End of Third Year DPhil Report

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1 From evolutionary robotics to tactile pac-man: An enactive way of explaining mind

In my DPhil, I develop a methodological framework to explain certain aspects of human cognition in an *enactive* way. Applying these ideas, I investigate the sensorimotor basis of our experience of simultaneity with this framework.

The enactive approach to cognition[18, 17] sets itself apart from traditional symbolic/information processing approach in a number of ways: It emphasises the autonomy of the cognizer, the embodiment and situatedness of behaviour and the irreducibility of behaviour and experience to material substrates. There are important methodological consequences to adopting the enactive paradigm, and from a conceptual analysis of these paradigmatic issues I develop the framework I propose, which combines evolutionary robotics simulation models [5] and minimal empirical perceptual supplementation experiments with humans [6]. I sketched this framework, e.g., in [4, 13, 9], and I present some of the more general methodological issues to do with the enactive paradigm in detail in [3] and [11].

The practical part of my DPhil puts the interdisciplinary enactive methodology that is described and developed in the theoretical part of my DPhil to use. Firstly, the simulation experiments I conducted throughout the years of my DPhil ([8, 7, 4] and further unpublished work) serve to illustrate and confirm the conceptual argument I develop about the different scientific functions evolutionary robotics simulation models can have. This applied part of my thesis will culminate in the presentation of an interdisciplinary research project that I conducted in order to investigate how adaptation to sensory delays impacts on the experience of simultaneity in humans, and that combines evolutionary robotics simulations and minimal empirical perceptual supplementation experiments.

This report briefly summarises my activities in the past year, before I will give a more detailed account about the structure of my planned DPhil dissertation and a schedule for the coming 9 months.

2 Record of the Academic Year 2006/2007

The third year of my doctoral studies was centred around a five months research stay at the Technical University of Compiègne (UTC) in France (September 2006 – February 2007), where I designed and conducted an empirical study with human subjects to investigate adaptation to sensory delays. I complimented this empirical model with an evolutionary robotics simulation, to thereby implement and test the interdisciplinary methodology that I develop in the theoretical part of my DPhil.

In the run–up of this research stay, I modelled a perceptual crossing study previously conducted by the GSP group at the UTC [1], as a first test bed for the usefulness of the interdisciplinary framework I outline. The simulation model turned out to be a rich source of experimental hypotheses. The results from my simulation were received very well when I presented them at the SAB'06

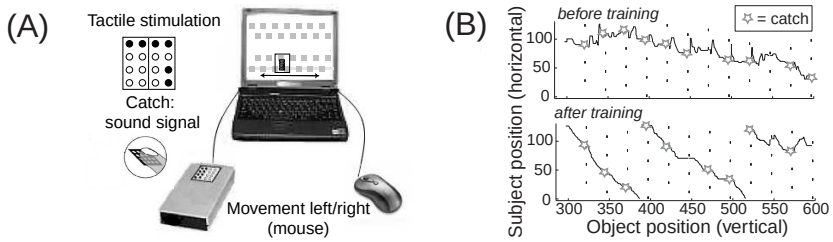

Figure 1: (A) A diagram of the experimental set up for the empirical study. (B) Human trajectories before (top) and after (bottom) training, presented with a sequence of 16 lines of evenly spaced objects (black bars), both without delay: Even though the behaviour has clearly been transformed, the performance on the task is similar.

Workshop on Behaviour and Mind as a Complex Adaptive System (presentation of long abstract [9]) in Rome. In an extended collaboration with E. Di Paolo and H. Iizuka, these results were included in a paper submitted and accepted for publication in a special issue of the journal *New Ideas in Psychology* on dynamical systems approaches [4]. Another simulation experiment I worked on at the time was a model of the first experimental set–up I had had on my mind, which made me realise why this set up was fundamentally flawed. This work is not published and will probably only be mentioned as an anecdote in my PhD.

In Compiègne, I spend three months familiarising myself with the facilities and methods used in the GSP group, developing an experimental protocol and conducting a series of piloting experiments to optimise the parameters of the task. This work was a collaboration with Olivier Gapenne, Charles Lenay, Dominique Aubert and John Stewart. The final experimental design was the winning submission to a competition for experimental protocols to the French Cognitive Science Conference (ARCo06) in Bordeaux in December 2006 ([12], in French).

