Case for Support: Sensory Delays and Simultaneity Perception

Marieke Rohde[1], Ezequiel Di Paolo[1], Marc O. Ernst[2]
[1]EASy/CCNR, Department of Informatics, University of Sussex
[2]Max Planck Institute for Biological Cybernetics, Tübingen, Germany

I. Part: Previous research track record

1. The fellow

I have been a DPhil student at the Sussex Centre for Computational Neuroscience and Robotics (CCNR) since 2004, funded by the School of Science and Technology with a teaching assistantship. For my DPhil, I develop and apply an interdisciplinary methodological framework combining experimental work and evolutionary robotics modelling. **Estimated DPhil completion:** 31.05.2008.

My background is in Cognitive Science (BSc at the University of Osnabrück, Germany, grade A with distinction) and Evolutionary and Adaptive Systems (EPSRC funded MSc at the University of Sussex, passed with distinction). This interdisciplinary education involved coursework in the areas of Mathematics, Computer Science, Artificial Intelligence, Neuroscience, Psychology, Philosophy of Mind, Linguistics, Artificial Life and Evolutionary Theory. As part of my undergraduate studies, I worked on a third year student project at the Intelligent Dynamical Systems group at the Fraunhofer AIS in St. Augustin, during which I first learned about evolutionary robotics simulations (BSc project on the dynamical properties of self–regulating neurons [PL12,PL11]; self references refer to publication list PL). I specialised in evolutionary robotics during my MSc at Sussex and was offered the opportunity to do a DPhil at the same department (CCNR/EASY group).

The overarching question of my DPhil research at the CCNR is how evolutionary robotics models can be applied to different strands of empirical research on human behaviour and cognition. In the first year of my DPhil studies, I extended my MSc project [PL10] on motor synergies as a simplifying principle for non-linear motor control of the human arm. The evolutionary robotics modelling work [PL4] was well received by experimental physiologists working in the area (cited in [7]). In another project, I worked on value system architectures in neuroscientific theory, using evolutionary robotics simulations to critically analyse the logical consequences and implicit premises entailed in this type of architecture [PL5,PL6]. In these studies, the evolutionary robotics models illustrate and prove logical principles in an idealised, abstracted and simplified simulation.

Over the last 18 months, I have developed and applied an interdisciplinary framework for research on human sensorimotor adaptation. Psychophysics and psychological experiments frequently test human participants in simple virtual environments, just like the simulated environments used in evolutionary robotics. If the same simulation is used in the experiment and the model, both generate data that is identical in format, which makes it possible to draw strong analogies between the two. This close match between model and empirical experiment is very different from the 'proof of concept' approach I previously took. It is a novel method, and it has helped to understand and explain the embodied dynamics of perceptual crossing [PL2,PL7] and adaptation to sensory delays [PL3]. The piloting project on sensory delays involved a five months ERASMUS research exchange to the perceptual supplementation group (GSP) in Compiègne (France), to complement the modelling work with hands–on psychological experimental work [PL9].

This research has a very strong methodological emphasis. I argue for the importance and merits of dynamical systems approaches in the study of cognition and behaviour in several places [PL1,PL5,PL6]. Tools for dynamical analysis as the ones I devise are needed by such new dynamical approaches. I discuss the benefits of my interdisciplinary framework in [PL2,PL5,PL8]. The project proposed for funding will put this scheme to work at a large scale. Results from my piloting research on adaptation to sensory delays (collaboration with GSP) feed into the proposed research (see II. Part).

My work has been published in international journals and I had the chance to orally present it on more than ten occasions at national and international workshops, conferences and invited talks, as well as to the British public at the 2006 Cheltenham Festival of Science (national newspaper coverage). I have actively strengthened the links between the CCNR and its partner universities in the ERASMUS intensive programme 'NUCOG – new perspectives on cognition' (ERASMUS research exchange, teaching at 2006 NUCOG winter school, attendance of NUCOG seminars). In addition, I have taught undergraduate and postgraduate courses, engaged in the organisation of academic events and maintained the CCNR webpage.

2. Host Organisation: EASy Group/CCNR at the University of Sussex

The Evolutionary and Adaptive Systems Group (EASY, founded in 1991) and the closely related Centre for Computational Neuroscience and Robotics (CCNR, founded in

1996) at Sussex is one of the largest and best known groups in the world working at the interfaces between the biological and computational sciences. They have pioneered the fields of evolutionary robotics and evolutionary electronics and run the highly successful EPSRC-funded MSc in Evolutionary and Adaptive Systems, one of the largest MScs in Sussex. The group has considerable research strengths in artificial life, evolutionary computing, adaptive robotics, creative machines, insect navigation, neuromodulation, computational neuroscience and the theory of adaptive systems.

