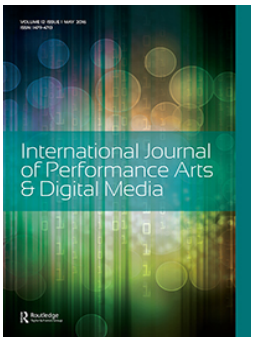

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cellF: a neuron-driven music synthesiser for real-time performance

Darren Moore[a], Guy Ben-Ary[b], Andrew Fitch[b], Nathan Thompson[b], Douglas Bakkum[c], Stuart Hodgetts[d] and Amanda Morris[e]

[a]Department of Global and Interdisciplinary Studies, Hosei University, Tokyo, Japan; [b]SymbioticA, the Centre for Excellence in Biological Arts, University of Western Australia, Perth, Australia; [c]Department of Biosystems Science and Engineering, ETH Zurich, Basel, Switzerland; [d]Spinal Cord Repair Laboratory, Western Australian Neuroscience Research Institute (WANRI), School of Anatomy, Physiology and Human Biology, University of Western Australia, Perth, Australia; [e]Faculty of Performing Arts, LASALLE College of the Arts, Singapore

ABSTRACT
cellF is the world's first neuron-driven synthesiser. It is a collaborative project at the cutting edge of experimental art and music that brings together artists, musicians, designers and scientists to create a cybernetic self portrait. *cellF* an autonomous, bioanalogue electronic musical instrument designed to operate independently and interact with human musicians. The instrument is controlled by a bioengineered neural network or 'brain' derived from skin cells using induced pluripotent stem cell (iPSC) technology that is housed in a custom built synthesiser 'body'. This paper introduces the *cellF* project highlighting the background, biotechnology, embodiment, design and performance capabilities.

KEYWORDS
cellF; neural synthesiser; experimental art; music; stem cell; neural networks

Introduction

cellF[1] is the world's first neuron-driven synthesiser. It is the result of a four-year collaboration led by artist Guy Ben-Ary to create a cybernetic self portrait. The project brought together artists, musicians, designers and scientists to create a real-time interface between living cells that have been altered through biotechnology and human musicians. It is an autonomous instrument that consists of a neural network bioengineered from Ben-Ary's skin cells that control a custom built synthesiser housed in a fully functioning biological laboratory. There is no programming or computers involved, only biological matter and analogue circuits; a 'wet-analogue' instrument. With *cellF*, the musician and musical instrument become one entity to create a cybernetic musician, a rock star in a Petri dish.

cellF premiered on 4 October 2015 in Perth, Western Australia as part of the Neolife: The Rest of the World, Society for Literature, Science and the Arts 2015 conference hosted by Symbiotica, the Centre for Excellence in Biological Arts at the University of Western Australia (UWA). Tokyo-based, Australian musician Darren Moore performed together with *cellF* on drum set and percussion with sounds from his drum set being fed as electrical stimulations into the neural network and the neurons responded by controlling a synthesiser to create an improvised posthuman sound piece (Figure 1). The project aimed to move beyond pure data translation or sonification of neuronal activity toward the

CONTACT Darren Moore darren@darren-moore.net

development of an entity that has the potential to exhibit emergent behaviour or very basic musical characteristics. In order to realise Ben-Ary's self portrait in the form of a cybernetic musician, the team first had to address how to culture neurons from his cells to create an external 'brain'. On achieving this goal, they had to decide on what type of 'body' should embody the external 'brain'; what form should it take and how would it function? Lastly, how could *cellF* exhibit musical characteristics and what would they be? Addressing each of these research questions informed the direction for each stage in the project which culminated in the creation of *cellF*. This paper traces the development of the project, highlighting the background, bio-technology, embodiment, synthesiser design, design of the sculptural object and finally an overview of the premiere performance.

Project background

In 2012, Ben-Ary, researcher at SymbioticA the centre for excellence in biological arts at the University of Western Australia, was awarded a Creative Australia Fellowship from the Australia Council of the Arts that resulted in four years of research toward the *cellF* project (http://guybenary.com/work/cellF/). The creative team assembled to realise the project consisted of stem cell expert Dr Michael Edel, neuroscientist Dr Stuart Hodgetts, neuroengineer Dr Douglas Bakkum, musician Dr Darren Moore, electrical engineer and synthesiser builder Dr Andrew Fitch and designer and new media artist Nathan Thompson. Ben-Ary's role within the project included artistic direction, project coordination and the development of biological and bioengineering protocols. In this collaborative project, each member played an important role in shaping the final outcome.

