Linköping Studies in Science and Technology

Dissertation No. 1551

Simulations

by

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Linköping 2013

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Cover artwork “Refinements” by Serge Thill

ISBN 978-91-7519-491-2
ISSN 0345-7524
Printed by LiU-Tryck 2013

URL: <http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-98050>

Preface

The thesis consists of a coherent, but condensed and partly updated, description of the contents and contributions of the included papers (as well as the previous licentiate thesis) and the included papers themselves, as follows:

Paper I Svensson, H. & Ziemke, T. (2005) Embodied representation: What are the issues? In: B. G. Bara, L. Barsalou & M. Bucciarelli (Eds.), *Proceedings of the Twenty-Seventh Annual Conference of the Cognitive Science Society* (pp. 2116-2121). Mahwah, NJ: Erlbaum.

Paper II Svensson, H., Lindblom, J., & Ziemke, T. (2007) Making sense of embodiment: Simulation theories of shared neural mechanisms for sensorimotor and cognitive processes. In T. Ziemke, J. Zlatev & R. Frank, M. (Eds.), *Body, language and mind. Volume 1: Embodiment* (pp. 241-270). Berlin: Mouton de Gruyter.

Paper III Svensson, H., Morse, A. F., & Ziemke, T. (2009) Neural Pathways of Embodied Simulation. In: G. Pezzulo, M. V. Butz, O. Sigaud & G. Baldassarre (Eds.), *Anticipatory Behavior in Adaptive Learning Systems*. LNCS, 5499 (pp. 95-114).

Paper IV Svensson, H., Morse, A. F., & Ziemke, T. (2009) Representation as Internal Simulation: A Minimalistic Robotic Model. In: N. Taatgen & H. van Rijn (Eds.), *Proceedings of the Thirty-First Annual Conference of the Cognitive Science Society* (pp. 2890-2895). Austin, TX: Cognitive Science Society.

Paper V Thill, S., & Svensson*, H. (2011) The inception of simulation: a hypothesis for the role of dreams in young children. In: L. Carlson, C. Hoelscher & T. F. Shipley. (Eds.), *Proceedings of the Thirty-Third Annual Conference of the Cognitive Science Society* (pp. 231-236). Austin, TX: Cognitive Science Society.

Paper VI Svensson, H., Thill, S. & Ziemke, T. (2013) Dreaming of electric sheep? Exploring the functions of dream-like mechanisms in the development of mental imagery simulations. *Adaptive Behavior*, 21, 222-238.

* Both authors contributed equally to the writing of the paper (Thill & Svensson, 2011). The paper consisted of three parts: (A) *Introduction*, (B) *The role of dreams in the inception of simulations*, and (C) *Discussion*. Although a joint effort, Thill wrote most of the second half of A, the first half of B, the first half of C, and Svensson wrote most of the first half of A, the last half of B, and the remaining half of C. Thill also finalized the paper and submitted it. An anecdotal detail is that the main idea of the paper was conceived during a coffee break conversation between Svensson and Thill.

Additional work

Other contributions of the author include the following papers:

Lindblom, J. & **Svensson**, H. (2012) Kognitionsvetenskapens historia [The history of cognitive science]. In: J. Allwood & M. Jensen (Eds.), *Kognitionsvetenskap* [Cognitive Science] (pp. 35-45), Studentlitteratur. [in Swedish]

Malmgren, H., Hemeren, P. E., **Svensson**, H. & Haglund, B. (2012) Begrepp och mentala representationer [Concepts and mental representations]. In: J. Allwood & M. Jensen (Eds.), *Kognitionsvetenskap* [Cognitive Science], (pp. 175-190) Studentlitteratur. [in Swedish]

Thill S., **Svensson**, H. & Ziemke, T. (2011) Modeling the development of goal specificity in mirror neurons. *Cognitive Computation*, 3, 525-538.

Acknowledgements

It took me a tad longer than expected to complete this thesis, nevertheless, it was mostly a great journey and I bring with me from this experience many happy memories (the agonizing moments and doubts, that I must have had, are already forgotten). The completion of the thesis can be said to have progressed through three different stages with different persons contributing to the process in each stage during roughly ten years, but with one constant - my supervisor Professor Tom Ziemke. I am forever grateful for all the help and advice that Tom has bestowed upon me during all this time.

But, as I said, the work has progressed in stages and I have more people to acknowledge. Lets begin with the final stage (by which time I actually had an office of my own). I am very much indebted to Serge Thill, also my co-supervisor, for providing the inspiration and motivation to produce the papers that finally lead to the completion of the thesis. I am also grateful for his advice and comments on the thesis. I also would like to extend my thanks to Anne Moe for support and guiding me through all the administrative procedures at Linköping University during this stage.

The middle stage happened when I shared office with among others Anthony Morse, and Robert Lowe, who were working hard on a then ongoing research project and made it a very interesting work place. I am grateful for our discussions, and especially grateful to Tony, for pushing me into starting programming and building my own computational models as well as advice and comments on papers.

The first stage was mostly about trying to find a direction for the thesis, exploring many different alternative paths of research. During this stage I shared office with Jessica Lindblom and Tarja Susi, who had started their projects a couple of years earlier than me and could provide useful discussions, advice and comments on what eventually became my Licentiate thesis, for which I am most thankful. Jana Rambusch and Maria Nilsson also provided valuable comments and discussions on the Licentiate thesis.

I am also grateful to have been working at the University of Skövde with great colleagues, especially in the cognitive science group, but who shall remain nameless because of my fear of forgetting someone that mattered.

Privately speaking, I could not have finished the thesis without the support of my family: My Mom and Dad (thanks for your never ending support), the love of my life Jennie (who makes me happy), and eventually my children Stella and Theo (who gave new meaning and joy to my life).

Abstract

This thesis is concerned with explanations of embodied cognition as internal simulation. The hypothesis is that several cognitive processes can be explained in terms of predictive chains of simulated perceptions and actions. In other words, perceptions and actions are reactivated internally by the nervous system to be used in cognitive phenomena such as mental imagery. This thesis contributes by advancing the theoretical foundations of simulations and the empirical grounds on which they are based, including a review of the empirical evidence for the existence of simulated perceptions and actions in cognition, a clarification of the representational function of simulations in cognition, as well as identifying implicit, bodily and environmental anticipation as key mechanisms underlying such simulations. The thesis also develops the “inception of simulation” hypothesis, which suggests that dreaming has a function in the development of simulations by forming associations between experienced, non-experienced but realistic, and even unrealistic perceptions during early childhood. The thesis further investigates some aspects of simulations and the “inception of simulation” hypothesis by using simulated robot models based on echo state networks. These experiments suggest that it is possible for a simple robot to develop internal simulations by associating simulated perceptions and actions, and that dream-like experiences can be beneficial for the development of such simulations.

This work has been supported by the University of Skövde, where the author has been employed during his PhD studies.

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Populärvetenskaplig sammanfattning

De flesta av oss kan forma olika typer av mentala bilder i huvudet. Till exempel om jag ber dig att tänka på ett äpple kanske du formar en inre bild av ett grönt äpple och kanske till och med kan känna den syrliga smaken när du sätter tänderna i äpplet. Den grundläggande tesen i den här avhandlingen är att många av våra högre tankeförmågor som förmågan att forma mentala bilder, begreppsbildning, och språk är grundade i våra kroppsliga förmågor. Att du förstår vad ”begripa” betyder är grundat i din förmåga att gripa tag i något – precis som du kan gripa tag i något kan du gripa tag i ett ämne eller en idé.

Mer specifikt handlar avhandlingen om hur vi kan forma inre kedjor av sådana här återaktiverade kroppsliga tillstånd som ofta endast då är representerade i hjärnan och som vi därför kallar för simuleringar. Men dessa simuleringar kan ibland även synas i kroppsliga funktioner. När vi tänker på fysiska aktiviteter som till exempel att springa en runda i skogen kan vår andning och hjärtfrekvens öka i takt med att vi föreställer oss att vi springer fortare (dock inte lika mycket som när vi faktiskt springer).

Genom att sammankoppla simulerade perceptioner och handlingar på ett sätt som indikerar vad som kommer hända härnäst kan vi förklara vår förmåga att dels tänka på saker som inte finns här och nu men också vår förmåga att agera på ett så bra sätt som möjligt i en komplicerad värld där vi måste testa en del idéer i vårt huvud innan vi testar dem i verkligheten.

Avhandlingen utvecklar också hypotesen att en funktion av våra drömmar under vår barndom är att hjälpa hjärnan att utveckla förmågan att skapa den här typen av simuleringar som också kan användas medan vi är vakna. För att testa denna idé konstruerades en enkel robotsimulering där roboten fick ta del av drömliknande stimuli innan den skulle lära sig att forma simuleringar vilket visade sig vara fördelaktigt i jämförelse med roboten som inte fick dessa drömliknande stimuli.

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1 Introduction

The word simulation is used in a variety of domains, from computer games to the design of factories. The term often implies a process or mechanism that can be used *as if* you are using something not actually present in time and/or space. This is also an important aspect of the notion of simulation developed in this thesis, where simulation is applied to cognition. For example, Rumelhart, Smolensky, McClelland, and Hinton (1986) suggested that a neural network could construct a mental simulation by having a network take an action specification of an action to be executed and produce a prediction of the perceptual consequences of that state, consequently using the prediction in stead of environmental inputs:

... [a] relaxation network, which takes as input some specification of the actions we intend to carry out and produces an interpretation of 'what would happen if we did that.' Part of this specification would be expected to be a specification of what the new stimulus conditions would be like. Thus, one network takes inputs from the world and produces actions; the other takes actions and predicts how the input would change in response. This second piece of the system could be considered a mental model or the world event. ... Now, suppose that the world events did not happen. It would be possible to take the output of the mental model and replace the stimulus inputs from the world with inputs from our model of the world. ... we could 'run a mental simulation' and imagine the events that would take place in the world when we performed a particular action. This mental model would allow us to perform actions entirely internally and to judge the consequences of our actions, interpret them, and draw conclusions about them. (pp. 41-42)

This quote illustrates two aspects of simulation important to this thesis, namely that

1. simulated actions can be predictively associated with simulated perceptions and
2. the cognitive agent could explore the world *as if* he or she was actually interacting with the world (i.e., constructing a decoupled inner world).

This thesis further emphasizes that the simulated actions and simulated perceptions are *reactivations*, an idea dating (at least) as far back as the British empiricists and associationists (e.g. Bain, 1868, cited in Hesslow, 2002). For example:

Alexander Bain [1868] suggested that thinking is essentially a covert or 'weak' form behaviour that does not activate the body and is therefore invisible to an external observer ... 'Thinking', he suggested, 'is restrained speaking or acting' (Hesslow, 2002, p. 242)

This idea of restrained actions was also popular among some of the behaviorists, perhaps most prominently Watson, who viewed cognition or thinking as “...motor habits in the larynx” (Watson, 1913, p. 84, cited in Hickok, 2008). While the idea of reactivation in these early theories of simulation was rather underspecified and susceptible to criticism, such as the finding that paralysis induced to the muscles by curare did not have any observable effects on thinking (Smith, Brown, Toman, & Goodman, 1947; cf. Hesslow, 2002), modern theories of simulation and reactivation (e.g. Hesslow, 2002, 2012), further specify the nature of the reactivations (i.e. simulated actions and perceptions) based on both behavioral studies using elaborate experimental setups and a large body of neuroscientific evidence. Thus, as far as this thesis is concerned, the notion of simulation has two basic ingredients:

- *reactivation* – cognition is the reactivation of various brain areas, especially areas along the sensory and motor hierarchies, and
- *prediction* – the “restrained” or simulated actions can directly evoke sensory activity that would have corresponded to the activity derived from the sensory organs had the action been executed in that context.

1.1 Simulation theories

Simulation has been implicated in most cognitive abilities covered in a standard cognitive psychology textbook (e.g. Smith & Kosslyn, 2006), such as

- action planning and execution (e.g. Wolpert, Ghahramani, & Jordan, 1995),
- motor imagery (e.g. Jeannerod, 1994; Decety, 1996, 2002),
- visual imagery (e.g. Finke, 1989; Moulton & Kosslyn, 2009),
- bodily imagery (e.g. Gibbs & Berg, 2002, Thomas, 1999),
- perception (Meyer and Damasio, 2009; Möller, 1999),
- memory (e.g. Damasio, 1989),
- mental representation (e.g. Grush, 1995; 2003, 2004),
- different aspects of social cognition (e.g. Barsalou, Niedenthal, Barbey & Ruppert, 2003; Hurley, 2008; Gallese, 2003a),
- emotion (e.g. Damasio, 1994),
- higher-level thought processes (e.g. Barsalou, 1999; Gallese, 2003b; Rumelhart, et al., 1986), and
- language (e.g. Glenberg & Kaschak, 2002, 2003; Zwaan, 2004).

As perhaps expected given such a wide range of phenomena, as well as, a wide range of disciplines (e.g. psychology, linguistics, and neuroscience), these “simulation theories” are not entirely coherent in their particular details of implementation and hypotheses about the mechanisms. They also differ with regard to their view of knowledge and the relation between the cognitive agent and his or her environment (**Svensson**¹, 2007). However, they do to some extent share a commitment to either the reactivation or prediction hypotheses, as they will be further defined in this thesis.

This thesis and related previous work (e.g. **Svensson**, Morse, & Ziemke, 2009a[III]²; **Svensson**, Thill, & Ziemke, 2013[VI]) take as a starting point the simulation theory developed by Germund

¹ To highlight contributions made by the author of this thesis, the authors surname is put in bold text in the publications he has been part of.

² The papers included as material towards this thesis, and attached at the end of the thesis, are indicated by roman numerals within brackets.

Hesslow (1994, 2002, 2012). Hesslow argued that his “simulation hypothesis”³ rests on three basic assumptions; “simulation of actions”, “simulation of perception”, and “anticipation”.

- (1) Simulation of actions: we can activate motor structures of the brain in a way that resembles activity during a normal action but does not cause any overt movement.
- (2) Simulation of perception: imagining perceiving something is essentially the same as actually perceiving it, only the perceptual activity is generated by the brain itself rather than by external stimuli.
- (3) Anticipation: there exist associative mechanisms that enable both behavioral and perceptual activity to elicit perceptual activity in the sensory areas of the brain. (Hesslow, 2002, p. 242)

The basic idea is that the brain develops in a way that associations are able to form such that the brain can (based on *reactivations* in frontal/premotor/motor areas that correspond to movements at different levels of abstraction) generate the sensory/perceptual consequences of movements without actually initiating any movements. The *predictive* associations may form directly between motor and sensory areas, or between sensory and motor areas, but inter-modal and cross-modal sensory connections also exist (e.g. Meyer & Damasio, 2009). Furthermore, the reactivation hypothesis states that brain activation in simulations closely corresponds to the activations during overt interaction with the environment. For example, when you think back on the meeting with your employer about your salary increase, the activation of your brain will show some significant overlap (in somatosensory, perceptual, emotion, and perhaps motor related areas of the brain) with the corresponding activities during the event itself.

1.2 Thesis overview

This thesis presents work (Svensson & Ziemke, 2004, 2005[I]; Svensson, Lindblom & Ziemke, 2007[III]) that was carried out towards and also presented in a monographic licentiate thesis (Svensson, 2007), as well, as work carried out after the licentiate thesis towards the current doctoral thesis, which includes (Svensson, Morse, & Ziemke, 2009a[III],b[IV]; Thill & Svensson, 2009[V]; Svensson, Thill, & Ziemke, 2013[VI]). The main contributions of the licentiate thesis were the following:

- a) Clarification and explication of the kind of mechanisms and processes of simulation theories.
- b) A review of the empirical evidence given in support for the existence of simulation processes.
- c) Further development of the Representation-As-Simulation Hypothesis.

The current thesis recapitulates some of these points in Chapters 2 (point c) and 3 (point b), but with some additions. This thesis also shares some of the aims of the licentiate thesis, but does differ in the following areas:

- a) The clarification and explication of the kind of mechanisms and processes of simulation theories in the licentiate thesis were mainly aimed at comparing the different mechanisms and processes of the previously proposed simulations theories, such as Barsalou (1999), Damasio (1989, 1994⁴), Grush (2004), and Hesslow (2002) and the previous computational models of simulations (e.g. Baldassarre, 2002; Gross, Heinze, Seiler, & Stephan, 1999; Ziemke, et al., 2005). The current thesis extends this by focusing to a larger extent on the neural mechanisms (in terms of anticipatory

³ Hesslow (2012) used the term simulation theory, but the original term simulation hypothesis (Hesslow, 2002) is preferred to set it aside from other simulation theories.

⁴ Damasio (1989) is about memory, while Damasio (1994) is about emotion.

mechanisms) involved in causing the reactivations (i.e., simulated perceptions and actions) as well as refining the previous ideas.

- b) The presentation of the empirical evidence for simulations has been extended both in terms of the evidence for reactivation, but also concerning the mechanisms involved in causing the reactivations.
- c) The Representation-As-Simulation Hypothesis is in this thesis mainly used to clarify the role of simulation, and pointing out some requirements for simulations⁵.
- d) The licentiate thesis was based on a theoretical analysis of the empirical work of others. This thesis extends this with the author's own empirical work on computational models of simulations (Svensson, Morse, & Ziemke, 2009b[IV]; Svensson, Thill, & Ziemke, 2013[VI]). It also presents his own categorization of predictive mechanisms in simulations (Svensson, Morse, & Ziemke, 2009a[III]) and a novel hypothesis about the role of dreaming in the inception of simulation jointly developed with co-supervisor Serge Thill (Thill & Svensson, 2011[V]; Svensson, Thill & Ziemke, 2013[VI]).

Thus, the current thesis provides a refinement of the previous licentiate thesis extending it with additional insights that provide further knowledge, ideas, and inspiration to the field of simulations theories in general.