Dr. Ezequiel Di Paolo is Reader in Evolutionary and Adaptive Systems at the Department of Informatics (EASY group, CCNR). His background is in physics and nuclear engineering. Di Paolo has been working in the area of evolutionary robotics for the past twelve years (DPhil at CCNR, Sussex; postdoc at the GMD/Fraunhofer AIS in St. Augustin, Germany; lectureship at Sussex since 2000). His recent work includes evolutionary robotic models of homeostatic adaptation, social coordination and habit formation, as well as philosophical work on autopoiesis, play and the origins of intentionality and autonomy [2,3,LP2,LP5]. Di Paolo's experience in evolutionary robotics, dynamical systems theory and methodological issues in computational modelling make him invaluable as co-investigator on the project. As my DPhil and MSc supervisor, Di Paolo has contributed significantly to my previous work. This approved and productive research collaboration will be continued and exploited for the theoretical and formal part of my project.

I will also draw on the expertise of **Dr. Inman Harvey** and **Dr. Anil Seth** at the CCNR, who have worked with evolutionary robotics models at the interface between computer science and cognitive science/behaviour research for many years. **Dr. Romi Nijhawan** (Department of Psychology) will advise on the psychophysics aspects of the project during the time in Sussex. Nijhawan works on the flash lag phenomenon, an optical effect that relates to the perception of simultaneity. Harvey, Seth and Nijhawan are not funded by the project.

3. Overseas Organisation: MPI for Biological Cybernetics.

The Max Planck Institute for Biological Cybernetics (MPIfBC) in Tübingen works in the elucidation of cognitive processes. Research comprises the areas of psychophysics, neurophysiology, statistical learning theory and brain imaging. At the end of 2006 the institute employed 208 people (scientists, junior scientists, visiting researchers and third-party funded scientists). The independent junior research group **Multisensory Perception and Action**, headed by co-PI Ernst, investigates how multimodal and kinaesthetic information is integrated in the brain. The group works at the life sciences interface, combining psychophysical and neuropsychological methods with Virtual Reality techniques and Bayesian models of sensory integration. They dispose of cutting edge experimental facilities for psychophysics and neuropsychological experiments such as multisensory feedback platforms, high resolution motion tracking systems and high fidelity VR systems. Areas of research include multimodal time perception, perceptual learning and visuomotor coordination. The proposed research is strongly inspired by previous work at the MPIfBC [1].

Dr. Marc Ernst heads the multisensory perception and action group and works on human perception with a focus on multimodal integration and visual-haptic interaction. Ernst has studied physics and has been working in the area of perception research and psychophysics since 1996 (PhD at the MPIfBC, postdoc at UC Berkeley, researcher at MPIfBC since 2001). He uses quantitative computational/statistical models together with psychophysical and neuropsychological (e.g. fMRI) methods. He has shown that humans combine multimodal information in a statistically optimal manner (using maximum–likelihood–estimation) in different multimodal scenarios [5], [6] and rely on co–occurrence of signals [4]. His expertise in experimental psychophysics on sensorimotor integration make him the ideal co–investigator for the experimental part of the project.

Prof. Charles Lenay from the GSP at the UTC in France will act as external advisor on the project to give advice on technological impact and possible transfer during the evaluation phase.

My interdisciplinary experience allows me to work comfortably within the different disciplines and methods involved in the project. The proposed research partnership brings together two laboratories with a strong record of behaviour based research at the life sciences interface that will provide the ideal conditions for my interdisciplinary project to be realised, as local facilities and expertise of the co-PIs are tailored to support me during different phases of the project. Both co-PIs have extensive experience in multi-partner research grant management.

References

[1] Cunningham, D.W., Billock, V.A. and Tsou, B.H. (2001): Sensorimotor adaptation to violations of temporal contiguity.

[2] Di Paolo, E. A., and Iizuka, H. (2007): How (not) to model autonomous behaviour. BioSystems Special issue on Modelling Autonomy.

[3] Di Paolo, E. A., (2005). Autopoiesis, adaptivity, teleology, agency. Phenomenology and the Cognitive Sciences, 4(4): 429 - 452.

[4] Ernst, M. (2007): Learning to integrate arbitrary signals from vision and touch. Journal of Vision 7(5:7), 1-14.

[5] Ernst, M. and H. Bülthoff (2004): Merging the Senses into a Robust Percept. Trends in Cognitive Sciences 8(4), 162-169.

[6] Ernst, M. and M. Banks (2002): Humans Integrate Visual and Haptic Information in a Statistically Optimal Fashion. Nature 415, 429-433.

