of the game ("Free Catching"), the same ADL-relevant information was available, but it was not augmented. The third version of the myogame ("Interceptive Catching") does not simulate any aspect of an ADL prosthesis task. It only uses the same EMG-interface as both our prosthesis and the two other myogames.

The overall aim of this study is to determine whether a task-oriented myogame, that is a myogame that utilizes ADL-relevant feedback, can elicit transfer to a prosthesis task. In order to find out, we used a pretestposttest design. First, we checked for in-game learning effects by looking at the change in catching accuracy after training the myogames. Subsequently, we compared the change in prosthesis skill after training either the Adaptive Catching game with ADL-relevant feedback or training the Free Catching game without such feedback, and compared the effects to training the Interceptive Catching game without ADL similarity whatsoever and to controls that learned to play a video game that did not use a myoelectric interface. If participants increase their myoelectric skills in a task-specific way, we expect the Adaptive Catching game to have better performance on an ADL prosthesis task in comparison to all other groups. We expect this to be reflected in (i) their ability to scale the myoelectric hand aperture to the size of the objects, and (ii) in an improved ability to compress objects less. Moreover, as the Free Catching game allows for the use of ADL-relevant information, we expect training in this game to increase prosthesis skill more than either training the Interceptive Catching game or Controls. Finally, despite the myoelectric interface, taskspecificity implies that the Interceptive Catching game will not improve in these respects over Controls.

4.2 Methods

4.2.1 Participants

Forty-one able bodied adults participated (mean age 21.63 (SD 2.24) y); 22 men and 19 women. All participants (1) were right handed, (2) had normal or corrected to normal vision, (3) were free of any (history of) disorders of the arms or upper body, and (4) had no prior experience in the use of myoelectric devices. The study was approved by the local ethics committee and an informed consent was obtained from all participants prior to the start of the experiment. Upon completion of the experiment all participants received a gift voucher.

4.2.2 Materials

Three myogames were created. These were all video games and ran on a laptop computer. Two pairs of self-adhesive electrodes were connected to a desktop computer via a Porti-5 data acquisition device (TMS International, The Netherlands) that sampled the data at 500 Hz. Custom LabView software (National Instruments Corporation, USA) digitally rectified and filtered the signals (high pass filter, cutoff frequency 10 Hz; low pass filter, cutoff frequency 20 Hz) and fed the EMG signals from the electrodes to the laptop via UDP at 100 Hz. The games resampled the EMG signal at 25 Hz and logged all changes on the screen during play to a text file. As a sham training, a platform game called "Super Mario Bros" was run on a Nintendo Entertainment System (Nintendo Co. Ltd, Japan). This game was connected to a standard 32 cm (CRT) TV monitor. To resemble a myoelectric upper-extremity prosthesis for a transradial amputation level as closely as possible, a myoelectric simulator was developed (Figure 4.1) (Bouwsema et al., 2008, 2010b; Romkema et al., 2013).



Fig. 4.1. Top view of the myoelectric simulator while grasping the medium sized cylinder. The goniometer is attached to the thumb and index finger. The starting position of each trial is the square on the pad seen at the bottom edge of the tabletop.

> This simulator consisted of a myoelectric hand attached to an open cast in which the hand could be placed, and a splint that was adjustable in length and attached the simulator to the forearm with a Velcro sleeve. The myoelectric hand was a MyoHand VariPlus Speed (Otto Bock Healthcare

products, Austria) with proportional speed (15–300mm/s) and grip force control (0-~100N). During the myoelectric simulator task three wooden cylinders and 3 compressible objects were grasped. The wooden cylinders were 10 cm in height and were either 2 cm (small), 4 cm (medium) or 6 cm (large) in diameter (see Figure 4.1). The compressible objects consisted of two metal plates (Figure 4.2) with a spring in between $(6 \times 3.5 \times 9 \text{ cm})$. Each spring had a different resistance (low-resistance object (c = 0.17) N/mm); moderate-resistance object (c = 0.57 N/mm); and high-resistance object (c = 5.31 N/mm). The resistance of each compressible object was indicated on the object by a text ("low," "moderate" or "high"). To determine the amount of compression of each object, a slide with a metric scale was attached to the object (see Figure 4.2). In order to measure the aperture of the myoelectric hand during grasping, a goniometer (Cermet PC300 potentiometer, Contelec, Switzerland) was attached to the thumb and index finger of the hand. The goniometer was connected to a NI-USB 6009 data acquisition device (National Instruments Corporation, USA) and sampled the angle of the hand at 2000Hz. This data was sent to the laptop computer.



Fig. 4.2. Example of one of the compressible objects with a slide scale at the front of the object used to measure the amount of compression after each trial.

4.2.3 Design

The experiment was conducted over the course of 5 days and consisted of 4 training sessions. On the first day a pretest was performed after which the first training session followed. The remaining training sessions followed on the second, third and fourth day. On the fifth day a posttest was performed. Participants were randomly assigned to either the Adaptive Catching group (n = 12), the Free Catching group (n = 12), the Interceptive Catching group (n = 10) or to the Control group (n = 9).

4.2.4 Experimental groups

Adaptive Catching

The Adaptive Catching group trained a myogame in which the objective was to catch falling objects with a grabber so that the objects did not hit the ground. A screenshot of the game is shown in Figure 4.3. The falling objects had different shapes, each having a different color (light blue, blue and red). The objects were given a random size (that never exceeded the maximum aperture of the grabber). The objects that needed to be caught fell straight down from a "barrel" at the upper center of the screen. The grabber used to catch the objects remained stationary at the bottom center of the screen. In order to catch the falling objects, the closing and opening movement of the grabber (i.e. its aperture) was controlled using the myoelectric signals from the flexor or extensor muscles of the wrist respectively. The speed of the change in aperture of the grabber was proportional to the amplitude of the EMG signals. Two sources of feedback were made relevant to attaining the goal of the game. First, the aperture of the grabber needed to be adapted to the size of the falling objects. If the aperture exceeded the diameter of the falling object more than 1.7 times, the grabber started to vibrate and give off "sparks" (shown in Figure 4.3). Subsequently exceeding the diameter of the object by more than 1.9 times would cause the grabber to force closing rapidly. Second, the three shapes and colors of the falling objects represented their fragility (light, medium, strong). In this game the speed of closing the grabber therefore needed to be adapted to the fragility of the object. If the virtual force exerted on the

object by the closing speed of the grabber exceeded the object's threshold, the object would break. $^{\rm 1}$



Fig. 4.3. Screenshot of the Adaptive caching game. The opening and closing of the grabber at the bottom of the screen was controlled using the myosignals of the wrist muscles. The goal of the game was to catch falling objects with a grabber so that the objects did not hit the ground (see text for details).

Free Catching

The Free Catching group trained a myogame which was identical to the Adaptive Catching group in all respects except for the augmented feedback. In the Free Catching group, the augmented feedback was absent. The grabber did not vibrate, give off sparks or was forced to close when its aperture changed, nor did the objects break when closing the grabber too rapidly.

Interceptive Catching

The Interceptive Catching group trained a myogame in which the objective was to intercept falling objects with a grabber so that the objects did not hit the ground. The game was identical to the Free Catching group except

¹The object's fragility was actually implemented by giving it a second, virtual, diameter (a percentage of its visual diameter) and by having the grabber continue to close virtually, that is, invisible to the player. If the grabber then closed beyond the predetermined virtual diameter, the object would break. The shape and color of the object determined the relative breakpoint of each object.

now the aperture of the grabber was fixed throughout the game and the objects that needed to be caught fell downwards from a "barrel" at the upper center of the screen in any random direction (Figure 4.4). Thus not the aperture of the grabber, but the grabber's movements to the left and right were controlled using the myoelectric signals from the flexor or extensor muscles of the wrist, respectively. The speed of the grabber was proportional to the amplitude of the EMG signals.



Fig. 4.4. Screenshot of the Interceptive Catching game. The speed of the grabber at the bottom of the screen to the left and right was controlled using the myosignals of the wrist muscles. The goal of the game was to intercept falling objects with the grabber so that the objects did not hit the ground (see text for details).

Control group

The Control group trained in playing Super Mario Bros. In this game the objective was to control an avatar and safely guide the avatar through a world by jumping platforms and avoid enemies. The game was played using a standard hand held Nintendo controller, so this group did not perform any specific myosignal training.

4.2.5 Procedure

Fitting of the electrodes

Prior to playing one of the myogames, the electrodes were fitted by palpating for the most prominent muscle bellies of the extensors and flexors of the wrist during contraction. The self-adhesive electrodes were subsequently placed at those sites. The signals were digitally processed and sent to the game computer. In the game environment both signals were calibrated by determining the minimum and maximum value of each electrode independently and scaling each signal to a standard range before the game began. The signal was scaled and amplified so that the minimum movement speed of the grabber required 10% of the maximum voluntary contraction (MVC) of the muscles and the maximum movement speed required 75% of MVC. Moreover, a delay of 150 ms between the signals and the movements of the grabber was implemented. We implemented these constraints in order to approximate the EMG-response of the myoelectric hand. The fitting procedure was repeated each day for each individual participant before training started.

For controlling the hand of the prosthesis simulator at the pre- and posttest, the sites for fitting the electrodes were similarly determined. The electrodes were subsequently placed by attaching the prosthesis simulator to the participant's arm. The sensitivity of the electrodes was adjusted to the upper threshold for each participant individually, so that the maximum EMG signal that could be sustained for 2 seconds of each participant corresponded to ca. 80% of the maximum opening and closing speed of the myoelectric hand.

Pretest and posttest

The pretest was equal to the posttest. These tests were used to determine the improvement in skill in playing the myogames and in using the prosthesis simulator. To determine the improvement in playing a myogame, participants were asked to play one level of the game they played during their training sessions. In this single level (level 1) 25 objects fell down and needed to be caught by controlling the grabber. The Control group played one level of the Adaptive Catching game, just as the Adaptive Catching group did. The level started when the experimenter pressed start and finished when the last object was caught or fell down. The participants received verbal instructions explaining the goal of the game and how to control the grabber.

In order to find out whether improvement in playing any of the myogames transferred to using the prosthesis simulator, the change in performance during a simple grasping task was measured. In this task participants sat in a comfortable position in front of a table wearing the prosthesis simulator. Prior to the start of the task each participant was asked to maximally open and close the hand to calibrate the signals of the goniometer by establishing the signal values belonging to the minimum and maximum aperture. Starting with a closed myoelectric hand, participants were then asked to grasp one of three wooden cylinders or one of three compressible objects that was placed directly in front of them at 21 cm from the edge of the table, lift the object slightly, and then place it back at its original position (see Figure 4.1). Each of the six objects needed to be grasped five times. The order in which the objects were presented was randomized. The participants were instructed to be as accurately as possible in grasping, emphasizing not to focus on speed of performance but rather to focus on not dropping the objects while grasping. For the compressible objects they were additionally instructed to compress the objects as little as possible.

Training sessions

In each session all myogaming groups trained by playing their game for 20 minutes. Each game consisted of three levels that only differed (1) in the amount of objects to be caught before advancing to the next level and (2) in the speed with which the objects fell down. At higher levels, more objects needed to be caught and the objects fell at greater speeds. The participants received concurrent feedback during their performance: they could for example monitor the number of objects that needed to be caught to advance to the next level, the current number of objects caught or missed and the number of objects that still remained. They also received feedback on the number of points scored (with each object caught). Upon finishing a level, a summary of these results was presented and, depending on the number of objects caught, the player would then

either advance to the next level or try again. After playing all three levels, the participants started again at level 1. The games had no sound.

The Control group played Super Mario Bros for 20 minutes per session. The participants only played the first four levels of the game (i.e. level 1-1 to 1-4) and then start over. The game was muted so that it had no sound.

4.2.6 Data analysis

Using customized Matlab (The Mathworks Inc., USA) scripts, all dependent variables used to determine in-game performance were calculated from the output file provided by the myogames. As playing the games proficiently required a high degree of accuracy in catching the objects, we looked at accuracy for in-game learning effects. The accuracy was determined as the number of objects caught divided by the total number of objects that dropped from the "barrel."

Changes in the use of the myoelectric simulator were determined from the angular data from the goniometer using customized Matlab scripts. The angular data was filtered using a low pass filter (cutoff frequency 20 Hz). To determine the maximum hand opening (MHO) and the mean opening and closing velocity of the hand, the start and end of the opening as well as of the closing of the hand were determined from the data.

We expected the Adaptive Catching group to outperform the Free Catching group in the ability to control the prosthesis simulator. We expected no difference in the ability to control the prosthesis simulator for the Interceptive Catching group compared to Controls. Improvement in controlling the prosthesis is shown as an ability to better adjust the hand opening to the size of the wooden cylinder; requiring a smaller MHO during grasping as they learned to use the prosthesis (Bouwsema et al., 2010b; Castiello, 2005; Meulenbroek et al., 2001; Smeets & Brenner, 1999). Such an improvement in adjusting the hand to the size of the cylinders may also be visible as a decrease in mean opening velocity of the prosthesis hand (Bouwsema et al., 2010a). As the goniometer was sometimes repositioned between participants and sessions, we normalized the angular data to a value between 0 and 1 based on the measured minimum and maximum value of each participant prior to analysis. We also expected that increased prosthetic

skills would show less compression of the compressible objects.18 That is, if the Adaptive- and Free Catching games enabled dexterously closing the myoelectric hand, participants would be able to adjust the closing of the hand so that the compressible objects would be compressed less in comparison to the Interceptive Catching group and Controls. We expected such adjustment to further show in a decrease in the mean closing velocity of the prosthesis hand.

In order to determine both learning and transfer effects, the change in performance was calculated from pretest to posttest and this change was compared across groups. Prior to these analyses univariate ANOVA's were conducted to check for initial differences in pretest performance. If this test yielded any differences between groups, the pretest value was added to the subsequent analysis as a covariate. To determine in-game learning effects, an ANCOVA was conducted on the change in accuracy with group (Adaptive Catching, Free Catching, Intercept, Control) as a between subjects factor. To determine what group showed the greatest transfer on grasping the wooden cylinders, ANOVA's were conducted on the change in mean opening velocity of the hand and on the change in maximum hand opening, with cylinder (small, medium, large) as within subjects factor and group (Adaptive Catching, Free Catching, Intercept, Control) as a between subjects factor. To quantify the change in aperture over the posttest for all participants a linear regression line was fitted to the aperture on all consecutive trials for each cylinder during the posttest. To test for changes between groups an ANOVA was conducted on the slope of the regression line, with cylinder (small, medium, large) as within subjects factor and group (Adaptive Catching, Free Catching, Intercept, Control) as a between subjects factor. Finally, to determine transfer on grasping the compressible objects, ANOVA's were conducted on the change of mean closing velocity of the hand and on the change in compression, with object (low, medium, high) as a within subjects factor and group (Adaptive Catching, Free Catching, Intercept, Control) as a between subjects factor. Effect sizes were calculated using generalized eta-squared (η_{G}^{2}) (Bakeman, 2005; Olejnik & Algina, 2003). Follow up comparisons were done using Tukey's HSD. All analyses used a significance level of $\alpha = .05$.

4.3 Results

4.3.1 In-game performance

The accuracy² of all myogaming groups and the controls can be seen in Figure 4.5.



Fig. 4.5. Mean accuracy (and standard error of the mean) on the pretest, the four training sessions and the posttest for all groups. Note that all groups were tested and trained on a different myogame with the exception of the Control group that was tested on the Adaptive Catching game. As can be seen from the pretest accuracy, level 1 of the Free Catching and Interceptive Catching game was comparatively easy and participants mostly trained their myogaming skills by playing level 2 (and 3). To characterize the learning process across sessions therefore, the mean accuracy on the first performance of playing level 2 for all myogaming groups is shown for each session.

As can be seen in Figure 4.5 all groups improved their in-game performance across training sessions. To quantify this improvement, we analyzed the change in in-game accuracy from pretest to posttest. However, this measure is based on three different myogames and visual inspection of the data suggests that there were initial differences in difficulty at the pretest. In order to determine differences in initial scores, we therefore compared the pretest level of accuracy for each group. An ANOVA on the pretest accuracy with group as a between subjects factor revealed a significant difference between groups ($F(3,37) = 17.16, p < .001, \eta_G^2 = .58$). As this difference in pretest performance might have affected the performance in

²All analyses on the accuracy were repeated with the accuracy transformed to z-scores. However, this did not affect any of the results. the posttest, analyzing the change in accuracy from pre- to posttest only therefore does not suffice to reveal training effects.

To look into the training effects we therefore performed an ANCOVA on the pre-to-posttest difference in accuracy, with the pretest accuracy as a covariate and group as between subjects factor. The change in accuracy after the training period for all groups, corrected for the pretest values, can be seen in Figure 4.6.



