An integrated model of superior colliculus and basal ganglia controlling directed action (D3.5.1 – SGA2)

Figure 1: An integrated model of the mammalian brain controlling directed action in the WhiskEye robot

A version of the current MammalBot cognitive architecture, including components modelled on the superior colliculus, basal ganglia and cerebellum, was demonstrated controlling the WhiskEye robot platform at the HBP Annual Summit in Maastricht, October 2018. Here, WhiskEye interacts with Mariya GABRIEL, European Commissioner for Digital Economy and Society using vision and whisker touch. For further details, see Section 2.

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Document Title:	An integrated model of superior colliculus and basal ganglia controlling directed action
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SciTechCoord Review:	Martin TELEFONT, EPFL (P1)
Editorial Review:	Annemieke MICHELS, EPFL (P1)
Description in GA:	Demonstration of the model on the SP10 Neurorobotic Platform and mammal-like robots (T3.5.5)
Abstract:	"MammalBot" is a layered control system architecture, modelled on the mammalian brain, that is capable of generating motivated real-time behaviour in a range of different target physical robot platforms. The initial MammalBot architecture, has been integrated on to the WhiskEye robot platform to allow the expression of exploratory behaviour using models of brain systems including the basal ganglia and superior colliculus, and was demonstrated at the HBP Annual Summit in Maastricht in October 2018. This deliverable summarises how the architecture is being developed to operate on the WhiskEye platform, for neurorobotic and neuromorphic computing investigations, on the MiRo robot platform for public engagement, education, and to demonstrate paths to knowledge transfer, and on the HBP Neurorobotics Platform as a tool for community programming and development. The report also describes how the architecture is being made modular, platform-independent and able to integrate heterogeneous model brain systems at different levels of abstraction.
Keywords:	Cognitive architecture, real-time robot control, system integration
Target Users/Readers:	HBP Partners: Developers of functional models of brain systems capable of specifying real-time perception, cognition, and action. Neurorobotics and neuromorphic computing developers. Translators working to develop applications for brain-based robotic systems. Users of the Neurorobotics Platform.

Table of Contents

Table of Figures

1. The MammalBot Cognitive Architecture

Task T3.5.5, “MammalBot layered control architecture” for which this is an interim Deliverable, is developing a layered control system architecture, modelled on the mammalian brain, that is capable of generating motivated real-time behaviour in the HBP Neurorobotics Platform and in a range of different target physical robot platforms, including the purpose-built HBP mammal-like robot platform WhiskEye, and the commercial brain-based robot MiRo.

1.1 Overview of the MammalBot Architecture

Modelled on a theory of the brain as a layered control architecture (Kleinfeld, 2006; Prescott et al., 2015; Prescott, Redgrave, & Gurney, 1999), the MammalBot system is composed of a set of nested sensorimotor loops in which lower loops can function without the help of higher loops, whilst higher loops operate by modulating the behaviour of those lower down.

The lowest-level loops correspond to the spinal cord and hindbrain, implement reflexive or patterned behaviours (including CPGs), and can provide rapid responses to sensory information that make limited use of memory and signal analysis.

Mid-level loops correspond to the brainstem and make use of short-term memory and within- and cross-modal signal relationships to implement behaviours that require co-ordination across motor systems and orienting to distal stimuli.

High-level loops modelled on forebrain systems, including cortex and hippocampus, use arbitrarily deep memory and inter- signal relationships to implement extraction of invariance, model-based learning, and planning.

Figure 2 (left) illustrates this layered/nested-loop architecture for the rat vibrissal system as drawn by Kleinfeld (2006).

However, nested-loops are not enough to account for the flexible goal-directed behaviour generated by mammalian brains. Specifically, across this layered architecture, integrative systems modelled on the basal ganglia are required to ensure appropriate selection of actions and to provide support for habit-based learning, whilst cerebellar-based learning algorithms are required to support tuning of sensor filters and maps, and timing of movement patterns (Prescott et al., 2015; Prescott et al., 1999).

A key component of the MammalBot architecture is the superior colliculus viewed as a multimodal head-centred salience map that, together with the model basal ganglia, supports responses to stimuli with directed action (e.g. orienting) (Mitchinson & Prescott, 2013). This system, alongside models of spinal cord and brainstem systems for defensive and approach behaviours, can provide the robot with a basic behavioural repertoire of reflexes, orienting behaviours, and fixed action patterns that can simulate the exploratory behaviour of a rat.

A model of the hypothalamus, and of related areas of the limbic system, currently under development, will support a richer brain-based model of the mammalian drive/arousal/emotion system that can support additional forms of learning such as a classical conditioning.

Figure 2 (right) shows an abstraction of the nested loop architecture integrating some of these additional components and considered as a control system that can generate real-time behaviour for robots. This is the system we are seeking to construct, evaluate, and disseminate through the MammalBot task.