[7] Shemmell, J. , Z. Hasan, G. Gottlieb and D Corcos (2007): The effect of movement direction on joint torque covariation, Experimental Brain Research, 176, 150-158.

II. Part: Proposed Research

1. Overview

The human brain constantly compensates for existing intersensory delays to enable us to perceive multimodal stimuli as simultaneous. Recent work by Cunningham et al. at the MPIfBC [4], [5] shows that such compensation mechanisms are plastic, i.e. that the human brain can adapt to artificially delayed sensory feedback in some situations. These findings contrast with earlier similar studies in which participants could not adapt to such sensory delays [17]. What characterises situations in which adaptation is possible is an open question.

The proposed research aims to address this question using an interdisciplinary evolutionary robotics modelling and experimental psychophysics approach to investigate human adaptation to sensory delays in the meso timescale ($50ms <$ delay $< 1s$). The experimental part of the project is based on the following **main hypothesis**:

> *The principles of adaptation to sensory delays and simultaneity perception depend on the dynamics of sensorimotor behaviour in a given task and are best described in dynamical and statistical terms.*

Based on Cunningham et al.'s [4] and my own previous work [PL3], I hypothesise that adaptation to delays will only take place if a task features the necessity to act fast (time pressure) and a structured sensory input signal that allows anticipation (signal complexity). In this hypothesis, dynamical properties of the sensorimotor behaviour and the structural couplings with the environment play a central role. Therefore, it is very different from alternative hypotheses that propose brain mechanisms to automatically correct for intermodal lags in the input data independent from the behavioural domain or task (e.g. [18]).

The **aim of the project** is to formally describe the dynamics of human adaptation to sensory delays on the basis of the experimental data, with the help of evolutionary robotics models. Such a formal account will further our understanding of simultaneity perception and the adaptive mechanisms at work and, at the same time will be relevant for temporal issues in digital technology (e.g., in adaptive autonomous robot control and HCI).

As steps towards this goal I identify the following **objectives:**

- To experimentally test the hypothesised minimal conditions for adaptation to sensory delays that will be induced artificially into virtual task environments.
- To test the modality dependence of adaptation to sensory delay in further experiments with human participants, using multimodal feedback devices.
- To identify the scope of the adaptive mechanisms in the context of other sensorimotor perturbations (such as increase in inertia, stimulus ambiguity, spatial displacement) through further experimental work.
- To implement evolutionary robotics simulations of all experimental conditions in order to guide experimental design, data analysis and investigate sensorimotor dynamics in idealised and controllable settings.
- To perform a thorough analysis of the experimental data, the behavioural recordings and the simulation models in order to formalise the sensorimotor principles of adaptation to sensory delays.
- To derive design guidelines for digital technology and adaptive robot control and to draw methodological implications for dynamical systems approaches to perception.

Sensorimotor dynamics and their relation to perceptual experience are difficult to formalise and understand. There are no established tools or recipes for this kind of problem yet. The project will approach this multi-facetted problem applying and extending the **novel interdisciplinary framework** I developed and applied during my DPhil [PL2,PL3,PL8] that complements hands–on experimental psychophysics with theoretical evolutionary robotics modelling and dynamical systems analysis. This approach makes it possible to give details about *how* humans adapt to delays, rather than to just detect *that* they adapt.

By the end of a successful project, I will have generated an encompassing theory on adaptation to sensory delays based on experimental and simulation results. I will have formalised the principles of simultaneity perception in terms of sensorimotor contingencies [15]. Understanding why and when humans can adapt to prolonged sensory delays will be a crucial step towards explaining the embodied basis of time and simultaneity perception. A formal account of this adaptive behaviour and the robotics models be relevant for autonomous robot control, and knowledge about the mechanisms of temporal adaptation will point out novel training methods and design principles for HCI and other digital technology that interfaces humans in real time with computers.

2. Background

Cunningham et al. report patterns of adaptation to artificially prolonged sensory delays in human participants in different sensorimotor tasks [4], [5], [6] that are strikingly similar to those obtained in experiments with spatial displacement. Firstly, over training, the initially impaired performance is recovered and the annoying delay disappears from conscious experience. Secondly, re–adaptation to the normal condition is marked by a strong negative after effect, i.e., participants' performance on the unperturbed condition without delay is worse after training.