Fig. 4.6. Mean difference in accuracy (and standard error of the mean) from pretest to posttest for all groups, corrected for the pretest accuracy. All groups improved significantly compared to the control group.

The analysis revealed a significant effect for the pretest (F(1, 36) = 29.90, p < .001, $\eta_G^2 = .29$) and for Group (F(3, 36) = 11.96, p < .001, $\eta_G^2 = .35$). Post hoc comparisons of the groups showed that all groups improved significantly over Controls (p < .05). Moreover, after correcting for the pretest scores, the Free Catching group improved significantly over all other groups (p < .05). Together these findings show that training a myogame resulted in better performance within that game, also when correcting for differences in initial performance. Moreover, in-game learning was highest for the Free Catching group that also had the highest level of initial performance. Having established these in-game learning effects, we can now move to our main hypotheses and determine whether these learning effects transfer to performance on a prosthesis task.

4.3.2 Transfer to prosthesis use

Adaptation to cylinder size

Typical examples of individual trials of the hand aperture for each group are shown in Figure 4.7. Note that in the majority of trials, the participants tend to fully open the myoelectric hand, regardless of the size of the cylinder.



Fig. 4.7. Representative examples of the hand aperture during the posttest for each group. The time (s) is shown on the x-axis, the normalized aperture on the y-axis. Each black line represents a single trial of grasping a small cylinder, the dark grey lines represent a trial grasping the medium cylinder and the light grey lines represent a trial grasping the large cylinder. For each group the examples were taken from the same participant. The four round markers on each line represent (from left to right) the start of the opening, the end of the opening, the start of the closing and the end of the closing of the hand.

First, we looked into changes in the hand's opening velocity. The mean opening velocity on both the pretest and posttest for all groups is shown in Figure 4.8.

An ANOVA comparing the mean opening velocity on the pretest showed no significant differences between groups. Therefore, a univariate ANOVA



Fig. 4.8. Mean opening velocity (and standard error of the mean) from pretest to posttest for all groups. For each group, the three cylinders are shown on the x-axis, the mean velocity on the y-axis. The velocity is expressed in normalized units per second. When opening the hand at 2 units per second the hand reaches its maximum opening in 0.5 seconds.

on the change in mean opening velocity from pretest to posttest was performed with Cylinder (small, medium, large) as within subjects factor and Group (Adaptive Catching, Free Catching, Intercept, Control) as between subjects factor. The analysis revealed a significant effect for group $(F(3,37) = 4.05, p = .01, \eta_G^2 = .24)$. There were no other significant main or interaction effects. Post hoc comparison of the group effects revealed that the Adaptive Catching group decreased the mean opening velocity significantly in comparison to all others groups (p < .05), while there were no differences among the other groups.

To reveal task-specific changes in prosthesis control, we looked at the maximum hand opening. The maximum aperture on the pretest and the posttest for all groups on all cylinders is shown in Fig 9.



Fig. 4.9. Mean maximum aperture (and standard error of the mean) on the pretest and posttest for all groups. For each group, the three cylinders are shown on the x-axis, the normalized aperture on the y-axis.

Visual inspection of the data suggests some initial differences between the Adaptive Catching group and the Free Catching group. An ANOVA comparing the maximum aperture on the pretest revealed no significant differences between groups. That is, taking the Interceptive Catching group and the Control group into account, differences in pretest performance do not hold statistically.

A univariate ANOVA on the change in maximum aperture with Cylinder (small, medium, large) as within subjects factor and Group (Adaptive Catching, Free Catching, Intercept, Control) as between subjects factor revealed a significant effect for group ($F(3, 37) = 3.34, p = .03, \eta_G^2 = .21$). There was also a significant interaction effect Cylinder x Group (F(4.83, 59.55) = $3.45, p = .009, \eta_G^2 = .21$). Post hoc comparison of the group effects revealed that the Adaptive Catching group decreased the size of the maximum aperture significantly in comparison to all others groups (p < .05). There were no differences among the other groups. Thus there appeared to be a significant improvement in the Adaptive Catching group in adjusting the aperture to the cylinders. The Cylinder x Group interaction however, suggests the Adaptive Catching group is not just decreasing the maximum aperture, but they might be decreasing the aperture relative to the size of the different cylinders. Before drawing any conclusions about these effects however, we need to take a closer look at the change in the maximum aperture during testing.

In the foregoing the trials performed in the pretest and posttest were treated as a static block. However, during testing participants could have increased or decreased the aperture over time, each implying different learning effects. If they increased the maximum aperture, this may mean that the overall improvement in aperture adjustment, learned from training with the myogame, disappeared as the prosthesis task did not require it. On the other hand, if the aperture decreased over time, i.e. the adjustment improved within the posttest, this may imply that participants increasingly incorporated their gaming-experience into the prosthetic task. To establish which of these processes are at work, the maximum aperture of the myoelectric hand on all successive trials for each testing session is depicted in Figure 4.10. In the Adaptive Catching group, there was little adaptation across trials in the pretest, but the posttest showed a stably increasing difference in aperture between cylinders across trials. The Free Catching group appeared to adjust the aperture to the size of the small cylinder in both pre- and posttest. However, the mean maximum aperture is slightly higher on the posttest and the decrease across trials appears

equal in both sessions. Both the Intercept Catching group and the Controls did not show any systematic change in adjusting the aperture over time.

To quantify the change in maximum aperture over the posttest a regression line was fitted to the maximum aperture on the consecutive trials shown in Figure 4.10. This was done for the posttest for each cylinder and for each individual participant. The slopes of these lines are presented in Table 4.1.

Tab. 4.1. Mean (SEM) of the slope of the change in accuracy during the posttest for all groups and all cylinders. For presentation purposes, the slope is multiplied by 100. Note that as the scaling of the trials within the posttest and time intervals of the x-axis of Figure 4.10 are arbitrary, only the difference between values of the slopes are relevant here.

Group	Cylinder	Slope
Adaptive Catching	Small	-5.14 (1.41)
	Medium	-0.29 (0.94)
	Large	0.26 (041)
Free Catching	Small	-0.54 (1.54)
	Medium	-1.01 (1.05)
	Large	-0.35 (0.47)
Interceptive Catching	Small	0.12 (1.54)
	Medium	-1.41 (1.05)
	Large	-0.10 (0.47)
Control	Small	-1.55 (1.63)
	Medium	-0.45 (1.10)
	Large	-0.74 (0.50)

A univariate ANOVA on the slope of this regression line with Cylinder (small, medium, large) as within subjects factor and Group (Interceptive, Free, Adaptive, Control) as between subjects factor revealed a significant interaction effect Cylinder x Group ($F(4.79, 59.17) = 2.95, p = .020, \eta_G^2 = .19$). There were no other significant effects.

Contrasting the maximum aperture in the final trial of the small and medium cylinder, and of the medium and large cylinder for each group, revealed that the Adaptive Catching group significantly differed in the maximum aperture for each cylinder (p's < .05). In the Free Catching and Interceptive Catching groups, only the difference between the medium and large cylinder reached significance (p's < .05). There were no differences between cylinders for the Control group. Taken together these analyses confirm our hypothesis that the Adaptive Catching group transferred their



Fig. 4.10. Mean maximum aperture (and standard error of the mean) for all trials within the pretest and posttest for all groups. The black lines represent the small cylinder, the dark grey lines represent the medium cylinder and the light grey lines represent the large cylinder. For both the pre- and posttest, the five trials of each cylinder are ordered on the x-axis, the normalized aperture is on the y-axis.

ability to adjust the hand aperture to the size of the objects that needed to be grasped and that the Interceptive Catching group did not improve over controls. Contrary to our expectations, the Free Catching group however also did not appear to have improved over controls.

Adaptation to compressibility

To qualify the adaptation of the prosthesis hand to the compressibility of the objects, we first looked at the mean closing velocity of the hand (see Figure 4.11).



Fig. 4.11. Mean closing velocity (and standard error of the mean) from pretest to posttest for all groups. For each group, the three compressible objects are shown on the x-axis, the mean velocity on the y-axis. The velocity is expressed in normalized units per second. When closing the hand at 2 units per second a fully opened hand closes in 0.5 seconds.

An ANOVA comparing the mean closing velocity on the pretest showed no significant differences between groups. A univariate ANOVA on the change in mean closing velocity from pretest to posttest with Object (low, moderate, high) as within subjects factor and Group (Adaptive Catching, Free Catching, Intercept, Control) did not reveal any significant mean or interaction effects.

The amount of compression on pretest and posttest for all groups on all objects is shown in Figure 4.12. An ANOVA comparing the compression on the pretest revealed no significant differences between groups.

A univariate ANOVA on the change in compression with Object (low, moderate, high) as within subjects factor and Group (Adaptive Catching, Free Catching, Interceptive Catching, Control) as between subjects factor revealed a significant effect for group ($F(3,37) = 4.20, p < .012, \eta_G^2 = .25$). There were no other significant main effects, nor were there any significant



Fig. 4.12. Mean amount of compression (and standard error of the mean) in cm from pretest to posttest for all groups. For each group, the three compressible objects are shown on the x-axis, the amount of compression on the y-axis.

interaction effects. Post hoc comparison of the group effects revealed that the Adaptive Catching group decreased the amount of compression exerted on the objects significantly in comparison to others groups (p < .05). There were no differences among the other groups. In sum, these results confirm our hypothesis that the Adaptive Catching group transferred an ability to compress objects less while the Interceptive Catching group did not improve over controls. Contrary to our hypothesis the Free Catching group did not appear to have improved over controls.

4.4 Discussion

This study is the first to demonstrate transfer effects from a myogame to a myoelectric prosthesis task. First, it showed in-game improvement over controls so that changes in prosthesis-use can be attributed to motor learning effects. Subsequently, the study fleshed out the contribution of ADL-specific feedback and task-similarity on transfer of myoelectric skills. In accordance with our hypothesis, training the Interceptive Catching game, which had no task similarity except its EMG control scheme, had no effect on our prosthesis task beyond controls. The Adaptive Catching and the Free Catching group also used this EMG control scheme but moreover simulated a basic grasping action. Despite simulating the same grasping action however, only the Adaptive Catching game, that made ADL-relevant information matter to goal attainment in the game, was able to elicit transfer to our prosthesis task.

Our results thus suggest that transfer effects following myogame training are not a matter of course. Although all our myogames evoked in-game

learning beyond controls, only the Adaptive Catching game was able to improve prosthesis use. Somewhat surprisingly, the Free Catching game did not elicit any transfer—despite using the same basic task as both the Adaptive Catching game and the prosthesis task. However, when grasping with a prosthesis, as well as during the Free Catching game, several strategies are available to complete the task. Apart from scaling the hand to the size of the objects—as typically found in intact hands participants could use a simple on/off strategy as neither opening the hand very far nor closing it too fast had any adverse effect on their goal attainment. Indeed, as can be seen in Figure 4.8 and Figure 4.9, in as far as any change was elicited from pre- to posttest, both the Free Catching and the Intercept group seemed to tend towards transferring this crude but effective strategy.

By contrast, in controlling intact hands the most effective strategy for grasping is to scale the hand aperture to the size of the object to be grasped (Castiello, 2005; Meulenbroek et al., 2001; Smeets & Brenner, 1999). This is also found in skilled prosthesis users (Bouwsema et al., 2010b). Research has shown that such scaling of the hand is achieved by learning to perceive the size of graspable objects in terms of the aperture of one's hand (Linkenauger, Witt, & Proffitt, 2011). In order to pick up on this "body-scaled" information for grasping, in the Adaptive Catching game we made the relation between object size and the aperture of the grabber matter to attaining the goal. Similarly, by making the virtual objects fragile so that they would break if the grabber closed too quickly we again made sure that the strategy used to close the grabber mattered to goal attainment. In both cases, this resulted in transfer of the skill to the prosthesis task.

The transfer effect of the Adaptive Catching game on scaling the hand aperture was not a matter of failing to explore beyond the constraints previously imposed by the game. Rather, as Figure 4.10 showed, the opposite seems to hold. In the absence of the feedback provided by the game, the participants start out opening the hand too widely in the posttest. However, rather than thus continuing an on/off strategy, the participants in the Adaptive Catching group progressively started to scale the aperture to the object size. Research has shown that providing augmented feedback can cause learners to rely on this feedback up to the point of performing poorly in its absence (Goodman, Wood, & Hendrickx, 2004). In the short training period of our study, our participants did not show this reliance. Rather, they showed an ability to start adjusting the prosthesis hand to the size of the object in the absence of any augmentation of this information.

Our results further suggest when scaling the prosthesis hand to an object's size or timing the hand to stop closing as a compressible object is grasped, the hand's opening or closing velocity may not be contributing to this adjustment directly. Although all our myogaming groups had the possibility of learning to control the velocity of their grabber or catcher, only the Adaptive Catching group showed improvement over controls after training. Moreover, as we did not find an interaction effect with the differently sized cylinders the effect of the myogame training on the mean opening speed was a relatively poor characterization of the changes in performance. The Group x Cylinder effects on the MHO and the change in MHO across the posttest by contrast suggest that our training elicited task-specific effects on the ability to control the relative aperture of the hand. Similarly and surprisingly, when grasping a compressible object, we did not find changes in the closing velocity while we did find changes in the resulting amount of compression. This may suggest that controlling the timing of the end of closing the hand, rather than the speed of closing is important to such a grasping task. Despite looking into many other general outcome measures (e.g. peak velocity, duration of the MHO) our transfer effects seem to be captured best by task-oriented measures of performance.

Most myogames developed so far have not yet been tested for transfer to prosthesis use (Armiger & Vogelstein, 2008; Lovely et al., 1990; Ma et al., 2010; Oppenheim et al., 2010). Our results strongly suggest that research should start prioritizing transfer. So far, myogames focus on offering fun and motivating tasks that are far removed from prosthesis use. It seems tacitly assumed that using the same musculature as in a prosthesis task so that the gaming task can focus on game play (Dupont & Morin, 1994; Gordon & Ferris, 2004) or using the same mapping between EMG signals and end-effector (Ison, Antuvan, & Artemiadis, 2014) is sufficient for promoting myoelectric skills in ADL. However, our results imply that although these aspects may be necessary for transfer, they are certainly not sufficient. All our myogames used the same proportional relation of the EMG signal to the speed of the end-effector and all used the same musculature. Moreover, we approximated the EMG-interface of our prosthetic device as closely as possible. Based on measurements of both the EMG signals to our prosthesis simulator and its subsequent movements, we estimated the delay of our myoelectric hand and incorporated that into our myogames, and we notably trained the participants at a range of their MVC close to that of the prosthesis (cf. Anderson & Bischof, 2012; Pistohl et al., 2013; Radhakrishnan et al., 2008). Despite all these precautions, the only myogame that led to improvement in prosthesis skills was the game that incorporated ADL-task relevant feedback. It would be interesting, both clinically and theoretically, to determine what constraints muscular and EMG features pose on transfer effects.

We believe maximizing transfer will be enabled by adopting a task-oriented perspective. This perspective implies that both the ADL task as well as the gaming task should be viewed in terms of goal-attainment. Specifically, before designing a serious game the relation between the goal of the ADL task and the actions available to accomplish this goal, need to be established. Because a serious game cannot simulate ADL completely (nor can any other virtual reality application for that matter, see Lathan, Tracey, Sebrechts, Clawson, & Higgins, 2002) a serious game should focus on at least simulating, and perhaps augmenting, information that specifies the relation between the goal of ADL and the actions of the player that allows for adaptively coordinating those actions. Importantly, the task-oriented perspective suggests task-specificity has another clinically important consequence.

Learning a specific task means that over time a learner progressively notices differences in tasks (J. J. Gibson & E. J. Gibson, 1955; Jacobs & Michaels, 2007). That is, one learns to differentiate tasks on the basis of the actions that are available and that enable goal-attainment. For example, although our Free Catching game allowed for basic grasping movements similar to a prosthesis task, the fact that the movement was utilized in a (time-constrained) catching task, can make the on/off strategy more effective. Thus, over time, the grasping with a prosthesis and the Free Catching game could afford different actions to a participant. In order to make sure that, despite this tendency for learners to capitalize on differences in tasks, a serious game is effective in eliciting transfer, it needs to add ADL-relevant feedback to the game. Crucially, the task-

oriented approach is therefore task-oriented in two ways: first both the game and the ADL task need to be aligned in terms of the available actions and goals. Second, any augmented information added to the game should not only bear on ADL performance but should moreover be implemented in such a way that it matters to in-game goal-attainment. Thus a learning, differentiating, player may benefit in ADL from training a serious game.