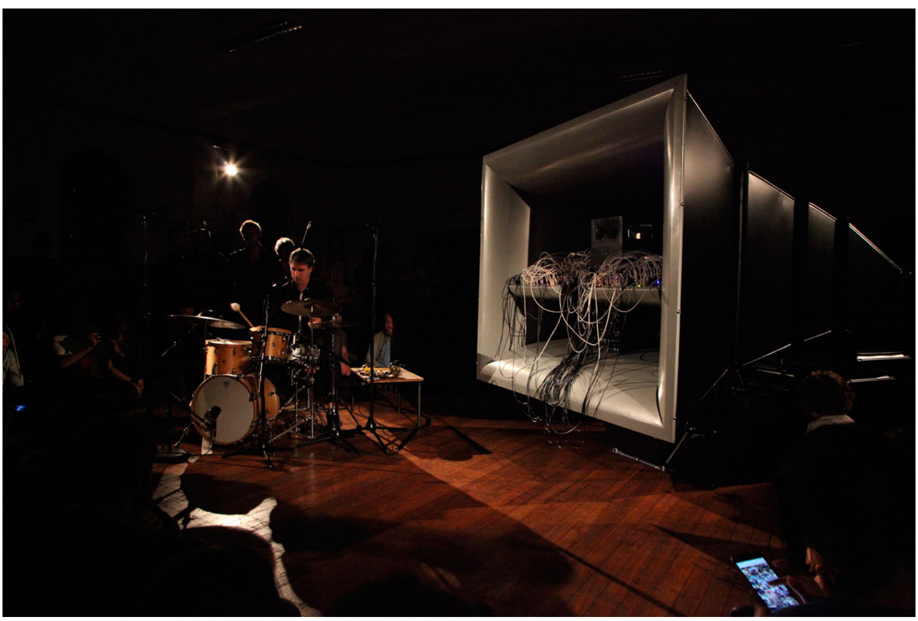

Figure 1. Darren Moore performing live with *cellF*, 2015.

cellF is a continuation of Ben-Ary's previous collaborative works *MEART* (*2001*), *Silent Barrage* (*2009*) *and In-Potentia* (*2012*) which address his 'interest in problematizing new bio-technologies and contextualizing them within an artistic framework' (Ben-Ary and Ben-Ary, forthcoming). His work lies at the intersection of art and science resulting in interdisciplinary projects that bring together artists, scientists and engineers. His work investigates themes of life and death, cybernetics and artificial life through using biotechnologies in subversive ways to put forward absurd and futuristic scenarios to seduce the viewer and allow critical engagement with the artworks.

Biotechnology

For *cellF*, Ben-Ary reprogramed his skin cells (fibroblasts) taken from a biopsy into induced pluripotent stem cells[2] (iPSCs) and transformed these iPSCs into neurons using special differentiation media to create a functioning neural network. The neural network was grown over a multielectrode array (MEA) that consisted of sixty electrodes that can record neural signals and also send back electrical pulses to stimulate the neurons. The MEA functioned as a 'read and write' interface to the external 'brain'. The neural interface enabled communication between the human performer and the neural network by transducing human generated sound into electrical stimulation of the neurons and transducing neural activity into voltages to control an array of custom built modular analogue synthesisers (Figure 2).

The starting point of the process was to obtain fibroblasts so that they could be cultivated and then reprogrammed to become iPSCs that have stem cell properties