The thesis, the previous licentiate thesis (Svensson, 2007), and the included papers (I-VI; see Section 6.2) contribute to research both in terms of advancing the theoretical aspects of simulation and the empirical grounds on which simulation theory is based. The main theoretical contributions of the thesis are briefly summarized as follows:

- a) Clarification of the possible role of simulation in cognition (as off-line representations) (Chapter 2, Svensson & Ziemke, 2005[I]; Svensson, 2007).
- b) Introduction of the notions of implicit, bodily and environmental anticipation as mechanisms underlying simulation (as off-line representations) (Chapter 4, Svensson, Morse, & Ziemke, 2009a[III]).
- c) Developing (together with Serge Thill) the inception of simulation hypothesis (Chapter 5; Svensson, Thill, & Ziemke, 2013[VI]; Thill & Svensson, 2011[V]).

The main empirical contributions of the thesis are briefly summarized as follows:

- a) A comprehensive review of the empirical grounds for the reactivation hypothesis, as well as, implicit, bodily, and environmental anticipation⁶ (Chapter 3 & 4; Svensson & Ziemke, 2004; Svensson, 2007; Svensson, Lindblom & Ziemke, 2007[II]).
- b) A review and categorization of different types of computational models of simulation (Section 5.1; Svensson, 2007; Svensson, Morse & Ziemke, 2009b[IV])
- c) The development of computational models of simulation based on echo state networks (Svensson, Morse & Ziemke, 2009b[IV]).
- d) The development of computational models of the inception of simulation hypothesis (Chapter 5; Svensson, Thill, & Ziemke, 2013[VI]).

The thesis is organized as follows: *Chapter 2* introduces the field of situated and embodied cognition briefly, and discusses various problems with the notion of representation. The purpose of this discussion is to point out some of the requirements and pitfalls that need to be considered both when analyzing the role of simulation in cognition and also for identifying the mechanisms that realize simulation. *Chapter 3* re-presents the empirical evidence for the reactivation aspect of simulations presented in the licentiate thesis, but with a necessary update of the field, as well as a

⁵ The term Representation-As-Simulation Hypothesis is, however, not used in this thesis.

⁶ In relation to explanations of cognition, the terms anticipation and prediction are treated as synonymous in this thesis

discussion of the open issues. *Chapter 4* presents a categorization of different types of predictions that are thought to be involved in simulations (for a full treatment, see **Svensson**, Morse, & Ziemke, 2009a[III]). *Chapter 5* reviews previous computational models of simulation, as well as, the authors own empirical work (but implementation details are omitted and the reader is referred to the individual papers (**Svensson**, Morse, & Ziemke, 2009b[IV]; **Svensson**, Thill, & Ziemke, 2013[VI])). The final chapter concludes the thesis with a discussion on future work and a summary of the papers included in this thesis. Each chapter is headed by a matrix indicating the relationship to the papers included in the thesis, including the previous licentiate thesis (see Figure 1).

		Chapter			
		2	3	4	5
Paper	I	●	○	○	○
	II	○	●	○	○
	III	○	○	●	○
	IV	○	○	●	●
	V	○	○	○	●
	VI	○	○	○	●
	LIC	●	●	○	○

Figure 1 The matrix describes how the different papers relate to the chapters of the thesis. Black circles indicate a strong relation, whereas grey circles indicate a weaker relation. LIC is the previous licentiate thesis (**Svensson**, 2007).

	Chapter				
	2	3	4	5	
I	●	○	○	○	
II	○	●	○	○	
III	○	○	●	○	
IV	○	○	●	●	
V	○	○	○	●	
VI	○	○	○	●	
LIC	●	●	○	○	

2 Representation and simulation

This thesis takes a situated and embodied cognition perspective on simulation. This perspective includes, in general terms, that:

- cognition is situated and embodied (e.g. Anderson, 2003; Brooks, 1991; Chrisley & Ziemke, 2003; Varela, Thompson & Rosch, 1991; Clancey, 1997; Clark, 1997; Lakoff & Johnson, 1999),
- the traditional notion of representation is problematic and needs to be cast in situated, embodied, and interactive terms to be a viable explanatory concept (e.g. Bickhard & Terveen, 1995; **Svensson & Ziemke, 2005[I]**),
- “sensory and motor experiences are part and parcel of the conceptual representations that constitute our knowledge” (Pezzulo, Barsalou, Cangelosi, Fischer, McRae & Spivey, 2011), and
- models of cognition can and should be built from the bottom-up starting with simple sensorimotor processes (Beer, 1995; Pfeifer & Scheier, 1999)

It is perhaps not clear whether situated and embodied cognition should be considered a unified paradigm, or whether it is better described as a “conglomerate” of diverse theories and models. Nevertheless situated and embodied cognition has brought new⁷ tools and perspectives to cognitive science and in this chapter, the focus will be on some parts of the discussion of the role of representations in explanations of cognition.

2.1 Representation

The notion of representation, while being the common currency in theories of cognition throughout the history of cognitive science, was much debated with the advent of situated and embodied theories of cognition and has been debated ever since. To simplify matters, **Svensson and Ziemke (2005[I])** made a two-sided distinction of the representation debate in embodied cognitive science; those who reject their very existence or usefulness (e.g. Beer, 1995; van Gelder, 1995) of representation, and those who argue that such a rejection would be to “throw out the baby with the bathwater” (Clark, 1997; cf. also for example Clark & Grush, 1999; Dorffner, 1999; Vogt, 2002; Steels, 2003; Wilson, 2002).

⁷ As is often the case in cognitive science, the ideas are not entirely new but often have roots in earlier philosophical ideas, such as Heidegger (Dreyfus, 1992), Kant (Ziemke, 2001), and Merleau-Ponty (Anderson, 2003).

These debates also illustrate the elusiveness of the term representation. Beer (2003) noted in his response to the open peer review that

despite the enormous explanatory weight that the notion of internal representation is required to bear in cognitive science, there seems to be very little agreement about what internal representations actually are. (p. 304)

The open peer review comments had described Beer's example model as both representational and non-representational. In the same vein, some simulation theories are framed as theories of representation (e.g. Grush, 2004; cf. also Clark & Grush, 1999), while others are explicitly anti-representational (e.g. Hesslow, 2002).

According to Haselager, de Groot, and van Rappard (2003), a possible reason for this type of confusion is that the current definitions of representation are not capable of identifying real physical states that are representational or separating them from other non-representational physical states. The representations, according to this view, need to be not mere theoretical entities used to predict empirical data, but actual physical (neural) states (cf. Wheeler, 2001). While this might be a useful criterion, it must be viewed in the context of other representational problems, as discussed in the following subsections, organized following Chemero's (1999) distinction between metaphysical and empirical anti-representationalism.

2.2 *Metaphysical anti-representationalism*

Metaphysical anti-representationalism, in a nutshell, is a claim about the nature of the world and borders on the debate about what representations are (Chemero, 1999). The claim is that the world is not the sort of thing to which anything inside an agent can stand in the correct relation. Instead, the cognitive agent (and its interaction with the environment) constructs its world, rather than represents it (e.g. Agre & Chapman, 1989; Smith, 1996; Varela, et al., 1991). One problem often discussed in this context is the well-known homunculus problem. If representation is to perform primary epistemological functions, then it cannot assume the very abilities it is explaining (Bickhard, 2007); "the explanandum should not inadvertently make its way into the basic assumptions of the theory." (Di Paolo, 2005, p. 434). Following constructivist approaches to cognition, the homunculus emerges (together with other problems) because of an objectivist epistemology (e.g. Bickhard, 2000, 2007, 2009; Varela et al. 1991; Stewart, 1996; Lakoff and Johnson, 1999). In particular, objectivist epistemology influenced how representations and other explanatory entities in traditional cognitive science were conceived of and realized in artificial systems. Dorffner (1999) described the objectivist epistemology underlying cognitivist views of representation as follows:

The underlying view is an objectively existent outside world which must be mapped onto a faithful image in the cognitive agent in order for the latter to act intelligently. (...) For instance, to say that a symbol 'CHAIR' represents the category of chairs, one must not only specify the symbol, but must also assume that a category chair exists in the world, independently from whether the observer or the agent to be modeled interacts with the world. (Dorffner, 1999, p. 24)

This objectivist epistemology implies that the mental representations of humans are formed independently of the individual subject, and only establish a reference to something in the external world. This is particularly evident in Newell's (1990) law of representation (cf. Figure 2).

Figure 2 Newell's (1990) Representation Law: "decode[encode(T) encode(X)] = T(X), where X is the original external situation and T is the external transformation." (p. 59) (Redrawn from Pfeifer & Scheier's (1999, p. 45) drawing).

Bickhard (2007) has termed this type of representations *encodings*, and reserves the term representation for processes that allow epistemic access to the world. An encoding establishes a relationship between two elements that covaries, causally or non-causally (cf. also Dorffner, 1997, 1999). For example, a telegraphist knows that three short beeps ("...") means "s". According to Bickhard (2007), these kinds of relations are often taken to be representational relationships. To go beyond informational relationships in the form of natural or conventional co-variations, the model cannot assume an internal or external observer (e.g. the telegraphist) that already represents the element encoding another element. The important aspect to note with these informational relationships is that they already presuppose an epistemic agent that represents both the element that encodes and the element that it stands in for.

Insofar as the aim is to model representation in and of and for a system itself, however, such adversion to external observers or designers is not acceptable. ... observer or designer models of representation have simply moved the homunculus outside the organism and acknowledged its presence, but they still do not have a model of the homunculus's interpretations and representations—the representations of the designer or observer or user or explainer" (Bickhard 2007, p. 173).

Observer-free models of representation, or rather cognition, has also been a key aspect of the autopoietic theory (enactivism), as pointed out by (Di Paolo, 2005)

"[The theory of autopoiesis] proposes a distinction between two valid kinds of scientific discourse, the operational and the functional/symbolic, and bases itself on the first kind. Operational discourse belongs to the contemporaneous domain of physical processes operating in the living system (for instance, descriptions of physico-chemical or neural processes) and functional/symbolic statements are those formulated by an external observer given relational knowledge of the interaction and historical contexts (for instance, explanations of behaviour in terms of evolutionary advantages). This strict separation allows the theory to reach some of its boldest conclusions and justify them as implications of autopoiesis: cognizers cannot make use of internal representations; communication is not the exchange of information [cf. (Bickhard 2007)], etc. Much of the interest generated by autopoiesis is due to this strict systemic grounding of cognitive and biological terminology, so it should not be easily discarded. In itself, the rejection of teleological language is not a problem for the project of grounding sense-making. On the contrary, it is necessary for this grounding to work that the explanandum should not inadvertently make its way into the basic assumptions of the theory." (Di Paolo, 2005)

Although enactivism often discards any talk of representation it is rather observer-based models of representation that are problematic. But a model of representation based on an

operational discourse that ties into the domain of physical processes in living systems might be possible (Bickhard, 2007).

Von Glasersfeld also presented a similar view about the problems of a cognitivist or observer-dependent model of representation. Von Glasersfeld (1990, 1999) argued that the refusal to accept representation (for radical constructivists) is mainly related to the connotation of representation that is consistent with the German word *Darstellung*, which means that something is being replicated, such as a picture of something. Using representation in the sense of the German word *Vorstellung* is less problematic, since it refers to something like a conceptual construct (von Glasersfeld, 1990, 1999; cf. Dorffner, 1997). The cognitivist notion of representation mainly interpreted representations as *Darstellung*⁸, which meant that they almost literally saw representations as information carrying tokens that mirrored aspects of the world, while constructivists and enactivists would view representation simply as *Vorstellung*⁹, which means that it is a concept for a cognitive function; not an explanation of that function (cf. Dorffner, 1997; Malmgren, Hemeren, Svensson & Haglund, 2012). Representations in the sense of *Darstellung* could not be used as an explanation of *Vorstellung*, since they presuppose a cognitive agent.

To summarize, an agent gains access to the world via representations, not via encodings (observer-identified informational relationships). Therefore, a model of representation that serves primary epistemological purposes must not assume the very representational properties it is trying to explain. Encodings must depend on representations and can only be established between elements in the external world. Encodings cannot be used to gain access to the world, but can stand in for things not currently present. The theoretical entity representation, according to this interpretation of the term, is in this way restricted to the ability to gain access to the world, to provide meaning to the cognitive or epistemic agent. While possibly a representation, an encoding does not suffice to provide representationhood or representational meanings, in this sense.

Enactive and (radically) constructivist views have not gone undisputed. A possible criticism is that they deny the reality of the external world. Although the topic is beyond the scope of this thesis, there are some reasons to doubt such criticism; rather the problem might be more severe for standard models of representation (Bickhard 2000, p. 67). Enactivism and interactivism emphasizes interactions with the external world as basis for cognition. This means that any primary epistemological relation to the world is established through interactions (even though the world does not determine it, e.g. Maturana & Varela, 1987). It is not the very existence of an external world they are skeptical about, only the impossibility of a direct epistemological access to the world, especially via encodings (cf. von Glasersfeld, 1990). The radical constructivism framework (e.g. von Glasersfeld, 1995) and the enactive cognition framework (e.g. Maturana & Varela, 1987; Varela, et al., 1991) in fact emphasize interactions with the environment. Cognition and knowledge are the active construction of a subject, rather than passive representation of an external reality. For example, von Glasersfeld (2001) argued that the purpose of cognition was “a tool in the organism’s adaptation to the world as it is experienced” (p. 39).

2.2.1 *Misrepresentation and system detectable error*

A further and even stronger constraint derives from the above discussion of the homunculus problem and is an extension of autopoietic theory through the concept of adaptivity (Di Paolo 2005). The consequence of an observer based or symbolic description of representation is that:

whatever the special kind of representation constituting relationship between mind or organism and world is taken to be—whether causal, lawful, structural, or purely informational—it either exists in a particular case or it does not. If it does ... the representation exists ... If the special relationship does not exist, then the representation does not exist. (Bickhard 2007, p. 173)

⁸ *Darstellung* would seem to correspond with Bickhard’s (2007) notion of encoding and Dorffner’s (1997) notion of symbol.

⁹ *Vorstellung* would seem to correspond with Bickhard’s (2007) notion of representation and Dorffner’s (1997) notion of concept.

The problem arises because there is a third representational phenomenon that one clearly must be able to model and that is representational error, such as an illusion (cf. Slezak, 2002). But this seems impossible to model with correspondence models since there only is representation or there is not; there is no representation that is mistaken. Although several theories have addressed the problem (cf. e.g. Cummins, 1996), they address it from the perspective of an external observer of the system or organism (Bickhard 2007). Making the organism its own homunculus strengthens the problem of error because of the constraint that the organism must have some ability to detect whether it is in error – it must be capable of “system- or organism detectable representational error”. This can also be derived from Di Paolo’s (2005) extension of autopoiesis through the concept of adaptivity. He argued that since autopoiesis (through the notion of conservation) is an “all-or-nothing norm”, it does not, for example, allow bacteria to swim towards higher concentrations of sucrose. The existence of this all-or-nothing norm is derived from the concept of conservation, i.e., all perturbations have the same status as long as they are non-lethal, preserving the organization of the organism. According to the conservation definition of autopoiesis, “balancing at the edge of a cliff is a perfectly viable behaviour, so is falling over the edge – both are interactions that conserve autopoiesis. It is only crashing against the ground that is bad for the organism” (Di Paolo 2005, p. 436). This means that to achieve cognitively interesting behaviors there must be some means for graded normativity. Going ahead ignoring some of the details of his argument, Di Paolo (2005) argued that re-adaptation only occurs if the self-affirming patterns of perception and action are given a chance to discover that something has gone wrong. The predictive associations underlying simulations might be a way to detect behaviors that eventually will lead to a situation detrimental to the conservation of autopoiesis (see further discussion in Section 2.4.1).

2.2.2 *A possible homunculus in classical representation*

As already hinted at above the classical model of representation is likely not able to function as an operational theory of representation, i.e., in terms of the processes of the actual organisms or systems. Here we highlight some possible criticisms using Markman and Dietrich’s (2000) formulation, which is an extension of Palmer’s (1978) analysis of representation. According to this view, representation consists of five claims:

- (1) representations are mediating states of intelligent systems that carry information; (2) cognitive systems require some enduring representations; (3) cognitive systems have some symbols in them; (4) some representations are tied to particular perceptual systems but others are amodal; and (5) many cognitive functions can be modeled without regard to the particular sensor and effector systems of the cognitive agent. (Markman & Dietrich, 2000, p. 471)

Only the first claim is addressed here since claim 3 is derivative of the first claim, and the others are additional specifications that are not necessarily part of the classical model of representation. The first claim states that there are internal states that have the role of mediating information. Markman and Dietrich (2000) defined the first claim in similar terms as Palmer (1978):

In order for something to qualify as a mediating state, four conditions must be satisfied. First, there must be some representing world. The representing world consists of the elements that serve as the representations. Second, there must be some represented world. The represented world is the information (either within the system or external to it) that is being represented. Third, there is a set of representing relationships that determine how elements in the representing world come to stand for elements in the represented world. Finally, there are

processes that use the information in the representing world. (Markman & Dietrich, 2000, p. 471)

While the definition may be valid it is important to note that there is nothing in this definition of representation that allows a theory of representation or misrepresentation in the operational sense as defined in the two previous subsections. There seems to be a potential problem with this definition that could go unnoticed. According to the classical definition, it is (at least implicitly) assumed that there is already an informational relationship, which has to be operationally explained, not taken as an explanation of representational meaning. If this goes unnoticed, one may not see the necessary requirements for a theory of representation(al content).

2.3 Empirical anti-representationalism

Empirical anti-representationalism is a claim about cognitive architecture; that there is nothing in the brain that stands in the proper relation to objects in the (pre-given) world to be called a representation (e.g. Brooks, 1991; Beer, 1995; van Gelder, 1995). According to Chemero (1999), arguments of empirical anti-representationalism are of the following kind: “Here is a model of some cognitive phenomenon. There are no representations in this model. If cognition in general works like this model does, there are no representations in cognition either”.