Such *semi-permanent adaptation*, in which simultaneity perception is adjusted to integrate the delay, has not been found in earlier [17], [8], [10] or later [18] work on adaptation to sensory delays. In those studies, participants adapt only very partially, or they compensate for delays logically–cognitively, e.g., by slowing movements down, but do not suffer negative after effects. Cunningham et al. hypothesise that it is *inherent time pressure* that makes their experiments different and forces participants into more profound forms of adaptation [4]. My piloting work ([PL3][PL9], journal paper in preparation) tested this hypothesis. I did not find the hypothesis confirmed but from the enhanced body of experimental data, I was able to derive the new hypotheses underlying the current project, i.e., that a complex signal structure that allows anticipation is necessary as well.

Adaptation to delays and its effect on simultaneity perception touches on a larger issue: The physiological (neural, bodily) basis of perceived time and how it differs from physical time. Experimental research, such as Libet's now classical studies about how decisions are made in the brain even before participants become aware of it [12], show us that our perception of time and simultaneity is a subjective construct. Many approaches to this topic (e.g., Varela's neurophenomenology [20], Piaget's developmental psychology [16], Merleau-Ponty's corporeal phenomenology [13]) have identified the central role of embodied action–perception dynamics for time perception. My proposed research concentrates on such behavioural dynamics. The problem links to issues in more traditional psychophysics research (e.g., the flash lag effect [14] or illusory motion).

Understanding the principles that allow us to predict when and how adaptation to delay happens can have a large technological impact. Psychophysically established thresholds for perceptible delays are usually considered fixed and this assumption underlies the design of real–time human computer interaction devices [3]. As Cunningham et al.'s work shows, this assumption is not an accurate. In a similar way, robot control latencies in autonomous robotics are usually dealt with by fixed lag prediction mechanisms and forward models. The interdisciplinary project on delay compensation links to dynamical systems approaches to forward model learning in robot control (e.g. [19]).

3. *Programme and methodology*

The following **measurable objectives** are set in order to achieve the scientific goal of formalising the adaptive mechanisms of delay compensation in humans and their scopes and limits.

- To experimentally test the minimal conditions for adaptation to delays. (WP1)
- To test modality–dependence and the role of a prior concept of simultaneity in further experimental work. (WP2)
- To explore temporal ambiguity in further experimental work. (WP3)
- To implement evolutionary robotics simulation of experiments in WP1-3 to guide and inform experimental design, data analysis and evaluation of results. (WP4)
- To formalise the dynamical principles of adaptation to delays and simultaneity perception by means of dynamical and statistical analysis of experimental recordings and idealised and controllable simulation models. (WP5)
- To derive design guidelines for digital technology and autonomous robot control and argue the methodological benefits and commitments of the approach for dynamical systems approaches. (WP6)
- To convene a workshop. (WP7)

Programme:

I will spend six months in the CCNR, 18 months in the MPIfBC, and twelve more months in the CCNR, i.e., the project timeline is **6+18+12**. The six–months periods of the project are referred to as: UK1, DE2, DE3, DE4, UK5 and UK6, to indicate both their time and their place.

The initial phase will comprise of evolutionary robotics simulation and conceptual work (WP4+6). The research abroad will centre around the experimental work (WP1-3), but formal and conceptual work (WP4-6) will be pursued at a low priority during that time, to complement and feed into the experimental practice. In the last year, work will focus on thorough data analysis (WP5), more simulation modelling (WP4) and the theoretical implications of the project results (WP6). The six work packages are organised so as to ensure optimal local support, exploitation of facilities and efficient collaboration with the co-PIs at both research organisations. A workshop will be held in the last year (WP7) to disseminate results across the communities and foster collaborations.

Me and my collaborators will hold monthly project meetings by video–conferencing and I have budgeted travel expenses for the respectively external co-PI to attend project meetings every six months to ensure consistency. Travel expenses for the external HCI technology advisor are covered to convene once during the experimental phase (e.g, DE3) and once during the evaluation phase (UK5/UK6).

Detailed Methodology:

My interdisciplinary approach combines the following methods:

Experiments in psychophysics will provide the empirical data that my project is based on. The overseas organisation dispose of a variety of cutting edge experimental facilities for psychophysics and neuropsychological experiments, including multisensory feedback platforms, high resolution motion tracking systems and high fidelity VR systems that allow to study the human 'in the loop'. They rely on virtual environments into which artificial sensory delays will be induced in order to test the hypotheses about sensorimotor dynamics and adaptation to delays. Behavioural and sensory data from the experiments can be recorded for dynamical analysis and evolutionary robotics modelling.

Evolutionary robotics simulation modelling is an artificial intelligence technique that models behaviour embodied and embedded in a virtual environment. Such models help to understand and explore complex interaction dynamics in idealised, simplified and fully controllable settings. They are therefore particularly suitable for dynamical modelling of closed-loop sensorimotor behaviour [9]. My previous work [PL2,PL3] illustrates how such generative modelling can generate hypotheses and proofs of concept to inform and guide experimental work and data analysis on human sensorimotor adaptation.