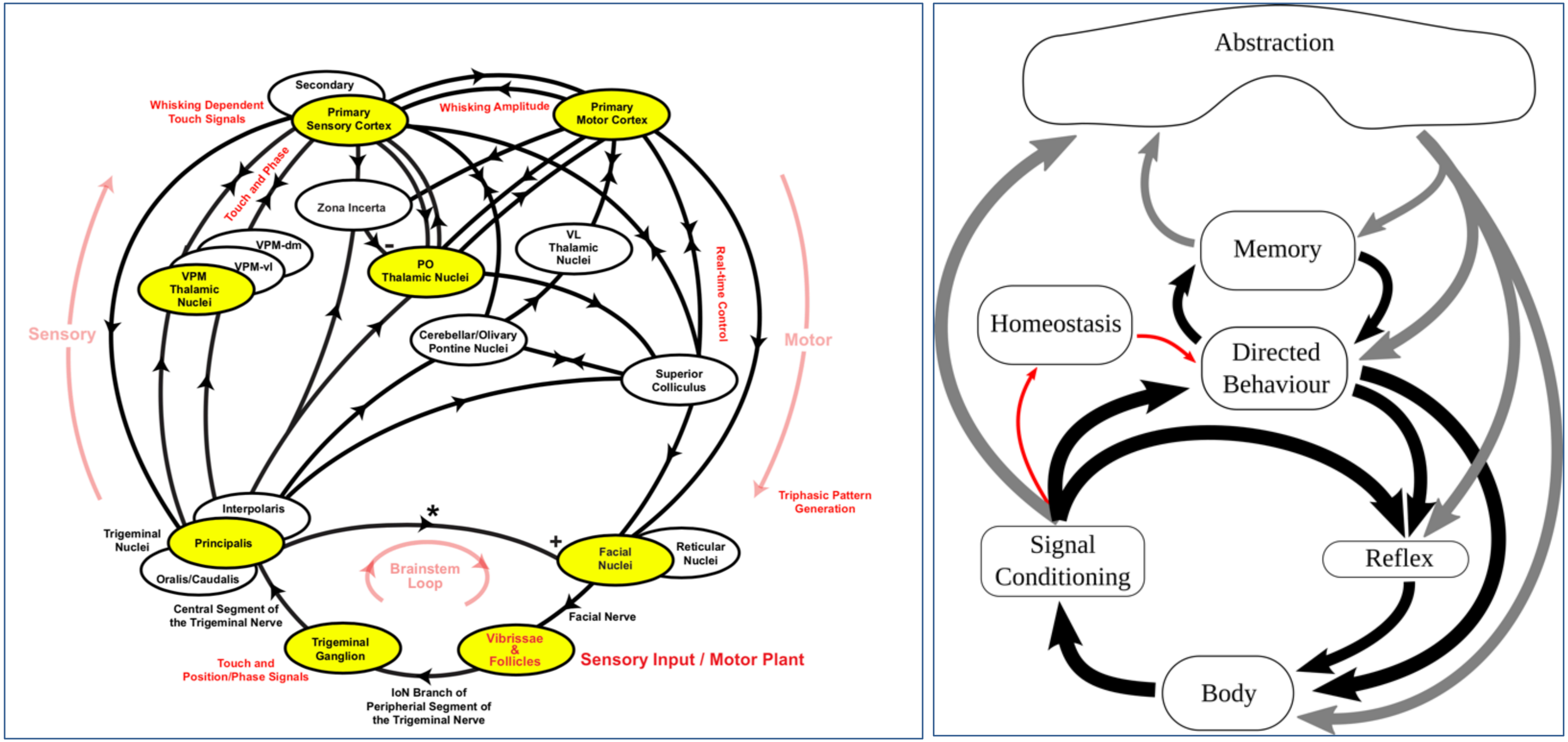

Figure 2: The MammalBot nested loop system architecture

Left: nested loop architecture of the rat vibrissal system. Right: abstracted circuitry of the MammalBot control system architecture. Key sub-systems in the mammalian brain, such as the nested loops shown left can be mapped onto the abstracted components of the MammalBot architecture, illustrated right.

1.2 Deliverable overview

Sections 2-3-4 of this Deliverable outline how the MammalBot architecture is being developed to operate on (2) the **WhiskEye robot** for neurorobotic and neuromorphic computing investigations, (3) the **MiRo robot** for public engagement, education, and to demonstrate paths to knowledge transfer, and (4) for the **HBP Neurorobotics Platform** as a tool for community programming and development. Section 4 also describes how the architecture is being made modular, platform-independent and able to integrate heterogeneous model brain systems at different levels of abstraction (e.g. spike-based, numerical rate-coded/population coded, algorithmic). Section 5 summarises some related SGA2 **publication outputs and impacts**, while Section 6 summarises how HBP partners can **access the model software** and related resources and contribute to the future development of the architecture.

2. System integration for the Whiskeye Robot

The initial MammalBot cognitive architecture, has been integrated on to the WhiskEye robot platform, constructed by UWE, and follows a largely algorithmic implementation extending previous work at USFD/UWE in SGA1 and earlier EU FET projects (Prescott et al., 2015). This implementation allows the expression of exploratory behaviour in real-time in both simulated and physical WhiskEye robot platforms. This will be progressively extended to incorporate brain sub-system models with richer dynamics and greater functionality, including those developed by other HBP partners.

The current implementation of the architecture for WhiskEye was **demonstrated at the HBP Annual Summit in Maastricht**, in October 2018, as illustrated in Figure 1. A movie demonstrating WhiskEye's exploration and orienting behaviour is available in the MammalBot Collab and in Annex 1, Figure 8.

The brain-based model components for the current WhiskEye implementation include (abbreviations in red indicate structures shown in Figure 3):

- Cer: Cerebellum <NUMERICAL> @500Hz
  - Granule cell matrix represented as array of Alpha functions
  - Purkinje cell weights updated using covariance learning rule
- SC: Superior colliculus <RATE CODED: NUMERICAL> @50Hz
  - Continuous attractor model of neural activity
  - Winning node represents most salient point in head space
- BG: Basal Ganglia <POPULATION CODED: NUMERICAL> @500Hz
  - Based on the Gurney, Prescott, and Redgrave (2001) model of action selection
  - Populations of neurons that inhibit / dis-inhibit actions based on saliency of task
- Fn: Facial nucleus <RATE CODED: NUMERICAL> @500Hz
  - Central pattern generator (CPG) based model of whisk pattern generation

In the remainder of SGA2 this system will be extended to include models of hippocampal and cortical systems that can support spatial learning and memory as developed in Task T3.3.3 and elsewhere.