Empirical anti-representationalism has largely focused on the distinction between the reactive nature of the controller/control system, on the one hand, and the (externally observable) reactive behavior of the agent (e.g. Nolfi & Floreano, 2000). This distinction can be seen in Agre and Chapman’s (1989) two meanings of planning. Firstly, they argued that “to plan” can have the general meaning of reasoning about action without talking about the mechanism. For example, a slime mold’s behavior might be described as goal-directed even though the slime mold has no encoding or representation of its goal (cf. Anderson & Rosenberg, 2008; von Uexküll, 1934/1992). Secondly, planning can be used in a more restricted sense referring to the process of constructing plans (or programs) to be executed in a step-wise manner (Agre & Chapman, 1989). Planning in the *restricted* sense is independent of the general meaning of planning because there could be other means than constructing plans to achieve planning in the first *general* sense. In fact, one might not have to use anything like a representation. In other words, anticipation does not have to involve anticipations, and representation does not have to imply representations, if representation and anticipation are defined in behavioral terms from the observer perspective. Representation in this sense contributes in a different way to the explanation of cognition than in the sense of representation described in the previous section. Instead, representations are internal models in the sense of Holland and Goodman (2003):

The basic characteristic of any model, internal or external, might seem to be that it is some sort of process or structure that in some way resembles [corresponds to] whatever it purports to model. However, when the model is to be used for some purpose by the control system of a robot, the model will be represented within some internal information processing system, and the sole requirement is that information processing operations involving the model should yield appropriate outputs in relation to the aspects of the situation being modelled (Minsky, 1968). There is no intrinsic requirement for the model itself to correspond to reality in any other way. (Of course, this does not preclude the use of models which do have a clear resemblance to whatever is being modelled.) (Holland & Goodman, 2003, pp. 78-79)

This means that it is important not to confuse functions as derived from observed behaviors for mechanisms causing the behavior (which has also often been argued in the context of evolutionary robotics, e.g. Nolfi & Floreano, 2000). This also mirrors one problem with external symbols, discussed in the previous section, whose properties cannot be taken as direct clues about properties of the representations or symbols that underlie the understanding of the external

symbols themselves. Several experiments in behavior-oriented AI, using both connectionist and evolutionary learning algorithms, have investigated the means by which control by internal states or representations can be replaced by reactive mechanisms when coupled with a robot morphology situated in a (dynamic) environment (cf. e.g. van Darter, 2005; Nolfi & Floreano, 2002; Scheier, Pfeifer, & Kuniyoshi, 1998; cf. Izquierdo-Torres & Di Paolo, 2005). Of course, it is possible to include such coupled dynamics in the class of representational machines (van Darter, 2005), but it might be difficult to constrain that kind of notion of representation sufficiently (cf. Wheeler, 2005).

... we discuss simple machine vision systems developed by artificial evolution rather than traditional engineering design techniques, and note that the task of identifying internal representations within such systems is made difficult by the lack of an operational definition of representation at the causal mechanistic level. Consequently, we question the nature and indeed the existence of representations posited to be used within natural vision systems (i.e. animals). We conclude that representations argued for on a priori grounds by external observers of a particular vision system may well be illusory, and are at best place-holders for yet-to-be-identified causal mechanistic interactions. (Cliff & Noble, 1997, p. 1165)

There is, as pointed out earlier, a possibility that representation becomes something like a piece of art whose beauty lies in the eyes of the beholder. The term representation seems to be stretched to its limits, torn between the needs of continuous online interaction with the environment on the one hand, and representation hungry problems on the other (cf. Clark & Grush, 1999). Although the field of embodied AI is constantly progressing with more efficient methods, the initial reliance on simple reactive controllers seems often to have focused on less complex forms of cognition, consistent with the bottom-up approach. For example, Vogt (2002) noted that

But is this true? Are symbols no longer necessary? Indeed much can be explained without using symbolic descriptions, but most of these explanations only dealt with low-level reactive behaviors such as obstacle avoidance, phototaxis, simple forms of categorization and the like. (Vogt, 2002, p. 430)

As described by Chemero (1999) empirical anti-representationalism works by observing the computational or biological agent's competencies and concluding that they are not using representations. The somewhat opposite argument is exemplified by Vogt's call for symbols in situated and embodied cognition, which can be rephrased roughly as "Here we have a number of models without representations solving problems that do not require representations. Therefore, these models cannot say anything about representations in agents or whether representations are needed for cognition". It could be argued that it is at this point that meta-physical anti-representationalism and empirical anti-representationalism must converge. To determine whether a model is representational would then not only be to show models of behaviors that do not involve representations (in Bickhard's sense), but also to show models of behaviors that can be described as representational from an observer/holistic perspective (cf. Agre & Chapman, 1989, above). Which, can then be analyzed according to the some criterion for representationhood (Svensson & Ziemke, 2005[I]), for example, having "an identifiable physical state within a system that stands in for another (internal or external) state and that as such plays a causal role in (or is used by) the system generating its behavior" (Haselager et al., 2003, p. 8).

2.4 *Simulation as (off-line) representations*

The licentiate thesis (Svensson, 2007) argued for a view of simulation as a kind of off-line representation. However, here the focus will be on two particular aspects of the representational debate above, which relates to the notions of reactivation and prediction.

2.4.1 Avoiding the homunculus

According to the simulation hypothesis (Hesslow, 2002), it is possible to mentally execute actions in the absence of any visible movements of the agent or organism, and it is possible to internally activate the perceptual system even in the absence of sensory input. An anticipatory mechanism makes it possible for the internally generated actions or perceptions to elicit other internally generated actions or perceptions. According to Hesslow (2002), this means that it is not necessary to posit some autonomous agent or self as being the one performing the simulation. Rather, the anticipation mechanism will ensure that most actions are accompanied by probable perceptual consequences. Thus, anticipation mechanisms construct chains of simulated perceptions and actions that range several time steps into the future. Consequently, during normal overt behavior cognitive agents are (always) a few steps ahead of the actual events (Hesslow, 2002). Thus, simulations in this respect have the potential to avoid some of the main metaphysical anti-representationalist objections, by allowing the agent to achieve a form of graded normativity (Di Paolo, 2005, cf. Section 2.2.1), which can detect faulty or detrimental behavioral strategies. For example, Hesslow (2002) explained how rats could steer away from a potential harmful place ahead of time. As soon as a stimulus, that can be used as an indication for what comes next, comes into view, (1) it elicits the activation of action-preparatory neural structures (e.g. implicit predictions, cf. Chapter 4) leading to the reactivation of a particular action. The simulated action in turn (2) elicits a (via environmental predictions, cf. Chapter 4), the activation of sensory or somatosensory areas as in a previous situation (i.e. a simulation of perception) of an actually or potentially harmful situation (as established e.g. via some conditioning mechanism). The reactivation of the emotion or pain consequences would lead to the suppression of the simulated action, such that it is not executed.

Welche Thiere gleichen ein-
ander am meisten?

Kaninchen und Ente.

Figure 3 Example of an ambiguous figure. An early version of the duck-rabbit illusion from the 23 October 1892 issue of "Fliegende Blätter". Public Domain, via Wikimedia Commons (http://en.wikipedia.org/wiki/File:Kaninchen_und_Ente.png)

However, the world need not always be simulated in the correct way, since the predictions can be at fault and not simulate the previous or future interactions in an adaptive way. However, it is likely that it is more difficult for the cognitive system to find out that its simulations are faulty without trying out the consequences of the actions via interaction with the environment. For the system to find out that the predictions did not pan out, the system would somehow need to have enough memory capabilities to be able to ascertain the consistency of several paths of simulation. In line with this reasoning is the finding that it is more difficult to discover the alternative interpretation of an ambiguous (although not impossible) via mental imagery (Mast & Kosslyn, 2002) than by attending to a picture of the figure (see Figure 3 for an example of an ambiguous figure).

Thus, the anticipatory associations thought to underlie simulations could be construed as a part of the machinery that allows representational meanings to be established, without invoking a homunculus in the system. The need for environmental interaction to establish the validity of the simulations should not be underestimated. The human body changes and the environmental context also change, which means that the associations must be constantly updated to have any use for the agent (as also emphasized in the InSim hypothesis, see Chapter 5). In chapter 4, different types of associative mechanisms are outlined which could explain the ability to generate the type of simulation discussed here.

2.4.2 Reactivations

While the previous section outlined a somewhat more speculative but conceivable hypothesis of a more primary epistemological function of simulations, this section outlines a view of simulation as representation that relates to a less problematic interpretation of representation. This restricted sense of representation could be referred to as off-line representation (cf. Svensson, 2007) and can initially be defined in accordance with Webb's (2006) definition of representation.

... the ability to recreate internally something that has the same effect, or can be used in the same way, as an external situation, especially when that external situation does not currently pertain. (Webb, 2006, R185)

For example, simulation processes can have the same effect as being in a particular situation, but can also have the same effect as internal situations, such as causing feelings of sadness or joy in the absence of their usual bodily cause (Damasio, 2003)¹⁰. Thus, off-line representations accounts for the ability of the brain to decouple itself from the environment (and the "non-neural" body) and generate representations of the environment by itself. The concept of off-line representation therefore subtracts many of the epistemological functions of representation (such as accounting for the ability of representations to exist and at the same time being faulty, e.g. Bickhard, 2009).

Reactivations could be used to identify when and where a cognitive system has representations in this sense, and thus provide a way to overcome the problems of empirical anti-representationalism by allowing the identification of representation or rather internal models (Holland & Goodman, 2003) in an embodied system. Note, however, that the mere identification does not explain how the representational content emerges but only that it is present. Bickhard (2007) argued "it might be in principle possible to internally represent the external property and then set up an internal functional stand-in for the internal representation, but this assumes that the initial representational relationship already exists" (p. 174). In the context of reactivation, the argument would be that if the brain were to be re-activated in the *same* way, as when it is being activated by external perturbations in response to its own actions, it would possess the same representational meanings. Thus, the reactivations in themselves are not representations for the system, but they can borrow their representational contents and as such be a kind of internal encoding. However, it might also be seen as an external encoding in the sense that we can identify the reactivated states with some accuracy as for example correlations between the brain areas active during for example perception and mental visual imagery. This and other aspects of "sameness" will be reviewed in the next chapter.

¹⁰ There are some obvious limits to how similar a simulation can be, e.g. a simulated bullet is not likely to have the same effects as a real bullet.

2.5 *Representation: Summary*

This chapter pointed out some of the problems with the notion of representation as it has previously been used in explanations of cognition. Firstly, there is the problem of presenting an adequate theory of representation that does not presuppose the very abilities it is supposed to explain. While standard models of representation often intentionally or unintentionally invoke a homunculus, the associations underlying simulations may be part of representational mechanisms that are not dependent on an external interpreter (cf. Hesslow, 2002, 2012). Secondly, the notion of representation is not easily defined, especially when it comes to interactive cognitive systems, and it has been unclear whether there is a notion of representation that could be applied to such systems. Representation, here, must both be clearly representational, in that it is about something, but at the same time not be dependent on the correspondence to the world to be defined as a representation. Reactivations were argued to be able to allow states of the brain to be used as stand-ins for their own representational function as indicated by the effects of reactivation addressed in the next chapter.

	Chapter				
	2	3	4	5	
I	●	○	○	○	
II	○	●	○	○	
III	○	○	●	○	
Paper IV	○	○	●	○	
V	○	○	○	●	
VI	○	○	○	●	
LIC	●	○	○	○	

3 Reactivation of bodily brain states

The common notion of having a system behaving *as if* it was another system, that is, simulating another system is mainly reflected by the notion of reactivation in simulation. As noted in the introductory chapter the idea of reactivation is not new, but was put forward, for example, by empiricist theorists arguing that speaking is a form of restrained thinking. Similarly, according to Nyberg, et al. (2001) the idea that sensory and motor brain regions active during encoding are reactivated during retrieval of these memories has been a longstanding hypothesis in memory research dating back to the well-known psychologist William James. The empirical evidence in favor of the reactivation hypothesis has been extensively reviewed in previous publications included in this thesis (especially **Svensson & Ziemke, 2004**, **Svensson, Lindblom, & Ziemke, 2007**[II]; **Svensson, 2007**), and there are a number of other more recent relevant reviews of the empirical evidence (e.g. Barsalou, 2009a,b; Colder, 2011; Hesslow, 2012). The material presented in this chapter mainly serves the purpose of furthering the discussion of sameness in the previous chapter.

The chapter is organized as follows: Section 3.1 illustrates similarities with regard to neural overlaps observed between encoding and remembering in episodic memory, Section 3.2 describes observed behavioral correspondences between action and motor imagery, Section 3.3 focuses on the phenomenological similarities between visual perception and visual mental imagery, and Section 3.4 focuses on the bodily effects of motor imagery and as observed in social cognition. The Chapter concludes with a discussion of open issues tied to reactivation.

3.1 *Episodic memory: neural overlap*

There are different ways of defining episodic memory but a typical characterization is something like the following:

It is the kind of memory that renders possible conscious recollection of personal happenings and events from one's personal past and mental projection of anticipated events into one's subjective future. As such, it is the memory system that mediates mental time travel. (Wheeler, Stuss, and Tulving, 1997, p. 332)

One of the first neuroscientists to adopt the reactivation hypothesis of memory, including episodic memory, was Damasio (1989) who described memory processes as “time-locked multiregional retroactivation” (further described in **Svensson, 2007**). According to Damasio (1989),

perceptual experience depends on neural activity in multiple regions activated simultaneously ... during free recall or recall generated by perception in a recognition task, the multiple region activity necessary for experience occurs near the sensory portals and motor output sites of the system rather than at the end of an integrative processing cascade removed from inputs and outputs (Damasio, 1989, p. 26)

Neuroimaging experiments of memory have provided further support for the reactivation hypothesis and the assumption that the behavioral effects are due to the activation of the sensory and motor areas used to process the percept or associated action (for a brief review see Gandhi, 2001). Using Positron Emission Tomography (PET), Nyberg et al. (2000) found that remembering visual words that had been presented together with sounds at the encoding stage activated some of the auditory brain regions that were active during encoding. Moreover, this effect was present even when the subjects did not have to explicitly remember the sound, but only determine whether the word was part of the original list. This effect also transfers to other types of information, such as spatial location (Persson & Nyberg, 2000, cited in Nyberg, et al., 2000), and vivid visual information (Wheeler, Petersen, & Buckner, 2000). Furthermore, Nyberg et al. (2001) found that both overt enactment and imaginary enactment of the to be remembered action phrase are accompanied by encoding-retrieval overlaps. In summary, the neural areas involved in explicit recollection of memories overlap with sensory and motor regions involved in the encoding of those memories (cf. also Rugg et al., 2000). The overlap consists mainly of activation in secondary sensory and motor areas (for details of the neural areas involved see Nyberg, et al., 2000; Nyberg, et al., 2001; Wheeler, et al., 1997).

Similar findings of neural reactivation of sensory and motor *brain areas* have been found in other cognitive abilities, for example, spatial working memory (Awh & Jonides, 2001), motor imagery (Munzert, Lorey, & Zentgraf, 2009; Macuga & Frey, 2012), and language (Hauk, Johnsrude, & Pulvermüller, 2004). In conclusion, there is a general trend of reactivating brain areas for perception and action in other cognitive functions.

3.2 *Motor imagery: behavioral effects*

Mental chronometry experiments, which measure the duration of behavioral and mental responses, have found that the time needed to mentally execute actions in several conditions closely correspond to the time it takes to actually perform them (Jeannerod & Frak, 1999; Papaxanthis, Pozzo et al., 2002; Papaxanthis, Shieppati et al., 2002; for a review see Guillot & Collet, 2005). For example, Decety and Jeannerod (1996) found that Fitt's law (that is, the finding that execution times increase with task difficulty) also holds for motor imagery. Decety, Jeannerod, and Prablanc (1989) compared the durations of walking (blindfolded) towards targets placed at different distances and mental simulation of walking to the same targets. Interestingly, it seems that while errors increase with distance in naïve subjects, subjects using a mental imagery strategy do not suffer from increased error with increased distance (Decety et al., 1989, p. 39). Similarly, isochrony is preserved in motor imagery (Grush, 2004). Fitt's law and isochrony go beyond what normal subjects would have explicit (propositional or conceptual) knowledge. This is because they are the results of intrinsic properties of the motor system in interaction with the task, which might not be easy to gain explicit knowledge about given the small differences in time and because it often goes against what is true in other cases, such as the walking experiment. Furthermore, Johnson (2000) found that motor imagery preserves "the path dictated by biomechanical constraints on joint rotation" (p. 64)¹¹. Similarly, Demichelis, Olivier, and Berthoz (2013) showed how the biomechanical constraints of oculomotor movements influence the memorization and execution of a spatial navigation task. By exploiting the fact that horizontal ocular movements are more efficient than vertical ocular movements, they were able to show that

¹¹ It should be noted that the study (Johnson, 2000) did not explicitly concern motor imagery but prospective action judgments, which might not qualify as motor imagery on the point of consciously feeling as if.

after subjects had studied an “allocentric map-like” representation, their performance on a consequent locomotor task to navigate to the goal following the route indicated on the map decreased when it involved vertical ocular movements but increased when it involved horizontal ocular movements. It is therefore likely that the memorization of the map was done by means of the ocular movements, which is then mapped on to (non-ocular) body movements (Demichelis, et al., 2013)¹².

Another example of behavioral effects is the “action-sentence compatibility effect” (Glenberg & Kaschak, 2002, 2003). Glenberg and Kaschak found that the sensibility of a sentence is modified by physical actions. Reaction times increased when subjects read “toward sentences” that implied action toward the reader, such as “Open the drawer” and had to give the answer through an incongruent action, namely moving the hand away from the body. Conversely, when subjects answered through an action congruent with the direction of the sentence, reaction times decreased. It might be worth noting that Glenberg and Kaschak (2002) included not only sentences describing concrete, physical transfers, but also sentences describing examples of abstract transfer, such as “Liz told you the story” (p. 560). The action-sentence compatibility effect was also present when reading these more abstract sentences. It should also be mentioned that Barsalou and his colleagues have performed a large body of behavioral studies on conceptualization that further indicate that somatosensory, sensory, motor and other bodily states are involved in conceptualization (e.g. Barsalou, 1999, 2009a,b).

In conclusion, the behavioral effects, either the timing similarities in performing a task mentally and the interference effects of doing a cognitive task while performing some type of action, provides indirect evidence for the reactivation of similar mechanisms during action and other cognitive abilities such as motor imagery, memorization of a path, and language.

