ERC Advanced Grant 2019
Research proposal [Part B1]

SOUNDS4COMA: Reaching to the Unconscious with Sound Technologies

PI: Jean-Julien AUCOUTURIER

Host institution: Comité National de la Recherche Scientifique (CNRS)

Title: Reaching to the Unconscious with Sound Technologies

Short name: SOUNDS4COMA

Duration: 60 months

ABSTRACT

Project SOUNDS4COMA aims to provide the knowledge and technology needed to use sound stimulation to study and provide care to patients with disorders of consciousness (DoCs). Research and clinical practice so far have used sound as a useful expedient, but paid no consideration to **what type of acoustic signals is able to best reach to these patients** and **what aspects of their cognitive processing indicate rich, memorable conscious experiences.**

SOUNDS4COMA builds on the PI's unique bi-disciplinary career spanning signal processing and neuroscience to propose a **radically novel approach:** instead of positing sounds a priori (e.g., a patient's own-name) in hope that they hit (and, often, miss) pre-specified markers of consciousness, we will **engineer acoustic stimuli that directly optimize the probability to observe these responses** in sleep, anesthesia and DoCs.

For instance, because DoCs are thought to result from the gating of sensory information by the thalamus, we will develop novel data-driven methods to analyse electrophysiological markers of arousals in response to large sets of sounds presented continuously to unconscious participants & reveal e.g. what type of fire alarm is most effective to wake people up, what medical alarm is least tiring for patients and staff, and **what type of stimulation is most likely to reveal awareness in DoC patients**. Similarly, we'll be able to determine e.g. **whether patients' facial expressions are reflex or volitional interactions, whether they still have a sense of self,** or **what they comprehend of the sonic environment around them**.

By **turning sound into a clinical technology**, SOUNDS4COMA will not only open avenues for theoretical and empirical research in the sciences of consciousness but, most spectacularly, **impact people's lives** around the world, giving them access to healthier sleep, safer anesthesia and, for the most critical of these patients, better diagnosis and more ethically-acceptable life support decisions.

Section a: Extended Synopsis of the scientific proposal (max. 5 pages)

> *"Sometimes, I remember the epileptic seizures I had as a kid. How I felt, just before they occurred. The absence. Of course, I don't remember falling. But waking up from them was so painful, so slow. Like ascending from depths. I was blind. I couldn't move - I could only hear. The people whispering, my mother and father, my brother… the little cracks and noises in the house. There were stages: sounds came first. Seeing was what came last. Then the feeling of the body, being able to move. But it was sounds which reconnected me; sounds, which brought me back. Sometimes I think I'd like my music to reflect some of this. I don't know how to say this... I've never told anyone before."*
>
> French composer Pascal Dusapin. *Entretiens sur la musique,* 2012.

The identification of consciousness, i.e. the ability to formulate subjective reports about oneself or the world (Dennett 1992), in non-responsive patients is not only one of the most vexing theoretical and empirical questions facing modern neurosciences (Miller, 2005), but also a major clinical issue (Owen, 2019). The possibility that a patient lying down with closed eyes may in fact, through the channel of sound, comprehend some or all of what is going on around them has far-reaching legal and ethical implications, as evidenced by the recent case of Vincent Lambert in France (Veshi, 2017). For the researcher as well as the clinician, the use of sound stimulation in the intensive care unit (ICU), either through verbal commands (Owen et al., 2006), standardized sound stimuli (Davis et al., 2007) or enriched sound environments (Lewinn & Dimancescu, 1978) holds tremendous promise to reach to these patients and provide them with better diagnosis and better care.

If we only had a principled way to use sound in the ICU, that is.

Yet, while auditory event-related potentials (ERPs) such as the mismatch negativity (MMN) or P300 in response to trains of pure tones or voice recordings are routinely used (André-Obadia et al., 2018) to evaluate cortical function in patients with coma and disorders of consciousness (DoCs), almost nothing is known about what type of sounds are able to reach the auditory cortex during these states. Indeed, one of the major theories for loss of consciousness in sleep, anesthesia and DoCs is a disrupted relay of sensory information to the cortex (Alkire, Haier & Fallon, 2000) and, from the sound alarm literature, it is well-known that sounds that may seem as interchangeable as a pure-tone or square-wave in fact widely differ in their capacity to wake people up from deep sleep (Bruck et al., 2009). When the sensitivity of standard MMN testing in the ICU can be as low as 32% (Fischer et al., 1999), could it be that patients denied a positive prognosis would show preserved responses if only they were tested with sounds that are more adapted to their individual neurological state?