This *generative* modelling approach aims at a qualitatively modelling of behaviour, which is different from the traditional quantitative and descriptive modelling of a data set. More traditional Bayesian modelling [7] will be employed to complement evolutionary robotics modelling. Evolutionary robotics is also different from, though related to, other robotic approaches to dynamical forward model learning (e.g. [19]). Usually, adaptive mechanisms are built into the robot control architecture, in whereas in evolutionary robotics, the adaptation criterion is implicit in the fitness criterion and the mechanisms of adaptation self–organise.

Statistical and dynamical data analysis will go beyond just hypothesis testing on the basis of participants' performance in the experiments. I will record the time series of the stimulation and the motion throughout the experiment and the resulting corpus of sensorimotor data will be analysed to look for further evidence and dynamical details of how adaptation to sensory delays proceeds.

I will combine straight forward statistical methods (covariance in time series, averages of sensorimotor values), Bayesian approaches and the analogy to the more tractable synthetic data generated by the evolutionary robotics simulations, which are open to more detailed analysis, as e.g. in [2]. Ultimately, I will express the principles of adaptation to delays in terms of sensorimotor contingencies [15]. An example of such a sensorimotor contingency formalisation on the basis of experimental data is Lenay's analysis of space perception [11].

Conceptual analysis is of particular importance for a research project as interdisciplinary as the one proposed to draw implications for time cognition, technology and interdisciplinary approaches to human sensorimotor adaptation. Such an encompassing analysis requires the acquaintance with literature from fields as different as psychophysics, neuroscience, cognitive science, psychology, phenomenology, philosophy of mind, artificial intelligence, autonomous robotics, ergonomics and HCI technology.

WP1 Minimal conditions for adaptation to delays: The study by Cunningham et al. [4] that first gave evidence for semi–permanent adaptation to delays, which was performed at the MPIfBC will be replicated introducing important modifications:

- The hypotheses tested will be that *time pressure* and *complex signal structure* are necessary for semi-permanent adaptation to delays.
- The dynamics of sensorimotor behaviour will be recorded and analysed.

Replicating a previous successful study and recording the participants' behavioural data makes sense as a first step towards understanding the dynamics of adaptation to sensory delays. Four groups of participants will be trained on the task with a visual delay. One group will perform the task in conditions identical to those used in [4]. The control conditions will be replaced by three different conditions in order to test the novel hypotheses. One control group will be trained in the absence of time pressure. The second control group will be trained with an impoverished visual signal. The third control group will be trained without time pressure and with an impoverished signal at the same time. If my hypotheses are correct, all three control groups will not adapt semi-permanently to delays.

Methods: Experiments on a visually guided obstacle avoidance task in a virtual environment. Analysis of performance and behaviour of participants.

Objective: Test the detailed hypotheses about adaptation to delay, generate behavioural data.

Time/place/co-PI: DE2, Ernst.

Deliverables: Hypotheses tested. A behavioural data set from participants adapting to sensory delays. 1 journal paper, 1 conference paper.

WP2 The origins of simultaneity and modality dependence: I will test participants on their capacity to incorporate delayed feedback in an unknown virtual environment that links sensory information from different modalities in a novel way. This experiment will allow us to investigate the origins and the modality dependence of perceived simultaneity. My hypothesis is that the principles of adaptation to delay transfer across modalities and even hold in such an unfamiliar sensorimotor task.

Bach-y-Rita has shown how people with vestibular disabilities can be trained to substitute for their missing sense with a tactile sensory substitution device that represents vestibular information [1]. I want to test how participants adapt to delays in such a 'artificial' sense of equilibrium as opposed to how they adapt to delays in their natural sense of equilibrium.

In a first experiment, blindfolded subjects will receive tactile stimulation that corresponds to equilibrium information of a simulated inverted pendulum they have to balance. This experiment is analogous to the condition investigated in [6], where participants rely on their natural vestibular sense for this task. Participants will be trained on the task with a sensory delay, controls without. If my hypothesis is correct, the level of adaptation to delay should be comparable to the one found for the natural sense of equilibrium [6].

Possibly, the experiment can be extended to a setting in which the natural and the artificial sense are combined (with and without intramodal delay). The emphasis of this experiment would be on testing the performance removing either of the redundant streams of information. With this experiment, I could test whether adaptation to delays or adaptation to novel stimuli supersede.

Methods: Experiments on a balancing task in a virtual environment, using a multimodal (tactile, vestibular) feedback platform. Analysis of performance and behaviour of participants.

Objectives: Test the hypothesis that the principles of adaptation to sensory delays is modality independent, generate behavioural data.