3.3 *Visual imagery: phenomenological similarities*

Given the reactivation hypothesis, one would expect (or at least not be surprised to sometimes find) a phenomenological similarity between simulations of perception and action and the corresponding perceptions and actions. For example, first person motor imagery involves feeling as if actually performing the action (Decety 1996; Jeannerod 1994). Visual imagery can, at least under certain conditions, be phenomenologically similar to our perception of reality to the point that they are hard to distinguish. Consider the experiment performed by Cheves Perky in 1910 described by Cotterill (1998, pp. 19-20).

Perky placed a subject in front of a translucent screen, onto which pictures could be projected from the rear, the brightness of projection being controlled by a rheostat (a voltage-control device). A favored example was a picture of a tomato, and the subject was periodically asked to report whether it had become visible, as the intensity was gradually increased from an initially zero value. Ultimately, of course, the subject indicated that the tomato had indeed appeared. Perky then switched off the projector and asked the subject, while staring intently at the screen, to try imagining the tomato at the location its image had previously occupied. Without divulging the fact, she switched the projector on again and gradually increased its brightness, taking note of the point at which the subject realized what was happening. In all cases, the intensity had achieved a value well above that at which the image had previously been reported as becoming visible. In other words, the subjects experienced great difficulty in distinguishing between an imagined picture and the real thing.

¹² The use of forward models (see Chapter 3) of the consequences of oculomotor responses to cancel out the sensory effects of motor initiated movement of the eye have been known for some time now (see e.g. Webb, 2004, Box 1 for a brief review). However, those processes are highly automatic and might not be utilizing the same kind of prediction mechanism as the ones used in the spatial navigation task described here (cf. Chapter 3)

This so called Perky effect is a striking example of the close resemblance of imagery and perception. The claim is not that reactivation always generates conscious mental images that we can only separate from its source of origin with some effort. Rather, this example only serves to illustrate the possibility and existence of phenomenological similarities. Although the reaction hypothesis does not predict that reactivation is followed by conscious mental images, it would be somewhat contradictory to find phenomenological states that are very different from the reactivated perceptual and motor states, in cognitive phenomena that are thought to be the re-experiencing of a previous situation. However, it should be noted that the conscious mental states involved in reactivations do not need to be of previous situations. Bar (2009) argued that the potential functional role of mental time travel is to:

...create new ‘memories’. We simulate, plan, and combine past and future in our thoughts, and the result might be ‘written’ in memory for future use. These simulated memories are different from real memories in that they have not happened in reality, but both real and simulated memories could be helpful later in the future by providing approximated scripts for thought and action. (p. 286).

The nature of the reactivations is thus dependent on the type of cognitive phenomena and the neural mechanisms involved in the particular type of simulation. This aspect is discussed later in this chapter (Section 3.5.3) and is also explained further by the mechanisms outlined in the next chapter.

3.4 *Imagery and social cognition: bodily effects*

Besides producing similar reaction times, motor imagery has been shown to produce similar, although smaller, physiological effects as overt actions. Sport psychological experiments have revealed that mentally practicing a specific action can enhance the performance when subsequently actually performing the previously mentally imagined action (Jeannerod, 1994). For example, Yue and Cole (1992; cf. Ranganathan, Siemionow, Liu, Sahgal & Yue, 2004) showed that mentally simulating oneself contracting a muscle could significantly (by 22%) increase muscle strength (actual training produced an increase of 30%). Jeannerod (1994) pointed out that there have been several interpretations of these results, for example, that motivational factors increase the physiological arousal and as result of this performance is increased. Another explanation is that if motor imagery, at least in part, involves the same neural structures responsible for overt action it is probable that motor imagery could “train” the neural structures used in subsequent execution of the previously imagined action (Jeannerod, 2001; Ranganathan et al., 2004; Yue & Cole, 1992). Besides strength increases, autonomic responses, such as the adaptation of heart and respiratory rates, which are beyond voluntary control, have been shown to be activated by motor imagery to an extent proportional to that of actually performing the action, and as a function of mental and actual physical effort (Decety 1996; Decety, Jeannerod, Germain & Pastene, 1991; Jeannerod, 1994; Jeannerod & Decety, 1995). For example, Decety, Jeannerod, Durozard & Baverel (1993) showed that when subjects imagined performing a leg exercise, their heart and respiratory rates increased. Furthermore, the involvement of proprioceptive organs in motor imagery is consistent with the finding that motor imagery respects both bodily constraints and time constraints (Lethin, 2005). On the other hand, as pointed out by (e.g. Lashley, 1951) for many behaviors, such as typing this text, there is not enough time for peripheral signals to reach the brain in time to have an effect on the consequent movement (cf. Chapter 4). Other bodily effects relating to social cognition have been observed and are discussed further in the next subsection.

3.4.1 *Embodiment effects in social cognition*

Barsalou, Niedenthal et al. (2003; see also Niedenthal, Barsalou, Winkielman, Krauth-Gruber & Ric, 2005) noted that there are at least four types of well-known phenomena in social psychology experiments, which support the reactivation hypothesis (cf. Lindblom & Ziemke, 2007; Nielsen, 2002). Firstly, perceived social stimuli can produce bodily states (for example, a more slumped posture in response to negative feedback). Secondly, social stimuli can induce bodily mimicry (for example, a smile in response to a smile). Thirdly, bodily states can produce and affect emotional states (for example, an upright posture tends to have a positive effect). Finally, compatibility between bodily states and emotional states leads to increased cognitive performance (for example, it is easier to pull a lever towards you in response to “positive” stimuli than in response to “negative” ones). These phenomena have in common that states of the body, such as postures, arm movements and facial expressions, change automatically without any conscious mediating knowledge structures in specific instances of social interaction (cf. Nielsen, 2002).

Another effect that relates to a bodily aspect is the Spatial-numerical association of response codes (SNARC) effect, which, among other things, includes the finding that numbers seem to have a spatial dimension where small numbers are located to the left and larger numbers to the right, such that small numbers are responded to faster with the left hand and large numbers with the right hand (Wood, Willmes, Nuerk & Fischer, 2008). In conclusion, a possible explanation of the activation of internal autonomic processes and the interaction effects between overt bodily states and aspects of (social) cognition is that the cognitive phenomena are induced by reactivations of the same brain structures used for interacting in these types of situations.

3.5 *Discussion: reactivation*

The selective review above shows that there are a number of different indications that sensory, motor and other types of brain areas involved in the control of bodily functions are reactivated in various cognitive phenomena. The remainder of this chapter further elaborates and clarifies issues concerning the role of reactivation in cognition.

3.5.1 *Neural re-use and reactivation*

The concept of reactivation is related to Anderson’s (Anderson, 2007a, b, 2010, 2012) organizational principle of neural re-use (or massive redeployment hypothesis), which provides a set of predictions of how the brain has become organized to support cognitive functions:

- (1) each brain area is typically redeployed in support of other cognitive functions, and such redeployment will not respect traditional domain boundaries. (2) nevertheless, redeployed areas play the same ‘role’ in each of the functional complexes they support, (3) more recent cognitive functions will utilize more, and more widely scattered brain areas, and (4) evolutionary older brain areas will be deployed in more cognitive functions. (Anderson, 2007a, p. 332)

The first prediction is central for simulation theories and it corresponds to the way that reactivation has been described so far. However, the focus in this thesis and simulation theories in general is to a large extent on the re-use of brain areas first evolved for sensing and acting on the world. Although this often means sensation/perception and movement/action, one should for instance not exclude emotional systems. Damasio (1994) for example suggested a type of simulation loop of the emotional system that could bypass the body-loop. Also, Anderson’s notion of re-use is not limited to these systems, rather any brain area can be re-used, but with the

constraints that older brain areas are more commonly re-used and, evolutionary recent, cognitive functions re-use more brain areas. Assuming that the early development of brains focused on relatively simple sensorimotor problems (e.g. to ingest food), brain areas developed primarily for sensation and movement would be the more common sources for reactivation. Many of Anderson's (2010) examples of re-use in cognitive functions do actually re-use sensory and motor areas of the brain, including the re-use of motor control circuits in memory, and the re-use of neural circuits for inner silent speech in working memory. Memory and inner silent speech are of course rather complex phenomena that could also involve re-use of several brain areas.

The second prediction suggests that brain areas (i.e. local neural circuits, Anderson, 2012), such as the prefrontal cortex, would do "the same thing" or "play the same role" in the various cognitive functions in which it partakes. An example of this would be the suggestion, detailed in the next chapter, that the action selection mechanisms of the basal ganglia are reused in other cognitive phenomena, such as working memory (cf. Hazy, Frank, & O'Reilly, 2007). This means that, even though a brain area participates in several cognitive functions, it is not a change in the brain areas' computation or information processing that enables different cognitive functions, but rather that a cognitive function is the result of a distributed neural network (a functional complex) consisting of many brain areas and connections between them. The finding that several different aspects of actions and perceptions are replicated in various cognitive phenomena is supportive of this interpretation.

3.5.2 *Epiphenomena, sameness, and further challenges*

Of importance to memory research, Rugg et al. (2000) pointed out that since most studies have been based on hemodynamic imaging techniques, such as fMRI, which have relatively low temporal resolutions it cannot be concluded whether or not the reinstatement is the consequence or the cause of successful recollection. That is, it is not clear whether the reinstatement actually is the means by which recollection is achieved or whether it is epiphenomenal, or has some other function. Furthermore, as pointed out by Gandhi (2001), the studies of episodic memory retrieval do not conclusively show that memories are stored in sensory cortices. Rather, it is equally probable that "brain mechanisms in common between retrieval and imagery project them back into sensory cortex" (Gandhi, 2001, p. R34). In that case, the storage of memories is either some higher association area or, rather, in the dynamic interplay between higher association areas and sensory areas as suggested by Damasio's convergence zone theory (Damasio, 1989; Meyer & Damasio, 2009). Thus, one has to ask to what extent it is possible to determine whether reactivation of early sensory areas and motor areas is causal or merely epiphenomenal. Meyer and Damasio (2009) raised and addressed this question:

Accordingly, integrated mental images would arise from the activity of neurons in higher-order association cortices (grandmother neurons, in the extreme view), and the activations in early sensorimotor cortices would merely reflect a non-functional byproduct. (p. 381)

Meyer and Damasio's (2009) response against this view was based on lesion studies that have demonstrated, for example, that damage to the early sensory cortices leads to severe problems with image generation.

First, disrupting early visual cortices by TMS impairs visual mental imagery [18]; second, TMS targeted at a specific part of the visual cortex impairs performance in a tactile orientation discrimination task [11]; and third, processing of visual stimuli in a mental rotation task is affected when TMS is used to disrupt primary motor cortices [24] (Meyer & Damasio, 2009, p. 381)

Corroborating evidence comes from the loss of color vision, which "...also precludes imaging color in recall (Damasio, 1985; Farah, 1989; and unpublished observations), that is, no other

cortices, and certainly no other higher-order, integrative cortices, are capable of supporting the recall of the perceptually impaired feature” (Damasio, 1989, p. 33).

In motor imagery, it is more likely that lesions higher-up in the motor hierarchy including the supplementary motor area (SMA) and premotor cortex would cause further impairment to the imagery process (Jeannerod, 2001). That is, the perceptual process is to a larger extent initiated at the sensory organs, but the action generation process is initiated and controlled by higher levels of the motor hierarchy and therefore higher lesions of the motor systems cause more impairment in motor imagery.

Mahon and Caramazza (2008) argued that sensorimotor systems are not necessarily causally involved in the construction and instantiation of abstract conceptual representations, but that the sensorimotor states only “color” the concepts, that is, they endow them with some additional information when the abstract representation in higher level areas leaks out into the sensorimotor system, which is in essence a weaker version of the claim that they have no function (i.e. being an epiphenomenon). Pezzulo et al. (2011), however, argued that evidence for the ability of sensorimotor processes to modulate the content of abstract conceptual representations, that is, that there are bidirectional synaptic pathways that allow both higher-level areas to modulate or reconstruct activity in lower-level areas and lower-level signals to modulate or activate higher-level areas (cf. Meyer and Damasio, 2009). Evidence for a causal influence of sensorimotor states on cognitive processes has been provided by the type of embodiment effects, mentioned above, which showed that “embodiment not only produces affect per se, but propagates this affect to other cognitive processes.” (Barsalou, et al. 2003, p. 53). For example, Riskind and Gotay (1982, cited in Barsalou, et al., 2003) showed that posture influences how much time subjects spend on a problem-solving task. Also, the many different effects (neural, behavioral, phenomenal, and bodily) associated with many different cognitive phenomena suggest that reactivations are in effect present and play a vital role for carrying representational content.

3.5.3 *Partial similarities*

Another aspect to discern is that the reactivation patterns rarely constitute a complete overlap between the evolutionary older functions of perceptions and actions at the neural, behavioral, phenomenal, and bodily levels. For example, at the neural level, activation of the early visual cortices (area 17 & 18) in mental imagery is conditional of, among other things, the task itself and individual differences (Kosslyn & Thompson, 2003). Also, some neural mechanisms of episodic memory are specific to encoding and retrieval respectively (Nyberg et al., 2001). At the bodily level, the effect on the autonomous nervous system is smaller during motor imagery of an exercise than during actual training. Neither is it possible to replace visits to the gym with motor imagery to build muscles.

At the phenomenological and behavioral level, there is a difference between visual perception and mental visual imagery. As mentioned earlier, it is often more difficult to reinterpret mental images, while this can be done (although not without effort) in external pictures (cf. Figure 3). This indicates that mental imagery cannot always replicate every aspect of agent-environment interactions.

From the perspective of theories of perception based on sensorimotor contingencies and using the world as an external memory (e.g. Myin & O'Regan, 2009), the problem of reinterpreting visual images can be understood more clearly. According to that type of theory, the perceptual experience of a unified and complete surrounding is false, but perception is rather highly task specific and we only direct our attention to the things that matter in a particular scene. This is, for example, seen in change blindness and inattention blindness (e.g. Simons & Chabris, 1999). This implies that reinterpretation of ambiguous pictures are affected by the way in which the figure was attended to (cf. Barsalou, 1999). From this it follows that simulations of perception need to replicate the visual exploration of the ambiguous figure that leads to reinterpretation. If the figure that was to be mentally imagined had not been attended to in that particular way it would be

difficult for simulations to result in a reactivation of the perceptual system revealing the alternative interpretation, since it has to rely on other information, for example similar situations or figures, to direct the simulations in the appropriate way.

3.5.4 *Abstraction*

There are two different but related ways of using the term abstraction in simulation theories. The first and perhaps more common usage refer to conceptualization (e.g. Barsalou, 2009; Pezzulo, et al., 2011), where simulations are thought to explain also the abstract nature of parts of cognition, that is, how it is possible to abstract generalities among several objects and situations. For example, Barsalou have described a number of different theoretical constructs, such as perceptual symbols and situated conceptualizations to explain this process, as well as, conducting and reviewing the empirical evidence supporting these claims (see e.g. Barsalou, 2009a,b; Svensson, 2007).

The other notion of abstraction relates to the underlying neural substrate of simulation. Fuster (1997, 2004) depicted the brain as organized according to two dimensions, (1) perception/perceptual memory and action/motor memory, and (2) different levels of abstraction. Both the sensory and motor side is often characterized in terms of hierarchies in which the processing of information takes different forms depending on its distance from the sensory inputs and motor outputs. For example, the primary motor cortex is thought to involve action processing in terms of muscles and details of the movements (e.g. Fuster, 2004), while the prefrontal cortex is thought to be able to integrate a large number of sources of information relevant to the action, such as relating it to previous episodes (Koechlin & Summerfield, 2007). Similarly, Meyer & Damasio (2009) argued that the highest level of the processing hierarchy includes the incorporation of many different “knowledge fragments” that can define a single object or situation in our autobiography. The purpose here is not to define the intricate relationship between the different levels of the hierarchy, but rather to emphasize Fuster’s claim that both feed-forward and feed-back connections exist within both the perceptual and motor memory hierarchies, as well as, bidirectionally between them at various levels of the motor hierarchy. This indicates that reactivations can occur at all, and sometimes at different, levels of abstraction. Thus, it might be argued that simulation need not always implicate activation of brain areas adjacent to sensory organs and muscles, but that reactivation can occur at all levels of the sensory and motor hierarchies (cf. e.g. Meyer & Damasio, 2009; Hesslow, 2012).

In conceptualization, the abstraction is achieved by the way and which parts of the lower levels of the hierarchies are reactivated, such that concepts are grounded in many of the details of our sensory and motor experiences, or more generally bodily, experiences (e.g. Barsalou, 2009; Lakoff & Johnsson, 1999; Pezzulo, et al., 2011). On the other hand, the phenomenological and informational content of the simulations could also depend on the level of the sensory and motor hierarchies at which simulations occur. For example, the amount of disruption to motor imagery may be related to the level of the motor hierarchy at which the brain damage occurs (cf. Jeannerod, 2001). However, as the reactivation often involve brain areas at different levels of the sensory and motor hierarchy (cf. e.g. the example of finger movements in the next section) it is likely this is the default in many cognitive phenomena, which means that any disturbance to this system is quite difficult to interpret.

3.5.5 *Internally or externally cued simulations*

One observable difference between different cognitive abilities, such as those discussed in this chapter is the degree to which they are evoked and perturbed by external cues. The observation of social stimuli can trigger reactivations, but in mental imagery, and in recalling episodic memories, there are fewer or no immediate cues from the environment. For example, in some cases we have even learned to deliberately control simulations. Guillot & Collet (2005) mentioned several

examples of how experts, such as marksmen and ballet dancers, can slow down and speed up the rate at which they imagine the skill they specialize in. At other times, reactivations are triggered automatically by the aspects of the environment, such as when reading action words (Hauk, Johnsrude, & Pulvermüller, 2004). Macuga and Frey (2012) compared three different conditions that differed among other things on their reliance on input from the environment and the body: observation, imagery, and imitation of simple finger movements. Consistent with the reactivation hypothesis they found that

...all three conditions were associated with increased bilateral increases in activity within a common set of frontal (premotor, pre-SMA), posterior parietal, superior temporal and primary sensorimotor areas, as well as subcortical (thalamus, putamen) regions traditionally implicated in visually-guided bimanual behavior. (Macuga & Frey, 2012, p. 2802)

To determine whether any difference in brain activity that could be accounted for by other factors than a simulation of the perceptual stimuli per se, they did further comparisons between the different conditions. Based on the assumption that imagining the finger movements would activate a motor plan and possibly the inhibition of executive structures, they found the following when comparing observation vs. imagery.