Second, a critical factor in separating vegetative states (VS) from minimally-conscious states (MCS) in patients awakening from coma is the identification of cortically-mediated behaviour (Naccache, 2017). In clinical practice, this criteria almost always translates to determining whether patients respond to verbal command (Owen et al., 2006; Claassen et al., 2019). Yet, it is well-known from the cognitive neurosciences that there is a great continuum of auditory processing abilities intermediate between purely subcortically-mediated behaviour (VS) and full-fledged language comprehension. For instance, even outside of conscious awareness, healthy participants are able to discriminate their own voice from someone else's (Rachman, Dubal & Aucouturier, 2019), to parse concurrent streams of voice (Legendre et al., 2019), to react discriminantly to sound sources that loom toward their body (Noël et al., 2019), and even to comprehend prosodic intonation and react with appropriate facial expressions (Arias, Belin & Aucouturier, 2018). Could it be, then, that by focussing on overt responses to verbal commands, we routinely deny a MCS diagnosis (and thus weight dramatically on decisions to withdraw life support, Demertzi et al., 2011), to patients who, yet, would react to looming sound sources, revealing a sense of self, or even covertly smile back at the positive intonation of a family member (Fiaccioni & Owen, 2016), revealing a capacity for social interaction?

Third, in typical ICU practice, all of such auditory testing is done intermittently, e.g. once at the acute phase of coma, and possibly once again in the chronic DoC patients. Yet, daily fluctuations in residual consciousness are a well-documented hallmark of DoCs (Cortese et al., 2015) and even in physiological states like sleep, recent evidence suggests that the same participant, a few hours or minutes away, may be able to detect or memorize auditory stimuli - or not - depending on the presence of slow oscillations (Blume et al., 2018) or rapid eye movements (Andrillon et al., 2017). In a technological era where EEG monitoring can be automatized and synthesized sound environments can be played continuously, does it still make sense to rely on scarse, isolated auditory testing and hope that the moment coincides with the patient's most elevated levels of auditory attention?

Finally, in a context where auditory stimulation appears so uniquely critical to a patient's diagnosis and rehabilitation, does it make sense that the modern ICU environment be so acoustically hostile, with average background noise levels reaching 70dBA (a 40dBA excess over World Health Organization's recommended levels; Wenham & Pittard, 2009)? With its constant alarms from cardiac monitors and respirators, today's ICU environment in effect relegates auditory testing to only the loudest of sounds and the least subtle of acoustic differences, and compells clinicians and researchers to exclude modern sound technologies such as 3D/binaural sound diffusion and audio virtual reality (Hong et al. 2017) from the array of diagnostic and rehabilitation options at their disposal. If we are able to deploy these technologies for recreative use (Miller & Cutaiar, 2018) or advertisement (Mayo, Blum & Roussel, 2018), why can't we bring them to the patients who most critically need them?

In summary, despite a mass of research and clinical practice, we still do not have a cognitively-principled and technologically-appropriate way to use sounds in the ICU. Taking stock of these contradictions, project SOUNDS4COMA aims to mobilize some of the most powerful techniques in modern signal processing and auditory neurosciences, and propose a radically novel approach to sound stimulation, unleashing its full potential for the study, diagnosis and care of patients with disorders of consciousness.

Creative use of novel methodologies.

The typical approach to using sound stimulation in the study of consciousness in sleep, anesthesia or DoCs (Chennu & Bekinshtein, 2012, for a review) has been largely unconcerned with the precise acoustical properties of signals presented to participants. Sounds are selected relatively arbitrarily, in view of their supposed saliency or relevance: pure tones (Cote, Etienne & Campbell, 2001), 40-Hz click trains (Krom et al., 2018), but also e.g. voice from a participant's own mother (Blume et al. 2018, Machado et al., 2007) or recordings of a participant's own name (Perrin et al., 1999; 2006). When sounds are explicitly compared, it is with highly inefficient experimental paradigms, e.g. testing each separately on their ability to wake people up in the middle of the night (Bruck et al., 2009), which only allows a limited number of comparisons. This practice of positing signal features a priori creates well-known interpretation issues. For instance, it is unknown if a subject's own name triggers robust P300 in sleep or DoCs because it is evaluated as personally relevant (Perrin et al., 2006), because it is simply recognized as speech (Davis et al., 2007), or even because its low-level acoustical properties just happen to contrast well-enough with the standard tones. More worringly, stimuli prerecorded for this type of research do not exhaust the many other types of sounds available for stimulation, and there is always the possibility that a response is missed that would otherwise be preserved with a slightly different tone (higher or lower) or voice (male or female, etc.) – a troubling ethical issue in the context of prevalent DoC misdiagnosis (Schnakers et al., 2009).