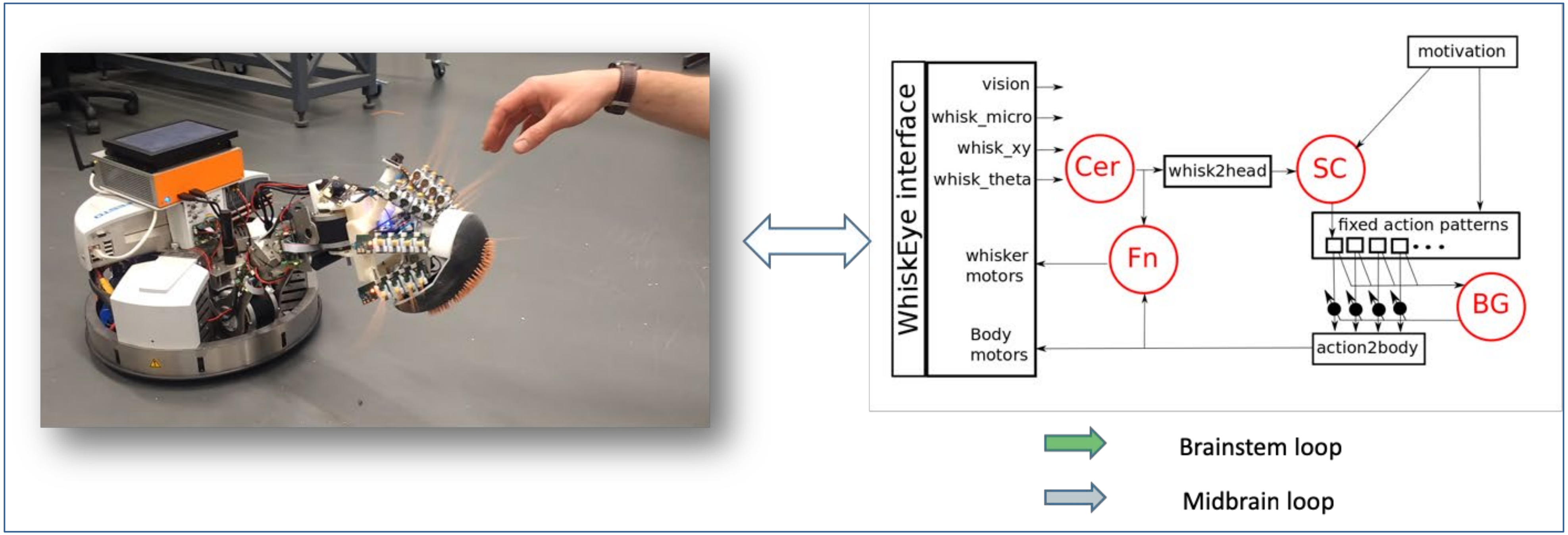

Figure 3: The WhiskEye robot

Left: the WhiskEye robot interacting using vision and whisker touch. Right: the bespoke version of the MammalBot cognitive architecture that operates WhiskEye. The control architecture as implemented on WhiskEye currently includes models of the brainstem and midbrain systems highlighted in red and briefly described above.

3. System integration for the MiRo Robot

MiRo is the world's first commercial brain-based robot (Mitchinson & Prescott, 2016), based on EU-funded research at the University of Sheffield, and created by a University spin-out *Consequential Robotics Ltd* (CQR). The MIRo robot is being developed towards applications in research, education, and therapy (note that CQR is not a direct beneficiary of HBP and that all code generated in HBP for this platform will be open-sourced).

In HBP, the MiRo robot is being used as a research platform for studying models of spatial memory (Task T3.3.3), for public engagement and education, and to demonstrate paths to knowledge transfer such as the use of brain-based control for robot-assisted therapy (Prescott, Mitchinson, et al., 2018).

To support activities in education and outreach, we have developed a **graphical user interface** to the MiRo control system to show activity in underlying brain-based sub-systems, this is illustrated in Figure 4 (upper panel). We are also able to show how the camera and microphone feeds are processed to produce a multisensory head-centred salience map in the model superior colliculus. This is illustrated in Figure 4 (lower panel) which shows how the 2D salience map evolves over a 4 second period as a person walks in front of the robot clicking his/her fingers. The hotspots (white areas) in the map act as targets for attention for the orienting system.