In this study we used able bodied participants controlling a simulator rather than a patient group using actual prostheses. Generalizations to patient groups should therefore be handled with caution. It has recently been shown that transhumeral amputees may be less accurate when myoelectrically controlling a cursor than able bodied participants (Johnson, Kording, Hargrove, & Sensinger, 2015). It may be interesting to determine to what extent task-oriented myogames will be able to influence such effects. Having finally elicited transfer in able bodied participants, it is time to start testing task-oriented myogames in patient groups in order to determine their training benefits and transfer effect.

4.5 Conclusion

This study demonstrated that using a task-oriented myogame that augmented ADL-relevant features results in transfer to a myoelectric prosthesis task. We showed that neither using the musculature nor using the EMG signals needed in prosthesis use is by themselves sufficient for transfer to occur. Rather our results suggest that similarity in goal-relevant features across tasks is necessary for transfer to occur. The study therefore emphasizes the need to prioritize transfer and take task-oriented considerations into account when developing a myogame.

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The emergence of an action system

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Abstract

This exploratory study examined the role of gaze in the emergence of a new action system for tool making. We designed an experiment in which a novel tool had to be created. Participants had to perform a task that required them to construct a tool for scooping, prodding, or cutting from a set of objects. We monitored gaze and the objects manipulated over learning. Performance got more efficient across Trials A through C: trial duration as well as the number of fixations decreased, whereas the goal-directedness of gaze (i.e., the percentage of fixations directed at the objects ultimately used in tool construction) increased. Trial A had only a few goal-directed fixations before trial-and-error constructing commenced. In Trial B the goal-directedness also started low but increased sharply during subsequent exploration. In Trial C, gaze was highly goal directed from the start and construction started immediately. This demonstrated that early in learning gaze is part of exploratory and performatory acts over a short time span, whereas later in learning gaze served a behavioral unit of a longer timescale. Gaze therefore gets organized to accommodate a new functional unit of action.

Hence, a whole series of fixations can be a single act of attention.

— James Gibson (1979, p. 213)

5.1 Introduction

Human evolution progressed, in part, by the human ability to create and use tools (Bril, Rein, Nonaka, Wenban-Smith, & Dietrich, 2010; Stout, 2002). This ability developed out of the need to attain difficult-to-get resources (Reed, 1996), such as getting the nutritious content from a nut by using a hammer and an anvil (Goren-Inbar, Sharon, Melamed, & Kislev, 2002) or using a hand ax to get both the meat and the valuable skin from a caught animal (Ambrose, 2001). From an ecological perspective, the ability to use tools is reflected in humans having developed specific 'action systems,' which are the focus of this chapter.

An action system is a functional unit, organized to perform a certain task (Reed, 1982). As a functional unit, an action system is organized by information specifying the affordance of the task. The action system is itself also composed of information-motor couplings at a smaller scale (cf. Bootsma, 1998). Before an action system for tool making can be organized, the information for making the tool is discovered by exploring the environment's resources (see J. J. Gibson, 1979, p. 198). The emergence of an action system for tool making is therefore characterized by an ongoing reorganization of established information-motor couplings as information for novel affordances becomes available during exploration (Bongers, 2001; Reed, 1996; A. W. Smitsman & Bongers, 2003). The current chapter aims to determine what this process of reorganization might look like by focusing on the role of gaze.

To perform a novel task, a functionally adapted action system that fits the agent to the available resources has to develop. Therefore, previously acquired action systems must be deployed and reassembled to fit the new behavioral needs. Previously acquired action systems have both an exploratory role, that is, they are geared to pick up information for the affordances in the environment, and a performatory role, by altering the environment and giving rise to new affordances and informational constraints (Reed, 1996). Over time, the information- motor couplings of these exploratory and performatory actions, constrained by newly discovered task-specific information, converge to a useful organization that constitutes a new functional unit that is tailored to the task. In other words, an action system has formed. In short, exploratory and performatory actions provide the basis on which new action systems can emerge. This chapter addresses the role of gaze in the emergence of an action system for tool making. Gaze is an important part of many exploratory activities (e.g. Itti & Koch, 2001; Yarbus, 1967). It provides the agent with the opportunity to sample the optic array for information to discover or perceive affordances (J. J. Gibson, 1966, 1979). Moreover, gaze helps to pick up information contained in the array to contribute crucially to performatory acts (Land, Mennie, & Rusted, 1999; Pelz & Canosa, 2001; Riek, Tresilian, Mon-Williams, Coppard, & Carson, 2003). As an embedded mechanism in action systems, gaze is controlled by information and this information organizes gaze according to the scale of behavior that is functional to the task at hand (Reed, 1996). As the action system forms a new functional unit at its own spatiotemporal scale, we hypothesized that gaze will reflect the emergence of an action system during learning a novel task.

In this study we were interested in how a new functional system for tool making evolves out of the reorganization of existing exploratory and performatory acts. Specifically, we were interested in whether gaze reflects the formation of such a functional unit of action. Despite the importance of gaze in exploratory and performatory activities and the importance of novel tool creation in human evolution, to our knowledge, gaze has never been used to study tool making in humans before and its role in the emergence of an action system has not been addressed earlier.

In our experimental task we compared the novel creation of a tool with the creation of the same tool after familiarization with the task. Participants were presented with several objects that could be used to create different tools and they were given a functional task (e.g., "Can you create a tool and use it to scoop this rice?") so as to elicit natural construction behavior. We investigated how the action system for tool making emerged over time. We aimed to discern phases that should be present in the data. In the first creation of a novel tool, we expected participants to take their time to look at the scene; they should explore the scene by fixating on

many different objects before starting to manipulate them. This behavior probably consists mostly of exploratory acts, with low task relevance of the objects of fixation. At some point in time, though, participants should start to manually explore the scene as well to discover and change available affordances, for example, using exploratory actions such as touching or rotating objects or by performatory acts that relate and attach multiple objects to each other. After this manual exploration, participants should commence combining different objects with which the final tool is actually constructed. This would be reflected by an increasing goal relevance of the points of gaze (i.e., on objects used for immediate tool construction) over time. Moreover, over trials, tools should be constructed faster. As the action system of tool making evolves over trials, the exploratory first phase may decrease or become highly goal directed, whereas construction immediately follows this phase because the need for allowing manual exploration diminishes. Thus the duration of these phases, and the characteristics of the gaze orientation within them (i.e., duration, goal relevance), were used to gauge the setting up of an action system.

5.2 Methods

5.2.1 Participants

In this experiment, 9 participants (2 males, 7 females, mean age 26.3 years, *SD* 3.2 years) participated. All participants had normal vision or corrected to normal vision and reported no problems with making movements with the arms and hands. All participants gave their informed consent preceding the experiment and were paid a small fee following the completion of the experiment.

Our behavioral analyses of the tool-making tasks were based on data from all 9 participants. However, the analyses of the change in gaze were based on 5 of these participants. This was due to the unconstrained nature of our experiment. Participants were not constrained in time and did not receive additional instructions or suggestions of how to solve the task; they did all tasks at their own pace and worked the way they seemed fit, which resulted in some variation in their behavior during the task. For instance, some participants bent over the table to check the objects, whereas others

picked up the objects and held them close to their eyes in order to see everything. Some of these behaviors impeded our measurements; the range of the head-mounted optics is limited and its accuracy close up is low, hence we could not analyze all data. Moreover, as participants constantly needed to look down at the table, eyelashes sometimes created interference with the reflection of the pupil, which hindered establishing the point of gaze.

5.2.2 Materials

Participants needed to create novel tools from 18 different objects presented in front of them. Objects were distributed across a space of 0.2 x 0.45 m on a piece of cardboard on a tabletop. The total work space was defined by the size of the cardboard, which was 0.5 x 0.7 m. The objects are shown in the left column of Figure 2.1 (A–L). The objects were all custom made and manufactured out of aluminum, with the exception of two steel rings and wire (Figure 2.1, I–J) and a rubber band (Figure 2.1, G–H). The objects were all between 1 and 5 cm in size except for the "handles" (Figure 2.1, A, C, E, G, K); those had a length of about 10 cm. The six tools that could be constructed from these objects can be seen in the right column of Figure 2.1; B and D are the spoons, F and H the forks, and J and L the knives.

All tools could be constructed easily. It was never required to apply much force to create the tool and thus never needed objects to be bent or broken. For most tools the constituting parts could be attached in only one way and in some cases a certain sequence to construct the tool had to be followed to get the intended tool (i.e., the tools depicted in the right column of Figure 2.1).

5.2.3 Apparatus

The point of gaze of the participants was determined using an Applied Science Laboratories eye tracker, model 501 head-mounted camera with infrared reflection (Applied Science Laboratories, Bedford, MA). The eye tracker measured point of gaze with respect to the head-mounted camera (factory specification: accuracy 0.5 deg; 0.7 cm on the tabletop, resolution 1.0 deg).

The point of gaze was sampled at 50 Hz and displayed as a crosshair superimposed on the camera image. This image was recorded using a digital video recorder.

Participants were calibrated before each session and accuracy was checked on the basis of reference points on the video images after each trial. Calibration was subsequently repeated between trials if necessary. A picture of the setup during the performance of a task can be seen in Figure 2.2.

5.2.4 Design

All tool pieces were presented on a tabletop. Participants sat at the table at a comfortable position (see Figure 2.2). The positions of the tool pieces were always identical for each trial and every participant, but their location on the table was random, as can be seen in Figure 2.2.

The participants needed to build six different tools: two types of tools for three different functions: (a) scoop rice from a bowl (scooping), (b) prick a polystyrene cube (prodding), and (c) cut a blue bar of clay (cutting). After having built all six tools in the familiarization session, the six tasks were repeated once as a testing session. Every experiment therefore consisted of 12 task performances altogether. A schematic representation of the experiment is shown in Figure 2.3.

All tools were built out of three parts and no part needed to be used twice (although the latter was not pointed out to participants). The goal of the task was always functionally defined. The bowls, the pieces of polystyrene foam, and the blue clay that needed to be used to complete the respective task were always present in plain sight and within arm's reach. After completion of each task, the pieces were placed back in their original position by the experimenter.

The tasks of the familiarization session were presented in random order across participants but for each participant the familiarization session



Fig. 5.1. All tools that were constructed. The left column shows the three objects that needed to be used to create the corresponding tools depicted in the right column. Pictures B and D are the spoons for scooping, F and H the forks for prodding, and J and L the knives for cutting.


Fig. 5.2. The layout of the tabletop display and the Applied Science Laboratories eye tracker can be seen while a participant is creating a tool to scoop rice.

was repeated once in the same order in the testing session. The total experiment commonly lasted about 45 min.

5.2.5 Procedure

Participants were asked to sit at the table with the objects in front of them. As long as the task did not start, the tabletop was occluded from sight by a screen. The screen that occluded the tabletop also contained the target

familiarization session			break		testing session						
scooping	scooping prodding pi	rodding	cutting	cutting		scooping	scooping	prodding	prodding	cutting	cutting
trial A	trial B					trial C					
time											

Fig. 5.3. The experiment consisted of two sessions: a familiarization session and a testing session. In each session all six tools were built once. The tasks of the familiarization session (creating a spoon, a fork, or a knife) were presented in random order, but they always occurred twice in succession. After a short break, the six tasks were repeated once in the same order in the testing session. Note that for the analysis on the changes in gaze only the first task in the familiarization session (Trial A), the third task in the familiarization session (Trial B), and the first task in the testing session (Trial C) were used.

points for calibration. Prior to commencing the first task, participants put the eye tracker with head-mounted camera on. This apparatus was lightweight and participants remained unconstrained in their movements (see Figure 2.2). The eye tracker was subsequently calibrated using a nine-point calibration.

After calibration participants were asked to construct a tool consisting of three objects from those in front of them (still behind the screen). Subsequently the recordings were started and the screen was removed. Participants could then start the task freely and entirely at their own pace. It is important to note that at no point in the study were the completed tools, or pictures of the completed tools, presented to participants, that is, participants had to construct tools at their own insight.

After completion of one of the tasks, the recordings were stopped, the tabletop was occluded from the participant, the created tool was taken apart, and the pieces were placed back into their original position. Participants were offered a break and if necessary the setup was checked and recalibrated.

Following the short break and/or recalibration, participants were then asked to perform the next task. If the task was the same as the former task, the instruction was to construct a different tool than the one that had been constructed.

5.2.6 Data Analysis

Point of gaze and the objects of action of both the left hand and right hand were identified using Anvil annotation software (www.anvil-software.de), a software package used to annotate behavioral data.

For each frame, point of gaze was considered directed at an object if the crosshair was stable relative to, and directed at, an object in the scene. The objects of action for the left and right hand were considered all instances in which the left or right hand clearly made contact with an object in the scene.

During each trial three separate phases were identified. At first, participants took their time to look at the environment (i.e., the objects from which the tools have to be constructed); they perused the environment by fixating on many different objects. It is important to note that this is a purely visual phase; the perusal is done before starting to manipulate the environment. This first phase was defined as the time taken from the first point of gaze directed at the environment until the first moment (video frame) an object is manually handled and hence is called the "visual phase." After this visual phase there was a phase in which manual exploratory object manipulation was alternated with visual exploring of the environment. This second phase is called the "manual and visual exploration phase." This phase was defined as the time from the end of the visual phase until the point at which construction began. Construction started with the last continued series of manipulation of at least two of the final three objects that were used for the construction of the resulting tool. A continued series of manipulations meant that there were no video frames in which the identified objects were put down or were no longer combined with each other. This continued series of manipulation is the third and final phase of each trial and is called the "construction phase."

Prior to statistical analysis two behavioral patterns were discerned: guiding and exploration behavior. We defined guiding fixations as all points of gaze where the gaze is directed at the same object as the hand(s) are at that time or following the next 100 ms. The remaining fixations were considered exploration fixations. Finally, working backward from the end of the trial, a part of the fixations was classified as goal-directed fixations, which were defined as the fixations on the objects that are also used in the final construction of the tool. For all within-subjects effects univariate ANOVAs with repeated measures were performed. If sphericity was violated Greenhouse-Geisser corrections were used. Because percentages, such as the percentage of goal-directed fixations, are bounded by 0 and 100, they are not considered normally distributed. Prior to conducting our analyses we therefore transformed all percentages using an arcsine transform (Mosteller & Youtz, 1961). Effect sizes were calculated using generalized eta-squared (η_G^2) (Bakeman, 2005; Olejnik & Algina, 2003). Follow-up comparisons were done using a one-tailed t test. All analyses used a significance level of $\alpha = .05$.

5.3 Results and discussion

Preliminary analyses of gaze behavior showed that the change in behavior was quite dramatic and evolved rather rapidly over learning. In the testing session performance became highly similar. We therefore limit our presentation of the data to the six trials of the familiarization session and the first two trials of the testing session. The three different phases (the visual phase, the manual and visual exploration phase, and the construction phase) were established for all these eight trials. The mean duration of each task decreased over these eight trials from 159.04 (21.93) [mean (SEM)] s to 18.92 (3.79) s. This decrease was largely accounted for by a decrease in the duration of the manual and visual exploration phase across trials (see Figure 2.4). There is a significant drop in duration of both the visual phase ($F(7, 28) = 7.93, p < .001, \eta_G^2 = .66$) and the manual and visual exploration phase ($F(7, 28) = 9.40, p < .001, \eta_G^2 = .70$) across trials. The duration of the construction phase did not change significantly ($F(7, 28) = 2.01, p = .077, \eta_G^2 = .34$).

As can be seen from Figure 2.4, the fourth trial deviated from the trend followed over the other trials. At Trial 4, 3 of the 7 participants were aiming to create a tool for cutting a piece of clay for the second time, and these 3 participants took the longest to complete the task. Although tasks were frequently accomplished using other combinations of objects from those shown in Figure 2.1, this was especially true for creating a tool for cutting. Of the 18 trials in which the task was to cut a piece of clay, the task was accomplished eight times using a "fork" (Figure 2.1H) or by combining other available objects, such as attaching the wire (Figure 2.1I) to the handles in Figure 2.1G. In Trial 4, this behavior accounted for all instances of creating a tool for cutting. Obviously, the task of creating a tool for cutting the other tools. Hence, creating the cutting tool called for prolonged manual exploration after a short phase of visual exploration (the visual phase).

In general, however, the global behavior during the task showed a gradual decline in trial duration as a result of a decrease in initial visual exploration and a decrease in the manual and visual exploration phase. On the basis of these analyses, as well as based on preliminary analyses of gaze behavior,

we therefore decided to limit our analysis of gaze behavior to three trials that best capture the changing organization of gaze: the first task in the familiarization session (Trial 1), the third task in the familiarization session (Trial 3), and the first task in the testing session (Trial 7; henceforth "Trial A," "Trial B," and "Trial C"; see Figure 2.3).

5.3.1 Characterization of Gaze Across Trials

To characterize the changes in gaze behavior over learning, we analyzed the durations of the point of gaze per object across Trial A, Trial B, and Trial C (see Figure 2.3). Figure 2.5 shows the evolution of the duration of the point of gaze per object through the three trials (rows) for 2 representative participants (columns).