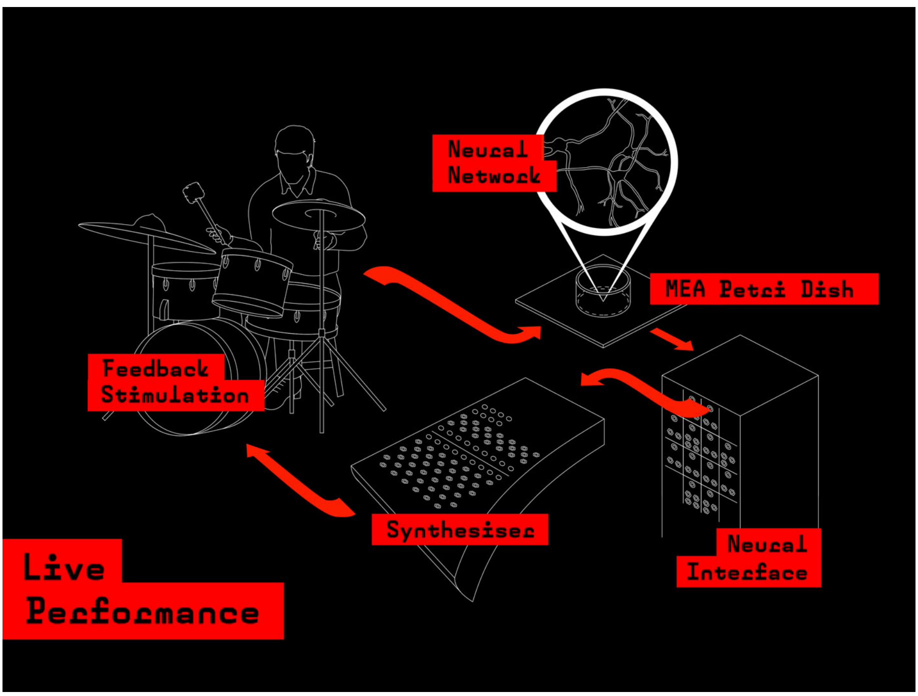

Figure 2. *cellF* system.

similar to embryonic stem cells. In 2012, Ben-Ary harvested his own skin cells from his arm in a biopsy and cultivated the flesh in vitro using standard tissue culture protocols at the laboratory of SymbioticA. The skin cells were frozen cryogenically and shipped to Barcelona where he worked with Edel to reprogram his skin cells into stem cells using the iPSC technique. After establishing the stem cell line, Edel and Ben-Ary 'pushed' the stem cells down the neuronal lineage to further differentiate the pluripotent stem cells into neural stem cells (NSCs). The NSCs were then cryogenically frozen and shipped back to UWA.

The next phase was to establish protocols to successfully and efficiently differentiate the NSCs to become mature neurons on an MEA dish and induce their electrophysiological activity. This phase posed enormous challenges, as there are few laboratories in the world that have established protocols that could be followed. Ben-Ary collaborated with Hodgetts and Dr Cornelia M. Hooper to establish the protocols to successfully differentiate the NSCs over the MEA dishes. The neuronal cultures became active after about 8–10 days from the initiation of differentiation and began to produce action potentials which are short electrical signals generated by the firing of neural synapses.

The neural networks that were used in the *cellF* project contained approximately 100,000 cells, which is roughly equivalent to the number of neuronal cells in a lobster brain. To put this into perspective, functioning human brains contain approximately one hundred billion neurons, interconnected via trillions of synapses. The 'brain' used to control *cellF* is essentially a symbolic one to entice the viewer to consider future possibilities that neuroengineering and stem cell technology might present. Although the neural networks used in the project are a fraction of the size and functionality of an actual human brain, they do produce a tremendous amount of data, respond to stimuli, exhibit properties of plasticity (learning) and are subject to a lifespan.

Bakkum, who was a collaborator with *MEART*, also played an important role during the beginning phase of the project. Bakkum is an expert in in vitro neuronal culturing and designing closed-loop 'embodiment' experiments and was involved in early meetings with the core creative team of Ben-Ary, Moore, Fitch and Thompson. Bakkum offered valuable insights regarding the way neurons work in vitro and behave over the MEA dishes and helped debug culturing protocols. In addition, he gave advice on decoding the neural signals and converting them into sound, as well as ideas on how to develop a closed loop electrical stimulation scheme to the neurons. This scheme was based on the idea of converting music made by humans into electrical stimulations and sending them spatially to the neurons using the 60 electrodes of the MEA dish.

The neuronal cultures used throughout the project were not trained or calibrated toward a desired behaviour or repeatable result. Their activity can be affected, for example, by applying electrical pulses or adding chemicals like dopamine to stimulate activity, but the compositional potential of the neuronal cultures extends only as far as the network's ability to 'learn'. With respect to the project, this consists of changes in 'neural plasticity' in response to electrical stimulation from the musician's sounds. To what extent neural networks exhibit 'learning', and furthermore what types of stimulation best tap into this, is unclear and an active field of study in neuroscience. Nevertheless, it is established that electrical stimulations change a neuron's activity state and its connectivity to other neurons, and that this happens across a wide range of time scales from milliseconds to years (Bakkum, Chao, and Potter 2008). A primary goal of the project is to allow any changes that do occur in neural activity to be perceptible to the accompanying musician(s) and audience.

Establishing and optimising the biological protocols to allow the differentiation of the neural stem cells into neurons over the MEA, so that they were healthy enough to develop quickly and produce detectable neural activity, was one of the major challenges. Scientific papers documenting such protocols could not be found, which led to a drawn out process of trial and error. This also involved some assessment of whether the cells growing over the MEAs actually had neuronal properties, other than similar morphology to typical neurons grown from brain tissues, as well as functional properties such as electrophysiological signals that resembled action potentials found in mature neuronal populations *in vivo*. Phenotypic tests performed in Hodgetts' lab using antibodies that recognise proteins produced by maturing neuronal cultures eventually confirmed that differentiation was proceeding toward the neuronal state or 'phenotype'. Optimising the combination of specific growth factors used in the cell-differentiation medium, to convert the NSCs into more mature neuronal phenotypes, involved multiple experimental cultures in order to produce as many neuronal cells as possible. As the NSCs differentiate to neurons and mature, they branch out 'neurites' over the electrodes (Figure 3). Streamlining this process toward achieving sufficient growth over a short period of time to meet the demands of the performance was inherently challenging, and took many months of intensive culturing to develop.