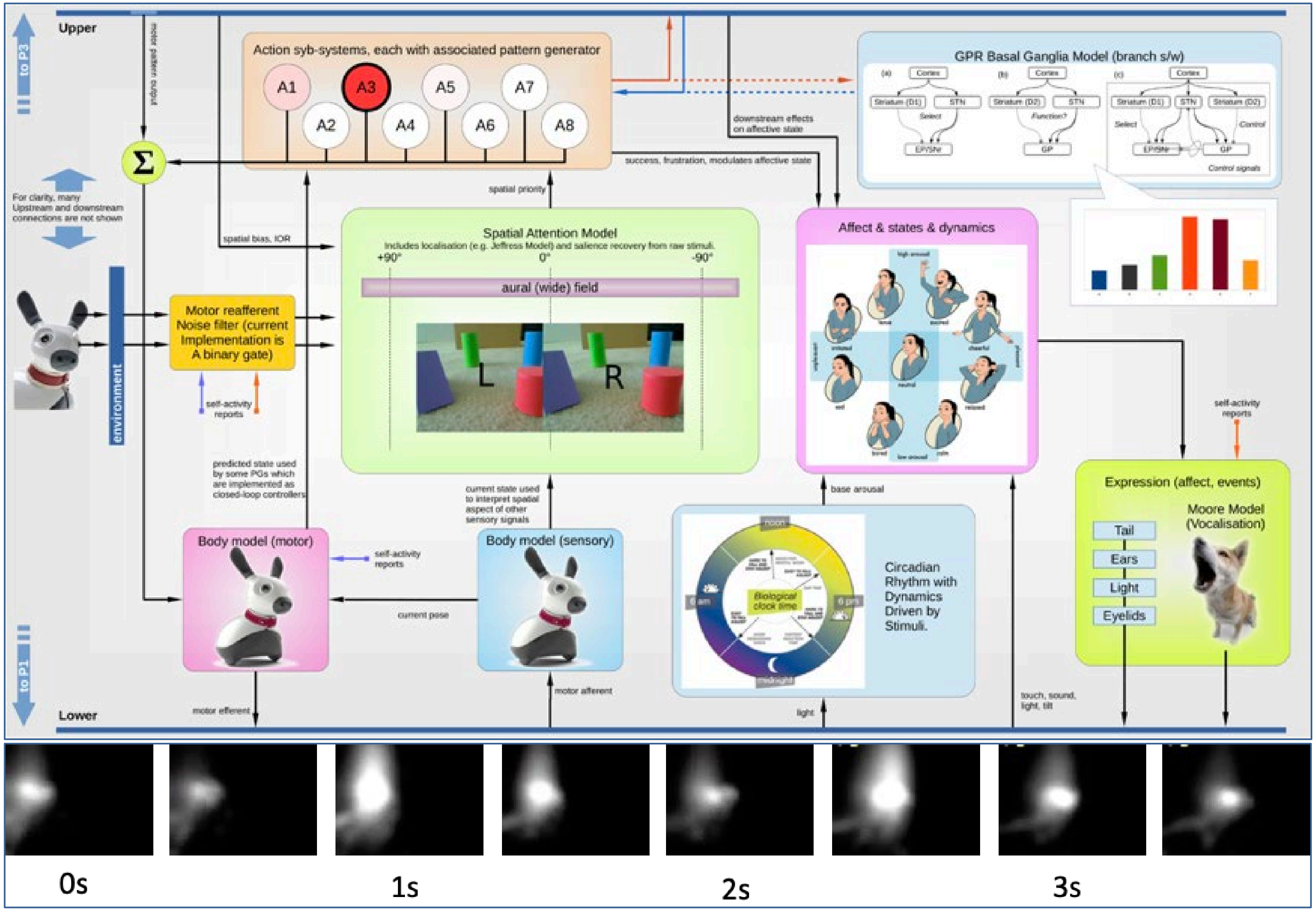

Figure 4: MiRo Robot Graphical User Interface and Salience Map

The upper panel shows a graphical user interface developed to show the brain-based components of the control architecture, clicking on each component of the GUI opens up a new display. The lower panel illustrates multimodal sensory processing for salience in the midbrain superior colliculus, highlighting the role of midbrain systems in driving attention.

4. System integration for the Neurorobotics Platform

The HBP Neurorobotics Platform (NRP) is, along with robot hardware, a primary target for neural modelling activities. Simulated robots offer several important advantages over physical hardware:

- Reduced resource requirements; models can be tested without expensive hardware purchases, without onerous space requirements, and more quickly than physical robots.
- Multiple experiments can be run simultaneously, and it is possible to rapidly iterate through different variations of a simulation and collect data automatically.
- There are no safety issues or concerns about equipment wear and tear.
- Perhaps most importantly, use of the NRP allows, not just the results, but the actual implementation of experiments to be easily shared with colleagues around the world, greatly expanding the potential for collaborative research.

However, to fully realise these benefits, we must develop a flexible, modular implementation strategy so that our models and methods are consistent and that as little time as possible is spent solving technical issues. Thus, in addition to the bespoke control system software currently implemented for WhiskEye/MiRo, we are developing a modular, extendable control system architecture that is capable of supporting real-time operation of models at different levels of neural abstraction, and of operating across different computational platforms, including neuromorphic, HPC, and workaday systems.

4.1 Technical integration approach

A prescribed approach to integration, in such a broad domain, risks generating onerous constraints that interfere with flexible development. We therefore propose an “agile” approach, based around a preferred set of software tools, listed below, several already in use in HBP, alongside standards for inter-domain interfacing (communication, synchronisation, management, etc.) and process management.

- **Common Interface**. Ultimately, all our modular components, whatever their underlying nature, express a common Python interface for management and real-time data exchange. Python is chosen for its flexibility and ubiquity to maximise the usefulness of the components in current - and future - systems. Actual information exchange mechanisms can then be defined on a per-configuration basis, avoiding prescription of this key element which can be arbitrarily constrained by system requirements.
- **PyNN/Spine-ML**: Building on work in HBP, we are using the SpineML and PyNN description languages to specify large-scale spiking neuron models in an implementation-independent manner that can take advantage of neuromorphic computing and/or GPU acceleration of these models.
- **BRAHMS:** Mapping model architectures to networks of onboard and offboard processors, requires a process management framework. We are adopting the BRAHMS integration framework, originally developed in the EU FP7 ICEA project (Mitchinson et al., 2010) and used in a number of large-scale initiatives for real-time brain-based computing, including the UK EPSRC Green Brain project.
- **BrainGlue**: We are developing a novel tool to facilitate the interfacing of neural modules whose interfaces are semantically-compatible but technically-incompatible. BrainGlue, which was presented at the 2018 HBP Annual Summit, uses a graphical approach to optimise communication between heterogeneous model systems.