All bars in Figure 2.5 represent fixations during the session; the height of the bars (z-axis) represent the duration of that fixation. The total length of the session can thus be found in these figures by adding all heights of the fixations, but note that fixations longer than 10 s were cut off for presentation. Comparing the sum of all fixations of the upper figures in Figure 2.5 with the lower figures of Figure 2.5 should make clear that Trial A took more time than Trial C did.

In Figure 2.5, the y-axis represents the time within the session. The bars on the x-axis represent a single object and keep the same gray color for each object used. Every tool was made up of three objects. The six objects making up the two versions of each tool function (scooping, cutting, and prodding) are ordered according to function (x-axis). Note that in each column the upper and lower figures in Figure 2.5 end with three bars of similar color (at y-axis is 100%); the same objects were fixated in the final construction stages because the same tool was made. The figures in the middle row in Figure 2.5 end at different locations on the x-axis, showing that the tool that was made in Trial B was different from that of Trials A and C.

In general the first trial, Trial A, (Figure 2.5, upper row) was characterized by many short fixations, directed on both task-relevant and irrelevant objects, whereas Trial C (Figure 2.5, lower row) showed most fixations on the final goal objects and hardly any fixations on goal-irrelevant objects.



Fig. 5.4. Duration of all three phases within the first eight trials. The upper panel shows the visual phase, the middle panel shows the manual and visual exploration phase, and the lower panel shows the construction phase. The x-axes list the eight trials. The y-axes represent the duration of each phase. Note that the scales of the y-axes are not the same over subplots. Every trial contained 9 participants (except Trials 2, 5, and 8: n = 8 and Trials 4 and 6: n = 7). The mean and standard error of the mean for each trial is represented by a black line with error bars. Each individual participant is represented by a gray line. The markers denote the different tasks that needed to be accomplished. Note that the number of occurrences of the different tasks was approximately equal in all trials. As can be seen in this figure, there is a gradual decrease in the duration of the visual phase and in the duration of the manual and visual exploration phase until the latter is absent in the final trials. Note the exception to this pattern in Trial 4, in which the three longest trials all involved creating a knife (see text for details).



Fig. 5.5. This shows the point of gaze at the first (Trial A), third (Trial B) and seventh trial (Trial C) for two participants. Each column shows the three trials for a participant. The first (upper) row shows trial A, the second (middle) shows trial B and the third (lower) row shows trial C. The figures show the objects of gaze (18 objects for tool making, plus the goal object, e.g., the bowls of rice, the table, and the environment outside the task) on the x-axis. The y-axis represents the session duration (0-100%) (the total duration of the trial is depicted), the z-axis denotes the duration of the fixations (>10 seconds are cut off). Comparing the upper and lower figures, we can clearly see that participants created the same tool in trial A and trial C as the bars at the end of both sessions are in the same row (same gray scale); the participant in the left column created a prodding tool, the participant in the right column created a cutting tool. Note that the tool that needed to be created in trial B (middle figures) was of a different type. See text for further explanation.

The fixations in Trial B (Figure 2.5, middle) showed behavior somewhere in between, generally having fewer short fixations and more fixations aimed at goal-relevant objects than Trial A, however, without achieving the high speed and high goal relevance in gaze direction we observed in Trial C. This pattern based on perusing the data is corroborated by statistical analyses. Before we examine this pattern in more detail we briefly describe the duration of the fixations across trials.

The figures in the upper row of Figure 2.5 show that in the first session, intervals of large numbers of short fixations were alternated with longer fixation periods. These long fixations usually represented fixations to facilitate the guiding of the hands during manipulations to inspect the objects. The distribution of the duration of all fixations did not differ much between the three sessions. The mode of fixation-durations in Trial A, Trial B, and Trial C is 0.12 s, 0.14 s, and 0.12 s, respectively. All trials were characterized by having a large number of short fixations. Trial A had 87.7%, Trial B had 86.7%, and Trial C had 79.5% fixations shorter than 1 s.

To examine whether the apparent differences between Trials A, B, and C exhibited in Figure 2.5 holds statistically, we analyzed several measures that represent gazing behavior with a repeated measures ANOVA, with trial (Trial A, Trial B, Trial C) as within-subjects variable. The results are presented in Table 2.1. The duration of the session became smaller from Trial A through Trial C. This decrease in the time in which the task was solved was accompanied by fewer fixations on different objects. So, in the first construction of a tool the number of fixations was highest and the number of different objects fixated was also highest, whereas these numbers decreased as a function of the trials that were performed. Moreover these fixations in Trial A were less directed at objects with which the final tool was constructed because the percentage of goal-relevant fixations (point of gaze directed at the objects that were used to construct the final object) did differ significantly between sessions.

The mean duration of these three phases are given in Table 2.2. Similar to the data in Figure 2.4, all phases were longer in Trial A compared with Trial C. It is important to note that the manual and visual exploration phase was practically absent in Trial C.

Tab. 5.1. Duration of the 3 trials and characteristics of the fixations within the 3 trials. Note that all values are means with standard error of the mean over all 5 participants between parentheses. Degrees of freedom of numerator, 2, and for denominator, 8.

	Trial A	Trial B	Trial C	F value	p value	η_G^2
Duration trial (s)	147.2 (24.15)	65.58 (20.32)	16.54 (1.62)	9.53	.008	.69
No. of diff. objects fix.	19.00 (1.26)	14.40 (0.75)	6.00 (0.89)	99.51	<.001	.88
No. of fixa- tions	121.6 (27.19)	40.00 (6.28)	10.00 (1.79)	12.91	.003	.68
% goal rele- vant fix.	25.20 (1.06)	40.80 (2.60)	64.40 (4.86)	45.97	<.001	.86

Tab. 5.2. Mean (SEM) and comparison of the duration (s) of the Visual Phase (VP), the Manual and Visual Exploration Phase (MAVE), and the Construction Phase (CP).

	Trial A	Trial B	Trial C	F value	<i>p</i> value	η_G^2
VP	20.70 (1.90)	11.72 (1.87)	6.98 (2.14)	10.78	.005	.68
MAVE	102.2 (24.33)	9.56 (3.43)	0.14 (0.14)	14.39	.002	.73
СР	24.24 (3.80)	44.28 (18.10)	9.42 (2.92)	2.53	.141	-

The mean duration of the fixations within each of the discerned phases is given in Table 2.3. There were no significant differences between fixation durations within the different phases between trials.

Tab. 5.3. Mean (SEM) of the duration of the fixations (s) within trials A, B, and C for the Visual Phase (VP), the Manual and Visual Exploration Phase (MAVE), and the Construction Phase (CP).

	VP	MAVE	СР
Trial A	0.37 (0.03)	2.54 (1.43)	10.52 (4.63)
Trial B	0.32 (0.05)	0.90 (0.41)	12.87 (3.95)
Trial C	0.31 (0.04)	n.a.	9.04 (3.96)

5.3.2 Evolution of Goal-Directedness

Besides the duration of the three phases and the duration of the fixations within them, we were also interested in the evolution of goal-directedness within and between trials. "Goal-directed fixations" were defined as the fixations on objects that were also used in the final construction of the tool. Goal-directedness is thus the percentage of the total number of fixations that were oriented on objects of which the final tool was composed. Figure 2.6 shows the mean goal-directedness for all phases of Trial A, Trial B, and Trial C. The goal-directedness of the manual and visual exploration phase

was calculated on the basis of 4 participants, as 1 participant did not show a manual and visual exploration phase in Trial B. As demonstrated with a repeated measures ANOVA on the goal-directedness in the visual phase with trial (Trial A, Trial B, Trial C) as within-subjects factor, the evolution of the goal-directedness of the visual phase showed a significant increase over trials ($F(2,8) = 46.19, p < .001, \eta_G^2 = .88$). Figure 2.6 shows that the goal-directedness in the visual phase of Trial C was very high in comparison with the preceding trials. The goal-directedness of the manual and visual exploration phase was only calculated for Trial A and Trial B, as Trial C had no manual and visual exploration phase. The goal-directedness of the point of gaze of the manual and visual exploration phase increased from 19.40(2.54)% in Trial A to 45.25(5.57)% in Trial B (n = 4). This was a significant difference (t(3) = 2.91, p = .031). The goal-directedness of the construction phase was very high by definition, and it showed no significant change throughout the trials.





5.3.3 The Manual and Visual Exploration Phase

Finally, having examined the different phases, we concentrated on the origin of the decrease in the total trial duration. This decrease in duration was largely due to a shortening of the manual and visual exploration phase from Trial A to Trial B (see Table 2.3 and Figure 2.4) and its absence in Trial C (mean duration 0.14 s). Moreover, this shortening of the manual

and visual exploration phase in Trial B was accompanied by an increase in goal-directedness of the manual and visual exploration phase and the construction phase. By Trial C, the manual and visual exploration phase was absent, but the goal-directedness in the visual phase was higher than before. To see how this goal-directedness in Trial C could have emerged, we now turn to a more detailed comparison of the changes in the manual and visual exploration phase from Trial A to Trial B.

As can be seen in Table 2.2, in Trial A there did seem to have been a long manual and visual exploration phase, about 100 s, in which participants were looking at and manipulating available objects without starting to complete the task. Interestingly, this time was largely reduced in Trial B. Of course a main part of this manual and visual exploration phase in Trial A originated from exploring the presented objects. In Trial B, however, participants had already created two other tools and thus discovered information for many of the objects' affordances. Nonetheless a manual and visual exploration phase was still present in this trial. As the discovery of tool-making opportunities arose out of the continuous manual exploration of the objects, we expected that the goal- directedness within the manual and visual exploration phase of both Trial A and Trial B increased over time. For analysis we have therefore divided the manual and visual exploration phase into two parts of equal duration. We expected to find a smaller percentage of goal-relevant fixations in Trial A compared with trial B and in the first half of the manual and visual exploration phase compared with the second half.

The percentage of goal-relevant fixations was larger in the second half of the manual and visual exploration phase than in the first half, both in Trial A (increasing from 17.40[3.50]% to 23.00[1.59]%) and in Trial B (increasing from 32.75[3.07]% to 57.5[9.61]%). However, it is possible that this increasing goal-directedness was influenced by the duration of the fixations within each half of the manual and visual exploration phase. That is, if one of the halves of the manual and visual exploration phase showed relatively more guiding fixations, this would confound our analysis. Because 2 of the 4 participants showed only fixations shorter than 1 s in the second half of the manual and visual exploration phase of Trial B (goal-directedness of these 2 participants was 25% and 33%), this could indeed happen. We therefore limited our control analysis to fixations shorter than 1 s.

A repeated measures ANOVA on the (transformed) percentage goal-directed fixations with trial (Trial A, Trial B), and block (first half, second half) as within-subjects factors showed that the goal relevance of the fixations increased significantly from Trial A to Trial B ($F(1,3) = 10.16, p = 050, \eta_G^2 = .47$). The effect of block was just above the significance level ($F(1,3) = 8.64, p = .061, \eta_G^2 = 19$) showing that across trials the first half of the manual and visual exploration phase was less goal directed than the second half of the manual and visual exploration phase. There was no significant interaction effect for trial and block. A follow-up analysis revealed a significant increase in goal-directedness across blocks in Trial B (t(3) = 2.40, p = 048).

5.4 General discussion

Our study is the first that described the functional reorganization of gaze in setting up an action system for tool making. Gaze gets organized differently as it changes gradually over learning from initially serving as part of multiple short- term exploratory and performatory actions to serving the long-term attainment of tool making.

In our study, at the initial stages of the first trial the agent relied on information-motor couplings with an exploratory function: visually scanning for perceivable opportunities for acting, reaching, grasping, and manipulating objects. These exploratory activities are actualized through performatory systems, utilizing information-motor couplings for manipulating the environment at the level of the properties of individual objects and some relations between the objects. This was seen in the initial phases within a trial; a low goal-directedness characterized the visual phase and the whole subsequent manual and visual exploration phase. This exploration gradually disclosed novel information for making the tool. Using performatory acts (e.g., fitting the two cups of Figure 2.1C together), new affordances were attained that in turn opened up new possibilities for acting. This could be observed in the trial-and-error construction in the manual and visual exploration phase and in the slow and generally inefficient tool making. The problem of creating a tool was eventually solved, but only through constant interaction with the objects available, until a solution became within reach of the current action possibilities. In the

initial stage of learning, the novel tool therefore gradually arose out of continuous exploratory and performatory activities, and with those activities information for tool making got disclosed.

As more information for the tasks became available, the agent's information-motor couplings reorganized to that constraint. This changed the opportunities for action this system had in its environment—opening up but also constraining new directions for exploration. As relevant aspects of the environment were constrained in this way, gaze got concentrated more on objects that now offered new opportunities for construction. This was seen in Trial B, where the role of gaze within the performance of the agent had changed. Trial B still showed the agent's inability to immediately solve the task (e.g., scooping rice) but also showed the point of gaze was constrained to but a few objects and the performatory actions increasingly allowed for exploring relations among objects. The goal-directedness of gaze and the efficiency of the performatory actions increased within Trial B, as was visible in the increasing goal-directedness during manipulation in the manual and visual exploration phase and in the overall duration.

At Trial C the information for tool making was fully disclosed, and the organism's action system was fully set up. The performance of the creation of a tool consisted of picking up the appropriate objects in the appropriate sequence and combining them efficiently. Every step in this process was guided by information-motor loops that included gaze and that were constrained by the discovered information for making the tool. Trial C was therefore characterized by a highly goal-directed point of gaze and behavior that was both fast and efficient. The increasingly goal-directed manual and visual exploration phase of Trial B had, by Trial C, been incorporated in the construction phase through visual-motor routines that already started in the visual phase. In other words, the visual phase and construction phase were stitched together by gaze, and performance was contracted into a single functional unit of perceiving and acting: it showed an action system. By discovering information for the affordance of the task, the scale of organization had thus "broadened" accordingly-from many short bouts of perceiving and acting to one large functional unit of looking and manipulating. It is interesting to note that the 1 participant who did not show a manual and visual exploration phase in Trial B (creating a knife, Figure 1L) had been exploring and using those same objects for scooping

rice on the previous trial. So this participant in fact already discovered the information for this tool and showed the contraction of the performance to a single functional unit early on.

The ability to make tools is often considered a hallmark of human cognitive evolution because it suggests that arbitrary objects (e.g., stones) are intentionally shaped according to a mental template (Wynn, 2002; see also Ambrose, 2001, McPherron, 2000. Such a mental template contains a specification of the end state of the tool, and so creating a tool out of any object is a matter of planning: the agent needs to determine how to get from the current state to the end state of the object (Johnson-Frey, 2003). This cognitive view of tool making has been criticized (e.g. Bongers, 2001; Bril et al., 2010; Cox & W. Smitsman, 2006; H. L. Dreyfus & S. E. Dreyfus, 1987; Ingold, 2001; Leudar & Costall, 1996; Lockman, 2005; Reed, 1996; Roux & Bril, 2005; A. W. Smitsman, Cox, & Bongers, 2005). Cognitive behavior is a continuing process in which the toolmaker gradually gets proficient in perceiving, using, and changing the constraints and opportunities of the environment. The evolution and development of cognition is therefore as much an evolution of the environment as it is of the agent. Typically, in tool use, the creation and use of tools coevolve within the development of action systems (see e.g. Ingold, 2000). In short, cognitive behavior is a situated, continuous, and gradual affair. Our empirical findings can best be taken as evidence for this point of view.

Our results suggest that learning to create a novel tool is best understood as an ability gradually emerging over time from small-scale exploratory and performatory acts in the environment. The role of gaze in setting up an action system is that of gradually attuning the agent to its environment. Gaze does so by serving the information–motor couplings that make novel task-specific information available. Moreover, by itself attuning to this novel information, gaze constrains established information-motor couplings further. The functional unit evident in Trial C thus cannot be understood properly without the gradual re- organization of performatory acts evident within and across the preceding trials. Moreover, the increase in efficiency in tool creation and the goal-directedness of gaze in general, and the contraction of multiple phases of looking and acting into one single unit in particular, suggest a strong mutuality of the action system and the environment in which it developed and to which it is adapted. This study is a first attempt at exploring the role of gaze in setting up action systems. We are aware that our empirical findings offer only limited support of the theoretical implications we see in our data. Studies in the field of gaze behavior under natural conditions generally have a small number of participants, and this study is no exception. Due to technical limitations, we only had sufficient data from 5 participants for our analyses of gaze. We therefore chose to use only very rough-grained and thus robust analyses. In future studies we aim to expand this new way of looking into the role of gaze from an action systems perspective and in those studies detailed analyses on the level of individual fixations will be performed.