We found that imagery of movements produced greater increases in activity in pre-SMA than observation of movements ... It has been suggested that an efference copy may be generated in SMA (Haggard and Whitford, 2004), because TMS over this region removes the sensory suppression effect for voluntary movements. Though the motor command is not physically executed for imagery, an efference copy could be generated and utilized in service of motor imagery (Grush, 2004). Alternatively, go/no-go experiments suggest that pre-SMA may play a role in motor response inhibition (Mostofsky et al., 2003; Sharp et al., 2010), and the need to inhibit movement execution during imagery may explain the increase here. (Macuga & Frey, 2012, p. 2804)

In the observation of finger movements there might not be a need to develop a chain of simulated actions and/or perceptions, partly because the next state of the movement is provided by the external sensory input and partly because there is no need to predict the intention and final goal of these finger movements. In imagery and situations where it would be useful to predict the final state of an initial movement (such as the movement being part of a potentially harmful action or when imitating a more complex action), the reactivated action/movement must elicit brain activations corresponding to the sensory consequences of performing the action, which can then trigger the activation of new actions or motor patterns that usually would be executed in this context and so on. The next chapter outlines some of the possible mechanisms for this kind of extended simulation chains. However, it should also be pointed out that in real time interaction with the environment, where internal and external information needs to be continuously integrated, it is more difficult to actually distinguish observation and imagery. For example, if one is blindfolded and has to walk from room to room in ones house, one would rely on internally generated reactivations (sometimes experienced as imagery), but at the same time the simulations and the behavior could also be influenced by “observations” derived from self-movement such as proprioceptive information from joints and muscles, as well as vestibular information about acceleration (cf. Etienne & Jeffery, 2004; Mittelstaedt & Mittelstaedt, 2001), and from the environment, such as bumping into furniture.

3.6 *Reactivation: summary*

Chapter 2 argued that if the brain were to be re-activated exactly as when activated by external perturbations in response to its own actions, it would possess the same representational meanings.

In this chapter, it was shown that there are extensive similarities in terms of neural, behavioral, phenomenological, and bodily effects, which is indicative that these reactivations are sufficient to act as internal stand-ins for representations (i.e. off-line representations). However, there are still open issues regarding the exact nature of reactivations in different cognitive abilities, and there are also differences between the reactivations at the neural level that needs to be explained. However, with regard to representation, the lack of a perfect overlap seems not be expected based on the view of representation outlined in the section on metaphysical anti-representationalism that was also largely influenced by an enactive or (radical) constructivist view. If cognition is an active construction of the cognitive agent, there are only continuously changing processes such that even our memories are new re-constructions that are influenced by the current context, it is to be expected that reactivations differs to some extent from previous interactions which could even be seen as differences in the neural, behavioral, phenomenal and bodily overlap. The degree of overlap and the nature and general extent of neural re-use is subject of ongoing research (cf. e.g. Anderson, Kinnison & Pessoa, 2013; Guillot, Di Rienzo, MacIntyre, Moran & Collet, 2012).

	Chapter				
	2	3	4	5	
I	●	○	○	○	
II	○	●	○	○	
III	○	○	●	○	
Paper IV	○	○	○	○	○
V	○	○	○	○	○
VI	○	○	○	○	○
LIC	●	●	○	○	○

4 Anticipation

Anticipation and the related notion of an internal world have been argued as major breakthroughs in the evolution and development of cognition (see e.g. Cruse, 2003; Gärdenfors, 1996; Dennett, 1996; Sjölander, 1995). Sjölander vividly illustrated the notion of anticipation and the notion of an inner world by the observed abilities of dogs and primates. “A dog which has done something forbidden will meet its master showing clear signs of distress, despite the fact that the master has no idea of what has happened and thus cannot give any conscious or unconscious clues to release this behavior.” (Sjölander, 1995, p. 6). Sjölander also mentions the yapping and twitching of the legs of a dog during sleep as indications of dreams, in some form and other anecdotal evidence which he takes to suggest that “it is hard to escape the conclusion that the dog must have a context-independent representational world, where simulated actions may take place according to certain rules where at least one step into the future can be depicted...[whereas] following multi-step chains into the future, however is something at least the great apes can do...” (Sjölander, 1995, p. 6). Here, the point was not to determine the predictive capabilities of different animals¹³ but to emphasize the importance of anticipation in the form of simulated actions that internally generate the consequences of that action had it actually occurred. In fact, anticipation is a key aspect of the notion of inner models. For example, Kenneth Craik’s notion of an internal “small scale model” puts anticipation to the fore by emphasizing the trying out of alternative actions in an internal milieu

If the organism carries a “small scale model” of external reality and of its own possible actions within its head, it is able to try out various alternatives, conclude which is the best of them, react to future situations before they arise, utilize the knowledge of past events in dealing with the present and future, and in every way to react in a much fuller, safer, and more competent manner to the emergencies which face it. (Craik, 1943, p. 61)

This type of detached representation (Gärdenfors, 1996) goes beyond a memory mechanism that simply keeps some, by the environment elicited, states active for some time. Instead, there must be some kind of mechanism that enables the chaining of several steps, whether it is forward or backwards in time. In some cognitive abilities, the mental time travel is (in humans) reportable as conscious experiences, such as episodic memory, at least in the sense of Ebbinghaus as “calling back into consciousness a seemingly lost state that is then ‘immediately recognized as something formerly experienced’” (cited in Perner, Kloos, & Gormik, 2007, p. 471), and mental imagery, which involves the recreation of previous perceptual experiences (e.g. Kosslyn, 1994). To what extent these abilities are accompanied by some type of conscious experiences in other animals are

¹³ Even invertebrate may be said to incorporate predictive mechanisms (Webb, 2004).

not discussed in this thesis. However, several accounts of cognition, suggest that it is not only these conscious mental time traveling phenomena that are related to anticipation, but that the neural circuitry of the brain suggests that the brain is wired towards anticipation in general (cf. e.g. Bar, 2009; Downing, 2007, 2009; Hesslow, 2002, 2012; Koehlin & Summerfield, 2007; Tian & Poeppel, 2012). Thus, it is likely that, at least in humans, anticipation is the rule rather than the exception. Chapter 2 also presented the avoidance of explanations invoking a homunculus as a criterion for the development of representations (cf. Section 2.4.1). This chapter outlines different types of anticipation, which are learnt via different types of neural mechanisms during interaction with the environment and consequently result in anticipatory associations that couple reactivations of perceptions and actions automatically.

As already established Chapter 1, anticipation or prediction is a key mechanism in many simulation theories (Hesslow, 2002). This chapter presents a categorization of three different kinds of anticipation (implicit, bodily, and environmental anticipations) thought to be involved in simulations (Svensson, Morse & Ziemke, 2009a[III]; cf. Downing, 2007; 2009).

4.1 *Implicit anticipation*

Action selection mechanisms can be seen as anticipations, but of an implicit (Butz, Sigaud, & Gérard, 2003) or procedural (Downing, 2009) kind. This kind of prediction, formed by evolution or learning, allows an animal to act as if it has access to some future goal state, but without the need to produce a (sensory) state that corresponds to that goal. In other words, implicit predictions generate actions, which mean that the only information about the external state is in the way that the animal coordinates its behavior with it. The hypothesis proposed here is that the simulating brain reuses the non-simulating brain's solution to the action selection problem. These mechanisms contribute to effective simulations by constraining them to a few simulation paths by means of implicit predictions, and potentially allow them to be directed towards future goals, without explicitly representing the goal (cf. the discussion on the development of goal representations in Thill, Svensson, & Ziemke, 2011). Implicit predictions are also reminiscent of Damasio's (1989) *type 2* convergence zones. In brief, convergence zones (cf. Meyer and Damasio, 2009) are neural circuits in the forebrain that aim to "inscribe temporal coincidences and aim at replicating them through simultaneous activation of several (caudal) brain areas". Convergence zones of *type 2*, which mainly relate to procedural memories, inscribe "temporal sequences and aim at replicating them" by firing "back in sequence, producing closely ordered activations in the target cortices" (Damasio, 1989). According to Damasio, this ability to preserve temporal sequences is a necessary component of any skill (cf. Lashley, 1951) and is thus coupled to phenomena associated with procedural memories. Damasio (1989) pointed out that in normal operation *type 1* (relating to declarative memories) and *type 2* convergence zones are cooperating as they interlock at multiple levels, but the main use of *type 2* convergence zones is then to underlie the ability to perform different types of skills including tool-use.

4.1.1 *Implicit Predictions in Humans and Animals*

The establishment of stimulus-response (S-R) associations has been a major theory of animal learning. In the context of this thesis, S-R associations can be seen as simple forms of implicit predictions. For example, eye blink conditioning can be explained in terms of (implicitly anticipatory) S-R associations. A neutral conditioned stimulus (CS), e.g. a tone, is followed by an unconditioned stimulus (US), e.g. a puff of air, which elicits a conditioned response (CR), a blink (Jirenhed, Bengtsson, & Hesslow, 2007; Mauk, Medina, Nores, & Ohyama, 2000). After training, the neutral stimulus directly elicits the conditioned response in anticipation of the unconditioned stimulus. The neural substrate of eye blink conditioning is discussed further in the next section. Cisek and Kalaska (2004) provided evidence for predictively activated (but not executed) motor representations in the dorsal premotor cortex of monkeys. More importantly, they also found that the predictive and performance related activity was strikingly similar. Thus, it implements a

predictive relationship between the stimuli and the about to-be-activated action. A similar finding is that the perception of objects automatically activates motor representations of the action normally performed when using the object (Tucker & Ellis, 1998). Another instance of behavior which could be seen as guided by implicit anticipations comes from actions slips, such as when a bus driver on his way home in his car stops at a bus stop (Heckhausen and Beckman, cited by Hoffmann, 2003). Although there may be alternative explanations to why the subjects perform these actions without any apparent conscious control or awareness, these behaviors might be largely controlled by learnt implicit anticipations.

Although many factors, processed in different parts of the brain, affect behavioral choices (Cisek, 2007), basal-ganglia–cortex loops (including amygdala influence) (Prescott, Redgrave, & Gurney, 1999) and cortico–cerebellar loops (Wolpert, Miall, & Kawato, 1998) are commonly considered crucial for action selection. These action selection mechanisms are in some respects anticipatory in nature since the agent's actions are directed toward a future situation. However, as described next, there are no explicit predictions involved in the anticipatory behaviors learnt by these action selection mechanisms (cf. Cotterill, 2001; Downing, 2009; Riegler, 2003). The neural structures that are likely to realize implicit predictions are the cerebellum (cf. Downing, 2009; Yeo & Hesslow, 1998), the basal ganglia (Downing, 2007, 2009; Prescott, et al., 2002), and the neocortex (Wise & Murray, 2000; Sanes, 2003). The roles of the cerebellum and basal ganglia in implicit predictions are detailed in *Svensson, Morse & Ziemke (2009a[III])*. Here, the focus is instead on one way, not addressed in previous work, in which the neocortex relates to implicit predictions.

Besides the cerebellar and basal ganglia mediated implicit predictions, there can be implicit predictions at even higher levels of the motor hierarchy (cf. Fuster, 2004) that are instantiated in the neocortex by the same mechanisms as for environmental prediction, but in the reverse direction from sensory to motor contexts. Such learning of visual-motor associations in the neocortex is known as conditional motor learning or motor mapping, the latter being less ambiguous and has been argued to involve the premotor areas, prefrontal cortex, inferior temporal cortex, basal ganglia and the hippocampus (Wise & Murray, 2000; Sanes, 2003). In these cases, the sensory stimulus is not the target of the action as in the standard motor mapping, but it is only a signal for an action, such as to associate the visual presentation of a stop sign (or bus stop) with a breaking activity.

One common interpretation of learning a new skill first involves a mainly conscious aspect such as forming arbitrary visuomotor mappings and after sufficient practice this becomes an automatic skill and encoded in procedural memory systems, such as the cerebellum and basal ganglia as described earlier. For example, Fuster (1997) argued that

[a]fter practice, frontal representations of action may become relocated in lower motor structures, notably the basal ganglia. Humans with frontal lesions cannot voluntarily perform complex movement sequences but retain their ability to perform automatic ones, even though these are just as complex and their learning originally required just as much willful effort. In the monkey, cortical lesions may disrupt the learning of new skills but not the performance of old ones. Neuroimaging confirms the relocation evidence. The prefrontal cortex is only activated at first in the learning of certain complex sequences. As the subject becomes proficient, cerebellar and striatal regions become progressively more active and cortical regions less so.

Sanes (2003), on the other hand, argued that, despite this, evidence suggests that these systems do interact. He noted for example that:

Behaviorally, response time advantages occur when elements of explicitly trained sequences are covertly imbedded in a skein of random response elements, even though participants evince no awareness of the explicitly trained sequence elements [29]. A functional MRI study using analogous methods provided clear evidence of interactions between the mechanisms

associated with implicit and explicit sequence knowledge [30]. Activation related to implicit knowledge and covert-explicit knowledge occurred in portions of the left inferior parietal lobule, left IFG and right putamen. Performance of an overt-explicit task activated the same areas as well as many additional regions in the neocortex and subcortex, including the thalamus and the cerebellum. The activation observed during the covert-explicit task and the accompanying reduced response time, even when participants had no awareness of the sequence elements, indicates that explicit knowledge can improve performance (and activate the same neocortex and basal ganglia) even without awareness. (Sanes, 2003)

Although the cerebellar and basal ganglia holds a somewhat privileged role in action selection, and simulation, this suggests that visuomotor mappings may also be involved and that one should not overemphasize the difference between declarative and procedural memories as they might be interacting in various ways (cf. Section 4.4.2).

4.2 Bodily Anticipation

Many models suggest that it is necessary to produce predictions of the (sensory) state of the body because of the inherent time delays in the sensorimotor system (e.g. Damasio, 1999; Frith, Blakemore, & Wolpert, 2000; Miall & Wolpert, 1996; Wolpert, Miall, & Kawato, 1998). One familiar phenomenon thought to be caused by these time delays and predictive models is the difficulty to tickle one self. To be successful, one might try and use a feather, but often, it is necessary for someone else to try and tickle oneself (using a feather). A possible explanation is that, since we have had extensive practice with, and can with some certainty know what actions we are about to perform, we can predict the proprioceptive signals. Blakemore and colleagues (Blakemore, Frith, & Wolpert, 1999, 2001; Blakemore, Wolpert, & Frith, 2000) argued that the neural mechanisms that produce this phenomenon are based on efference copies fed to the cerebellum. The cerebellum both predicts the sensory consequences of that action and compares it with the resulting sensory feedback from touch sensors, which attenuates the activity in somatosensory cortex if there is no discrepancy. This is usually described as that the cerebellum implements a so-called forward model of the world (e.g. Doya, 1999; Wolpert, et al., 1998). This means that the cerebellum implements a prediction of the state of the body or the sensory efference from the proprioceptive (and proximal sense) organs based on efference copies (e.g. Wolpert, et al., 1998).

Motor control experiments have also suggested that forward models are necessary because the motor system needs to act on predictive knowledge of future states to, for example, compensate for feedback delays (e.g. Frith et al., 2000; Kalaska, Scott, Cisek, & Sergio, 1997; Kawato, 1999; Wolpert et al., 1995). Motor control research deals with the problems of generating correct movements to achieve a desired state, which involve problems associated with learning, planning, and execution of these actions, as well as the evaluation of the consequences (Jordan & Rumelhart, 1992). It centers on the sensorimotor loop consisting of both transformations from sensory to motor and motor to sensory signals, where a central mechanism might be the internalization of these loops into internal inverse and forward models, respectively. One might also say that the inverse model is a controller while the forward model is a predictor (Frith et al., 2000). Basically and historically, the forward model concept has been associated with the efference copy or corollary discharge – a copy of the motor command that is to be executed – leading to a prediction of the consequences of that action. However, the interpretation and format, as well as the terminology, of the concepts efference copy and corollary discharge are not always clear (Webb, 2004). Still, Tian and Poeppel (2012) postulated different roles for the efference copy and corollary discharge in the explanation of auditory hallucinations. Forward models have also been used more generally in several other simulation (or emulation) theories (Grush, 2004; Pezzulo & Castelfranchi, 2009).

Many models argue that the forward models are found in the cerebellum, and that the forward models can be run off-line to generate covert simulations. For example, if motor activity

(generated by a cerebellar S-R association) does not lead to overt action, an efference copy might still be sent to the cerebellum to generate a sensory prediction. These kinds of covert simulations are likely to be closely tied to details of the execution and proximal consequences of bodily movement. Hence, the sensory predictions are related to proprioceptive signals and the proximal senses of touch (and perhaps taste).

There is also a possible connection to canonical and mirror neurons. Miall (2003) argued that mirror neuron related circuits could implement forward and inverse models. Miall reviewed Iacoboni's idea that mirror neurons form the interface between forward and inverse models. According to Iacoboni, superior temporal sulcus (STS) represents observed actions visually, which through area PF of the posterior parietal cortex projects onto mirror cells in area F5, which converts the "visual representation into a motor plan". Thus, it implements the inverse model. The forward model is implemented by reversing the projections from area F5 of the ventral premotor cortex, through area PF, and back to STS, "converting the motor plan back into a predicted visual representation (a sensory outcome of the action)" (as depicted in Figure 4). However, Miall (2003) argued that pathways incorporating the cerebellum, which has often been associated with the forward model concept in motor control, might implement similar transformations. Moreover, Miall pointed out that a possibly important difference is that mirror neuron activity reflects more general aspects of actions, whereas forward models in motor control, which have to estimate movement outcomes, must be more detailed (cf. Haruno, Wolpert & Kawato, 2003; Wohlschläger et al., 2003; Wolpert, Doya, & Kawato, 2003).