- **PyGates**: This tool is being developed to provide a transparency layer that separates the definitions of brain models from the definitions of the platforms (robots, bodies, simulators) on which they are run, and so to avoid locking in model development to the specifics of their embodiments.

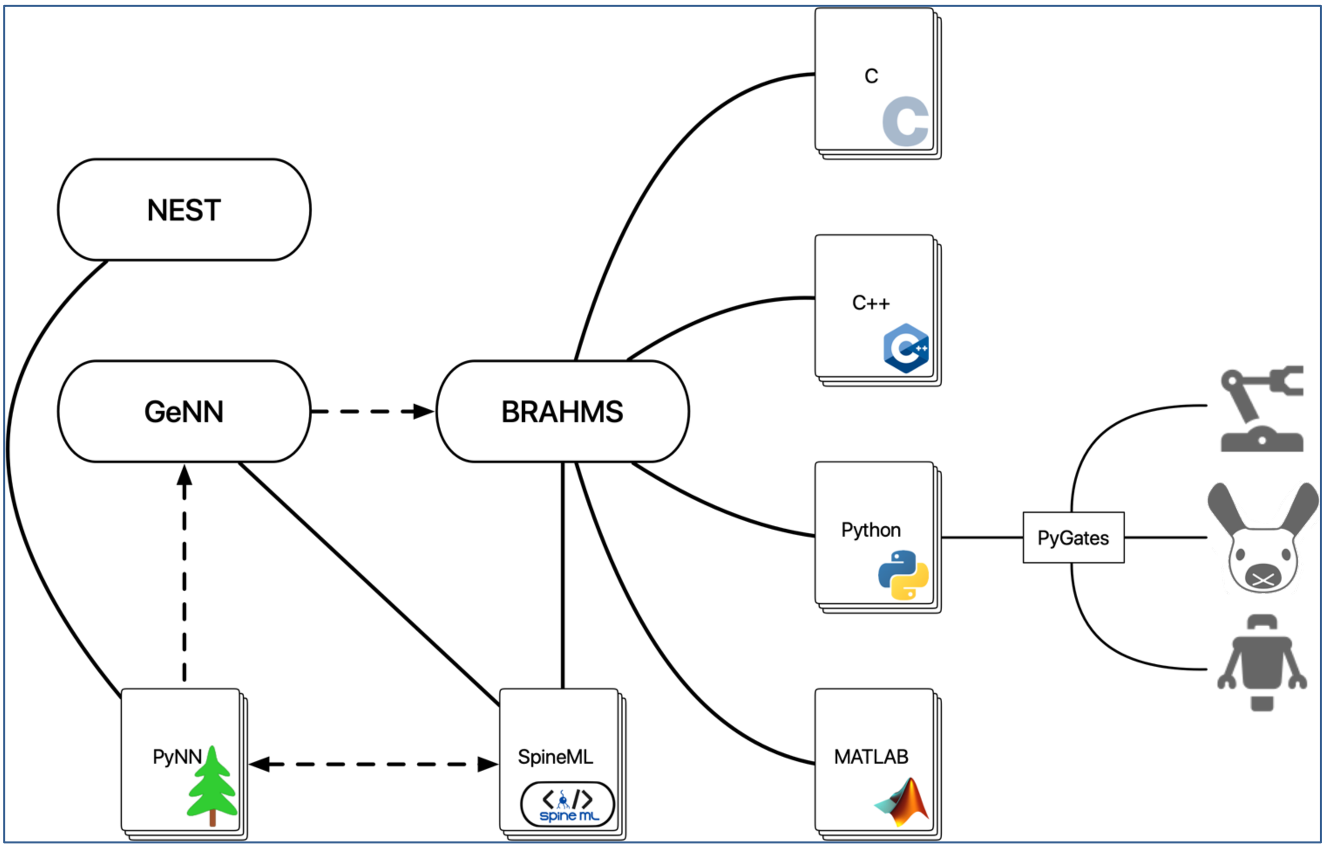

Figure 5: Framework for technical integration

Overview of the intended technical integration outcome. Solid lines indicate native compatibility between components, and dashed lines indicate where compatibility may be achieved via a conversion tool or wrapper utility. BRAHMS supports the execution of models with components written in a variety of languages, PyGates will enable easier deployment across a variety of robotics platforms via a unified Python interface, and existing PyNN models may be supported either via a PyNN-to-SpineML conversion or a GeNN wrapper for BRAHMS. The framework is intended to maximise inter-operability between different kinds of models and to minimise the difficulty of deployment on robot hardware.

4.2 Simulation of target robot platforms

Alongside the physical robots WhiskEye and MiRo, we have developed simulation models of both for deployment across local simulation engines and, where HPC is required, the NRP. The images below (Figure 6) illustrate the two simulated robots. Simulation videos are available via the MammalBot Collab.