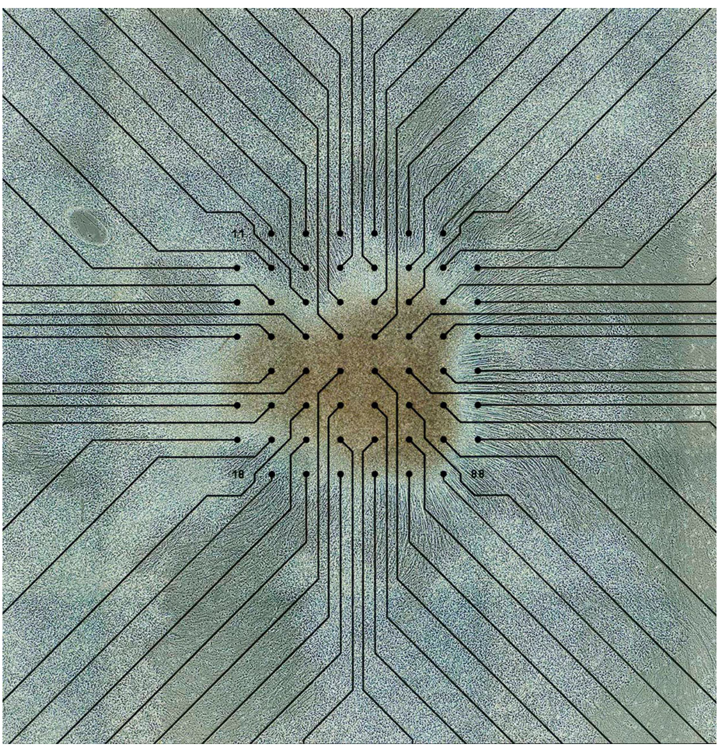

Figure 3. Microscopic image of neurons growing on an MEA.

Embodiment

Having successfully cultured a neural network by reverse engineering his own skin cells and transforming them into neurons, Ben-Ary began to consider what type of 'body' to give his external 'brain'? This question not only defined the nature of the project but was instrumental in guiding the selection of the creative team. Having worked on previous projects with Edel, Hodgetts and Bakkum (Bakkum et al. 2007; Ben-Ary and Ben-Ary, forthcoming), concerning the biological protocols of embodying neural networks, the continuation of this working relationship gave the project a solid biotechnological foundation. The decision to embody the external 'brain' with a musical entity guided him to put together the remainder of the creative team of Moore, Fitch and Thompson, all of whom are practicing electronic musicians in their own right.

As music had always been a passion of Ben-Ary's, he decided to revisit an adolescent dream of becoming a rock star and worked toward embodying his new 'brain' with the 'body' of a cybernetic musician. Ben-Ary contacted Moore with a proposal; 'How would you like to play a gig with me?' Knowing he was not a musician, Moore suspected that there was more to this question and his familiarity with Ben-Ary's body of work gave some indication that this was an invitation to work together on a project. The significance of this meeting was that Moore had unwittingly put forward a suggestion for the *cellF* 'body' which would later be realised.

Ben-Ary's previous experience with *MEART* and *Silent Barrage* (Ben-Ary and Ben-Ary, forthcoming) led him to consider robotic and movement-based solutions that could engage with musical instruments to create sound. *MEART* embodied a neural network with a 'body' composed of two pneumatic robotic drawing arms, whereas *Silent Barrage* created a 'parallel magnified immersive space' by representing the activity of a MEA dish with 32 columns 2.4 metres in height. The columns contained robotic parts that moved up and down according to the activity of neural networks in the MEA. Moore's proposal moved away from a robotic solution and suggested converting the amplified electrical signals generated by the neural network to create control voltage (CV) that would then control modular analogue synthesisers. CV is an electrical signal used to control the various parameters of a synthesiser and Moore had seen a parallel between CV and the electrical signals generated by the neural networks. After considering various options, Ben-Ary agreed that this would be a potentially exciting embodiment solution for *cellF*.