The experiment was inspired by a recent study by Cunningham et al. [2] in which a negative aftereffect was reported as a consequence of adaptation to a 200 ms visual delay in a sensorimotor task, which seems to bear on the perception of simultaneity. We adopted the author's hypothesis that adaptation to delays relies on a time pressure in the task. However, for our minimalist approach, we transformed the visual navigation task into a more simple tactile/auditory catch task (see Fig. 1). As winners to the competition, we could conduct our experiment in Bordeaux with the participants of the conference, data from

experiments with 20 subjects was gathered. The hypothesis to be tested, i.e. that a negative aftereffect would result as a consequence to the adaptation to delays in the developed framework, was not confirmed. This implies that the hypothesis of Cunningham et al. that it's the time pressure in the task that leads to the negative aftereffect is not as such true, there seems to be something more to their experimental set–up than just the time pressure.

The first half of the year 2007, I was mainly concerned with the analysis of the data resulting from these experiments, a project that is still ongoing. An initial statistical analysis of the data revealed some interesting patterns of change in some of the variables. From these findings, it seemed clear that, even though the results of the study were not confirming our initial hypothesis (or any other straight forward explanation), they were not fully random either. Therefore, we concluded that an in-depth analysis of the data could be a fruitful endeavour, which could help to understand what it was about the experiment that made it different from Cunningham et al.'s experiment, to understand why a negative aftereffect did not occur. Such insights would help to be able to design a better experimental protocol, in which an aftereffect is produced. It would also mean that the data had not been gathered in vain. The problem we faced with the data analysis is that the dimensionality of the data set is very high, as all sensorimotor trajectories for the 20 subjects have been recorded, and, given that there was no straight forward interpretation of the results, the possible dynamical or formal aspects to focus on in an in-depth analysis are vast.

The next step was to implement an evolutionary robotics model of the task to better understand the dynamics and the theoretical properties of the task in a controlled and simplified setting. The results from this simulation model are presented in a paper accepted for ECAL07 in Portugal [10], I also discussed them and their implications in the larger context of my experiments and the study of sensory delays in a presentation at the CCNR workshop *Computational Biology, Robotics, and Related Work* and in the Mind and Life reading group. Both times they were received with interest and sympathy.

At present, I am working on a draft for a longer (journal) paper that brings together the findings from the empirical and the synthetic study, and I am re–analysing the empirical data with hypotheses and predictions resulting from the computational model, some of which seem to be confirmed. I will briefly summarise the main predictions/results, for a more detailed description see [10].

- In the simulation, there is a systematic displacement of trajectories from the object location after adaptation that depends on the speed and direction of movement before first making contact with an object (see Fig. 2). It seems that (at least in subgroups of the subjects) such systematic displacements are also found in the empirical data set.

- The existence of either *reflex-like* or *reactive* strategies was identified. Reflex-like trajectories are characterised by stereotyped motor output sequences that are sensitive to the onset of a stimulus, but not of the ongoing

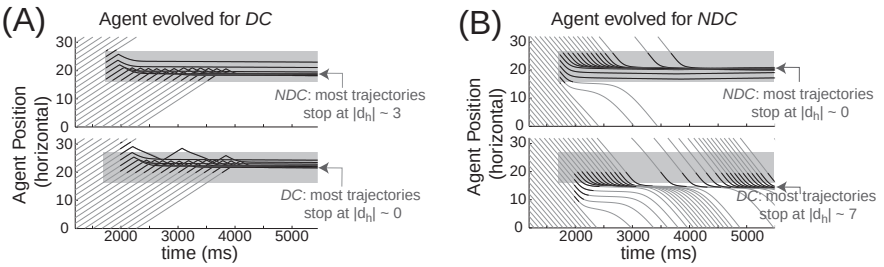

Figure 2: Trajectories from the simulation for different agent staring positions across time, presentation of a single object. Crossing the object (grey region) produces a (delayed) input stimulus I_1 (trajectories black during stimulation). Top: without delay (*NDC*), bottom: with delay (*DC*). (A) an agent evolved for the task with delay (*DC*) (B) an agent evolved for the task without delay (*NDC*).

change in signal magnitude during execution of this movement. Reactive strategies, on the other hand, depend on the ongoing perception of stimuli that represent the effect of previous actions. There can be intermediate or hybrid strategies as well. We hypothesise that these strategies are differently affected by the introduction/removal of a delay: A reactive strategy would compensate for the delay by slowing down, and a reflex–like strategy would produce a systematic displacement error as we found it in our simulation models.