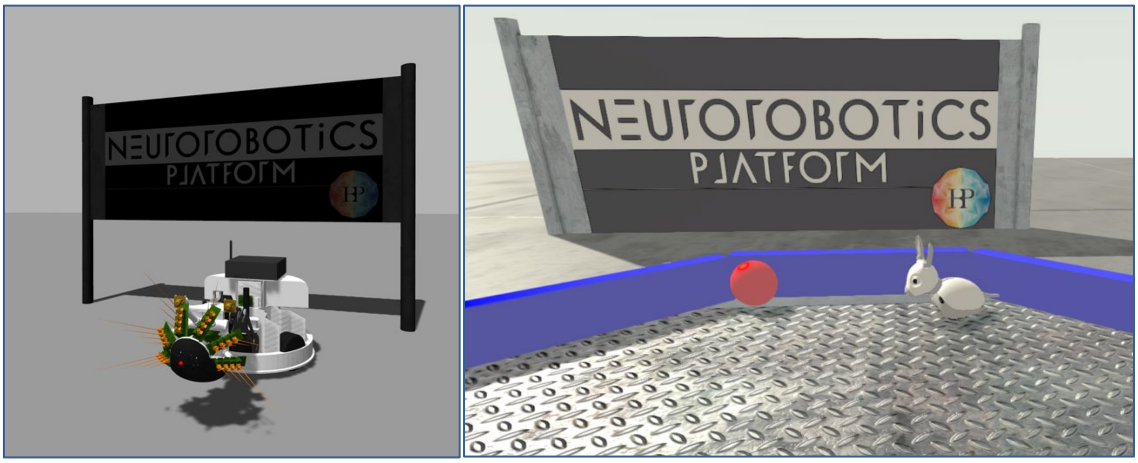

Figure 6: WhiskEye and MiRo models in the Neurorobotics Platform.

5. Publications and impacts

So far, in SGA2, we have developed and published an integrative review, for *Trends in Neurosciences*, on comparative structure, evolution and development of mammalian cortex (Krubitzer & Prescott, 2018), that will form the basis for defining the multisensory MammalBot cortical architecture. We have also published a conference abstract at the annual meeting of the *Alzheimer's Association* highlighting the potential of brain-based robots as therapy tools for people with dementia (Prescott, Mitchinson, et al., 2018). 2018 also saw the publication of the *Handbook of Living Machines* (Prescott, Lepora, & Verschure, 2018), edited by the USFD P.I. Tony PRESCOTT and featuring multiple contributions on brain-based control systems, including a chapter by PRESCOTT summarising the state-of-the-art mammal-like robotic systems.

The University of Sheffield is currently developing a spin-out company to exploit the commercial potential of the PyGates software system, developed as part of our technical integration activities, that provides a transparency layer allowing robot control system to operate on different robotic platforms.

With support from HBP and from the UK Arts and Humanities Research Council, brain-based control in the MiRo robot has been demonstrated at multiple public engagement events during the first twelve months of SGA2, including the BlueDot Science and Music Festival, CogX, Cheltenham Science Festival, Manchester Science Festival, the H2020 ICT Conference, and HBP public engagement events in the Netherlands and Italy. These activities are estimated to have directly reached an audience of 10,000+ people. We also contributed to the BBC Sunday Morning Live programme, which has an estimated audience of 700,000, with an interview and a robot presentation. These public engagement activities related are detailed in Annex 2: Public Engagement Activities.

Figure 7: The MiRo robot meets a member of the public at the BlueDot Festival

6. Resources

Information about this task including presentations, videos, documentation, and links to the software and models listed below, are available via the MammalBot Collab in the HBP Collaboratory. MammalBot-related models and software integration tools are available at the following locations.

Models:

- MammalBot cognitive architecture: https://github.com/ABRG-Models/MammalBot
- SpineML implementations of the GPR basal ganglia model with rate-coded (https://github.com/ABRG-Models/GPR-BasalGanglia) or spiking (https://github.com/ABRG-Models/GPR_Izhikevich) neurons, and SpineML implementation of an Izhikevich spiking neuron with associated explanatory notebook (https://github.com/ABRG-Models/IzhikevichABC)

Integration Tools:

BRAHMS:

- Information and documentation: http://brahms.sourceforge.net
- Download the latest version: https://github.com/BRAHMS-SystemML/brahms

PyNN:

- Information, documentation and download: http://neuralensemble.org/PyNN/
- PyNN interface to GeNN: https://github.com/genn-team/pynn_genn

SpineCreator (Frontend for creation of SpineML models):

- Information and documentation: http://spineml.github.io/spinecreator/
- Download the latest version: https://github.com/SpineML/SpineCreator

Pygates/BrainGLue

- In progress

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Krubitzer, L. A., & Prescott, T. J. (2018). The Combinatorial Creature: Cortical Phenotypes within and across Lifetimes. *Trends in Neurosciences, 41*(10), 744-762. doi:10.1016/j.tins.2018.08.002

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Prescott, T. J., Redgrave, P., & Gurney, K. N. (1999). Layered control architectures in robots and vertebrates. *Adaptive Behavior, 7*(1), 99-127.