MEART and *Silent Barrage* involved computers and the internet as an interface and mode of communication between the neurons and the embodied robotic entities. NeuroRighter, an open source electrophysiology system that digitises signals from the neurons and allows the creation of neuronal stimulation experiments or closed-loop experiments, was used in these projects as an interface controller. During the early stages of the *cellF* project, Fitch had observed that it was possible to bypass the use of NeuroRighter as an interface between the neurons and synthesiser due to a similarity in the way neural networks and modular synthesisers use voltages. There was little reason, aesthetically or functionally, to take an analogue signal from the neurons, digitise it and then convert it to analogue again. NeuroRighter remained a valuable tool throughout the project to routinely examine the activity of the neuronal cultures and calibrate the synthesiser, as well as being a standby interface before the custom-built interface was ready, but for performances the team decided on an all analogue system to highlight the neural network-modular synthesiser parallel.

Synthesiser design

The responsibility to create an all analogue system fell on Fitch who hand built the modular analogue synthesisers used in the project and the analogue interface that connected the neurons to the synthesisers and allowed them to receive external stimuli. Fitch's previous research and approach to synthesiser design complemented the aims of the project. His PhD in electrical engineering focused on memristor based chaotic circuits and artificial neural networks and his synthesiser design philosophy focuses on creating new types of circuits that encourage the operator to explore new sound possibilities.

During the project, Fitch worked closely with Moore to build the synthesisers, which were funded by a research grant from LASALLE College of the Arts, Singapore, and with Ben-Ary and Thompson to create the neural interface. Moore was responsible for overseeing the musical aesthetic of the project and he provided direction to Fitch concerning the sounds he intended to achieve whilst leaving scope for experimentation.

Using modular analogue synthesisers in the project allowed for a flexible system that was capable of creating complex and multifaceted electronic sounds. Modular synthesisers are composed of separate components that are connected via patch cords to create a signal flow through the various modules (patches). Regular synthesisers have a classic sound path consisting of voltage controlled oscillators (VCOs), voltage controlled filters (VCFs) and finally voltage controlled amplifiers (VCAs) that commonly use three types of signals; audio, CV and gates. Audio signals are electrical signals that can be heard, CV signals can be used to control parameters of the synthesisers, such as to vary pitch in oscillators, cutoff in filters and to turn audio on and off in amplifiers, and gates are used as timing signals, in the simplest sense, like a metronome. Some synthesiser designers prefer to view these signals as separate entities, but concerning the *cellF* system, they were viewed as variations of the same thing; electrical signals.

Figure 4. Synthesiser and neural interface, 2015.

The analogue synthesiser built into *cellF* contains a number of sections for interfacing with the neuron array. These include circuits to amplify the MEA signals and to extract neuronal action potentials to convert these signals into gates. There are also circuits to convert synthesiser signals into voltages and triggers that can be sent directly into the MEA to stimulate the neurons. The synthesiser contains a large proportion of unusual modules developed specially for the *cellF* project. The *cellF* synthesiser is capable of traditional electronic sounds but also contains chaotic signal generators, logic functions, nonlinear feedback circuits, quadrature oscillators, multi band distortion processors and matrix mixers. Additionally, large format 3U, 84HP panels were developed to house the modules (Figure 4).

Design of the sculptural object

The sculptural object that housed *cellF* was a self contained unit that incorporated the modular synthesisers and analogue interface with a fully equipped, high precision biological laboratory. The object was designed to allow for the complex biological protocols that are needed for the differentiation of the stem cells and the maintenance of the MEA neuronal cultures in field conditions, while at the same time being a functional performance instrument. A great amount of time was spent finding a suitable 'body' for *cellF* that acknowledged historical influences, housed multiple features and was robust and modular in design to accommodate touring and multiple installations.

Thompson was responsible for the design and construction of the sculptural object and worked with Ben-Ary to envision a design that was not only functional but was able to entice the viewer to explore and engage with the work. The appearance of *cellF* was informed by naturally occurring forms such as a floral stamen and designed to form an endless internal loop as a metaphor for a closed loop system. The horn-shaped opening, which serves as the main workstation containing the synthesisers, interface and neural network, also drew inspiration from the shape of the amplification chambers of early gramophones and Futurist Luigi Russolo's noise machines. The design aesthetic posits an alternate reality of an all analogue world void of a digital revolution.

Maintaining an optimum environment for the neurons was important for the success of the work. Regulated conditions of 37°C and 5% CO_2 were needed to ensure the neuronal cultures remained active and healthy. Initially, an off the shelf incubator was considered; however, finding something to match the size and dimensions proved to be difficult which led Thompson and Ben-Ary to construct a custom built incubator with assistance from Andrew Pelling from Pelling Labs. A class two sterile hood was also an essential element of *cellF*, which allows the ability to maintain the cultures in sterile conditions within performance spaces (Figure 5).