5.5 Conclusion

This study was meant to draw attention to a possible role of gaze in setting up action systems. It describes the functional reorganization of gaze in setting up an action system for tool making. Gaze gradually gets organized differently as it changes from serving as part of individual short-term exploratory and performatory actions to serving the attainment of the tool making as a new functional unit on a longer timescale. It helps to fit the action system to the scale at which the task's affordance is found. In our view, it is through active exploration and engagement with the world that an action system emerges and a meaningful environment, rich in opportunities for acting, is discovered. Interpreting gaze allocation from this perspective shows the way in which agents get situated in their world.

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Reductive and emergent views on motor learning

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Abstract

To allow different views on motor learning to inform rehabilitation research, this chapter aims to explicate a frequently missed yet fundamental difference in starting point of such views. By considering how rehabilitation in practice answers the question of what parts an activity consists of, reductive and emergent approaches to motor learning are identified and traced throughout rehabilitation practice. We show that when a task is cut up along reductive dimensions while also apparently relying on emergent components, this unequally favors the reductive approaches in practice, we hope to inspire an awareness that brings both approaches the opportunity to independently inform research so that new theories and practices can proliferate.

6.1 Introduction

The ultimate goal of rehabilitation is to improve a patient's activities in daily life (ADL). To guide rehabilitation towards this goal there are many, and sometimes conflicting, theories of motor (re)learning (e.g. K. M. Newell, Liu, & Mayer-Kress, 2001; Wolpert, 1997). Having multiple differing theories available enables researchers and practitioners to take different perspectives and come up with new and fruitful ways of approaching rehabilitation problems.¹ Such plurality should therefore be cherished. As we shall argue however, the practical implementation of theories in rehabilitation unequally favors one perspective on motor learning and thus threatens this plurality. In this chapter we aim to start alleviating this threat by explicating two fundamentally different approaches to motor learning and the way each is implemented in rehabilitation. By doing so we hope to inspire awareness in the field to these differences and to explain the importance of allowing both views the autonomy to flourish and independently inform rehabilitation research.

To guide our discussion we will look at a practical guestion that any clinician has to consider: the question of whether an activity should be practiced as a whole or whether it should be practiced in parts. When (re)learning an activity, a patient will often not be able to perform the task in one go. The task can for example be too complex or a certain part of the task might be too painful or difficult. Thus, in therapeutic exercise the question of whether an activity should be practiced in parts or as a whole is an important one. Central to our discussion moreover, will be to consider along which dimensions to cut up an activity if it needs to be practiced in parts-that is, the question of what we count as a "part" of an activity. A reasonable approach to the problem can be found in many undergraduate textbooks (e.g., Edwards, 2010, Magill, 2003; see also, Naylor & Briggs, 1963). They suggest that one practices an activity as a whole if it does not have meaningful parts with attainable sub-goals and one can practice an activity in parts when it does. For example, in cyclic activities such as walking or cycling, and more generally, in any activity where there is

¹It should be noted that here we do not consider the therapeutic approaches of practitioners who base their methods on practical experience, and the way such approaches may affect the advancement of knowledge. It is for example interesting to consider that such practice might offer a way of exploring for novel and fruitful approaches that do not (yet) conform to any of the "established" perspectives.

a strong temporal relationship between the movements making up the activity, the activity should be practiced as a whole. In this approach the "parts" are thus identified by the dynamics of the activity and its sub-goals. Below we will identify this view as implying an emergent approach to motor learning.

Informed by the anatomical and physiological underpinnings of the movements that make up an activity, a more analytic approach compartmentalizes an activity in terms of underlying structures and aims to practice those parts in isolation before transferring them to the activity. For example, in rehabilitation following an upper limb amputation, patients often first learn to control their myoelectric (EMG) signals on a computer screen, before they apply this control to a myoelectric prosthesis (Dawson et al., 2011). When patients are unable to perform a temporally tightly coupled activity this approach to the part–whole relationship is often chosen. For example, robot-assisted stepping aims to practice the whole activity, by targeting its underlying stepping motions. We will explicate this view as taking a reductive approach to motor learning. Although the emergent and reductive approaches to the part–whole relationship will equally stress their commitment to improving activities in daily life they approach the problem of how to do so completely differently.

We aim to show that if we, in rehabilitation, remain unaware of this fundamental distinction and its implications and therefore cut up activities along reductive dimensions while also apparently relying on emergent components, in practice we *de facto* apply only the reductive approach. If choosing the appropriate "parts" is just a pragmatic choice this would be no problem. However, as we will argue, both views on the part–whole relationship imply fundamentally different perspectives on motor learning and each enables a multitude of distinct ways of furthering the approach of rehabilitation problems. Although the perspectives that we wish to explicate only show in practice, one could call them "meta-theoretical," so as to discern them from the explicitly formulated methods, ideas and hypotheses of the scientific or therapeutic work itself.

A perspective, an angle of approaching motor learning problems in rehabilitation, enables and constrains the theories and practices that are available. Because of this constraining function that our perspective brings to both scientific and therapeutic practices we contend that it is imperative that both views are given equal room to develop. Although the reductive approach is a viable view and should be pursued as far as it can be taken, when applied without constraint, it risks drowning out equally viable alternatives. In the following, our main goal is to inspire an awareness of the two principally different approaches as they are applied to rehabilitation problems in order to make room for each to develop its ideas as far as they can be taken. We aim to inspire such awareness in all those participating in the field of motor rehabilitation—theorists, researchers and practitioners alike. We will do so by first explaining and exemplifying both approaches in theories and their implementation, and then comparing the perspectives on rehabilitation research directly. Before starting on this however, we will start with defining some concepts that both approaches share.

6.2 Common ground: Classification of function

In the International Classification of Functioning, Disability and Health (ICF) "body function" denotes the properties of anatomical parts of the human body (World Health Organization, 2015). For example, the elbow's function is to flex and extend and a muscle's function is to contract. In order to improve motor control in ADL, rehabilitation training frequently targets these body-functions. From this point of view training programs aim at the movements of body parts rather than on activities such as putting on a shirt. These training strategies have also been applied in training muscle force to improve climbing stairs (Skelton, Young, Greig, & Malbut, 1995), using robotic guidance to go through the arm motions of reaching (Kwakkel, Kollen, & Krebs, 2007), or training myocontrol for using a hand prosthesis (Smurr et al., 2008). Functions pertaining to aspects of movements (e.g. force, coordination or control), or their anatomical counterparts, (e.g. the joints and muscular tissue), will therefore be called "body-functions" here.

On the other hand, training can focus on everyday tasks. Such training would be categorized in the ICF as "activities." Examples of activities are picking up a cup or buttoning up a coat. Here, "function" pertains not to bodily movements, but to the *task* that the patient aims to accomplish with its activity. Patients practice goal-directed actions rather than perform

(repetitive) movements (i.e., displacement of body parts). For example, teaching a prosthesis user to pick up a cup, by having him pick up cups (Romkema et al., 2013) or training laparoscopic surgery by simulating a surgical task (Torkington, Smith, Rees, & Darzi, 2001; see also, Haque & Srinivasan, 2006). "Activities" we therefore define here as the adaptive coordination of the whole body to attain the goal of a task (cf. Bernstein, 1996; J. J. Gibson, 1979; Reed, 1996; K. M. Newell & Vaillancourt, 2001; Warren, 2006).

6.2.1 Two ways of relating body-functions and activities

Having introduced our two basic concepts, we need to look at the *relation* between them to identify a reductive and an emergent approach. If we look closely at motor learning in rehabilitation, we can discern two different ways of dealing with the relation between body-functions and activities. First, activities can be taken to be *reducible* to body-functions. That is, activities can be said to be explained by describing the totality of the body-functions that underlie it. For example, body-functions can be considered the "cause" of activities or activities can be considered to be "made up of" (constituted by) underlying body-functions. Second, activities can be said to be non-reductively related. Body-functions and activities are considered to be non-reductively related. Body-functions and activities can for example be considered as mutually constraining each other. Or they can be understood as different aspects of the same rehabilitation problem (see also Meijer & Roth, 1988).

Both the reductive and the emergent view on motor learning assume a layered structure in which activities belong to a higher level than the "underlying" body-functions do.² In general, taking a reductive stance on a subject matter then means that we understand or explain the behavior of a system at one level by looking at the basic underlying components and the relations between these components at a level below (Silberstein, 2002; for comparative issues within medical science see, Ahn et al., 2006, Engel, 1977). By contrast, an emergent stance claims that the higher level has its own intrinsic dynamics that deserves attention in its own right. It

²Note that there are many varieties of reduction and emergence (see e.g. Kim, 2003; Silberstein, 2002; Silberstein & McGeever, 1999). To make our point this most basic distinction will suffice.

denies that understanding the behavior of the underlying components is enough to understand the behavior at the level of the activity. Thus it aims to understand activities by looking at the dynamic at the level of activities itself. In this view thus, the underlying level may constrain the behavior at the higher level, but it does not dictate, prescribe or explain it.

To phrase the two ways of relating the level of body-functions and the activity level in terms of practicing an activity in parts: just as anatomical parts may be considered the proper parts of a human body, so too can body-functions be considered the proper parts of the *motions* of a human body (e.g. the possible displacements of its body-parts). In as much as an activity is reduced to nothing but a moving body, body-functions can therefore also be considered the proper parts of an activity. Learning an activity by cutting it up into body-functional units and training these units outside the context of the activity is thus consistent with a reductive approach. The proper parts of an activity can also be considered to be themselves smaller activities, with their own (sub)goals. That is, the component parts of an activity are then considered to be functional units of action that nest into one another to form the whole activity. Learning an activity by cutting the activity up into smaller units of action and practicing their goal-attainment is consistent with an emergent approach. Note that the emergent view does not deny that body-functions may be considered component parts of a (moving) body, it only denies that they are the relevant components to focus on when describing an activity.

We will get into the details of the two different approaches and exemplify them both with respect to the part–whole relationship in the following two sections. The main point of these sections will be to show how these different approaches to motor learning bear on theories and practices of rehabilitation and to show that in practice activities are often cut up into both body-functional units and units of action. Through examples of therapeutic and research practices, in the subsequent section the implications of focusing on activities while actually cutting these activities up along body-functional dimensions will be dealt with.

6.3 The reductive perspective: focusing on body-functions

In this section we will consider in some detail the reductive approach to the question of what counts as a "part" by looking at reductive theories and training programs. A reductive approach attributes the improvements at the level of *activities* to changes at the underlying level of *body-functions*. Therefore the reductive approach to motor learning targets body-functions, even though its therapeutic goal is to (re)learn an activity (i.e. at the level of ADL). This perspective on motor learning boils down to two assumptions: (1) activities are actually merely a collection of body-functions, and (2) motor learning is learning to control these body-functions. Together these assumptions imply a hierarchy in structure (see Figure 6.1). This *body-oriented* perspective on learning motor skills thus in principle cuts up the task along a vertical axis, along the arrows of Figure 6.1. Following the arrows the explanation of learning an activity is reduced to describing the behavior at lower levels of description.

6.3.1 The reductive approach in practice

The reductive perspective is actually the most dominant approach to motor learning in rehabilitation. To draw out the intricacies of the approach we will now highlight some examples of its theories and research areas within rehabilitation. First we will discuss a general class of motor control theories that find application in rehabilitation. We will then offer two examples of the practices of reductive research programs: the field of robot assisted walking and the field of serious gaming.

Internal models

A particularly dominant reductive approach to motor learning is the approach that stems from "motor program" theories (e.g. Keele, 1968; Schmidt, 1975) that grew out of "reflex arc" concept of the nineteenth century and the computer metaphor of the 1950's. In this approach goals and activities are valued greatly, but only as "representations" in the minds of the patients. According to such theories (e.g. Krakauer, 2006;



Fig. 6.1. The reductive perspective. The activity of picking up a cup using a prosthesis is considered to reduce to a set of body-functions. For example, a collection of muscles, tendons, joints and a certain EMG signal with properties such as speed (v), force and direction. Learning to coordinate all these body-functions is subsequently considered to be reducible to acquiring a control system that coordinates the body-functions.

Wolpert, 1997), motor control is a (computational) process of planning a series of movements based on this represented goal-state. That is, after an environmental goal has been internalized, the (neural) system assembles the appropriate anatomical components (the muscles, the joints or the limbs) and plans and monitors a movement pattern (i.e. sets and adjusts the appropriate velocity, torgue or power) that will move the body from its current position to the target position. At that point the current position will be identical to the represented goal-state and therefore the activity has been performed. The activity in this view thus does not play a direct role in control, rather it *supervenes* on the underlying mechanism and the body-functions it controls until the goal-state is reached.

This model of motor control has been extended and refined, but the premise is the same: activities are explained by their underlying components and interactions. A control system (e.g. an "internal model") chooses and coordinates body-functional parameters so that the body changes position in such a way that a goal is reached. Thus, it admits of a strongly reductive and hierarchical approach. The underlying bodyfunctions and the control system that coordinates them are together sufficient for accounting for motor control. Even the environmental goal of the activity is reduced to an internal (input) state for the underlying control system. By extension, motor learning is also approached in a strongly reductive manner. The key is to acquire a motor plan that chooses and coordinates the body-functions appropriately (see e.g. Dosen et al., 2015). Therefore, in this view the relevant parts of activities are their underlying body-functions. Accordingly, motor learning would be fostered by interventions aimed at improving these body-functions and, as we shall see, this is the approach employed.

Robot-assisted treadmill walking

In rehabilitation following a spinal cord injury, a stroke or cerebral palsy, a patient's walking ability can be trained on a treadmill while an exoskeleton (a robot) supports the weight of the patient and guides her stepping movements (Duncan, Sullivan, Behrman, Azen, Wu, et al., 2011). The aim of such training programs is to improve a patient's walking ability in daily life. To do so, the training program adopts many thoroughly reductive tenets. First, it is assumed that the *goal* of a walking activity is circumstantial and can be dispensed with. That is, the patient simply does not need to go anywhere in the real world while on the treadmill. Rather the activity is taken to be reducible to its underlying stepping-movements. Furthermore, it is assumed that it is inconsequential to the basic activity that these stepping movements neither generate nor make use of the perceptual (optic, proprioceptive) flow that accompanies walking in real life.

The robotic system treats any of these perceptual–motor dynamics as well as the (environmental) goal of the activity as if they are irrelevant to the basic activity. Furthermore, by having the robot do much of the work, many new perceptual–motor interactions are being introduced (Dobkin & Duncan, 2012). For example, even if the (perceptually impaired) patient can sense whether the robot is moving her leg or whether she is doing it herself, the patient's goal is now to get the leg moving correctly by learning to coordinate her effort in collaboration with the robot. As long as a stepping pattern is retained however, the reductive logic of the training system implies that these added perceptual–motor dynamics are just as irrelevant to the activity as the dynamics they have replaced. In other words, the coordinative dynamics at the level of the activity itself is taken to be inconsequential to learning an activity—they can be dispensed with or can even be replaced, without changing the essence of the activity: its body-functions.

Recently, Dobkin and Duncan (2012) published a critical review on robotsupported and related training systems. They conclude that despite more than twenty years of development, the effect of robot supported treadmill training has been slim to none and go on to identify several possible reasons for this. Apart from the fact that the importance of central pattern generators (i.e. an underlying "control system" mentioned above) in humans is questionable, they point out that the adaptive coordination at the level of the activity that is required for working the treadmill is completely different from that of walking in daily life. In terms of the partwhole relationship, despite the best efforts to maintain the whole activity, by simulating only the stepping movements used in daily life, the approach has cut the activity (i.e. walking) up along a body-functional dimension and reduced it to an underlying part (i.e. stepping movements). Focusing on the task-specific dynamics at the level of activity shows that robot-assisted walking has reduced the activity so strongly that it has come to have very little to do with the original activity its sets out to improve.

Serious gaming for rehabilitation

A field that is heading in a similar direction is that of serious gaming for rehabilitation. Serious games are (video) games that are fun to play and offer challenging goals while supplying players with skills useful in reality (Graafland et al., 2012). Serious games are basically designed so that a body-function used in ADL is given a fun and motivating role in a computer task. For example, when targeting the Center of Pressure (COP) that is found to be important in walking or sitting. In such games, the players need to actively displace their COP to pop virtual balloons (Gil-Gómez, Lloréns, Alcañiz, & Colomer, 2011). Likewise, the EMG-signals required for using a myoelectric prosthesis are targeted and used to make players hit musical notes (Armiger & Vogelstein, 2008). Thus, the method of serious gaming in rehabilitation embodies the body-oriented approach.