We have started to develop formal measures for reflex–like and reactive strategies. A preprocessed, laterally shifted average of trajectories and the mean square error for each individual (either fully, or also its variation across a sliding time window) seem to be good indicators of whether a strategy is reflex–like or reactive. We also believe that time series analysis tools such as Granger causality are potentially valuable to formalise these intuitive descriptions of strategies.

A third type of strategies we call *anticipatory* strategies, and it is characterised by sensitivity of motion to ongoing and past changes in signal magnitude, i.e. longer term structural dependencies between sensation and motion. These kinds of strategies are not possible in our minimal experiment, because there are hardly any longer term structural invariants. We believe that this is what made our experiment different from Cunningham et al.'s and hindered an adaptation to the delay with negative aftereffect. Therefore, our new hypothesis is that not just time pressure is necessary to produce a negative aftereffect, but time pressure and long term structural invariants that make anticipatory strategies possible.

These ideas about different types of behaviour are not yet presented, or even fully formalised, it is work in progress.

- The model also predicts that scanning velocity would decrease with the introduction of delays, regardless of the reactivity of the strategy. This does not appear to be immediately true for the empirical data.
- One observation that was not predicted by the model was a tendency of strategies to become more reflex–like across the adaptation with delays (i.e., smaller mean square error from average trajectory).
- A last set of predictions from the simulation model is that the behavioural performance is independent from the following factors:
  - Falling velocity of the object.
  - Behaviour in previous presentations of objects.
  - Reward signal if an object is caught.
  - Long term structural dependencies in object location.

  These predictions appear to be true, which makes the analysis much easier, but these independencies still remain to be formally confirmed.

At the time I was in Compiègne, the GSP conducted an experiment with a twodimensional variant of the experiments on perceptual crossing I had successfully modelled before[4] and asked me to make an evolutionary robotics simulation model. I coded the simulation, but did not immediately yield any interesting results, so the project was put aside in favour of more urgent projects.

The conclusions from the results of my research stay in Compiègne in the light of my entire DPhil project are very positive: The proclaimed explanatory potential of the interdisciplinary framework I developed for the theoretical part of my DPhil has been confirmed several times now and generated interesting insights about aspects of human cognition and behaviour, as well as new questions and hypotheses to be explored in future research projects.

A different line of research I pursued during and after my stay in Compiègne was a collaboration with John Stewart on the observer status of a scientist in the scientific study of autonomy, which is accepted for publication in a special issue of the journal *BioSystems* on modelling autonomy and which was discussed and presented at the workshop on modeling autonomy in San Sebastian (Basque Country) in March 2007.

I taught at Sussex during the spring and summer term (Adaptive Systems, Principles of Programming Languages, Introduction to Programming Paradigms). Other acitivities include webmastering the CCNR webpage, giving talks and the attendence of various conferences and schools. A more detailed break–up of my activities during the academic year 2005/2006 can be found in appendix A.

3 Plans for the Academic Year 2007/2008

The coming academic year will be mainly about writing up my DPhil. I will go on continuation in October 2007 and intend to hand in not later than six months

after that date. The structure of my planned DPhil dissertation is described and commented in the following section.

The write up of my DPhil will involve conducting further simulation experiments, or possibly even empirical experiments. Such further experiments will possibly lead to the spin–off of further scientific publications as well. The extent to which I will be able to do further experiments and tie up loose ends is, however, fiercely limited by material and administrative factors (deadlines and money). The following list is a prioritised list of possible completions of unfinished projects. Probably, it will only be possible to realise the top two or three items on this list.