Time/place/co-PI: DE3, Ernst.

Deliverables: Hypothesis tested. More behavioural data (lower dimensional) from a different modality. 1 journal paper, 1 conference paper.

WP3 Delays and temporal ambiguity: Understanding the principles of adaptation to sensory delays will give us the basis to construct temporally multistable stimuli, a 'temporal Necker cube'. A multimodal task environment will be designed in which a sensory pattern can have one of two different interpretations, depending on whether the participant has adapted to a delay or not. For example, as I argue in [PL3], sensory delays are frequently interpreted as an increase in inertia, not as an increase in latency, and this ambiguity can be exploited to create ambiguous stimuli. The exact experimental conditions for this kind of experiment, however, rely heavily on the results from WP2+3, and, to this extent, this work package is more speculative. Most likely, the experiment will be performed using a similar set–up to that described for WP2.

A temporally bistable stimulus will be a very powerful tool to test the principles derived about adaptation to sensory delays. By modifying initial conditions, it will be possible to 'push' subjects into either interpretation of the ambiguous stimulus. This technique will allow us to establish the link between experienced simultaneity and adaptation to delays without having to rely on subjective descriptions of subjects' experience of simultaneity.

Methods: Experiments on a stimulus recognition task in a multimodal virtual environment. Analysis of performance and behaviour of participants.

Objectives: Generate strong evidence for the principles of adaptation to delay derived from WP1+2 and behavioural data.

Time/place/co-PI: DE4, Ernst.

Deliverables: Hypothesis tested, more behavioural data. 1 journal paper, 1 conference paper.

WP4 Evolutionary Robotics Modelling: Evolutionary robotics models help to understand complex and embodied sensorimotor behaviour in idealised and controllable settings. I will model the experimental set-ups from WP1-3 even before conducting the experiment, to describe and understand possible behavioural dynamics and prevent logical errors in the experimental design. During dynamical data analysis, these tractable models will aid the process of formalising the principles of adaptation to delays.

Following the closely matched modelling approach [PL2,PL3], I will simulate the experiments such that data from the model will have the same format as the recorded data. Such idealised models can be exhaustively tested and analysed in order to generate predictions about systematic errors resulting from different strategies and to point out meaningful variables for data analysis. For instance, models of the different conditions in WP1 will probably lead to the evolution of different strategies depending on the presence or absence of time pressure or on the signal structure. Analysing such different solutions and how they react to the introduction and removal of a delay will generate predictions about the corresponding experiments, e.g., how to spot and identify different strategies and what kind of error, reactions and adaptation patterns to expect. Similarly, the simulation of the experiments in WP2 will generate predictions about how and whether adaptation of an established behaviour to delays differs from learning a novel behaviour in the presence of delays and how these differences are reflected in behavioural data.

I will use Bayesian modelling techniques [7] to describe and analyse the synthetic data generated by the evolutionary robotics models. This practice will illustrate the conceptual links between the modelling approaches previously taken by both laboratories. Again, an analysis of simplified evolutionary robotics simulations will generate benchmarks for the Bayesian modelling of the more noisy and complex experimental data. The evolved mechanisms for delay compensation will also propose solutions to the problem of control latency in autonomous robotics.

Methods: Evolutionary robotics simulation modelling, Bayesian modelling.

Objectives: Conceptual clarification, hypothesis generation, illustration, understanding possible adaptive mechanisms.

Time/place/co-PI: Throughout the project, but mainly UK1 and UK5, Di Paolo.

Deliverables: 3 simulation models, 2 conference papers.

WP5 Dynamical and statistical data analysis: The project will provide a detailed dynamical analysis of participants' behaviour. Thereby, I will not only be able to confirm *that* humans can adapt to delays, but also contribute to explaining *how*.

Even though formal data analysis will start from after the conduction of the first experiment (WP1), the major part of formalising the encompassing dynamical principles of adaptation to delay will fall in the finishing phase of the project (UK5+6). To formalise dynamical principles and analyse high dimensional behavioural data requires a large amount of work. As a first step, different measures to characterise behavioural data (smoothness, velocity, reaction times, reaction magnitudes, etc.) will be compared and analysed how they vary across adaptation time and between conditions. Then, Bayesian modelling, covariance measures and analysis of key events in the recordings will help to establish the links between perception and action and the sensorimotor strategies that subjects employ. The space of additional formal techniques that can be incorporated is open ended. Results from simulation modelling (WP4) will crucially guide and simplify this data analysis, as they did in my piloting research on delays (model [PL3], journal paper on experiment in preparation).