Despite the fact that serious games aim to offer therapy by offering an activity, the logic of current serious gaming is thoroughly reductive and body-function oriented. First, as in the robot assisted stepping, a body-function needed in an ADL task is taken out of that context and is practiced in a different (new and fun gaming) task. This step again crucially assumes that by isolating the underlying body-function of an activity, the essence of that activity is retained. This reduction implies a hierarchy in which activities are the resultant of body-functions, but body-functions are not the resultant of activities. For example, one can sit or walk because the COP is adequately displaced, rather than vice versa. Second, assuming the reductive hierarchy, serious games can simply "add" a new and fun gaming goal to training the body-functions. This step assumes that motor learning is a matter of learning to control these body-functions—independently of the task or the goal for which they are used. The goal is merely an addition to the underlying control of body-functions.

Using such serious games in therapeutic practice exemplifies a reductive view. In this view, the context in which a task is performed is considered to be incidental rather than essential to the activity that is learned. Thus for example, one can acquire an underlying faculty called "balance control" (Gil-Gómez et al., 2011) or the control of an EMG-signal ("myocontrol" Dawson et al., 2011; Dupont & Morin, 1994; Gordon & Ferris, 2004) independently of the task in which such control is exhibited. This underlying faculty is assumed to allow for transfer of performance across activities. Implicitly thus, in these practices the part–whole relationship is again cut along hierarchical lines: the activity is taken to reduce to its underlying body-functions and its control system.

To sum up, in order to improve activities in daily life the reductive approach to motor learning cuts up the activities it aims to promote along its underlying componential structure. As we have seen in our examples of robot assisted walking and serious gaming, such orientation towards underlying body-functional components is not without consequences for the way training programs are designed. As an alternative, we will now look at the emergent view as an activity centered approach to motor learning. To answer the question of what a system's "parts" are, the approach does not cut up the activity into underlying elements, but into goal-directed units at the level of the activity itself.

6.4 The emergent approach: keeping an eye on activities

Our question of whether there are discernible parts to an activity and how to discern them can also be answered in another way. The intuition not to cut up cyclic or otherwise tightly coupled temporal processes, such as reaching and grasping during prehension shows this. It shows that the dynamics of the activity itself may be essential to learning that activity. The *emergent* view on motor learning expresses the conviction that when we artificially break up coordinative structures by stripping activities of the relation to their goal, and furthermore strip the bodily coordination down to some of its components to arrive at body-functions, we do not get to the essence of the activity, but we lose it. In other words, the explanation of learning an activity is not sought below but within the activity's level of description. It implies therefore, that we ought to stick to the level of activities and try to establish what perceptual-motor dynamics align the patient to the environmental goal of the activity she performs and to what extent the activity can be meaningfully cut up into shorter bouts of activity with their own sub-goals.

6.4.1 The emergent approach in practice

To see how this emergent and thus activity-oriented perspective approaches motor learning and to further clarify the approach let us look at some examples of emergent theories and practices. We will start this discussion with a brief overview of action system theory (Reed, 1982), and dynamic systems approaches to motor learning (e.g. K. M. Newell et al., 2001). After that, we will turn to the well-known task-oriented approach to stroke rehabilitation. As we will argue, although this latter approach is sometimes misunderstood its background lies in the emergent view on motor learning.

The theory of action systems

According to the theory of action systems (Reed, 1982, 1988), when a patient is learning to perform a task, she is forming an action system. In forming an action system she learns to coordinate her body in order to attain a specific goal in the environment. Action systems are thus not defined by their anatomical parts, but by their overall goal. Because of that, an action system is flexible and made up of nested units of perceiving and acting—each of which has its own sub-goals. Learning an action system requires assembling and fine tuning the relations between these cycles of perceiving of, and acting on, environmental aspects relevant to the task at hand (Bingham et al., 2007; Jacobs & Michaels, 2007). Because an action system emerges from tuning the relations between perceiving and acting on particular task aspects, the system becomes highly dependent on the structure of the task (Chapter 5 of this thesis). Fine-tuning actions to this task structure is called "calibration." In action system theory, transfer from one task to another is expected based on the ability to re-calibrate an established action system to fit a novel task-structure.

To give an example of the importance of maintaining the goal-relevant perceptual-motor dynamics, in a series of studies Rieser et al. (1995)

demonstrated calibration of action systems by having people walk on a treadmill that was being pulled by a tractor. When walking under these conditions the environment seems to move, or "flow," past at a greater speed than would be expected during normal walking conditions. When participants are subsequently asked to walk (on the ground) to a target without using vision, they undershoot their target. That is, the tight temporal coupling between perceiving and acting is transferred from one situation to the next. Importantly, this effect of the calibration of action to the perceived rate of (optic) flow, transfers to tasks with similar goals such as side stepping, but not to tasks with a different goal such as turning in place or throwing a ball (Rieser et al., 1995). Action systems, in this case a system for locomotion, are thus calibrated to adapt to the specific way perception and action are attuned and, importantly, this calibration is specific to the goal of the activity and not specific to the underlying body-functional structures (for further examples see e.g. Bingham et al., 2007; Bruggeman & Warren, 2010; Withagen & Michaels, 2002).

Because action systems are highly context sensitive and assembled relative to a goal, when a task or activity is too complex to perform at once, action system theory will preferably cut up the activity into sub-tasks. The performance of any of these sub-tasks needs to be relatively independent from the whole in terms of their dynamics, but not in terms of their goal. For example, in natural prehension, there is a tight coupling between reaching and grasping and for that reason these two aspects of performance should not be trained in isolation (Jeannerod, 1984). However, when looking at prehension as part of the activity of tooth brushing, getting the tooth paste can be practiced independently of unscrewing the lid or brushing the teeth (Reed et al., 1995). As Reed et al. (1995) exemplified, many activities in daily life can be cut up into shorter, yet meaningful, units of activity. When an aspect of an action system needs to be performed by different means, for example when prehension needs to be achieved using a myoelectric interface, these means need to be incorporated into such meaningful units. As action systems are not constituted by body-functional units, i.e. by their (anatomical) means, but by the goal-directed dynamics of perceiving and acting the theory suggests that incorporating these novel means into the original goal directed activity will lead to the biggest transfer effects to activities with similar (sub)goals. Hence the largest improvement in ADL

too is expected when training goal-directed actions while incorporating novel means.

Dynamic system approaches

Out of the insights that also fueled action system theory (J. J. Gibson, 1979) and combined with the theory of non-linear dynamics (e.g. Kelso, 1997), dynamic system approaches to motor learning were born (Davids, Button, & Bennett, 2008, K. M. Newell et al., 2001; see also Carr & Shepherd, 1989, Law et al., 1996, for similar developments). These approaches also acknowledge the emergence of a coordinated activity, but stress how this coordination emerges from the self-organizing non-linear dynamics of the interaction between patient, the task, and the environment. The interaction of these three aspects leads to a dynamic "perceptual-motor landscape" of possible movement patterns that allows the patient to attain the goal and, depending on the phase of learning, this landscape has different regions in which the movement patterns for attaining the goal of the activity are most stable ("attractor states"). Learning an activity is conceptualized as taking place through self-organization in which exploring and moving around will organize the dynamics of the interactions between patient, the task, and the environment until it stabilizes around such a stable attractor state. Thus, the performance of the activity emerges from the dynamics of the patient-task-environment system (K. M. Newell, 1986, 1996).

Now, because the activity is a self-organizing property that emerges from these interacting dynamics, in practice aspects of either the task, the environment or the patient act to constrain or enable certain dynamics, but they do not dictate them (cf. the reductive, body-oriented approach). When learning, the dynamics of the patient-task-environment system need to organize itself within the boundaries set up by the constraints in order to reach the goal of the activity. The job of the therapist is thus to shape any of these aspects so as reshape the constraints which nudges the self-organizing system towards stable regions.

Important to dynamic system approaches is that the training process itself is part of the dynamics and therefore modulates and changes the perceptual–motor landscape over time (K. M. Newell et al., 2001). That is,

previous learning experience will continuously alter the shape and regions of stability in the landscape. Thus, the type and intensity of training will constrain the opportunities for learning. In fact, the dynamics of patienttask-environment of any performance are nested within the larger scale dynamics of learning and development. An interesting implication of this is that, although body-functions do not dictate performance, they can be made to (appear to) do so. For example, when training to isolate EMG patterns for learning to use a myoelectric prosthesis, this experience "carves out" an attractor in the perceptual-motor landscape that will constrain subsequent prosthesis performance. This of course offers opportunities for application, but should also give us pause: if we choose to target aspects based on body-oriented rather than activity-oriented considerations, we may end up with a system that performs great on body-oriented outcome measures but that is better adapted to the narrow confines of the lab than to the ever-changing and context-sensitive reality of activities in daily life.

Task-oriented training

Based on the above mentioned theories and ideas very close to them, the emergent approach to motor learning has found practical application in the form of task-oriented training (e.g. Winstein & Wolf, 2008). This training form has gained popularity in the field of neurorehabilitation—especially in rehabilitation training after a stroke. Task-oriented training brings some of the insights of action system and dynamic system theories to rehabilitation and centers on the idea that limitations in activity need to be targeted rather than impairments of body-functions. That is, it aims to improve the attainment of the goal of a task, rather than a focus on the bodily means to do so. For example, a task-oriented training program for improving the ability to reach for objects following a stroke showed that goal directed grasping to reach objects led to improved reaching performance as shown by arm kinematics and on an activity-level questionnaire. By contrast, resistance training that displaced the arm across similar distances did not lead to improved reaching performance (Thielman, Dean, & Gentile, 2004). In task-oriented training practitioners aim to challenge patients into achieving real, ADL-like, goals. The training program thus favors activities over body-functions. Although not widely applied outside stroke

rehabilitation and easily recast or applied in reductive terms (see for this worry also Winstein & Wolf, 2008), the effects of task-oriented training have been promising (e.g. Rensink, Schuurmans, Lindeman, & Hafsteinsdottir, 2009; Wevers, Van de Port, Vermue, Mead, & Kwakkel, 2009).

What all these examples of approaching motor learning share from an emergent viewpoint is an assumption that the coordination found at the level of activities is an emergent property that can only be understood by looking at the dynamics of the unfolding activity itself. That is, activities cannot be reduced to underlying structures and their relations. In terms of the part-whole relationship: the parts of an activity are functional units at the level of the activity rather than the movements of underlying anatomical components. If research resists focusing on body-functions in favor of explaining motor learning in terms of the coordinative dynamics of the activity itself, we propose it takes an emergent perspective. An emergent perspective attributes the improvements in performance of an activity to changes in its dynamics at the level of activities itself. So, while the reductive approach is shaped by a belief that in the end, activities will reduce to body-functions, the emergent approach takes this belief to be unfounded (Silberstein, 2002). From such a perspective, the level of activities needs to be studied in its own right—by looking at the details of the dynamical relations between parts of the body and their relation to the goal that should be achieved. If an activity needs to be cut up for training purposes, it needs to be compartmentalized in units of goaldirected actions.

6.5 Towards plurality in methods

The question of what the relevant "parts" of an activity are, as we have seen, is not just a pragmatic question, but it is a deep conceptual issue of which the answer has far reaching consequences for approaching rehabilitation problems. As we have seen from our examples of theories and training methods, any rehabilitation training program has dealt, explicitly or implicitly, with the question. We have argued that a reductive view approaches this question hierarchically and goes down a level to identify parts of the whole, while the emergent view approaches the question by looking around at the level of activity itself to identify its parts. Having exemplified both views, we can see how both approaches view each other's methods. This will show why the reductive view easily dominates the context sensitive emergent perspective.

6.5.1 Reduction dominant methods

We have seen that the reductive view is a viable view and that it should be pursued as far as it can be taken—and so should the emergent view. There is however a strong asymmetry between both views that should be avoided. This asymmetry in practice causes the reductive approach to drown out the emergent approach. Thus an apparent focus on training an activity combined with a body-functional decomposition (e.g. robot assisted treadmill walking), is actually only a reductive program. To see this, consider that with respect to the part-whole relationship, a reductive analysis can always be applied—there is no activity that will not submit to body-functional decomposition. In the emergent view on the other hand, activities that have no sub-goals or form a temporally tightly coupled whole cannot be decomposed. In spite of this, as we have seen in serious gaming and robot assisted stepping, in such cases the reductive approach is applied anyway.

Importantly, stripping an activity, any activity, from its unfolding perceptual-motor dynamics in this way, means that from an emergent point of view the essence of the activity is not retained, but it is lost. The asymmetry lies in the fact that while the activity-oriented compartmentalization preferred by the emergent approach does not conflict with reductive thinking (at worse it may be criticized for not probing "deep" enough), the body-oriented compartmentalization does conflict with that of the emergent view. From an emergent perspective, when one creates an activity to target body-functions more efficiently, one is not getting to the essence of the original activity, but one is introducing a new, and guite possibly, irrelevant one (e.g. robot assisted stepping or serious gaming). For this reason, an awareness of the fundamental differences in points of view is of primary importance for rehabilitation practice. Considering the part-whole relationship in practice, when apparently applying the compartmentalization along both the reductive and the emergent dimensions, from the emergent perspective this equates to applying only the reductive approach. Doing

so, in other words, creates a rehabilitation program that can only be made sense of from within the reductive perspective.

This asymmetry can perhaps be further illustrated by considering how to measure training effects in terms of body-functions. In Figure 6.2A, the conceptualization of such a measurement is depicted. Here, for characterizing a change in performing an activity with a myoelectric prosthesis, myoelectric control is gauged through a computer task where the goal for the patient is to match a real-time representation of the myoelectric signal to a predetermined point on a screen (see e.g. Anderson & Bischof, 2012; Gordon & Ferris, 2004). The asymmetry lies in the fact that while the reductive approach will interpret the results of such a test as evidence for the underlying body-function (e.g. "myocontrol"), the emergent approach will not. First, with respect to the performance of the test, according to the emergent view, performing the test should be considered as an activity in its own right. Thus, one should look at the behavioral goal of the test and the perceptual-motor dynamics involved to find out what activity was being performed. Crucially, this step re-conceptualizes the test not at a level below the original ADL performance, but next to it, at the same level (Figure 6.2B). This begs us to consider the "validity" of such a testing performance.



Fig. 6.2. (A). From a reductive perspective, the improvement in motor learning is measured by gauging body-functions. Thus, the assumption is that one "measures" at the level of the underlying structure. This is indicated by the 'thought bubble.' However, an emergent view (B) does not idealize the activity by neglecting the specific environmental coordination, goals and constraints involved in testing. The test for body-functions is therefore not positioned below the level of activity, but next to it at the same level. (see text for details).

Second, with respect to the outcome-measure extracted from the test, considered as an activity the chosen outcome measure may now no longer be
best suited to characterize the performance of the test (let alone the performance of ADL). For example, upon training a serious game to improve myoeletric prosthesis use, Anderson and Bischof (2012) reported only the amount of co-contraction during a computer task. In this task the object was to match a myoelectrically controlled line to a predetermined point in order to characterize their improvement. But the outcome measure made no reference to the goal of the activity that the participant was performing. To do that, the amount of myosignal would for example have to be related to the accuracy of matching (i.e. the goal of the activity). In other words, any measure of an "absolute" body-function reported from performing an activity, in an emergent view, lacks the theoretical importance it has to the reductive approach. Such measures can for example simply be considered a by-product, a consequence of rather than the cause of performing the activity (see e.g. Reed, 1988). The adopted perspective changes the framework that determines what counts as relevant and irrelevant to measure, target and improve.

Against this background, the importance of having the emergent view keep its independence relative to the reductive perspective becomes clear. The dominant reductive approach enthusiastically cuts up all tasks along hierarchical dimensions and makes research focus on body-functional measures that admit only of a straightforward interpretation within the reductive framework. That is, the inclusion of body-functional methods, and the tendency to design training tools to target body-functions makes it increasingly hard to escape the reductive framework and thus drowns out the development of other perspectives. Rehabilitation practices, methods and theories get increasingly forced to adhere to the reductive point of view at the expense of other, fundamentally different, ways of approaching the problems. What we need therefore, is to allow emergent perspectives to keep informing research.

6.5.2 Keeping an open mind: start with a focus on transfer

The principle tool that the emergent view brings to rehabilitation research is that of studying transfer. That is, quantifying the effect the performance (or training) of one activity has on the performance of another activity. Traditionally, the reductive view assumes that a transfer effect shows that across activities a common underlying body-function is shared. But as improvement of such a body-function can be measured more accurately by laboratory testing (Figure 6.2A), testing for transfer is often omitted in favor of measuring this improvement in body-function directly (this is especially true in the formative period of novel training programs, see Dobkin & Duncan, 2012; Goble, Cone, & Fling, 2014; Primack et al., 2012; Van Diest et al., 2013). As we have seen above, from the emergent view, such omission is both unwarranted and a fiction.