Figure 4 Schematic illustration of two ways of implementing a forward model predicting sensory outcomes via either mirror neuron related neural circuits or the cerebellum (dashed arrows.) Redrawn (in simplified form) from Miall (2003).

Another example of bodily anticipation is given by the as-if loops of Damasio (Damasio, 1994; Damasio, 2003), who argued that feelings could occur in the absence of their normal bodily causes by short-circuiting the body loop. Feelings are then simulated in loops involving the prefrontal cortex and the somatosensory cortex. The advantage, according to Damasio (2003), is that the connections between the prefrontal cortex and the somatosensory cortex, especially the insula, are very short, which means that the signaling can occur in hundreds of milliseconds while the body loop takes up to 1 second to complete due to the long, often unmyelinated, axons. In effect, the as-if feelings can be seen as established by bodily predictions, predicting some of the neural correlates of somatosensory states of the body.

To summarize, depending on the type of bodily property and the level of detail, different neural circuits establish bodily anticipations. Some of these are cerebellar centered while others are located in the cerebrum. A possible explanation of how the neocortex implements environmental prediction is outlined in the next section.

4.3 Environmental Anticipation

Environmental anticipation differs from bodily anticipation both in its function and neural substrate. The function of environmental anticipation is to generate predictions of future sensory states relating to objects and situations in the world external to the animal's body. Environmental predictions are similar to declarative predictions (Downing, 2009) in that the predictions are supposed to correspond to some aspect of the environment. In more detail, declarative predictions associate two neural states that correspond to states of the environment (Downing, 2009). This type of sensory-sensory association has also been suggested to establish reactivations (Hesslow, 2002). For example, Tani, Nishimoto, and Paine (2008) argued that inferior parietal lobe is able to produce predictions of future sensory states based on the current sensory (perceptual and proprioceptive) state and the goal of the task. They further argued that the sensory prediction could replace the actual sensory input creating a simulation loop.

Some simulation theories emphasize, as does this section, that motor patterns are often crucial in eliciting the sensory activity normally associated with the execution of the corresponding action (cf. Cotterill, 2001; Hesslow, 2002). The hypothesis is that this type of environmental prediction might be crucial for implementing longer and more specific or goal directed covert simulations.

4.3.1 Environmental Predictions in Humans and Animals

The type of response-effect predictions suggested by the notion of environmental anticipation has been found in several experiments with humans (reviewed in detail in Kunde, Elsner, & Kiesel, 2007). Furthermore, some of these experiments suggest that the effects are in the form of covert perceptions as suggested by simulation theories (Kiesel & Hoffmann, 2004; Kunde, 2003 in Kunde, et al., 2007).

Hesslow (2002) further argued that this could be generalized to human problem solving and planning of the type tested in the Tower of London task (cf. Dagher, Owen, Boeker & Brooks, 1999) or when we are talking to ourselves internally. Gulz (1991) argued that planned behavior couldn't simply be behavior directed by a goal representation, instead there must be internal generating and testing of actions as well.

Planning involves internal generating and testing of potential actions [simulated actions]. It is representations of actions and their consequences that are generated and tested, relative to one another and in relation to an overall goal. In brief, there is a testing of actions without acting. (Gulz, 1991, p. 51)

Imagery was extensively discussed in the previous chapter regarding reactivation, but another aspect of imagery is its dynamic nature, which to some extent is related to bodily and environmental prediction – reactivations in imagery phenomena come about via the mechanisms of environmental (and bodily) anticipation (cf. e.g. Grush, 2004; Jeannerod, 1997; Wexler, Kosslyn, & Berthoz, 1998; Rosenbaum, 1991, cited in Gibbs & Berg, 2002). One aspect of this is the view that the content of motor imagery is, at least sometimes, not merely the reactivation of motor areas of the brain because the feeling of action and movement is generated to a large extent by proprioception and perception (Gibbs & Berg, 2002; Grush, 2004; cf. also Jordan, 1998). Conversely, visual imagery might be accompanied by covert actions (Wexler, et al., 1998; cf. also Gibbs & Berg, 2002). The involvement of covert actions in mental imagery with mainly visual or other perceptual modalities has also been suggested. For example, Kosslyn (1994, cited in Gibbs and Berg, 2002) showed that mental rotation of an object is similar to physically turning it in our hands, which implies that this is not a purely visual process but the entire feeling of turning the object is involved (cf. also Thomas, 1999).

Similarly, Wexler, et al. (1998) suggested that at least visual (dynamic) mental imagery in the form of mental rotation is achieved by a planned but not executed motor action that predicts the

perceptual result. When an action such as a rotation of an object is performed, with the hand, the result is visible to us. In mental rotation, the action is instead simulated and instead of seeing the outcome (which we cannot, because the action is not physically carried out), we simulate the perceptual result of our planned action, effectively short-circuiting the action–perception cycle (Wexler et al., 1998, p. 79). This view has been supported by neuroimaging studies (Lamm et al. 2001; Vingerhoets et al., 2002).

Vingerhoets et al.'s study is a more direct result supporting the view of mental imagery as a prediction (of action effects) realized through the involvement of the motor system. However, while Lamm et al.'s experiment also found motor area activation in a mental imagery task, Lamm et al. provided an alternative interpretation of this activation. Lamm et al. (2001) investigated whether the premotor cortex was activated during a mental rotation task using 3-D cubes as stimuli. The subjects in the study reported that the objects rotated autonomously, which means that they did not experience the mental rotations as involving a physical interaction between them and the objects. Given that the subjects did not experience egocentric imagery, including experiences of bodily action, despite activation of several higher-level motor areas, Lamm et al. raised the issue of the function of the premotor cortex activity in this type of imagery. Their suggestion was the interdependence of action and perception of space, which is especially evident in the ontogenetic development of mammals (cf. e.g. Held and Hein, 1963). Action and spatial perception are coupled since there is no perception of space without movement and no movement without spatial feedback (Lamm et al., 2001, p. 280). However, as indicated by these two studies, there might still be a difference between the proximal effects relating to aspects of the body and distal effects relating to external objects, as suggested by the distinction between bodily and environmental predictions. The distinction between bodily and environmental anticipation in imagery has been further substantiated by lesion studies. Tomasino, Toraldo, and Rumiati (2003) for instance found a double dissociation between mentally rotating body parts and mentally rotating external objects. Patients with lesions to the left hemisphere were unable to complete a task associated with the rotation of the hand, while patients with right hemispheric lesions had trouble with mental rotation of external objects.

4.3.2 *Neural Substrate of Environmental Predictions*

The ability to predict sensory states that correspond to various external states is the final functional aspect of simulation to be addressed. The sensory predictions close the simulation loop such that agent-environment interactions can be rehearsed internally in various cognitive processes. They might provide the means to generate chained simulations at various levels of abstraction. There are at least three different neural circuits that could implement environmental predictions, which are located in the neocortex, thalamo-cortical loops, and the hippocampus (cf. Downing, 2009). The focus here is on the neocortex, but, as described in the last subsection, Downing (2009) argued that there is a common mechanism for these types of predictions.

Possible routes for predictions of sensory or perceptual consequences are located throughout the neocortex. The hierarchical structure of the motor and sensory cortices and the reciprocal connections between them at various levels of the hierarchy (Fuster, 1997, 2004; Hesslow, 2002) suggest the possibility of the cortex implementing both predictions from motor to sensory activity and the reverse. Anatomically, the connections between the sensory and motor hierarchies are long corticocortical fibers:

To support interactions between the two cortical hierarchies, long corticocortical fibers ... connect, both reciprocally and topologically, areas in the perceptual hierarchy with areas of equivalent rank in the executive one. Thus, premotor areas connect with relatively low areas of sensory association, whereas prefrontal areas connect with higher associative areas of posterior cortex.... Furthermore, there is anatomical evidence of an orderly descent of connections from prefrontal to premotor to motor cortex (Fuster, 2004, p. 144)

Similarly, Cotterill (2001) argued that the premotor areas send information back to the sensory cortex by way of axon collaterals. He further noted that “there are three such efference copy routes...One goes directly, another passes through the anterior cingulate, and the third goes via the thalamic ILN” (p. 22). Efference copy routes might indeed be a ubiquitous property throughout the sensorimotor hierarchy (cf. Hesslow, 2012). Gomez et al. (2004) have, based on their own experiments with the contingent negative variation and other corroborating studies, suggested that there exists an attentional-anticipatory system that

“include[s] not only the frequently described prefrontal, SMA, and primary motor cortices, but posterior parietal cortex, cingular cortex, and pulvinar thalamic nuclei too. The neural substrate of the perceptual domain is not so well-described, but, of course, the participation of primary sensory areas has been hypothesized” (p.67).

The study by Kastner, Pinsk, De Weerd, Desimone, & Ungerleider (1999) showed influence from frontal and parietal areas (possibly the frontal eye fields, the supplementary eye fields, and superior parietal lobule) on extrastriate cortex during covert attention shifts, suggesting the possibility of motor areas to influence the activity of sensory areas in an anticipatory manner. Meyer and Damasio (2009) also pointed out the ability of higher-level brain areas to influence early sensory cortices.

4.3.3 *Declarative Prediction Networks and Simulation*

Downing (2009) suggested a common model for how the kinds of declarative predictions are learnt in cortical, thalamo-cortical, and hippocampal circuits, which he called the general declarative predictive network (GDPN). Although his focus was the association of consequent sensory states, the neurophysiology behind this type of association might also explain the predictive association between a motor representation and its sensory consequence (at some or several levels of the sensorimotor hierarchy). The declarative prediction networks that Downing postulates provide an unsupervised learning scheme. This would work in the neocortex as described briefly in the following text. The neocortex is organized horizontally into layers, and vertically into groups of cells linked synaptically across the horizontal layers called cortical columns or microcolumns (Mountcastle, 1997). Even though their function is not agreed upon, it has been suggested that they are essentially predictive elements (Downing, 2009; Hawkins & Blakeslee, 2004). In brief, Hawkins (Hawkins & Blakeslee, 2004) explained it as follows:

Imagine you are a column of cells, and input from a lower region causes one of your layer 4 cells to fire. You are happy, and your layer 4 cell causes cells in layers 2 and 3, then 5 and the 6 also to fire. The entire column becomes active when driven from below. Your cells in layers 2, 3, and 4 each have thousands of synapses in layer 1. If some of these synapses are active when your layer 2, 4, and 5 cells fire, the synapses are strengthened. If this occurs often enough, these layer 1 synapses become strong enough to make the cells in layers 2, 3 and 5 fire even when a layer 4 cell hasn't fired[cf. (Hansel, Artola, & Singer, 1996)] - meaning parts of the column can become active without receiving input from a lower region of the cortex. (Hawkins & Blakeslee, 2004)

Given that a large number of the connections onto a column come from other parts of the cortex, it is likely that some of the predictive associations are made between the motor areas of the cortex and sensory areas of the cortex via the different routes suggested above. Furthermore, as noted above, it is possible that these associations form at different levels of the sensorimotor hierarchy. It is possible that the general declarative prediction network in the hippocampus is able to learn even more complex and abstracted sensory-motor and motor-sensory associations.

4.4 *Anticipation: discussion*

Anticipation has been a prominent aspect of many different theories of cognition, some of which is explicitly or implicitly based on simulation (e.g. Cotterill, 2001; Grush, 2004; Hesslow, 2002; 2012; Möller, 1999) and this chapter outlined a categorization of three different types of prediction which differed according to what they predict: actions (that lead to a “goal”), bodily effects, or environmental happenings.

4.4.1 *Components of simulations*

Myachykov, Scheepers, Fischer, and Kessler (in press) presented a taxonomy of different types of representational components in simulations. This taxonomy shares some commonalities with the different types of predictions outlined in this chapter and the taxonomy can be used to evaluate among other things the “degree to which a particular conceptual representation depends on the online constraints provided by the mental representation of the world” (Myachykov, et al., in press). Their taxonomy consisted of tropic, embodied and situated components. Tropic features are the stable or unchanging aspects of the environment, body and situational context (i.e. aspects determined by the physics of the world, such as gravity). Embodied features are features of the body, while situated features refer to momentary and often changing aspect of the context. The essential aspect of tropic components is that they are stable, which means that they are likely to become automated to their availability for training. Thus, tropic components are likely to be reactivated by implicit predictions. Embodied and situated components are less stable, which indicates that there is a need for other learning mechanisms, and possible can be achieved via bodily and environmental anticipation, respectively. Simulations involving tropic aspects would, according to Myachykov et al. (in press), require less depth of simulation. While they do not define the depth of simulations, that could involve both how far back or ahead in the time the simulation is about, or how widespread the reactivations are in terms of e.g. modalities and sensory/motor details. Embodied and situated components of conceptual representations would require more depth of the simulations. Thus, there is both a need then to either couple reactivations via implicit, bodily and or environmental anticipation to extend the simulations temporally or reactivate more areas of the brain via convergence and divergence zones (Meyer & Damasio, 2009).

4.4.2 *Barriers to re-use*

Downing (2007, 2009) argued, based on his extensive description of different neural mechanisms for procedural and declarative knowledge, that even though earlier cognitive functions may share some properties with later ones, neuroscience teaches us that there are some barriers to reuse. In particular, there are strong indications that there are separate neural mechanisms for declarative and procedural knowledge. This is indeed an important question for situated and embodied cognition and it certainly is a problem for any theory that argues that declarative knowledge is *only* procedural knowledge reused. Furthermore, Downing (2007) pointed out some of the questions needed to be addressed by simulation theories:

In general, our work has no direct conflicts with either simulation or emulation theories, but it centres on the question of how the predictive structures originate. ... The simulation promoters would receive similar questions regarding the posited relationships between lower- and higher-level representations and how each may influence the emergence of the other.

The interaction between different levels of abstractions is indeed an important question, which have received some attention in computational models of simulation (cf. Section 5.1) and has also

been addressed to some extent by Damasio's theory of convergence and divergence zones (in the neocortex) (Damasio, 1989; Meyer & Damasio, 2009). However, it is also relevant to view the discussion of the barrier to reuse in a more general sense in relation to this thesis. The view of simulation developed here is quite compatible with the view of prediction in the brain as described by Downing (2007; 2009).

The major barrier to reuse is the difference between the implicit predictions implemented by cerebellar and basal ganglia circuits and the bodily and environmental predictions largely residing in the neocortex. However, from the perspective of creating an inner world, the role of the implicit (or procedural) predictions and bodily/environmental (or declarative) is complementary in a similar fashion as Downing (2007) suggests:

Although the basal ganglia may be involved in pattern stabilization via their interactions with the frontal cortex, neither region seems wired to support spreading activation.

Using these two regions, one can sing a song perfectly but cannot, without the aid of external media (e.g. paper and pencil), recall and compare the seventh and twenty-third lines. Each word or phrase of the song may be stored in the cortex, but extraction is mediated by the combination of preceding cortical context (declarative) and basal ganglia wiring (procedural) (Downing, 2007, p. 97)

The role of the basal ganglia and cerebellum in simulation is mainly to constrain and guide what is being simulated, such that they replay their function as action selection mechanisms in simulation. Thus, since simulations couple implicit predictions with bodily and environmental predictions, simulations will reactivate neural structures responsible for both procedural and declarative knowledge (cf. Sanes, 2003, Section 4.1.1). The behavioral, bodily, and neural effects associated with motor imagery that shows involvement of both declarative and procedural knowledge in motor imagery support this.

	Chapter			
	2	3	4	5
I	●	○	○	○
II	○	●	○	○
III	○	○	●	○
Paper IV	○	○	●	○
V	○	○	○	●
VI	○	○	○	●
LIC	●	●	○	○

5 Simulations of simulation

The previous chapters have addressed simulation mechanisms from both theoretical and empirical perspectives, based on analytic methodologies, implying that the insights were derived from observations of natural systems. This chapter addresses simulation from a synthetic perspective, focusing on what can be learnt from the construction and observation of computational models of simulation, that is, simulations of simulation. Two of the earliest examples of simulation-like mechanisms modeled by computational agents were Chrisley’s (1990) “Connectionist Navigational Map (CNM)” and Mel’s (1991) robot (arm) “Murphy”. The theoretical motivation behind the connectionist map was the transition from non-conceptual to conceptual knowledge (cf. e.g. Barsalou, 1999). Later models have investigated the following types of behaviors:

- allocentric spatial knowledge (Hiraki, et al., 1998)
- learning the topological structure of a maze like environment, identified as successful navigation, either physically or mentally (Hoffmann & Möller, 2004; Jirenhed et al. 2001; Jirenhed, 2001; Nolfi & Tani, 1999; Tani & Nolfi, 1998; **Svensson**, Morse & Ziemke, 2009[IV]; Ziemke et al., 2005),
- goal-directed navigation: the robots are given a goal-configuration and should find the goal by using the cognitive map as internal/planning resource (Baldassarre, 2002; Hoffmann & Möller, 2004; Tani, 1996),
- obstacle avoidance (Gross et al., 1999), and
- problem solving (van Dartel, 2005)

This chapter discusses some of the issues addressed by these previous computational models and also describes an approach to model the development of simulation in robots inspired by the so-called inception of simulation (InSim) hypothesis (**Svensson**, Thill, and Ziemke, 2013[VI]; Thill and **Svensson**, 2011[V]). For a more complete review of previous computational models of simulation, see (**Svensson**, 2007). Note also that some of arguments for the InSim hypothesis have not been included in this chapter, but they are found in the attached papers (**Svensson**, Thill, and Ziemke, 2013[VI]; Thill and **Svensson**, 2011[V]).

5.1 *Unconstrained vs. constrained models*

Previous work towards this thesis (**Svensson**, 2007) distinguished two different types of approaches to modeling different phenomena by means of simulation: constrained and

unconstrained models. Constrained models use learning mechanisms that explicitly ensure the internally generated states to be similar to the externally generated states; if the mapping is learnable (e.g. Baldassarre, 2002, 2003; Hoffmann & Möller, 2004; Tani & Nolfi, 1999; Jirenhed et al., 2001; Svensson, Morse, & Ziemke, 2009b[IV]). Unconstrained models use learning mechanisms that do not ensure such similarity (e.g. Gigliotta, Pezzulo, & Nolfi, 2009; van Dartel, 2005; Ziemke, et al. 2005). The caveat with unconstrained models is that they do not explicitly enforce similarity between outputs, but this could also be an advantage as other unanticipated but valid solutions could develop (cf. Ziemke, et al., 2005) as discussed below.