Performance

The premiere *cellF* performance took place in front of an audience of around 150 people on 4 October 2015 at the Masonic Hall in the Perth suburb of Crawley, Western Australia. The performance began with Moore slowly fading in various patches of the *cellF* synthesiser before leaving it to run independently and moving to the drum set to begin the duo. The duet played out between *cellF* and Moore over a period of just over 35 minutes. The performance engaged the audience as they listened to a dialogue

Figure 5. *cellF* rear-view of sterile hood in the performance space with Moore's drum set ready for performance, 2015.

between Moore's reaction to the embodied neural activities spatialised throughout the room and changes in *cellF's* activity resulting from Moore's drumming. The concert ended by Moore standing up from the drums, walking over to *cellF* and slowly fading out the electronic sounds.

Improvisation plays a central role in the realisation of *cellF* as a performance entity. It allows performers to make contemporaneous reactions to sound emanating from *cellF*, which are fed back into *cellF* to create a dialogue between *cellF* and the human performer. Moore, reflecting on performing together with *cellF* at the premiere in his personal notes, had the following evaluation of the experience:

> As a performer, I approached improvising with *cellF* in the same way that I would with another human musician. However, *cellF* behaved in a unique manner that was different to any previous performance I had encountered so I decided to proceed slowly to let the sounds unfold rather than trying to dominate and force the situation. I chose to use a non-rhythmic, textural drumming approach using extended techniques[3] firstly, because I thought it would provide a complementary sound palette to the abstract synthesizer sounds and secondly, because I felt that abstract sounds contained less inherent meaning and are more open to interpretation. It was important that the focus of the performance was on the sounds themselves and highlighting the capabilities of *cellF* rather than creating a narrative.
>
> I felt the piece was well balanced compositionally in regard to timbral variation, space, density and form. Whether or not this was influenced by me, *cellF's* behavior or by chance is difficult to say, but I would posit it was probably a combination of all three. This was beyond my expectation as I was prepared for minimum interaction and unwieldy sounds from *cellF*. The sounds I produced were in reaction to the sounds I heard from *cellF* and it seemed like my sounds were affecting the behavior and sounds produced by *cellF,* yet to what extent was hard to gauge from a one-off performance. I believe that with repeated performances, the behavioral tendencies of *cellF* will begin to unfold.

The primary objective for the sound produced by *cellF* was to sonify the activity of the neurons via the modular synthesisers to reflect the complex nature and the specialised aspects of the neural activity when recorded over the MEA. This objective was addressed by two methods. Firstly, by creating patches through taking action potentials from similar regions in the MEA to create clusters of approximately three to nine outputs and secondly, by using the action potentials to spatialise the sound. The methods aimed to represent the neural activity in various zones within the MEA while reflecting the complex interrelationship between the zones. This was achieved through using signals adjacent to any given cluster to spatialise the sound from another cluster. The result was the creation of a parallel magnified immersive space derived from spatialising the outputs of the synthesiser via 4 matrix mixers to 16 separate speakers spaced evenly around the performance space. Being in the exhibiting space during the performance was like being inside of *cellF's* 'brain'.

There was a sense during the performance that the sonification of *cellF's* neural activity was articulated by the synthesiser and that there was a perceivable cause and effect between the neurons and Moore's drumming. Assessing the impact that Moore's stimulations had on the neural culture relied primarily on qualitative feedback from the audience as there were no quantitative experiments performed during the development stage or performance. Perth based musician and researcher Dr Adam Trainer who attended the *cellF* premiere related the following observations about the performance to the author in an email on 25 January 2015:

> The first live outing of *cellF* in late 2015 arguably evidenced the conceptual validity of the project. Darren Moore's subtle and responsive playing treats the drum set not as a rhythmically-based instrument but as a textural one, and was well matched to the modular synthesized noise that *cellF* emitted. Moore was able to gently coax an increasingly vibrant and responsive suite of textural electronics out of the network, using the occasion partly as an opportunity for improvisation, but also as a means of feeding the neural network so as to build the sound emanating from the synthesizers. Instead of careening wildly through stop-start percussive booms and crashes, Moore patiently encouraged and guided *cellF* through a series of restrained percussive approaches. This somewhat pensive improvisational approach paid off, with *cellF* responding gradually but with increasing certainty to the stimuli that it was fed. An encouraging start perhaps, for what could potentially become an increasingly complex and multifaceted project.

In an email exchange with the author on 27 November 2015, *cellF* designer Thompson related the following sentiment about the performance:

> The aural textures filling the venue on the premiere evening created a dynamic environment like I'd never experienced before. Moving around the space during the performance I was indeed able to bodily hone in on the synapse/activity at the petri dish in the incubator, coupled with its real time sentient reactions to Darren's live percussion, I found myself removed but heightened to an unusual primordial language that spoke to me at the very cellular level.