Annex 1: WhiskEye Movie

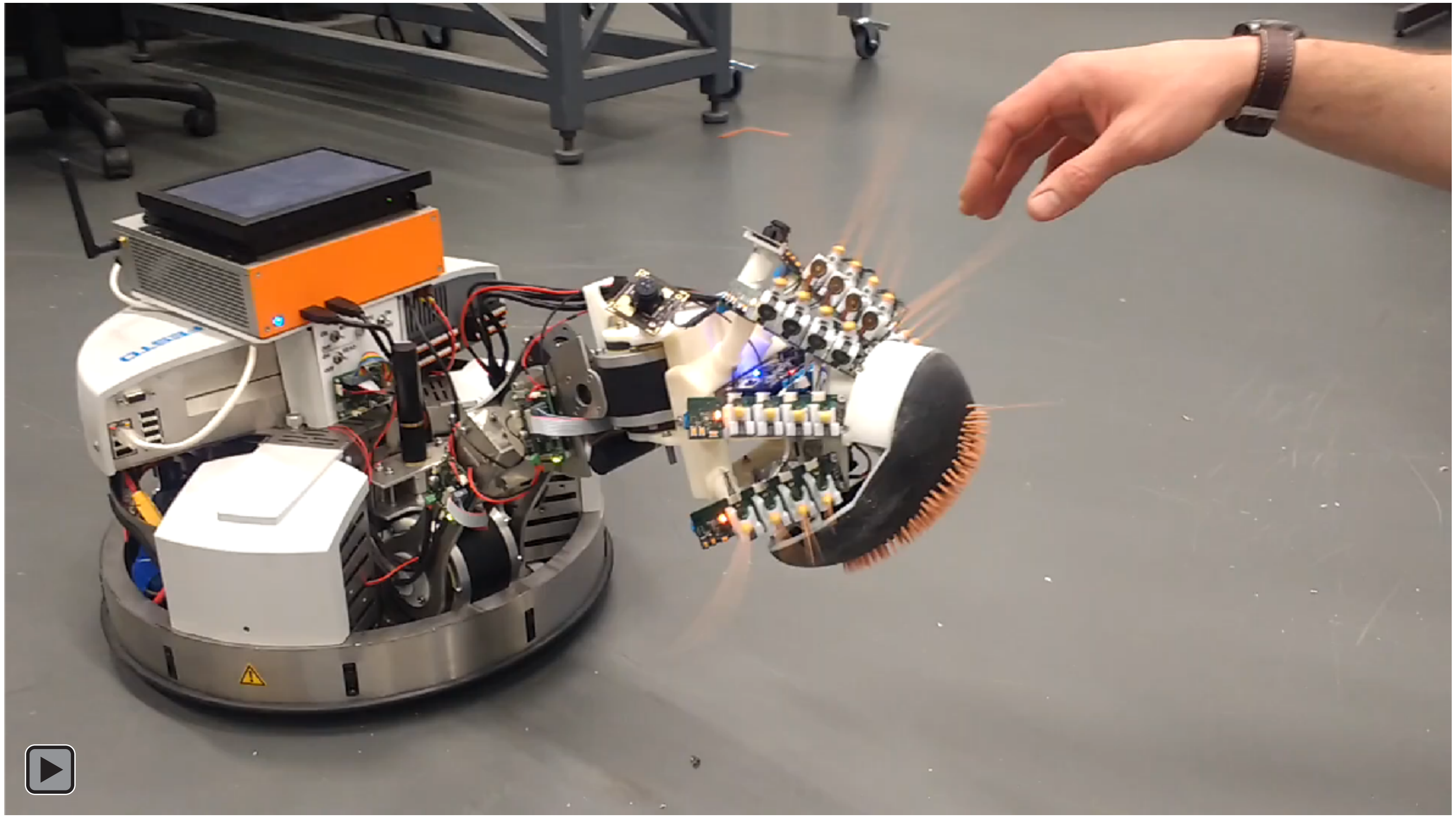

Figure 8: A movie demonstrating WhiskEye's exploration and orienting behaviour

Click to activate the movie. For older Acrobat versions, QuickTime or Windows Media Player may be required.

Annex 2: Public Engagement Activities

Human Brain Project Innovation Expo, Science Museum, London	
Date	23 March 2018
Activity Type	Exhibition
How many people?	500
Geographical Reach	International
Primary Audience	Professional Practitioners
Other Audience	Media, Policymakers, Public, Students
Result Description	We organised and provided an exhibit for HBP's Innovation Expo at the Science Museum in London.
URL	https://hbpinnovationexpoorg.wordpress.com/

AI Summit	
Date	13 - 14 June 2018
Activity Type	Trade Show
How many people?	10,000
Geographical Reach	International
Primary Audience	Industry/Business
Other Audience	Media, Policymakers, Professional Practitioners, Public
Result Description	We provided an exhibit for the Ai Summit at London's ExCel Centre. Organisers estimate over 10,000 people attended the conference over 2 days.
URL	https://london.theaisummit.com/

BBC Sunday Morning Live	
Date	8 April 2018
Activity Type	TV Broadcast
How many people?	700,000
Geographical Reach	National
Primary Audience	General public
Other Audience	
Result Description	We provided robot demonstrations for a live recording of Sunday Morning Live, BBC One, on 8 April 2018. Tony PRESCOTT also gave a short interview. Estimate average audience figures for this show is 700,000 per episode
URL	https://www.bbc.co.uk/programmes/p06d86rx

Bluedot Festival 2018, Jodrell Bank, Cheshire	
Date	19 - 22 July 2018
Activity Type	Science Festival
How many people?	
Geographical Reach	National
Primary Audience	General public

Other Audience	Media
Result Description	We provided an exhibit (for the second year running) for the Bluedot Festival of music and science at Jodrell Bank, Cheshire, from 19 - 22 July 2018. Organisers estimate an annual attendance of 30,000 people.
URL	https://www.discoverthebluedot.com/

Cheltenham Science Festival	
Date	5 - 10 June 2018
Activity Type	Event, workshop or similar
How many people?	5,000+
Geographical Reach	National
Primary Audience	Schools
Other Audience	Schools, Media (as a channel to the public), Policymakers/politicians, Public/other audiences, Industry/Business
Result Description	We provided an exhibit for the Cheltenham Science Festival, Cheltenham, UK.
URL	https://www.cheltenhamfestivals.com/science

CogX	
Date	11 - 12 June 2018
Activity Type	Science Festival
How many people?	6,500
Geographical Reach	International
Primary Audience	Industry/Business
Other Audience	Media (as a channel to the public), Policymakers/politicians, Professional Practitioners, Industry/Business
Result Description	We provided an exhibit for the 2018 CogX Festival of AI and Emerging Technology, focussed on industry and organisations. Organisers estimate 6,500 people attended at Tobacco Docks, London.
URL	https://cogx.co/