Constrained models have provided valuable insights concerning the ability of different architectures to simulate aspects of agent-environment interactions and how those simulations are able to guide behavior. The following subsections discuss particular aspects that have been investigated.

5.1.1 Prediction

A crucial aspect for models of mental imagery based on simulations of actions and perceptions is whether the robots can develop accurate predictions, that is, capture the relationship between actions and their effects, given the context. The models investigating prediction ability have generally used the following set up: (1) current (sensory) state + motor state (or context) are used as input and the output is the sensory state at the next time step, and (2) the predictions are learnt by comparing the expected sensory state to the actual sensory state. The assumption is that if you are able to acquire accurate one-step predictions, they can be used to generate simulations by allowing the predicted sensory state to be used to generate a new covert motor state/action, which generates a new predicted sensory state and so on. Indeed these models have shown both that they are able to produce accurate predictions and that they outperform purely reactive architectures (e.g. Gross, et al., 1999). However, the constrained models, which are committed to the idea that sensory predictions should correspond to states of the environment, have to deal with noise. If noise accumulates the predictions will drift and become increasingly imprecise. This is a problem if the simulation processes are to be used for planning future actions or some other task depending on a close correspondence between the simulated perceptions and actions, and the original ones. Gross et al.'s (1999) experiments showed that their model system had some trouble with very noisy data, but when noise was reduced their model was successful at prediction. Furthermore, Hoffmann and Möller (2004) found that there is an accumulation of error as the chains of predictions increase in length.

5.1.2 Abstraction

Abstraction in the previous models occurs through a mechanism that transforms actual sensorimotor patterns into concepts (Holland & Goodman, 2003; Nolfi & Tani, 1999; Stening, et al., 2005) or it can imply some kind of binding mechanism that does not preserve the actual sensorimotor patterns but still uses some of them (Baldassarre, 2001). The issue here is how to construct simulations at an optimal level of detail, which is important for cognitive economy and thus developing effective ways to solve more complex problems, as well as how to access low-level sensory information when needed. Wintermute (2012) suggested a hybrid architecture in which the latter could be achieved by mental imagery driven by simulated actions.

5.1.3 Planning

To mention but one example, Baldassarre's coarse planning approach (2001) also used a type of abstracted operators that implement abstraction by learning predictions of "macro-actions" instead of simple actions that takes the agent one step ahead. In the environment he used, the coarse planning approach outperformed the planning approach based on one-step predictions.

However, as noted by Baldassarre (2001), the macro-action approach might be difficult to generalize, for example, due to the kind of open environments used, where the direction of the optimal action is the same as the direction of the macro-action at most of the locations in the environment. The approach taken by Wintermute (2012) incorporates both low-level and abstract representations that are connected via a mental imagery driven by simulated actions and is an example of an architecture that attempts to address this type of issue.

5.1.4 Unconstrained models – implicit predictions

The unconstrained approaches discussed here, which do not explicitly enforce the predictions to be similar to environmental inputs or motor outputs, have found that the “reactivations” can be different from the actual inputs and outputs but nevertheless result in successful behavior (Gigliotta, et al., 2009; van Darte, 2005; Ziemke et al., 2005). Ziemke, et al. (2005) built a model based on evolutionary algorithms with a fitness function that did not reward prediction per se, but only successful behavior. Their finding was that the inputs generated through a prediction module, after training, were not similar to the corresponding (actual) sensory inputs (Ziemke et al., 2005). They noted, “the turning behaviors are actually not the same [in terms of the behavior of the controller], although they are functionally equivalent in the sense ... that they lead to very similar motion trajectories.” (p. 98). That is, although the observed behavior of the robot was similar in both regular navigation and blind navigation, the behavior generating mechanisms were different. Using a different type of agent and environment, Gigliotta et al. (2009) arrived at the same conclusions. Although some of the constrained models produce sensory predictions that are not perfectly accurate, they do not suggest qualitatively different “images” as was the case in these unconstrained experiments. Ziemke et al. (2005), commenting on the possibility of interpreting the self-generated input patterns as simulations of perceptions, straightforwardly argued that “the [self-generated and actual] input patterns are simply too dissimilar”. Consequently the robot does not construct a chain of sensory inputs corresponding to that experienced during the actual walk. However, using the categorization of different types of anticipation in the previous chapter, one might argue that this is a model of implicit anticipation, since the learning mechanisms implicitly favors correct S-R associations. Gigliotta et al. (2009), however, more generally concluded

In that respect, it is important to notice that the realization and the analysis of models implemented in embodied and situated agents can support or disconfirm alternative theoretical models and/or can highlight aspects that need to be incorporated in these abstract models. For instance, the results described in this paper support the hypothesis that internal models might had arisen for compensating the problems caused by the temporary unavailability of sensory information and the hypothesis that internal model can operate by producing a one-step prediction at the level of raw sensory data. *However they disconfirm the assumption, often made implicitly, that anticipation should be realized by generating states that encode the anticipated information in the same way in which it is encoded in sensors.* Moreover, our results demonstrate that the presence of a learning mechanism that drive the learning process on the basis of the prediction error (i.e. the difference between predicted and actual sensory states) does not necessarily represent a prerequisite for the development of an anticipatory capability. (emphasis added)

As discussed in Chapter 3, there is sometimes not a complete neural overlap between, for example, visual perception and visual imagery in that the early visual cortices (area 17 and 18) are not always reactivated in visual imagination, but nevertheless impairs visual imagery when damaged or interrupted by TMS (Meyer & Damasio, 2009; Thompson & Kosslyn, 2003). Thompson and Kosslyn (2003) argued that it might be that the early visual cortices are not the source of the visual experience of perception but rather only a necessary preprocessing step. The point with this line of arguing here is that it is not obvious what the phrase “encoded in sensors” should refer to when it comes to the human brain. As far as the reactivation hypothesis is

concerned, reactivation can occur at various levels of the sensory and motor hierarchies, and thus the degree of overlap, similarity or sameness can vary depending on a number of different factors, such as the type of representational component (Myachykov, et al., in press).

Evolutionary algorithms, however, have the advantage of not being as biased by the researcher's presuppositions, as is the case with the constrained models, which explicitly rule out any other solutions as seen in Gigliotta et al. (2009) and Ziemke et al.'s (2005) studies. Returning to the representational issues discussed in Chapter 2, this type of approach seems more suitable at generating and investigating knowledge about the emergence of representations, as opposed to encodings. These models can show how the computational model constructs inner models for its own use, rather than being the instantiation of a theory of how its representations should look like. While this should not invalidate constrained models as such, one should be aware that they are different methodologies, which also constrains the type of possible analysis and conclusions. Indeed, the concluding sections of this chapter describe the results from a constrained model of simulation, but which nonetheless has some similarities to the unconstrained model in that it focuses on how a less constrained world (dreams) can be used to form simulations in robots as well as explain the role of dreams during infancy and childhood.

5.2 *Dreaming robots*

It might sound somewhat contradictory to talk about dreaming robots given an emphasis on the situated and embodied nature of cognition, as robots are very much developed for acting (Brooks, 1991), but there are some advantages of dreaming. Adami (2006, p. 1094) argued that a robot could

...spend the day exploring part of the landscape, and perhaps be stymied by an obstacle. At night, the robot would replay its actions and infer a model of the environment. Armed with this model, it could think of—that is, synthesize—actions that would allow it to overcome the obstacle, perhaps trying out those in particular that would best allow it to understand the nature of the obstacle. Informally, then, the robot would dream up strategies for success...

Adami (2006) did not further elaborate on the implementation of dreaming, but Conduit (2007), commenting on Adami's, idea suggested that it might be a route for further investigation of dreams, by implementing "some form of "sleep" algorithm that randomizes memory and combines it in unique arrays" (p. 1219). Rather than affecting behavior directly, the InSim hypothesis (Svensson, Thill, & Ziemke, 2013[VI]; Thill & Svensson, 2012[V]) suggests that dreaming plays a role in the development of simulations as described in the following section, and is also investigated further by means of a simple robot model implementing "robdreams" (Section 5.4; Svensson, Thill & Ziemke, 2013[VI]).

5.3 *Inception of simulation hypothesis*

Thill and Svensson (2011) developed the inception of simulation (InSim) hypothesis which states that dreaming during infancy and childhood, the inception phase, may play a fundamental role in the inception of simulations while, as dreams reach an adult level of complexity, simulations instead support and guide the dreams as they do for mental imagery in waking. Figure 5 provides a representation of the different functions postulated by the inception of simulation hypothesis.

Figure 5 Schematic illustration of the functions involved in the InSim hypothesis. Dashed arrows indicate functions active in the inception phase, whereas thick arrows indicate functions associated with the mature phase. Early in the inception phase re-enacting of experienced sensorimotor perceptions within dreams shape internal simulations of the world the infant is living in (circle Formation simulation). Based on these simulations, the infant or young child will generate predictions which are then validated while awake (arrow from Simulation to Validation), leading to a fine-tuning of the simulation (circle Fine-tuning). As the child grows older, the “Formation simulation” mechanism ceases to play an important role and dreams simply use existing simulations (the route from Simulation via Higher-level cognition)

5.3.1 The inception phase

In infants and young children, sensorimotor experiences are hypothesized to be re-enacted within dreams, which leads to the formation of associative structures underlying simulations. This is the inception phase. Since this takes place in young infants, it is hard to know what the phenomenological experience of this phase is; it is therefore somewhat of an assumption that it exists (rather than the inception of simulations being a subconscious process). However, it seems likely that it is initially composed of a more or less direct repetition of the impressions of recent sensorimotor experiences. Once a simulation is active, dreams begin to use it, at which stage the phenomenological experience begins to increase in complexity, including the generation of event sequences that were not directly experienced but are rather predictions of what is possible.

The child can then test these predictions while it is awake, leading to a validation mechanism, which in turn is used to fine-tune the existing simulations. It is clear that simulations that depend on sensorimotor experiences are constrained by the infant’s abilities, which are continuously developing throughout childhood. The first decade of life is therefore likely to be spent considerably refining the simulations. It is worth pointing out that other models based on simulated actions and perceptions propose similar mechanisms. For instance, Grush (2004) proposed in his emulation theory of representation, a model based on Kalman filters (from control theory) in which the predictions produced by simulations (or emulations in his terms), are also used to update the emulations themselves by comparing them with the corresponding actual input.

5.3.2 *The mature phase*

At the same time, however, as simulations begin to be more complex, the predictions they generate during dreams can be used in other aspects of higher-level cognition for example mental imagery and episodic memory. The complexity is characterized both in phenomenological terms of the number of and relations between objects and situations, and at the neural level in terms of the ability to reactivate the neural substrate for actions and perceptions, without causing overt actions or conflicts with externally generated perceptions. We do not attempt to characterize its function in dreams in detail but this would for instance include functions of dreams such as proposed by Revonsuo's (2000) Threat Simulation Theory. In other words, as the need for fine-tuning is reduced, the function of dreams as support for higher-level cognitive mechanisms increases. In this mature phase, higher-level cognition defines the narratives of dreams (thick arrows in Figure 5), which increases in complexity as simulations increase in completeness.

The hypothesis is both consistent with available evidence and compatible with theories related to the functions of dreams in adults as well as the position taken by Domhoff (2001, 2011). The next section briefly outlines the main arguments for the InSim hypothesis.

5.3.3 *Dreams and simulations*

The InSim hypothesis suggests that research into dreams and simulations may benefit from each other. Domhoff (2011) also argued just that: "Recent research on mind wandering, daydreaming, and simulation provides a new avenue for those dream researchers who begin with the premise that systematic studies of waking cognitive processes and their neural correlates are the best starting point for developing a neurocognitive theory of dreaming and dream content" (p. 1169). It could be added that it is not a one-way street, but dream research can lead to new discoveries and theories regarding waking cognitive processes. The following subsections illustrate the basic motivation for involving dream research in simulation theories, and more specifically why dreams should be considered to play a role in the initial development of the ability to simulate.

5.3.4 *Developmental aspects*

The basic claim that dreams in young children can play a crucial role in the inception and refinement of simulations is motivated in part by the ontogenetic hypothesis (Blumberg, 2010; Roffwarg, Muzio, & Dement, 1966) of the function of children's dreams, namely that the large amount of REM sleep at the beginning of life can be explained by a need for endogenous stimulation of the nervous system, especially higher cortical areas, which "may be useful in assisting neuronal differentiation, maturation, and myelination" (Roffwarg, et al., 1966, p. 616) of these areas. Thus, the ontogenetic hypothesis focuses on the neurophysiological aspects of brainstem induced cortical and muscle spindle activity, rather than a possible function of the conscious experiential aspect. However, the activation of higher cortical areas during dreams is necessary for establishing associations between perceptual and motor areas of the brain that can be further validated and refined during waking behavior.

5.3.5 *Phenomenal aspects*

There are a number of phenomenological properties that can play a role in both the inception and the mature phase. Firstly, dreams are somewhat more unconstrained than other thought processes, e.g. dream imagery (during REM-sleep) is sometimes more bizarre than wake thoughts, self-reflection is absent in dreams, and dreams lack orientational stability (Hobson, Pace-Schott, & Stickgold, 2000). Thus, dreaming allows the emergence of paths of simulated actions and

perceptions that would not have been thought of while awake. Secondly, dreams might be useful for creating longer and more stable simulations as they contain several organizing aspects. Dreams integrate several different dream elements into a coherent story, intensified emotions are experienced which also seem to guide the narratives during dreams, and instinctual programs such as fight-flight mechanisms are also used to guide the dreams (Hobson, et al., 2000). Although dreams are sometimes bizarre and very unlike the waking state, studies have shown that the majority of dreams are rather closely tied to past, present and likely future situations even though there is a preference for threatening and dramatic situations (Domhoff, 2011), suggesting that, at least in their final adult form, dreams construct an internal replica of the outer world in which behavioral strategies can be tried out.

5.3.6 *Sharing of neural mechanisms*

Although the understanding of the neural substrate has advanced with the development of neuroscience, there are different views about which mechanisms are actually causing dreams to appear (e.g. Blumberg, 2010; Hobson, 2009; Hobson & Pace-Schott, 2002; Solms, 2000). It is also uncertain whether dreams in different stages of sleep share the same neural substrate. For example, Domhoff (2011) argued for a default network underlying dreams in general, which is also functional in waking activities, such as mind wandering and simulating past and future situations, while Hobson (2009) emphasized the role of REM-sleep and the associated changes in terms of variations in neurotransmitters that dominate brain activity in different points in time. However, drawing on evidence from dream research, it is possible to explicate a few similarities between the neural substrate implicated in dreams and those previously cited for simulations in, for example, mental imagery experiments (cf. Chapter 3). Actions in dreams are thought to be neurophysiologically similar to real actions except for not being executed (Revonsuo, 2000). In the language of the simulation hypothesis, actions in dreams are therefore simulated actions. Hobson (1999, cited in Revonsuo, 2000, p. 889) argued that “the experience of movement in dreams is created with the help of the efferent copying mechanism, which sends copies of all cortical motor commands to the sensory system”. Again, these insights are highly relevant to the simulation hypothesis as the use of efferent copies and input from all levels of the motor hierarchy (Fuster, 2004; for a comprehensive review see Thill, Caligiore, Borghi, Ziemke, & Baldassarre, 2013) has also been proposed as a possible neural substrate for establishing simulations generally (Cotterill, 2001; Hesslow, 2002, 2012). The anterior cingulate cortex has been suggested as an important area for dreams (Domhoff, 2011), as well as way station for efference copies from the premotor areas towards the sensory cortex (Cotterill, 2001). Furthermore, the spontaneous production of motor activity, including proprioceptive signals caused by limb twitching, during REM sleep (Blumberg, 2010), could play a significant role in triggering simulated sensations and perceptions. Proprioceptive signals originating in limb muscles have also been observed in motor imagery (Lethin, 2005). Even though the evidence on the neural level cited here is not conclusive, it points to some interesting overlaps in need of further investigation.

Finally, dreaming is a state in which the brain is largely decoupled from the environment, that is, there are a number of hardwired mechanisms which cause sensory inputs to be dampened and motor output to be blocked (e.g. Hobson & Pace-Schott, 2002). This is a crucial aspect of dreams for their potential role in the development of simulations, since it means that the latter can be formed without the necessary architectural requirements of the waking state in which imagined and real perceptions, on the one hand, and overt and covert actions, on the other, must be able to coexist. To illustrate just one possible advantage: the simulation hypothesis suggests that a simulated action in neural terms is an action except for (not) being executed. We therefore need to explain why simulated actions in thought processes do not cause an overt action. One possibility is that the neural activations in simulations do not reach the threshold for overt movement (Cotterill, 2001). A possible advantage of dreams would be that sensory and motor areas could be strongly activated (because of the induced muscle atonia), such that associative learning mechanisms can

function in similar ways as in the waking state (cf. Downing, 2009), before mechanisms that allow simulations to occur in the waking state (without overt execution of the simulated actions) have developed.

To summarize, the empirical evidence indicates that in the adult simulations are present in both dreams and mental imagery. Further, there appears to be a progression during the child's development from very impoverished but rudimentary simulations in dreams to more complex dreams featuring longer narratives and more resemblances to situations in waking life.

5.4 Robodreams

To investigate the validity of the InSim hypothesis, a proof-of-concept computational model of implementing robodreams was developed using a simulated E-puck robot. The term robodreams is used here to distinguish the robot's dreams from real dreams, indicating that not every aspect of dreaming is modeled. The motivation, experimental setup and result is briefly mentioned in the following subsections (see Svensson, Thill & Ziemke, 2013[VI], for details).

5.4.1 Motivation

The purpose of implementing "robodreams" was mainly twofold. Firstly, it could further refine the InSim hypothesis and therefore also further the understanding of simulation. Secondly, it can lead to new and better ways of developing mental imagery like abilities in robots, i.e., it can increase the robots abilities to form internal worlds. In the study, dreams were only modeled at a functional level, drawing inspiration from the phenomenological nature of dreams, especially REM-sleep dreams that are most common early in development.