From an emergent point of view, *any* test (and training task for that matter) is an activity—thus any performance measure is related to another measure in terms of a transfer effect (see Figure 6.2B). In this view two activities relate to each other, not by an assumed underlying structure, but only because both are performed by the same, learning and developing patient. A transfer-effect thus does not admit of a similarity per se, but it reflects the amount of continuity in the perceptual–motor dynamics from activity to activity. Such a reinterpretation of transfer enables us to reinterpret any (body-functional) test in emergent terms. Importantly moreover, it calls attention to the importance of focusing on transfer to ADL in the early stages of developing a training program. That is, rather than having transfer to ADL be the icing on the cake after all developments have been concretized, it suggests transfer to ADL tasks (rather than laboratory tests) should guide the development of training programs from the start.

6.6 Concluding remarks

Starting with the practical question of how to cut up activities when training for their improvement we uncovered two fundamentally different understandings of the part–whole relation stemming from two fundamentally different approaches to motor learning. As we aimed to show, both approaches emphasize very different aspects of performance and design, and measure the effect of their training programs very differently. Our analysis of the background assumptions underlying the reductive and the emergent approach showed that they looked for parts of the whole along different dimensions. While the reductive approach looks along the hierarchical levels, the emergent approach looks at the level of the activity itself for identifiable sub-actions. We have been stressing that the emergent view therefore resists compartmentalization where reduction can always proceed. There are however many reasons why tasks cannot be practiced in one go even when an activity-oriented analysis suggests the task cannot be further decomposed, so it would be a major practical shortcoming if the emergent view has nothing to offer in such situations.

However, that the emergent approach has not been brought to bear on the problem does not mean it cannot cope with it. One possible way of offering activity-oriented practices in such circumstances is to practice activities in artificially simplified or augmented environments, such as in virtual reality or in serious gaming environments. Crucially however, the task that is recreated there should closely simulate those dynamical aspects that are found to be relevant to the activity in daily life. For example, recreating optic flow when walking around in a virtual scene or retaining and augmenting the perceptual–motor relation between the actions of a prosthetic hand and the relevant characteristics of the goal of grasping (Chapter 4 of this thesis). To emphasize however, in order for such approaches to offer an alternative to the many body-functional initiatives, it needs to be understood in emergent terms. And the value of emergent training programs, as any training program, should be quantified in terms of transfer effects.

As our examples showed, many of the newest developments in rehabilitation research—especially those that are inspired by novel technological developments, such as rehabilitation robotics, virtual or augmented reality or serious gaming—are still strongly drawn towards a reductive, bodyfunctional, approach. This might be due in part to the success of reductive approaches in the field of mechanical and computer engineering. As we have argued, a learning patient does not need to be conceptualized in the same terms. It is our hope that an awareness of the different points of views that are implicit and explicit in motor learning theories, rehabilitation programs and outcome measures, will help give the emergent approach the room to flourish. Thus we hope it can contribute to the plurality in views on motor learning in rehabilitation and help to inspire new ways of making creative and fruitful use of the full potential technological innovation offers.

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Epilogue

7.1 Introduction

Through theory and applications, this thesis has argued for developing an outlook on rehabilitation medicine that takes inspiration from an actionsystems approach. Taking the use of serious gaming as a case in point, Chapter 2 started by showing that the current generation of serious games that aim to be useful in reality fail to do so. The chapter presents the very first study that tested for transfer from a myogame to prosthesis use, and showed that getting transfer between tasks, even if the game is successfully learned, is far from trivial. The chapter moreover highlights the task-specific nature of the skill learned when myogaming—an aspect easily missed if one does not adopt an activity based approach.

Faced with the lack of transfer effects, Chapter 3 showed what it takes for transfer to occur within the context of using EMG to perform a goal directed task. It showed that in the early formation of an action system both environmental and anatomical aspects, as well as the relation between the two equally contribute to the skill that is being learned. In particular, it showed that although an action system is a functional unit, at least in early learning, the function to which it pertains is also differentiated relative to the anatomical structure that enables goal-attainment. That is, while it may be unsurprising to find transfer based on retaining the same goal across performances, this study showed that merely retaining the same musculature for exploration will also enable transfer. The chapter ended by drawing out some of the theoretical and practical implications.

Capitalizing on these findings, in Chapter 4, the goal, musculature and settings of the myogame are chosen such that we could expect transfer to prosthesis use. Since there are nonetheless many factors that differ between a myogame and grasping with a prosthesic simulator in real time, it took implementing additional goal-relevant feedback to successfully set up an action system that incorporated a myoelectric interface in such a way that it could be adapted to a prosthesis task in daily life.

Exemplifying the theory of action systems further, Chapter 5 introduced its approach to learning through a study of tool making behavior. Chapter 5 showed how an action system for creating tools forms out of cycles of perceiving and acting. It emphasized principle direction in which learning, as the formation of an action system, moves. As one learns, the system comes to rely more and more on the particulars of the task it aims to perform. Learning, that is, is considered as a process of increasingly relying on task specific aspects of the environment.

Following these empirical studies, the thesis explored how the action systems perspective differed in its background assumptions from the traditional approach adopted in rehabilitation medicine. It was argued that the traditional "reductive" methods and theories inherently displace "emergent" initiatives. Consequently, it was argued that when it comes to motor learning the emergent perspective that gave birth to the theory of action systems should be given autonomy if it is to inform rehabilitation theories. Chapter 6 ended by concretizing the issues in terms of transfer. While traditionally transfer is a mere consequence of a covert learning process with little theoretical relevance, it was claimed that in the actionoriented approach transfer gains significance. Transfer, that is the change in performance of a task following the performance of another task, is taken as an empirical measure of continuity across tasks, which can help to understand the limits and possibilities of an action system.

In the remainder of this epilogue some of the most important implications of the findings presented above will be taken up and related to rehabilitation practice. The focus will be on three issues. First, it will revisit the notion of "transfer." Second, the use and limits of serious gaming will be discussed as they were encountered in this thesis. Third and finally, the epilogue will point out the value and reality of practice.

7.2 Transfer: from assumed similarity to visible differences

This thesis started by pointing out that embracing novel technology led rehabilitation science to increasingly remote and artificial solutions to motor (re)learning problems. The recent adaptation of serious games being a case in point. Learning to master such games, and moreover getting them to be relevant for the daily lives of patients, it was argued, is far from trivial (see Chapter 2, 4 and 6). This emerging technology inadvertently made a new case for the relevance of theories of learning within rehabilitation science, and hence, for a multitude of perspectives that may inspire them. The argument was that as engineering solutions increasingly change the tasks that patients need to perform in order to improve ADL, we need a perspective that gives us theories that point back to ADL. The action perspective does this by not assuming underlying (computational) similarity, but by primarily acknowledging the *differences* across task ecologies.

One of the most important empirical tools to do so is by measuring transfer. As we have seen in Chapter 6, from a reductive point of view, when learning a skill, an underlying faculty is developed inside the learner and this faculty is then supposed to be actuated across different situations. Finding transfer across tasks is then evidence for having retained this underlying faculty. Practically, this conceptual scheme leads scientists to favor laboratory tests that tap into the underlying faculty directly over doing "messy" testing of transfer to a prosthesis task, let alone to an ADL task—testing that is hard to standardize and control experimentally. This I believe is the reason why, before the publication of Chapters 2 and 5, myogaming research had never looked into transfer to prosthesis use.

Similarity across tasks, from an emergent point of view, is achieved as a continuous *outcome* of situated performances over time and not the internal source of such performances. The limited case of transfer, from this point of view, is simply repeating a task. As one learns, having performed a task once readies the learner to refine on the next task performance (i.e. it allows one to do it better the next time around): there is thus arbitrarily "transfer" in learning a task from one performance to the next. The very fact that a task has been performed before makes a (quantifiable) difference to subsequent performance. During learning, the functional fit between the organism and its environment grows tighter (see Chapter 3 and 5).

However, in order to remain functionally adapted to an ever changing environment it has been stressed in this thesis that learning should be conceptualized as a process of "differentiation" (J. J. Gibson & E. J. Gibson, 1955). Through exploration, the system aims to notice differences, rather than similarity, across situations (see e.g. Chapter 3 and 5). Within a task, learning a skill thus cultivates a selective openness to new possibilities for action (H. L. Dreyfus & S. E. Dreyfus, 1987; Reed, 1996; Rietveld & Kiverstein, 2014). By remaining open to adapt to the environment, a continuity across performances emerges despite changes in the environment (in which case one is said to have a "skill"). It is this continuity in the dynamics of the organism–environment system that is quantified in different ways by measuring either learning or transfer effects.

From this point of view, finding transfer across tasks, as we did in Chapter 3 and 4, thus teaches us something about the continuity in or stability of the fit that the organism-environment system has established as a whole. With respect to the acting organism, it shows to what extent the organism had remained open enough to achieve continuity in its relation to the changing environment over time.¹

Notice that this way of thinking about transfer is a reversal of the traditional view. If similarity is an emerging outcome of a developing organismenvironment system, rather than the source of an organism's performance, then a transfer effect is an empirical measure that characterizes the functional limits of the developing organism–environment system—that is, it helps to determine what aspects of a task are functionally relevant to the system as it has developed so far. As shown in Chapter 3, testing for transfer is then the principle method at our disposal for quantifying the development and functional limits of an action system.

7.3 The limits and use of serious gaming

Serious gaming in rehabilitation is a technological answer to a motor learning problem. Of course, serious games can have aims other than motor learning even within the context of prosthesis use. The loss of a limb has psychological and social dimensions that might be targeted, and serious games could also turn out to be beneficial in for example reducing pain, improving a patient's image of the body, or reducing muscular atrophy.

¹One theory that comes close to formalizing this idea is the theory of direct learning (Jacobs & Michaels, 2007). It differs from the view I am trying to get at here, in that this theory assumes yet another, even more abstract, underlying similarity (in information) to account for the continuity over time. In the foregoing discussion I have been trying to get away from this assumption.

These possible applications however are beyond the scope of this thesis. In this thesis I have focused on the aim of serious games to provide skills that are useful in reality (Bergeron, 2006; Graafland et al., 2012), the question whether they have actually done so however, at least within the field of myogaming, remains to be determined. Herein lies an important task for future research.

An important reason why getting myogaming skills to be useful in reality is far from trivial is the reductive assumptions on which the design of serious games is based. The thesis has taken up the issue of a reduction of activities to body-functions at length. However, there is a second type of reduction that was not discussed and that serious gaming engenders: the reduction of the activity of the learner to the movement of an avatar (end-effector) on the screen.

Considering the reduction of the activity to its end-effector has not been explored in this thesis, but it is potentially of great importance. Looking at the experiment presented in Chapter 3 most of the situation that enables the myogaming tasks to be performed remains constant over sessions and across tasks. From the interaction with the experimenters, to the chair and layout of the room as well as much of what happens on the screen, all persists as a background to both training and testing performance. Rather than focusing narrowly on the goal on the screen, we should take note of the background coordination of the actual participant in the particular (and social) behavioral setting with which he is learning to cope (see e.g. the classic work of Lee & Aronson, 1974, see also Schöner, 1991, to get an idea of the importance of such background coordination).

In other words, the goal of the participant was not just to achieve a high score on the game, it was also to cope with a largely unfamiliar experimental situation—for which the game was merely a means. If, as I have suggested, transfer is a function of the continuity of the organism-environment system, then maintaining such standardization might be doing more than reduce unwanted "contextual interference." Minimally, it is the way this setting is furnished that allows for the events on the screen to make a difference to its behavior (Danziger, 1997; Heft, 2007), but it might also be this background coordination that accounts for much of the transfer (i.e. achieved similarity) across otherwise widely differing tasks. A true

ecological theory of learning within rehabilitation science will have to start dealing with this. Future research needs to focus on this—both in its theory and in experiments—as it may be an important aspect to understand when aiming to transferring skills from virtual reality to that of the rest of our ecological niche. Moreover, the same principle might apply when transferring skills from experimental and clinical settings to the daily life of a patient.

7.3.1 A new hope

All this being said, the emergent perspective and the theory of action systems in particular offer important ways in which virtual technologies (chiefly serious games, but also virtual and augmented reality) might benefit skill acquisition. In Chapter 6 it was argued that serious gaming tends to cut up skills along body-functional rather than along task-functional dimensions. That is, if learning a skill is learning to differentiate and find the distinctions in the environment that matter to goal attainment, one way in which virtual technologies might foster motor learning is by adapting the task to the performers' level of skill and then capitalize on the differentiation process to get the performers to the task of daily life it ultimately aims for. This can be done first by remaining close to the task of ADL and then adding particular feedback that enables the calibration process to function across tasks and second by simplifying the ADL task so that the exploration of the task space can be guided until the proper system has been set up. Let us briefly look at both in turn.

In Chapter 4 it was shown that if we add feedback to a gaming task that emphasizes the relative opening (and the closing force) of the virtual hand in such a way that it mattered to goal attainment, participants attend to these aspects in the prosthetic simulator task as well. From an action system perspective, this can be understood as having developed an action system in the training task that can be re-assembled and calibrated to fit the testing task. Such an interpretation also fits the observation that the opening of the prosthesis grew better adapted during the posttest as a proper calibration was achieved (see Figure 4.10). By having a gaming task be similar to the testing task (or the task in ADL) with respect to the information used for calibration, the game might enable transfer across performances. The next generation of serious games might hopefully develop such a theory further and design games accordingly.

A different way to get the most out of virtual technologies might lie in simplifying the task that the developing action system needs to perform. This can be achieved by making it easier to obtain and maintain a proper relation to perceiving and acting and then slowly but surely increasing the difficulty until the task gets a sense of ecological validity. In this way, serious games or other virtual technologies might help guide the exploring and differentiating action system towards the best, i.e. most ADL relevant, fit with its environment. In Chapter 3 we find some evidence for this idea in the fact that in an undifferentiated system, even a task such as intercepting a ball can help the system to improve performance of a grasping task despite a lack of similarity in goals. A possible interpretation of this finding was that the way in which the musculature was starting to get used, differentiated the system in such a way that it enabled an ability to quickly explore the testing task along a relevant dimension.

In principle, simplifying the task can be done not only by simplifying the action necessary to perform it, but also by simplifying the perceptual effects used to guide this action. Experimental evidence of this comes from Mechsner, Kerzel, Knoblich, & Prinz, 2001, who had subjects rotate two pegs with their arms at a relative phase of 4:3. Normally, such a pattern is almost impossible to perform. However, by transforming the pattern visually to "simple" in-phase (1:1) movements of the pegs, the 4:3 movement pattern was guickly learned. Although transfer to more complex perceptual feedback needs to be determined (see but Kovacs, Buchanan, & Shea, 2010), it will be particularly interesting both practically and theoretically, to find out to what extent such processes can help in the development of an action system. Virtual environments offer the appropriate tools to do so. They might offer an important way to scaffold a task to an individual's needs in such a way that it will transform a virtual gaming skill to an everyday activity in daily life. It will be very interesting to see how future research might make use of these findings.

7.4 The reality of practice

In this thesis, we have seen the many realities of practice. First, the importance of transfer of skill was given new theoretical significance. It allowed us to bring out the importance of differences across concrete performances rather than remain focused on abstract similarities. Second and related, the action system approach brought into view the fact that a "virtual" task is a concrete task like any other and one that often has more differences than similarities with the tasks they "simulate." Virtual reality is thus still a practical reality as any other. Third, the continued and even increasing importance of patients practicing and getting skilled for assistive technology to become effective technology was reasserted. This suggests that our ability to adapt and become skillful should not be engineered away but should be embraced and made use of—and serious games, as was argued above, might actually offer a way of doing so. Fourth, in this final section, one last reality of practice will be drawn out.

What this final dimension of practice aims to make clear is that the methods and tools at the disposal of rehabilitation science, as well as large parts of human movement sciences, force us down a particular reductive direction of inquiry. In this reductive view we start to look for the source of action in their "underlying" movements (see also Chapter 6). As Reed reminded us however: movements need not be considered the constituents of action but can be viewed as measurable consequences of action. That is, by tracing displacements over time, we can focus on persistent aspects of action. Or we can, for particular purposes, define action in terms of stability or flexibility of movement (Schöner, 1995). We can even define them in terms of their environmental relata or in fully relational terms (e.g. Chapter 2 and 5). The thing is however, that none of these operationalizations (although often useful in particular cases) gets to an essence of action. They are always quantifying an aspect of action—and hence entail a transformation of that phenomenon, enabled by much more actions then we can hope to explain.

This does not make actions less real—quite the contrary. But it does make them harder to reduce to a quantity. As William James pointed out, the perspective that takes movements as the source of action can be viewed as "abandoning the empirical method of investigation" (James, 1890/1950, p. 224). That is, our methods and definitions should not start to live a life of their own and taken as the source rather than the consequence of action. The final dimension of our reality of practice is thus the reality of our own scientific practice. It urges us to stop taking our empirical method for granted and take the merits and its limitations of our own empirical devices much more seriously—this is the most important recommendation for future research this thesis offers.