DigiFest	
Date	6 - 7 March 2019
Activity Type	Event, workshop or similar
How many people?	More than 500
Geographical Reach	National
Primary Audience	Professional Practitioners
Other Audience	Schools, Policymakers/politicians, Professional Practitioners, Public/other audiences, Industry/Business
Result Description	We provided an exhibit at DigiFest, JISC's edutech conference, at the Birmingham ICC.
URL	https://www.jisc.ac.uk/digifest

Dutch Brain - Human Brain Project Open Day, Amsterdam	
Date	2 March 2018
Activity Type	HBP Outreach Event

How many people?	101 – 500
Geographical Reach	International
Primary Audience	Postgraduate students
Other Audience	Schools, Media
Result Description	We contributed robot demonstrations to the Human Brain Project's open day in Amsterdam, Netherlands.
URL	https://www.flagera.eu/dutchbrain-national-outreac h-event-of-the-human-brain-project/

Edinburgh International Science Festival	
Date	2 March 2018
Activity Type	Public Talk
How many people?	250
Geographical Reach	National
Primary Audience	General public
Other Audience	Media (as a channel to wider audiences)
Result Description	Tony PRESCOTT presented an invited talk "Are Friends Electric? Our Future Lives with Robots" to the 2018 Edinburgh International Science Festival sponsored by the British Computing Society (BCS)
URL	http://www.edinburgh.bcs.org/events/2018/180331.htm

Esperienza Insegna, Palermo, Italy	
Date	20 February 2018
Activity Type	HBP Outreach Event
How many people?	More than 500
Geographical Reach	International
Primary Audience	Schools
Other Audience	Media
Result Description	As part of the Human Brain Project's contribution to Esperienza Insegna, hosted by Universita di Palermo in Palermo, Italy, we demonstrated robots and engaged with Sicilian pupils about robotics and psychology.
URL	https://tgs.gds.it/programmi/telegiornale/2018/02/24/alluniversita-di-palermo-il-progetto-esperienza-insegna-7aa7e72f-743b-4733-bd53-f8ee4d8c3a13/

Sheffield Festival of the Mind, Futurecade	
Date	20 - 27 September 2018
Activity Type	Science Festival
How many people?	2,000+
Geographical Reach	Regional
Primary Audience	General public
Other Audience	Media, Professional Practitioners, Industry/Business
Result Description	For the 2018 Festival of the Mind, we created an 'artists' collective', which presented 2 works of art related to robotics and the Futurecade theme of 'utopia/dystopia', which stayed on permanent display at the Millenium Galleries, Sheffield.
Most important impact	Audience reported change in views, opinions or behaviours
URL	https://festivalofthemind.group.shef.ac.uk/

Human Brain Project Open Day 2018, Maastricht	
Date	15 October 2018
Activity Type	Event, workshop or similar
How many people?	More than 500
Geographical Reach	International
Primary Audience	Professional Practitioners
Other Audience	Policymakers/politicians, Public, Industry/Business, Postgraduate students
Result Description	We contributed to the Human Brain Project Open Day, in Maastricht, Netherlands
URL	https://www.humanbrainproject.eu/en/follow-hbp/news/hbp-open-day-2018-the-flagship-reaching-the-half way-mark/

ICT 2018: Imagine Digital - Connect Europe	
Date	4 - 5 December 2018
Activity Type	Event, workshop or similar
How many people?	More than 500
Geographical Reach	International
Primary Audience	Policymakers/politicians
Other Audience	Media, Professional Practitioners, Public, Industry/Business
Result Description	We contributed to the HBP exhibit at the ICT 2018: Imagine Digital - Connect Europe conference in Vienna, Austria, 4 - 5 December, 2018, demonstrating robots to 4800 visitors, including many EU policy-makers and related European industry stakeholders.
URL	https://ec.europa.eu/digital-single-market/en/events/ict-2018-imagine-digital-connect-europe

FutureFest	
Date	6 - 7 April 2018
Activity Type	Event, workshop or similar
How many people?	4,000+
Geographical Reach	International
Primary Audience	Public
Other Audience	Media, Professional Practitioners, Policymakers/politicians
Result Description	We organised an exhibit at Nesta's FutureFest at Tobacco Docks, London, 6 - 7 April, 2018, at which we spoke to approximately 4,000 delegates, including First Minister of Scotland Nicola Sturgeon and TV presenter and author Ruby Max, and recorded segments for a number of media outlets and (international) shows, including Radio 5 Live's Suzi Perry.
URL	https://www.futurefest.org/

Our Robot Friends, Manchester Museum of Science and Industry	
Date	20 January 2018
Activity Type	Science Outreach Event
How many people?	1,100
Geographical Reach	National
Primary Audience	General public
Other Audience	Schools, Media

Result Description	We offered engaging hands-on demonstrations and talks at the Manchester Museum of Science and Industry's PI: Platform for Investigation series, called Our Robot Friends. Organisers estimated that we saw and spoke to around 1,100 people that day
URL	https://www.scienceandindustrymuseum.org.uk/whats-on/platform-for-investigation

Prince's Trust Gala	
Date	11 June 2018
Activity Type	Event, workshop or similar
How many people?	500+
Geographical Reach	International
Primary Audience	Industry/Business
Other Audience	Media, Policymakers/politicians
Result Description	We attended the Prince's Trust Gala Dinner at the Tower of London on 11 June 2018, to open London Tech Week.
URL	https://tmt.knect365.com/london-tech-week-opening- dinner/

Robotics in Paediatrics Showcase	
Date	14 February 2018
Activity Type	Workshop
How many people?	50
Geographical Reach	Regional
Primary Audience	Researchers
Other Audience	Policymakers/politicians, Professional Practitioners
Result Description	We attended NHS Sheffield Children's Hospital to demonstrate how robots can transform children's health care in the future.