The testimonies from attendees of the premiere performance points to a cause and effect behaviour between *cellF* and Moore. Although knowing how to elicit specific behaviours and what is causing certain reactions from *cellF* is not yet fully understood, especially in the absence of analytical computer programs, 'reading' the data as an aural experience suggests a perceivable correlation between the two entities, highlighting the potential for further exploration in this area.

Conclusion

Art plays an important role in encouraging critical reflection on a unique cultural moment where we are witnessing the unprecedented evolution of biotechnologies and various modes of liminal lives that defy traditional understandings of life. Art has the potential to initiate public debate on the challenges arising from the existence of these liminal lives, by problematising the influence of current and emergent biotechnologies on the shifting forces that govern and determine life, death and sentience.

cellF is an absurd and a subversive proposition – a rockstar in a Petri dish. However, its Frankensteinesque narrative, complex processes, along with its visual and sonic aesthetics lure the viewers' exploration and draws them into a dialogue about the future of these technologies, and encourages them to re-evaluate their own perceptions and beliefs. In what directions will current and emergent biotechnologies take us in the future? What are our responsibilities to the liminal lives we create? What kind of ethical boundaries will need to be established around these living liminal entities? Artworks using neurons have the potential to evoke or elicit responses in regard to shifting perceptions surrounding understandings of 'life'. By bringing possible scenarios to life, neural artworks confront the viewer, both instinctively as well as intellectually, by calling into question the liveliness of the differential categories of life and death, human and nonhuman.

cellF's journey beginning with the culturing of neurons from skin cells through to the design of the synthesiser, interface and sculptural object culminated in the premiere performance at the Neo-life conference. The performance demonstrated the realisation of one of the primary goals of the project to create a 'wet-analogue', neuron-driven synthesiser that could operate independently, interact with human musicians and learn. The objectives to sonify the neural activity and spatialise the sound while maintaining the integrity of neural action potential signals were achieved. *cellF* was crude in its functionality as a musical entity and required a considerable amount of patching and calibrating to achieve the desired outcomes. Its 'musicality' pertained to the ability to receive external stimuli that could affect the behaviour of the neuronal culture and the activity of the electrical outputs used to drive the synthesiser and spatialise the sound. This feedback loop echoes the basic elements of collective improvisation which involve listening and reacting (or not reacting). The creation of a feedback loop between *cellF* and Moore within the system was an essential element that highlighted the potential for the future development of cybernetic musical entities that may have the ability to listen, react and learn. On a broader scale, *cellF* demonstrated the potential for neuronal cultures to control electronic circuitry and suggested that analogue self-learning machines based on neural plasticity could be a possibility for the future.

Epilogue

The final pops and clicks from *cellF* at the end of the premiere performance warranted a well deserved sigh of relief from the creative team. By all accounts, the first performance was a resounding success. This point marked the official 'birth' of *cellF* and the end of a four year journey to develop this ambitious collaborative project. The journey was not without its setbacks which saw the creative team work tirelessly to reach their deadline and achieve their main objective; make *cellF* work.

The biological and bioengineering protocols were a continual battle for Ben-Ary, who had to overcome contaminated cultures and many dead ends. Having set himself the enormous task of designing both the synthesiser and the interface to the neurons, Fitch devoted a great deal of time to the project and had to deal with the reoccurring issue of system noise. Thompson worked tirelessly to make sure the incubator and sterile hood were operating within optimum conditions and devoted a great deal of time to the design and manufacturing of the sculptural object to be ready in time for the premiere performance. Lastly, Moore was pressed for time to patch and calibrate the synthesisers and only had several hours to interact with the fully operational system with his drum set before the performance. With all the obstacles and the complexity of the project, it was nothing short of a miracle that the show was not only successful but went beyond the expectations of the team.

The project team aims to continue exhibiting *cellF* with the next series of performances scheduled on 10–12 June 2016 in Sydney, Australia, at The Cell Block Theatre at the National Art School. Renowned Australian musicians Chris Abrahams, Jon Rose, Claire Edwards, Clayton Thomas along with Moore have been invited to perform with *cellF* to explore how different musical approaches might influence the neurons. Future performances will also look at enhancing the methods to interact with the neurons and address issues that arose in the development period.