1. Extension of the simulation to explore 'value system architectures' and journal paper (both draft for a paper and the further unpublihsed experiments are 80% done already)

2. Development of an improved experimental set–up to investigate the adaptation to sensory delays and an exploration in simulation (evolutionary robotics, not started yet)

3. A further empirical study with the revised experimental set–up (not started yet).

4. The completion of the evolutionary robotics simulation experiments on perceptual crossing in 2D (50% done).

5. The empirical investigation of some of the hypotheses generated from the evolutionary robotics simulation of perceptual crossing in 1D [4], possibly involving the experimental tactile feedback platform built at Sussex for a research collaboration with E. Di Paolo, W. Bigge, H. Iizuka, H. De Jaegher and R. Wood. In particular, it would be interesting to investigate genuine interactive perceptual crossing vs. interaction with a recorded previous interactive perceptual crossing (not started yet).

6. Further experiments to investigate linear synergies as a principle in motor control, in particular the role of gravity in a physically more plausible simulation. This would make it possible to extend the work presented in [8] such that it would be sufficient for a journal publication (50 % done).

I will also coorganise and attend the CNRS summer school *Enaction and Cognitive Science* in Fréjus, France (06.-12.09.2007), present a poster at ECAL'07 in Lisbon, Portugal (10.-14.09.2007) and present my work at the Institute for Biomedical Research at the National Autonomous University of Mexico (UNAM) end of September 2007. This talk will be given during a three week holiday in Mexcio. I also want to do some commissioned teaching, and I will start to research and apply for postdoctoral positions/grants.

I am confident that these activities, including the write–up of my DPhil dissertation will not take more than nine months, so I will be able to hand in my dissertation at latest in March 2008.

3.1 Proposed Structure for my DPhil

- Introduction

FIRST PART: Methodology

1. Background: Enaction vs. Cognitivism

   In this chapter, I will outline the general conflict between the classical cognitivist and the enactive paradigm. I will bring in material from our book chapter on enaction [3], many well known criticisms of GOFAI and cognitivist approaches and some ideas of my own that I have not yet presented anywhere.

2. Methods

   This chapter will outline the interdisciplinary framework I developed and later applied during my stay in Compiegne. It will be based on the presentation of the enactive approach in the previous chapter and first feature a general methodological analysis. For instance, it will discuss the role of the observer in science. Some of these ideas have been published in [11] and [13] and involve the question of ascription and generative mechanisms and the role of experience in the study of cognition (first (phenomenology), second (interview) and third person (scientific measurement)).

   Then, I will introduce evolutionary robotics[5] and perceptual supplementation [6] as concrete methods of investigation and, based on the previous theoretical debate, outline why and how I think these methods and their combination are useful for enactive cognitive science and what kind of question they can tackle, what kind of knowledge they can generate.

3. ER can generate proofs of concept and hypotheses for science: Linear synergies as a principle in motor control

   I will present the simulation described in [8] to support the claims about how ER experiments are a useful tool in science. This study from my first year has generated a number of hypotheses and proofs of concept about the benefits of linearly scaling motor torques applied to different joints in a simulated arm. There is empirical work going on to investigate this principle in human motor control, and the physiologists involved in these studies have reacted enthusiastically to our paper, they cited it and proposed further simulation experiments to us. Therefore, this project illustrates well the potential of ER simulations for science.

4. ER can illustrate and verify conceptual arguments: An exploration of value system architectures

   In this chapter, I will present the simulation model published in [7] to illustrate a different explanatory potential that ER simulations possess, i.e. to illustrate and fortify conceptual arguments and generate new ideas and concepts for description. This simulation caricatures value system

architectures, as proposed e.g., by Sporns and Edelman[14], to illustrate how a toy version of this architecture is insufficient to explain adaptivity as a general phenomenon. It helps to identify the implicit additional premises underlying that kind of architecture.

5. A first test of the interdisciplinary framework: Perceptual Crossing in 1D

   This chapter will describe the experiments presented in [4], which is a first application of evolutionary robotics to simulate work in perceptual supplementation, as I propose in the framework I develop, even though I was not personally involved in the perceptual supplementation experiments on perceptual crossing [1] that my simulation models. This model was possibly the first ER model to generate a prediction about human behaviour that was later empirically confirmed, and generated a number of other predictions and proofs of concept, such that it confirms the principal usefulness of the framework I propose.