It is in fact the main change in perspective that this thesis has aimed to bring about. The perspective inspires to see the possibilities and limitations of our own scientific gains (see Chapter 1 and 6). It begs us not to let either the engineering protocols or empirical methods dictate the reality we are after. If we can adopt such a way of looking at our scientific practices, then we might just be able to remain open enough to allow for fundamentally new ways of approaching problems to emerge—and we may learn to see the value in developing theories along the paths less traveled.

Knowledge and skill

A

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Abstract

Recently Stanley and Krakauer (S&K) (2013) argued against a tendency in neuroscience to treat skills independently from knowledge. Although we are sympathetic to this aim, in this commentary we suggest that S&K's philosophical treatment still propagates such independence, as they give ontological priority to knowledge from the onset. The authors fail to see that they argue against a philosophical perspective that aims to overcome exactly this tendency of giving ontological priorities. Contrary to S&K's claim, Dreyfus' tradition does not deny the reality of knowledge or any other aspect of human life typically assigned to lower levels of description. However, it does deny the re-conceptualizing of these aspects as states below apparent behavior. Recognizing this "horizontal" approach corrects S&K's assertion that neuroscience has to date been mirroring this philosophical tradition. S&K refreshing look at neuroscientific data rightfully showed that both knowledge and skill co-exist as aspects of human life. But to make this claim stick, rather then dismissing modern philosophy, they ought to embrace it in full.

A.1 Introduction

In this commentary on "Motor skill depends on knowledge of facts" by Stanley and Krakauer (2013) (henceforth, S&K) we aim to sketch an apparent contradiction in S&K's argument on the dependence of skills on knowledge of facts. We contend that S&K's plea for this dependence stems from another form of independence of knowledge and skills—namely an "ontological" independence. We show what this means by introducing the difference between theories that are hierarchically organized, where one level has priority over another level, and theories that do not assume such an organization. We believe neuroscience and psychology have a lot to gain by taking note of these distinct attitudes, as they lead to radically different directions of inquiry and explanation. We shall show this by explicating the attitudes throughout S&K's argument, as that will go toward resolving the apparent contradiction.

In their thought provoking article S&K call into question the generally accepted view that skills are independent of knowledge of facts. After sketching a historical and philosophical context, S&K provide clarification of often confusingly applied notions as propositional or declarative knowledge, perceptual acuity, and the likes. The authors carefully argue against giving necessary and sufficient conditions for either skills or knowledge. To make their claim against independence S&K propose, to our delight, to look for knowledge and skill within the situation in which they are shown.

In making their claim, S&K seem to draw an analytical distinction between knowledge of facts and skills. As agents always need to "know what to do to initiate the actions that manifest a skill" (Stanley & Krakauer, 2013, p. 5),¹ S&K assert that skills cannot be said to be independent of knowledge of facts. Neuroscientific data too, such as those from studying HM, are taken to show that HM always needed "explicit" instructions and needed to "use that knowledge each time" (p. 8) in order to learn a skill. In fact, because HM did not show his skills without these instructions, he cannot be properly said to have skill at all. Rather, he has what S&K call "motor acuity."

¹All subsequent page numbers in this Appendix refer to (Stanley & Krakauer, 2013).

With this reasoning S&K however, do not only argue against the independence of knowledge and skill, they make the stronger claim that knowledge is always *prior* to skill. They assert that knowledge is minimally a state with propositional content used for guiding actions (p. 1). Together, knowledge thus, works as a distinct state that first initiates and subsequently guides motor acuity. As such knowledge is treated as an isolated state that, together with motor acuity, underlies skill. So although S&K claim knowledge and skill should not be taken to be independent, their account shows that the dependence is a superficial one. That is, S&K argue for physical dependence by creating ontological independence. Not only are knowledge and skill thus, still independent entities, *ontologically* knowledge is even prioritized. It is this perspective that prompts S&Ks conclusion that skills depend on knowledge of facts.

Although we are sympathetic to the claim that skills and knowledge of facts are strongly dependent notions, it is this ontological priority we aim to argue against here. We will start with a brief correction of S&K's historical overview, as we believe it both shows and propagates a misunderstanding at the heart of their view. Subsequently, we will argue for a point that S&K did not recognize, namely that the tradition of Merleau-Ponty, Wittgenstein, and Dreyfus was aimed at overcoming exactly the tendency to find ontological priorities. That is, for them knowledge and skills stand on equal footing, rather than the one underlying the other. Once we showed this, S&K's reading of these philosophers is easily identified as inappropriate. On a proper reading the question of (ontological) priority should not come up. Finally, we assert that taking Dreyfus seriously indeed makes a good argument against the independence of skills and knowledge of facts, and from this perspective S&K's re-interpretation of HM and other neuroscientific data offer a new look at neuroscientific literature. However, we shall argue that this is not, as S&K suggest, because we finally free neuroscience from the influence of the "predominant" 20th century tradition. Rather, it is by finally embracing such a tradition that neuroscientific data can be seen afresh.

A.2 Modern philosophy and neuroscience

Before moving on to our main argument, it is worth pausing at one of the historical claims S&K made. They assert that the anti-cognitivist view of Dreyfus, which follows the tradition of Merleau-Ponty and Bourdieu (and we may add Heidegger and Wittgenstein) is in fact the dominant view in philosophy and the social sciences, and that neuroscience mirrors this philosophical literature (p. 2). Their overview suggests thus, that neuroscientific theorizing is held hostage by an anti-cognitivist perspective that separates knowledge of facts from skill and empirical studies in neuroscience do no more than mirror this philosophical thesis.

This, we believe, is a false rendition of the history of cognitive neuroscience and its psychological and philosophical antecedents. The dissociation of knowledge of facts from skill in neuroscientific literature echoes the distinction between (perception), cognition and action that comes with the dominant computer metaphor (of input, processing, and output) of the 1960's onward (see e.g. Boden, 2006; Hurley, 2002; Posner & DiGirolamo, 2000). The computationalist view that cognition is the computational manipulation of representations (e.g. A. Newell & Simon, 1976) in turn has its roots in Cartesian philosophy of the 17th century that placed the mind in a the mechanistic body (Boden, 2006). This idea was propagated in philosophy, and re-affirmed in psychology as thought and action were made to fit the emerging psychophysical methods (through e.g., Wundt and Titchener), ending up with cognition as an invisible internal state that constructs percepts from incoming sensations, and coordinates movements by outgoing motor commands.

Notice how in this historical picture theorizing is informed by a belief that for understanding the mind, it makes sense to look for underlying elements that cause it. Direction of inquiry is thus, vertically directed. For example, perception is made up of underlying elementary sensations, and skills are nothing but movements guided by cognitive commands (what S&K would call "knowledge of facts"). It is exactly this analytical, intellectualist attitude that Dreyfus, Merleau-Ponty, but also Ryle and Wittgenstein, each in their own way, aimed to displace. But their role has thus, certainly never made the impact on (cognitive) neuroscience S&K claimed it does. To date it has been limited to but a view prevailing non-representational or non-computational approaches to psychology (e.g. Chemero, 2009; J. J. Gibson, 1979; Reed, 1996; Kelso, 1997; Thelen, Smith, Karmiloff-Smith, & Johnson, 1994).

A.3 A horizontal approach

So much for the groundwork, now on to our main argument, because the view S&K claim Dreyfus' tradition holds is itself also misguided. For this we find it useful to distinguish two basic ways of directing inquiry in philosophy (and psychology). First, there is the attitude that we just exemplified in the preceding section. It roughly conceives the world to be composed of supervening layers, e.g., going up from atoms to cells to brains and minds. This is often associated with reductionism (though it need not be), internalism about mental life, and with physicalism; conceiving of cognitive states—like knowledge—as something you have as a (physical, informational) state or process. Elsewhere, we have called this approach to psychology a "vertical worldview," as it shows a tendency to explain (empirical) phenomena by analyzing downward to underlying (and often hidden and abstract) essentials (Van Dijk & Withagen, 2014).

In contrast to a vertical worldview, Wittgensteinian and Heideggerian traditions approach their subject more horizontally. Metaphorically, this attitude does not start out with a layered structure, and phenomena are not relocated along a vertical axis, but keeps to a horizontal plane. That is, the attitude resists the urge to analyze beyond the phenomena in search for essence, and locates both large and small scale phenomena at the same level (Van Dijk & Withagen, 2014). This means that understanding phenomenon requires seeing in what particular, concrete situations it actually does or does not play a role. To explain a phenomenon, such as knowledge, a horizontal approach thus, looks at the particular, concrete situation in which it actually comes up, rather than treating all particular cases as similar and trying to derive abstract underlying essences from that (see also Wittgenstein, 1969, §10).

Importantly, a horizontal approach does not deny the reality of cognitive states or any other aspect of human life typically assigned to lower levels of description. However, it does deny this reconceptualizing of knowledge as a state below apparent behavior. So, for example, Merleau-Ponty's denial that skilled behavior manifests cognitive states (p. 2) is not a denial of experts having knowledge, but a denial of the identification of cognition (knowledge) with an underlying (guiding) state. In short, much like S&K, the horizontal approach aims to direct attention to the concrete performances of skill in particular situations to explain knowledge of facts. However, the focus of inquiry remains with these concrete performances and does not subsequently analyze to an ontological priority beneath it.

It is much more fruitful, we feel, to also read Dreyfus' work from this horizontal perspective. In his phenomenological analysis of skill acquisition, Dreyfus brings to view the fact that as one learns, one grows into a concrete situation; getting more in touch with the world, rather than abstracting away from it by constructing abstract rules (e.g., propositional knowledge) to guide engagement. To Dreyfus, skill acquisition is not a vertically directed process of going from concrete sensorimotor couplings (e.g. Piaget, 1954) upwards and inwards to abstract generally applicable rules. Rather, skill acquisition moves horizontally from abstract instructions (because they lack application) to concrete, highly adaptable, perceptual–motor behavior.

Thus, from a horizontal approach Dreyfus' assertion that expertise does not require unconscious rules should not be read as a plea against experts having knowledge, but against assigning knowledge one level below concrete behavior to a hidden state (with unconscious propositional content). That experts do not fall back on explicit rules when performing therefore, does not mean that they lack knowledge or are not knowledgeable, in fact, it shows that they have knowledge galore. Interestingly, S&K argue basically the same, however, they feel the urge to subsequently suppose that having this expert knowledge requires a hidden layer of propositional content. Dreyfus' horizontal attitude, by contrast, resists such an analytical abstraction away from the actual phenomenon.

We believe that because S&K have given an overly vertical reading of Dreyfus, their argument misses the mark. Their rendition of the historical and ontological commitment of Dreyfus' tradition shows that the authors might themselves be deeply influenced by an intellectualist, vertical approach to psychology and (cognitive) neuroscience. Because of this S&K failed to see how close to Dreyfus they actually get.

A.4 Concluding remarks

In this short commentary we hope to have shown the limits of S&K's analysis of the relation between skills and knowledge and its history in philosophy. We did so by pointing to an ontological distinction between vertical and horizontal approaches to the subject. We believe a study of skills, knowledge, and any other aspect of human behavior has much to gain from considering a horizontal approach. The horizontal view on skill acquisition and the role of perceptual and motor acuity has for example important consequences for developing theories and hypotheses in motor control and important implications for neuroscientific research.

We believe that S&K have offered us a compelling empirical argument against the independence of skills and knowledge and an important reinterpretation of seminal neuroscientific literature. They showed that both knowledge and skills are aspects of one and the same world of everyday life. But rather than dismissing Dreyfus' tradition, we hope to have shown that they ought to embrace the tradition fully to make their claim against independence. Maybe this will inspire neuroscience to consider a horizontal approach to their role in psychology. This, we feel, would have mutually beneficial effects for both psychology and neuroscience.

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Abstract

The aim of this thesis is to introduce an action systems approach to rehabilitation science. More precisely, this thesis aims to promote a perspective that gives action, or activity, primacy in thinking about motor learning issues in rehabilitation. It will do so by focusing on the assumptions on which the adoption of serious gaming for prosthesis use is based.

To make room for considering a novel perspective on motor learning in rehabilitation, the first chapters of the thesis will empirically evaluate the current generation of myogames. Such games are of particular interest because they are used to train patients to become dexterous at using a prosthesis, yet they have never been tested for their effect on prosthesis skill. Moreover, the use of myogames requires learning to modulate electric currents that are usually only a by-product of a goal directed action. It will be argued that the rationale for conversely using electric currents to control such actions is typical for the traditional view on motor learning.

In Chapter 2, a simple myogame called "Breakout-EMG" is introduced. Using a pre-posttest design with a control group it is shown how the ability to play this game is quickly learned: the experimental group increases its accuracy in playing significantly over controls. Such motor learning however has no measurable consequence for the ability to use a prosthesis in a transfer-task. Using a simple prosthesis task in which participants needed to grasp objects, we were unable to find any changes in performance measures relative to controls. Crucially, it is shown that during the learning of the game, a highly task-specific modulation of the myoelectric signal occurs. The experiment showed that getting myogaming skills to transfer to a prosthesis task is far from easy and suggests that "myoelectric control" might not exist independently of the task in which such control is shown. Chapter 3, explores this idea further by studying a different myogame in which falling objects needed to be caught or intercepted. Three experimental groups and a control group were used in a pre-posttest design. The aim was to determine to what extent the goal of the game and the specific muscles involved in generating the signal matter to goal attainment. The study systematically varies a myoelectric gaming task and looks for transfer to a standardized myogaming task. The observed change in accuracy indicated that retaining the goal of the task or the musculature used will equally increase transfer performance relative to controls. Conversely, changing either the goal or the musculature will equally decrease transfer relative to training the test. The results presented in this chapter suggest that early in learning the task to which the system pertains is not specified solely by either the goal of the task or the anatomical structures involved. It is suggested that functional specificity and anatomical dependence might equally be outcomes of continuously differentiating activity.

Capitalizing on the findings presented above, in Chapter 4 an empirical experiment is presented in which several myogames are compared to a myogame that includes additional task-relevant feedback. Based on the functional nature of action systems, specific forms of augmented feedback might offer a way of increasing the continuity in performances across tasks. Again, a pre-posttest design with controls is used. After showing in-game learning effects for all experimental groups, it is shown that the ability to adapt the aperture of the prosthesis hand to the size of the object that needs to be grasped, as well as the ability to adjust the hand to the compressability of the objects improves only in the group that was provided with relevant in-game feedback. It is concluded that in order to have myogaming skill transfer to prosthesis use the game needs to incorporate feedback that is relevant to the gaming task but also, crucially, to the prosthesis task it sets out to improve.

Having provided empirical reasons for doubting the effect of the currently generation of myogames that grew out of the traditional perspective on motor learning in rehabilitation, and having provided positive evidence that a task-centered action systems approach might provide a more promising framework, this thesis focuses on the (meta-)theoretical underpinnings of the action systems approach.

In Chapter 5 the notion of 'action systems' is introduced through an empirical experiment. In this experiment participants created tools out of different unfamiliar materials while their eye movements are recorded. Participants had to perform a everyday task that required them to construct a tool for either scooping, prodding, or cutting. We monitored gaze and the objects manipulated over learning. Performance got more efficient across trails: trial duration as well as the number of fixations decreased, while the goal-directedness of gaze increased. The first trial had only a few goal directed fixations before trial and error constructing commenced. Halfway through learning, the goal-directedness also started low but increased sharply during subsequent exploration. Finally, having learned to create the proper tool, gaze was highly goal directed from the start and construction started immediately. The point of this chapter is thus to show how an action system for creating tools forms over time, and how cycles of perceiving and acting (looking and manipulating) nest within one another to form functional unities at increasingly broad scales. The theoretical implications of this chapter are taken up further in the thesis' Appendix.

In an action systems approach, the function of any anatomical aspect (such as the electric signals in the first chapters and the eye movements in Chapter 5) depends on the function of the action system it is involved in. Finally, Chapter 6 explicates exactly what this means and how this relates to the traditional view on motor learning in rehabilitation. By considering how rehabilitation in practice answers the question of what parts an activity consists of, reductive and emergent approaches to motor learning are identified. The chapter shows that when a task is cut up along reductive dimensions while also apparently relying on emergent components, this unequally favors the reductive approach and acts to limit the views on motor learning available. This theoretical chapter aims to explicate a fundamental departure from the traditional view on motor learning that is required for an action systems approach to inform rehabilitation research. It requires prioritizing the task-specific and context sensitive constitution of action.

In the epilogue some wider implications of this view are discussed, the topics of transfer is revisited and the merits and limits of serious gaming are discussed from an action system perspective. Based on the perspective promoted in this thesis the epilogue ends with a plea for acknowledging the reality of practice.