Notes

1. Pronounced self.
2. iPSC technology was pioneered by Professor Shinya Yamanaka (Takahashi and Yamanaka 2006) who showed that the introduction of four specific gene could convert adult cells into pluripotent stem cells. The iPSC method transforms adult specialised cells into a form that is equivalent to stem cells by reprogramming their genome and converting them back into an embryonic state that can be differentiated into any other type of cell in the body (e.g. skin, liver, muscle, neuron).
3. Extended techniques are unconventional methods of playing an instrument to elicit unusual sounds or timbres.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Notes on contributors

Darren Moore is an Australian drummer, electronic artist, event organiser and researcher based in Tokyo. Creative improvisation is central to his practice maintaining a through-line in his approach to varying projects and activities. From 2006 to 2015, Darren was a lecturer in Music at LASALLE College of the Arts, Singapore, and he is currently a part-time lecturer at Hosei University in

Tokyo. Darren completed a Doctorate of Musical Arts at the Queensland Conservatorium in 2013 which explored the adaptation of Carnatic Indian rhythms to the drum set.

Guy Ben-Ary is an artist and researcher at SymbioticA, Center for Excellence in Biological Arts at the University of Western Australia. Recognised internationally as a major artist and innovator working across science and media arts, Ben-Ary specialises in biotechnological artwork, which aims to enrich our understanding of what it means to be alive. His work has been shown across the globe at prestigious venues and festivals. Ben-Ary's main research areas are cybernetics, robotics and the interface of biological material to robotics.

Andrew Fitch completed a BEng (Hons) in 2010 and his PhD in 2015, at The University of Western Australia. His main research focused on memristor based chaotic circuits and he has published a book, journal articles and book chapters describing the results of this work. He has been building analogue synthesisers since 1998 and currently runs Nonlinearcircuits, producing a wide variety of unique designs intended for use in experimental music. http://nonlinearcircuits.blogspot.com.au/.

Nathan Thompson is a designer/artist working in multiple media and sound. He builds machines that play along the blurred edge of the interactive while showing independent thought only slightly tethered to the audiences actions. His work often questions the role of humans in the natural landscape through unknown sonokinetic territories to build greater understanding of our inhabited space. His machines are self built, analogue and lifelike in their behaviour. In a live performance setting he both controls and is controlled by the mechanics of these unique lifelike instruments. Nathan is a recipient of an Art Development Grant from The Australian Council for the Arts.

Douglas Bakkum is a scientist and group leader in the Department of Biosystems Science and Engineering at ETH Zurich, Switzerland. He received his PhD in Neuroengineering from the Georgia Institute of Technology and Emory University in Atlanta, GA, USA. His interdisciplinary background includes training in neuroscience, mechanical engineering, robotics and artificial intelligence. He currently leads projects to find the fundamental rules neurons use to communicate with each other and how such rules can scale to produce learning, memory and creativity.

Stuart Hodgetts is currently Director of the Spinal Cord Repair Laboratory in the School of Anatomy, Physiology and Human Biology (UWA). After obtaining his PhD in the UK and postdoctoral work in the USA, he joined UWA in 1998, conducting research in cell based transplantation for neuromuscular diseases and since 2004 in spinal cord repair using stem cells, including iPSCs, in particular in collaboration with Ben-Ary. A longstanding advocate of this cross-disciplinary research, he is currently Symbiotica's Scientific Consultant and an invited speaker internationally as well as exhibited works in collaboration with Symbiotica.

Amanda Morris is the Dean of the Faculty of Performing Arts at LASALLE College of the Arts, a leading contemporary arts institution in Singapore. She has worked in Australia at the National Institute of Dramatic Art and in New Zealand at the University of Canterbury, and received her PhD from the University of Sydney. She is well known for developing new and innovative education programs in the performing arts, as well as for her BAFTA award winning interactive CD program *StageStruck*.

References

Bakkum, Douglas J., Z. C. Chao, and S. M. Potter. 2008. "Spatio-temporal Electrical Stimuli Shape Behavior of an Embodied Cortical Network in a Goal-directed Learning Task." *Journal of Neural Engineering* 5 (3): 310–323.

Bakkum, D. J., P. Gamblen, G. Ben-Ary, Z. C. Chao, and S. M. Potter. 2007. "MEART: The Semi-living Artist." *Frontiers in Neurorobotics* 1 (5): 1–10.

Ben-Ary, G., and Ben-Ary, G. Forthcoming. "Bio-Engineered Brains and Robotic Bodies: From Embodiment to Self-Portraiture." In *Robots and Art: Exploring an Unlikely Symbiosis*, edited by D. Herath, C. Kroos, and Stelarc, New York: Springer.

Takahashi K., and S. Yamanaka. 2006. "Induction of Pluripotent Stem Cells from Mouse Embryonic and Adult Fibroblast Cultures by Defined Factors." *Cell* 126 (4): 663–676.