6. (If I have time to finish my work on perceptual crossing in 2D, it would go here...)

SECOND PART: Investigating the experinene of simultaneity

1. Background: The Experience of Time and Simultaneity

   In this chapter, I would introduce the rather complex and vast background literature on time, delays, simultaneity etc.

   This would involve a general background description, summarising classical phenomenology, Piaget's work on the child's conception of time, empirical work such as the research on the flash lag phenomenon, neuroscience work such as Libet's traditional experiments, other empirical work on sensorimotor disruption, etc. ...

   The more concrete part of this chapter would introduce a review of experiments with delay and how they failed to produce negative aftereffects [16], Cunningham's study[2], Stetson et al.ś citestetson attempt to replicate their results. From this, the hypotheses adopted for my experiment in Compiegne are derived.

2. The empirical study

   This chapter will describe the experimental set–up and the (apparantly uninteresting) results from my experiment in compiegne.

3. The robotics simulation

   This chapter will describe the simulation model, as it is described in [10], and the hypotheses it generates

4. The combined evaluation

   This chapter will describe the findings that result from bringing together the simulation and the empirical study, from revisiting the data. This is what I work on at the moment, drafting a journal publication.

5. Further experiments? (actual or possible)

   What this chapter covers (or whether it will just be one chapter) depends on the results from my ongoing work and on how the write up of my DPhil proceeds.

- Conclusions

3.2 Schedule

Time	Activity	Result
1 month	Finish data analysis and the draft paper about my research on sensory delays	Journal publication (Draft)
1 month	start write-up of DPhil	DPhil thesis
1 month	conferences + holiday (Summer-school, ECAL, Mexico)	2 talks, 1 poster
6 month	Write–up with possible further experiments and papers	DPhil Thesis (possibly 2 journal publications)

NOTE: ALL MY PUBLICATIONS LISTED HERE ARE ACCESSIBLE FROM MY RESEARCH WEBPAGE

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A Activities

- *Maintaining the CCNR webpage* as additional paid activity.
- *Teaching.* I have been assisting in the courses Adaptive Systems (AS), Introduction to Programming Paradimgs (IPP) and Principles of Programming Languages (PoPL).
- *Presentations/Conferences/Schools*:
  - 29.05.-03.06.2006: Enaction Summer School. Constructivism and Enaction: A new paradigm for Cognitive Science. Ile d'Oléron (France)
  - 09.-14.7.2006: 50th Anniversary of Artificial Intelligence Summit, Ascona, Switzerland.
  - 30.09.2006: SAB'06 Workshop on Behaviour and Mind as a Complex Adaptive System, Rome, Italy.
  - 09.10.06 Talk at the GSP, Université de Technologie de Compiègne: Retards sensorimoteurs et contiguïté temporelle: Un approche interdisciplinaire
  - 06.-08.12.2006 ARCo'06: Colloque de l'Association pour la Recherche Cognitive, Bordeaux, France.
  - 22.-23.03.2007: Modelling Autonomy workshop in San Sebastián, Basque Country.
  - 13.04.2007: Interplay of empirical and synthetic methods in sensorimotor approaches to cognition. Talk at the CCNR workshop on Computational Biology, Robotics, and Related Work. University of Sussex, UK.
  - 18.04.2007: Sensory delays and the experience of simultaneity. Life and mind seminar 16, University of Sussex, UK.
  - 03.06.2007: From evolutionary robotics to tactile pac-man: The enactive way of explaining mind. A talk I gave to my flatmates (lay audience) to explain my work.
- Co-authoring our submission to *New Ideas in Psychology* about the evolutionary robotics simulation of the experiments on perceptual crossing.
- Five month research stay in Compiègne, in which an the experimental protocol for an experiment was developed and the study conducted.

- Level 3 (of 6) French course at the UTC (passed with B).
- Co-authoring a paper for a special issue of the journal *BioSystems* on modeling autonomy.
- An evolutionary robotics simulation of the empirical experiment conducted in Compiègne.
- Authoring a submission to ECAL 07 about the model of the empirical experiment on adaptation to delays.
- Data analysis of the results from the empirical experiments on adaptation to delays.