By the end of successful data analysis, the principles of adaptation to delays will be formalised in terms of *sensorimotor contingencies* [15], characterising how – given experimental conditions and behavioural strategies – perception, sensation and motion relate. Such a general and integrative formalisation of my results will be at the core of a journal publication to evaluate my research in the larger context of the sensorimotor basis of time perception. The techniques and measures employed to generate this formal description will exemplify how to generate this kind of formal descriptions of sensorimotor contingencies from behavioural data.

Methods: Statistics, dynamical systems analysis.

Objectives: Formalisation of the dynamics and the principles of adaptation to sensory delays.

Time/place/co-PI: from DE2 till the end, but mainly UK5+6. Di Paolo.

Deliverables: Formal description of results, new tools for dynamical analysis, 1 journal paper.

WP6 Theoretical Implications: Conceptual work will be most important during the preparatory and finishing phase of the project. In a project of high scientific novelty like the one proposed, it is essential to explicate and justify methodology, the experimental hypotheses and ideological commitments beforehand. Similarly, assessing the approach taken afterwards is of crucial importance, additional to the conceptual integration of the results from WP1-5. With the help of the external technological advisor (Lenay), I will identify lessons from my work for the design of digital technology to ensure dissemination of my work to technology. Identifying future research avenues for CCNR and the transfer of the resulting principles and mechanisms to adaptive robot control is a task that also falls into this WP.

Methods: Analysis of theoretical impact, writing of joint-authored position papers.

Objectives: Identifying and disseminating methodological, technological and scientific implications.

Time/place/co-PI: throughout the project, but mainly UK1 and UK6. Di Paolo, Ernst, Lenay (external advisor).

Deliverables: 3 position papers (1 UK1, 2 UK6)

WP7 Organisation of Workshop: During UK5, a workshop will be held on 'The sensorimotor basis of time cognition'. The workshops will be small scale and mainly invitation based, aiming to bring together the project partners and external researchers from different disciplines working on related issues (e.g., Douglas Cunningham, Rafael Nuñez, Kevin O'Regan, Jun Tani). An edited special issues will result from the workshop.

Objectives: Network the international and interdisciplinary relevant community and will contribute crucially to the dissemination of results.

Time/place/co-PI: UK5. Di Paolo.

Deliverables: Edited special issue.

4. Relevance to beneficiaries

Understanding the sensorimotor basis of simultaneity perception through the study of adaptation to sensory delays will be a milestone towards an embodied theory of temporal cognition. Therefore, researchers working on time cognition, behavioural and brain plasticity, time perception and human sensorimotor adaptation will profit from the project results.

The formalisation and identification of mechanisms of delay compensation in humans and evolved artificial agents will be relevant for the problem of control latency in autonomous robotics and research in anticipatory robot learning.

Identifying the exact conditions under which the brain can adapt to delays and the after effects of adaptation has implications for technology that interfaces humans in real time with computers such as VR, HCI, BCI, Ergonomics and Sensory Substitution. My research will indicate areas of application and methods of training that render delay minimisation a low priority design issue and identify the side–effects of adaptation to sensory delays. Users of such technology, who will indirectly benefit from my work, include: Disabled people using BCI or Sensory Substitution prosthetic devices; pilots, drivers, rescue workers training in VR; commercial users of HCI and VR technology.

The development and implementation of an innovative and interdisciplinary methodological framework will provide novel tools for dynamical systems analyses. The advance of my interdisciplinary experimental and modelling framework will benefit researchers working in embodied and dynamical systems approaches to perception research and cognitive science.

The collaboration between the host and overseas organisation paves the way for further collaboration, helps CCNR to expand its interdisciplinary work and to become integrated in existing international research networks and furthers the UK's competitiveness in the area.

5. Justification for the Fellowship

As term dates are not relevant to the proposed research, I propose to start the project two months earlier than the academic year.

The project will allow me to realise this interdisciplinary and innovative research project combining the expertise and facilities of two internationally renowned laboratories. Many of the hypotheses and methods underlying the project result from my primarily methodological DPhil research. It is the right moment to put the methods I developed into practice at a large scale, investigating a specific problem interdisciplinarily over the course of three years. The problem of adaptation to sensory delays is an intriguing open issue with relevance to both cognitive science and engineering. Compensation for sensory latencies is inherently a problem of sensorimotor integration and therefore perfectly suited for exploration through my interdisciplinary sensorimotor approach.

It has to be stressed that the project goes far beyond my earlier work or the work of other researchers in CCNR in this area, which has been mainly robotics, simulation and theory based. This includes the work of my current supervisor and co-PI Di Paolo, even though the local expertise in evolutionary robotics and dynamical systems analysis will be invaluable for the theoretical parts of the project. Similarly, although the MPIfBC have previously worked experimentally on adaptation to sensory delays, they have not worked on a dynamical systems formalisation of the principles of and mechanisms for adaptation.