In particular, the focus was on the fact that dreams produce sensory experiences that are sometimes similar to previous waking situations, distortions of waking situations, or non-experienced situations (cf. e.g. Domhoff, 2011; Hobson, 2009; Revonsuo, 2000). Thus, robodreams should incorporate non-experienced events as well as distorted versions of previously experienced events that can later be refined during waking encounters with the environment. Although there is little previous evidence from robotic research, this could be beneficial for the development of simulations: it is for instance possible that robodreams sometimes produce sensory perceptions of non-experienced situations, but which can be similar if not exactly the same as a future environmental state, leading to faster acquisition of true predictions in the waking state. Thus, the purpose is to investigate whether the inception phase may establish associations that produce sensory inputs that improve the quality of simulations by pushing the simulated paths toward the optimal solution. Robodreams may also reduce the amount of training examples necessary to develop simulations of a particular environment. The next section describes the details of the experimental set-up used to provide a proof of concept of the utility of robodreams.

5.4.2 Proof-of-concept experimental set up

The absence of previous work on how to model dreams in robots, at least on the phenomenological level, makes this an explorative experiment: therefore different ways of implementing phenomenological aspects of dreams in robots are investigated. Firstly, two different ways of modeling the nature of the sensory impressions during dreams were used: randomization and recombination. Randomization alters previous sensory impressions randomly such that another sensory impression is created. As discussed earlier, distortions of different kinds are common in dreams (Hobson, et al., 2000); further this follows Conduit's (2007) suggestion of randomizing memories. In recombination, the actual sensory inputs change place rather than get distorted. Figure 6 (left) illustrates how this is done. This aspect somewhat resembles dreams' lack of orientational stability and frequent shifts of attention (Hobson, et al., 2000). Secondly, two different ways of timing the occurrence of robodreams were implemented: in the beginning of

each run (after a short (5%) waking period) and intermittent (after a short (5%) waking period) robodreaming, cycling between waking and robodreaming. Although it is possible to determine, to some extent, the development of the amount of dreaming from infancy to adult (Roffwarg, et al., 1966), it is not necessarily beneficial for informing the current experiments except for the general insight that dreams may have a larger impact on simulation-forming mechanisms during infancy as the InSim hypothesis states. With regards to the simulation hypothesis, the current experiments are limited to the “critical assumption of the theory that perceptual simulations can function as stimuli” (Hesslow, 2012, p. 73), i.e., that the self-generated sensory activations are sufficiently similar to those caused by the environment. Thus, contrary to earlier in experiments (e.g. **Svensson**, Morse, & Ziemke, 2009b[IV]), the ability of simulated actions to generate the sensory predictions was not part of the model.

Figure 6 Schematic representation of the e-puck robot and the environment. (*Left*) The hexagons represent the placement of the infra-red proximity sensors. The sensors are numbered from 1-8 and the numbers in parenthesis represent how the sensor inputs were recombined in condition C. (*Right*) A somewhat simplified schematic depiction of the world used in the current setup. The arrow represents the robots direction and the dashed arrows represents the infra-red sensors.

The experiment was based on a simulated E-puck robot (www.e-puck.org) running on a robot simulation platform (Webots 6.4.1). The e-puck has a circular body with a diameter of 75 mm, and is equipped with 8 infrared proximity sensors around its body with a range of approximately 6 cm. It has two motors, which independently control the two wheels, one to each side. The task of the robot was to develop simulations that reactivate the sensory experiences that would occur if the robot were to navigate through a square shaped environment (see Figure 6, right) similar to previous worlds used to investigate the simulation hypothesis (**Svensson**, Morse, & Ziemke, 2009b[IV]). The robot was controlled (both during learning and testing) by a simple behavior program (cf. Braitenberg, 1986) that allows the robot to move along the corridors clockwise, but never influences the simulations directly. The architecture for implementing the predictions was an Echo State Network (ESN), which is an architecture that shows some biological plausibility as a model for environmental anticipation (**Svensson**, Morse, & Ziemke, 2009b[IV]).

This initial proof-of-concept experiment focused particularly on investigating the effects of robodreams on the rate of acquisition of simulations in waking states. According to the InSim hypothesis, waking periods are used during the inception phase to fine-tune the simulations. Thus, after a period of robodreaming, simulations should be acquired faster than waking states alone.

5.4.3 Conclusions

Although the study was somewhat limited in its complexity, it was able to show that robodreams have a positive effect on the development simulations. The results suggested that periods of dream-like sensations make the learning based on real sensory input more efficient, since simulations were established faster when they were preceded by a period of robodreaming. Although dreams may be seen as a somewhat random replay of previous interactions, the results suggest that the way in which the sensory impressions get replayed is important and affects the performance of waking learning, which indirectly supports dream theories that attribute roles to phenomenological states, such as Revonsuo's (2000) threat simulation theory.

However, future work might want to more closely model different aspects of the phenomenological content of dreams as it was not entirely clear from the results which type of phenomenal aspect were most efficient and neither were they optimized. For example, the recombination condition could be extended to more closely model different types of attentional shifts and orientational instabilities observed in dream reports.

The InSim hypothesis is developmental in the sense that the function of the model evolves over time by shifting the focus from one phase to the other, which results in a shift from using dreams primarily as a way of re-fining simulation to using dreams as a way to generate simulations that can be used in other aspects of cognition. The focus here was on the inception phase, but a further question not addressed in this kind of set up, which should be further investigated, is the interdependencies of the two phases, as they are likely to overlap and to some extent coexist. Another aspect for developing mental imagery in robots is switching during on-line interactions between simulated and experienced states to allow the robot to go beyond off-line "(day) dreaming" to use mental imagery in real time problem solving. This point extends beyond the InSim hypothesis to most models of simulation, where the interplay between on-line and off-line behaviors are not always easily implemented and not investigated to a sufficient extent.

5.5 Summary

This chapter briefly reviewed the attempts to model simulation by means of computational agents (for a more comprehensive review see **Svensson**, 2007) and described the inception of simulation hypothesis and the initial robot experiments testing the plausibility of the hypothesis (**Svensson**, Thill & Ziemke, 2013[V]; Thill & **Svensson**, 2011[V]).

		Chapter				
		2	3	4	5	
Paper	I	●	○	○	○	
	II	○	●	○	○	
	III	○	○	●	○	
	IV	○	○	○	○	○
	V	○	○	○	○	○
	VI	○	○	○	○	○
LIC		○	○	○	○	○

6 Summary

In the licentiate thesis (Svensson, 2007), the following aims for the further work towards a doctoral thesis were set up:

- Further deepen the theoretical understanding of embodied simulation as off-line representation.
- Further deepen the understanding of the role and relevance of embodied simulation as off-line representation in relation to situatedness and embodiment.
- Develop the methodology of using situated and embodied computational models to investigate simulation processes, in particular, simulation processes as off-line representations

This thesis has deepened the understanding of simulation in different ways. It has described in more detail the different meanings of representation and representational problems (Chapter 2) and how they are related to reactivation (Chapter 3) and anticipation (Chapter 4; Svensson, Morse, & Ziemke, 2009a[III]). It has also showed how dreams can be used to influence embodied computational models of simulations (Chapter 5). It has to, some extent, addressed questions regarding the situatedness and embodiment in terms of reactivation and prediction, but the thesis did not pursue these issues explicitly. That is, there are still many open issues regarding the extent to which different embodiments affect the simulations and the development of simulation, and as discussed below, it is not known exactly how information derived from the sensorimotor interaction with the environment is integrated in an efficient manner with information from simulations. The thesis has also further described the neural mechanisms underlying simulations.

6.1 Future work

Pezzulo et al. (2011) argued more generally that grounded or embodied cognition need to develop computational models that can drive embodied cognition theories to be more detailed such that they can lead to more testable predictions.

Given the established empirical foundation, and the relatively underspecified theories to date, many researchers are extremely interested in embodied cognition but are clamoring for more mechanistic implementations. *What is needed at this stage is a push toward explicit computational models that implement sensorimotor grounding as intrinsic to cognitive processes.* With such models, theoretical descriptions can be fleshed out as explicit

mechanisms, idiosyncratic patterns across experiments may be explained, and quantitative predictions for new experiments can be put forward. (p. 1)

One of the reviewers of the previous paper (Thill & Svensson, 2011[V]) argued in a similar way that the InSim hypothesis was also underspecified. In the later paper (Svensson, Thill & Ziemke, 2013), the hypothesis was further refined in such a way that testable predictions were derived. However, the InSim hypothesis is still in an early stage of development and more work is needed to couple the idea to the neuroscience of dreaming as well as more detailed computational models of specific cognitive phenomena. A more detailed model could possibly be more directly compared to behavioral and neuroscientific data (cf. Pezzulo, et al, 2011)

Another open issue that has not been addressed explicitly in this thesis is how the brain can switch between simulating an action or perception and acting and perceiving (cf. Svensson, 2007). Although it is likely that what gets to be perceived and what gets to be executed in the adult brain is an emergent phenomenon of many different aspects including the neural, bodily, environmental (physical and social) context, it is necessary to see what kinds of mechanisms are involved in determining the influence of different sources of information including simulations. Grush (2004), for example, used Kalman filters as an analogy of the general process by which humans do this. The InSim hypothesis argued that dreams are special in this sense, since there are specific neurophysiological mechanisms that dampen the sensory inputs and motor outputs, which allows simulations to have a large influence on cognitive processing. In waking life such crude mechanisms are obviously not sufficient since there need to be a more fluent and fast integration of external and internal sources of information.

By continuing to investigate the extent of reactivations in different types of brains, the neural pathways of predictive mechanisms contributing to reactivations, and building computational models of simulation based on these ideas, it might be possible to further determine in which ways, for example, the dog in Sjölander's example is (1) simulating and (2) dreaming about things.

Dogs also dreams and their behavior when dreaming (e.g. running movements of the legs, yapping as when hunting) indicates that something is 'going' on inside the brain like the 'scenes' in the mind of small children ... (Sjölander, 1995, p. 6)

6.2 Papers included in the thesis

The following sections very briefly summarize the papers included in the thesis in *abstract like* format (and therefore lack references).

6.2.1 Paper I

Published as: Svensson, H. & Ziemke, T. (2005) Embodied representation: What are the issues? In: B. G. Bara, L. Barsalou & M. Bucciarelli (Eds.), *Proceedings of the Twenty-Seventh Annual Conference of the Cognitive Science Society* (pp. 2116-2121). Mahwah, NJ: Erlbaum.

This paper addresses some aspects of the representational debate in situated and embodied cognition (cf. Chapter 2). A common theme of many discussions among embodied cognition researchers is whether or not cognition is making use of representations. This debate has been called a "debate for the sake of appearance" because there is no agreed upon way of identifying what is a representation. Therefore, instead of arguing for a particular position on whether embodied cognition uses representation, the debate is clarified by (1) reviewing three possible types of representations of embodied cognition that might be considered candidates for representationhood and (2) outlining criteria for what is or is not a representation in embodied

cognition. The three types of representations are interactive potentials, simulation or emulation theories, and external representations or externalism. The criteria for representationhood present in embodied cognition are: (1) representations need to be active constructions of the cognitive agent and not merely correspondences between the external world and the cognitive agent identified by an external observer, (2) representational systems must have the ability to detect that they are wrong, (3) representations must be able to guide actions, and (4) representations must be able to guide behavior in the absence of sensory input.

6.2.2 Paper II

Published as: Svensson, H., Lindblom, J., & Ziemke, T. (2007) Making sense of embodiment: Simulation theories of shared neural mechanisms for sensorimotor and cognitive processes. In T. Ziemke, J. Zlatev & R. Frank, M. (Eds.), *Body, language and mind. Volume 1: Embodiment* (pp. 241-270). Berlin: Mouton de Gruyter. (The paper is an extension of a previous paper: Svensson, H. & Ziemke, T. (2004) Making sense of embodiment. In: K. Forbus, D. Gentner & T. Regier (Eds.), *Proceedings of the 26th Annual Conference of the Cognitive Science Society* (pp. 1309-1314). Mahwah, NJ: Lawrence Erlbaum.)

This paper describes and argues for simulation theories by providing an extensive review of the empirical evidence in support for the reactivation hypothesis (cf. Chapter 3). Although an increasing number of researchers are convinced that cognition is embodied, there still is relatively little agreement on what exactly that means. Notions of what it actually means for a cognizer to be embodied range from simplistic ones such as “being physical” or “interacting with an environment” to more demanding ones that consider a particular morphology or a living body prerequisites for embodied cognition. Based on evidence from neuroscience, psychology and other disciplines addressing phenomena such as imagery, gestures, and language, the paper argues that a key to understanding the embodiment of cognition is the “sharing” of neural mechanisms between sensorimotor processes and higher-level cognitive processes. The paper also relates simulation to canonical neurons and mirror neurons. The main point of the paper is that higher-level cognition is embodied in the sense that cognition make use of (partial) simulations or emulations of sensorimotor processes through the re-activation of neural circuitry also active in bodily perception and action.

6.2.3 Paper III

Published as: Svensson, H., Morse, A. F., & Ziemke, T. (2009) Neural Pathways of Embodied Simulation. In: G. Pezzulo, M. V. Butz, O. Sigaud & G. Baldassarre (Eds.), *Anticipatory Behavior in Adaptive Learning Systems*. LNCS 5499 (pp. 95-114).

This paper describes three different types of anticipation and their role in simulation (cf. Chapter 4). Simulation theories have proposed that a cognitive agent's "inner world" can at least partly be constituted by internal emulations or simulations of its sensorimotor interaction with the world, i.e. covert perception and action. This paper further integrates simulation theory with the notion of the brain as a predictive machine. In particular, it outlines the neural pathways of covert simulations, which include implicit anticipation in cerebellar and basal ganglia circuits, bodily anticipation by means of forward models in the cerebellum, and environmental anticipation in the neocortex. Implicit anticipation suggests that action selection mechanisms can be seen as anticipations, but of an implicit or procedural kind, which allows an animal to act as if it has access to, e.g., some future goal state, but without the need to produce a (sensory) state that correspond to that goal. Bodily anticipation involves the ability to produce predictions of the (sensory) state of the body, which have, for example, been considered a necessary component of motor control. Environmental anticipation is the ability to generate a prediction of a future

perceptual state of the environment external to the agent's body. The paper also discusses, to some extent, possible implications of the neural pathways of covert simulation for the frame problem, and the relation between procedural and declarative knowledge in covert simulations.

6.2.4 Paper IV

Published as: Svensson, H., Morse, A. F., & Ziemke, T. (2009) Representation as Internal Simulation: A Minimalistic Robotic Model. In: N. Taatgen & H. van Rijn (Eds.), *Proceedings of the Thirty-First Annual Conference of the Cognitive Science Society* (pp. 2890-2895). Austin, TX: Cognitive Science Society.

This paper argues for three different types of anticipation in simulations and also for simulation as off-line representations (cf. Chapter 4). The paper also describes a simulated robot that develops simulations based on external (i.e. environmental) predictions implemented by an echo state network (cf. Chapter 5). Embodied cognition theorists have proposed that a cognitive agent's "representations" or "inner world" can at least partly be constituted by internal emulations or simulations of its sensorimotor interaction with the world, i.e. covert perception and action. The paper, thus, includes a brief review of the empirical evidence for the existence of simulation and also includes a summary of the arguments for the existence of implicit, internal and environmental anticipation mechanisms. It also briefly argues for echo state networks as being a somewhat plausible model of environmental predictions via cortical columns in the human brain. The paper also presents an analysis of the robot model's behavior while navigating a simple environment based only on simulated input.

6.2.5 Paper V

Published as: Thill, S., & Svensson, H. (2011) The inception of simulation: a hypothesis for the role of dreams in young children. In: L. Carlson, C. Hoelscher & T. F. Shipley. (Eds.), *Proceedings of the Thirty-Third Annual Conference of the Cognitive Science Society* (pp. 231-236). Austin, TX: Cognitive Science Society.

This paper introduces and argues for the inception of simulation hypothesis, which connects research on the functional role of dreams with simulation theories (cf. Chapter 5). It argues that although theories that describe the refinement of simulations exist, the origin of these simulations is, usually, not considered in detail. Similarly, research into the functional role of dreams has tended to focus on adults, with less regard to the dreams of young children. The main point of the paper is that a functional role of dreams in infants through to early childhood is the inception of these simulations. The paper presents theories and results from dream research as well as research on the simulation hypothesis in support for the proposed model.

6.2.6 Paper VI

Published as: Svensson, H., Thill, S. & Ziemke, T. (2013) Dreaming of electric sheep? Exploring the functions of dream-like mechanisms in the development of mental imagery simulations. *Adaptive Behavior*, 21, 222-238.

This paper further refines the inception of simulation hypothesis and provides further arguments for its validity including a proof-of-concept robot experiment (cf. Chapter 5). According to the simulation hypothesis, mental imagery can be explained in terms of predictive chains of simulated perceptions and actions, that is, perceptions and actions are reactivated internally by our nervous system to be used in mental imagery and other cognitive phenomena.

Previous research shows that it is possible but not trivial to develop simulations in robots based on the simulation hypothesis. While there are several previous approaches to modeling mental imagery and related cognitive abilities, the origin of such internal simulations has hardly been addressed. The inception of simulation (InSim) hypothesis suggests that dreaming has a function in the development of simulations by forming associations between experienced, non-experienced but realistic, and even unrealistic perceptions. The paper proposes an experimental set up based on a simple simulated robot to test whether such dream-like mechanisms can be used to instruct research into the development of simulations and mental imagery-like abilities. Specifically, the hypothesis is that “robodreams” informing the construction of simulations lead to faster development of accurate simulations during waking behavior. The experiment uses a simulated E-puck robot (www.e-puck.org) running on a robot simulation platform (Webots 6.4.1). The task of the robot is to develop simulations that reactivate the sensory experiences that would occur if the robot were to navigate through a square shaped environment similar to previous worlds used to investigate the simulation hypothesis. The paper also presents and discusses the initial results in favor of the inception of simulation hypothesis.

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