An EPSRC fellowship at the Life Sciences interface will provide the optimal conditions for me to realise this project, which crucially relies on the described international collaboration to make the combination of high standard practical experimental work and theoretical work possible.

6. Dissemination and exploitation

Papers about experimental (WP1-3) and modelling (WP4) results will be published in respective domain specific journals (e.g., Nature Neuroscience, Perception, Behavioral Brain Research, Artificial Life, Neural Computation, Adaptive Systems, Biological Cybernetics) and conferences (e.g., Enactive Interfaces, TWK, SAB, ALife, ECAL).

The dissemination of theoretical results (WP5+6), i.e., the integration of results and its implications for time cognition, technology and methodological debate, will be ensured by publishing conceptual and position papers (Trends in Cognitive Science, Minds and Machines, Human Computer Interaction, Cognition) in the initial and final phase of the project.

The Workshop organised under WP7 will bring together the relevant community and lead to the publication of a special issue I will edit.

A publicly accessible project website/blog will provide a point of reference for the project partners and the research community about progress on the project.

References

[1] Bach-y-Rita, P. (2004): Tactile sensory substitution studies. *Ann N Y Acad Sci.* **1013**: 83-91.

[2] Beer, R. (2003): The dynamics of active categorical perception in an evolved model agent. Adaptive Behavior 11(4), 209-243.

[3] Card, S. Moran, T. Newell, A. (1983): The Psychology of Human-Computer Interaction, Lawrence Erlbaum Associates, 1983.

[4] Cunningham, D.W., Billock, V.A. and Tsou, B.H. (2001): Sensorimotor adaptation to violations of temporal contiguity.

[5] Cunningham, D.W., A. Chatziastros, M. von der Heyde and H.H. Bülthoff (2001): Driving in the future: Temporal visuomotor adaptation and generalization. Journal of Vision 1(2), 88-98.

[6] Cunningham, D.W., B.W. Kreher, M. von der Heyde and H.H. Bülthoff (2001): Do cause and effect need to be temporally continuous? Learning to compensate for delayed vestibular feedback. Journal of Vision 1(3), 135a.

[7] Ernst, M. O. and H. H. Bülthoff: Merging the Senses into a Robust Percept. Trends in Cognitive Sciences 8(4), 162-169.

[8] Ferell, W. (1965): Remote manipulation with transmission delay. IEEE Trans, hum. Factors Elect., 1965, HFE-6, 24-32.

[9] Harvey, I., Di Paolo, E., Wood, R., Quinn, M. and Tuci, E. A. (2005). Evolutionary Robotics: A new scientific tool for studying cognition. Artificial Life, 11(1-2): 79-98.

[10] Held, R., A. Efstathiou & M. Greene (1966): Adaptation to displaced and delayed visual feedback from the hand. Journal of Experimental Psychology 72 (6), 887-891.

[11] Lenay C. (2003) Ignorance et suppléance : la question de l'espace, HDR 2002, Université de Technologie de Compiègne.

[12] Libet, B. (2004): Mind Time: The temporal factor in consciousness. Perspectives in Cognitive Neuroscience. Harvard University Press.

[13] Merleau-Ponty, M. (2002): Phenomenology of perception. Trans. C. Smith, Routledge Classics Edition, London and New York.

[14] Nijhawan, R. (2002) Neural delays, visual motion and the flash-lag effect. Trends in Cognitive Sciences, 6: 387-393. Factors Elect., 1965, HFE-6, 24-32.

[15] O'Regan, K. and A. Noë (2001): A sensorimotor account of vision and visual consciousness. *Behavioral and Brain Sciences* 24 (5), 939-1011.

[16] Piaget, J.: The child's conception of time. Routledge, 1969

[17] Smith K.U. and W. M. Smith: Perception and motion: an analysis of space-structured behavior. Philadelphia, Saunders, 1962.

[18] Stetson C, Cui X, Montague PR, Eagleman DM (2006). Motor-sensory recalibration leads to an illusory reversal of action and sensation. Neuron. 51(5), 651-9.

[19] Tani, J. (1996): Model-based learning for mobile robot navigation from the dynamical systems perspective. IEEE Trans. on Systems, Man, and Cybernetics Part B: Cybernetics, Vol.26, No.3, 421-436.

[20] Varela, F. (1999), The specious present: The neurophenomenology of time consciousness, in: J.Petitot, F.J. Varela, B.Pachoud and J.M.Roy (Eds.), Naturalizing Phenomenology, Stanford University Press.