For all these reasons, in recent years, a series of powerful data-driven paradigms (built on techniques such as reverse-correlation, classification image or bubbles; see Murray 2011 for a review) were introduced in the field of psychophysics and cognitive neuroscience to discover relevant signal features empirically, by analyzing participant responses to large sets of systematically-varied random stimuli (Adolphs et al., 2016). In the visual modality, these techniques are used to study cognitive mechanisms such as face recognition (Mangini & Biederman, 2004) or emotional expressions (Jack et al., 2012). Combined with electrophysiology, data-driven techniques can be used to reverse-correlate passive physiological responses on stimulus properties (e.g. with the visual N170 potential, Jaworska et al., 2018) or reveal where and when task-relevant information is processed in the dynamic response of the brain (Zhan et al., 2019).

Project SOUNDS4COMA offers to bring the power of data-driven techniques to the vast domain of auditory processing under loss of consciousness, and doing so, establish a radically novel methodology. Instead of positing sound features a priori (e.g., a patient's own-name) in hope that they hit (or, often, miss) certain pre-specified markers of consciousness, we will engineer acoustic stimuli that directly optimize the probability to observe electrophysiological responses.

For instance, because it is unknown what exact type of sound is favored for transmission by the thalamocortical relay during loss of consciousness (Alkire, Haier & Fallon, 2000), we will present participants in sleep, anesthesia and coma with a large quantity of subthreshold sounds, with systematically-varied properties in their spectrotemporal modulation spectrum (i.e. abstract sweeps of various rate and scale, Venezia, Hickok & Richards, 2016), source-filter vocal parameters (i.e. voices of various timbre and pitch; Burred et al. 2019), or motion in the 3D auditory field (e.g. looming or receding sources, McCarthy & Olsen, 2017). By reverse-correlating the presence of evoked EEG or cardiovascular markers of arousals (Catcheside et al., 2002, Blume et al. 2018) on the properties of these sounds, we will crack the code of thalamic gating and reveal, on an individual basis, what type of sound is most likely to evoke arousal. Findings from this paradigm will allow the project to design better fire alarms (37% of US fire fatality occur during sleep; Ahrens 2008), less intrusive medical alarms during anesthesia or critical care (in which 60% of patients report insomnia or sleep deprivation; Waye et al., 2013), and optimize and personalize test sounds for standard MMN and P300 testing for DoC patients.

Similarly, because distinguishing volitional from reflex behaviour is a major clinical difficulty in DoCs (Fischer & Truog, 2015), we will present awake participants with active auditory tasks with randomly-manipulated stimuli (e.g. detecting whether spoken sentences are pronounced with a smile – Arias, Belin & Aucouturier, 2019), reverse-correlate what acoustic information is associated with their behaviour (i.e. what spectral properties of speech drive recognition and facial imitation of auditory smiles), let participants fall asleep or into sedation as they do the task (Kouider et al. 2014 ; Krom et al., 2018), and then use information-theoretic measures (Jaworska et al., 2018) to continue tracking where and when this task-relevant information is processed from their single-trial EEG after loss of consciousness. Findings from this paradigm will allow the project to design new speech-prosody-based tests of residual consciousness and provide family and caregivers with single-trial feedback about whether DoC patient behaviours (smiles, gestures) are sensorimotor reflexes or genuine social interactions

Finally, because little is known about what participants comprehend and remember of the sonic environment experienced during loss of consciousness (Andrillon et al., 2017), we will present sleeping and sedated participants with continuously-varied sequences of music and environmental soundscapes and test, upon awakening, for their recognition of the same material (sensory encoding) or material of the same sound sources (semantic encoding). We will then reverse-correlate post-test stimulus familiarity on the EEG spectra measured during unconscious exposure, to reveal markers of auditory recognition/encoding. Findings from this paradigm will allow the project to design biomarkers of anesthetic depth, to study the circadicity of auditory attention in DoC patients, and test whether standard behavioural (CRS-R) or MMN/ P300 procedures are improved when administrated during peaks of these measures.

In short, by adapting modern data-driven techniques from visual neurosciences to the auditory modality, SOUNDS4COMA will not only establish the first principled way to design and optimize sounds for the clinical testing of DoCs, but also completely overhaul how information processing is studied in the larger sciences of consciousness.

A well-principled continuum of experimental models, and three times the impact.

Besides pioneering the use of data-driven methods in DoCs, the other major methodological insight of the project is to progress on a continuum of experimental models spanning sleep (physiological, endogenous, reversible loss of consciousness; Ogilvie, 2001), general anesthesia (pharmacologically-induced, reversible; Uhrig, Dehaene & Jarraya, 2014) and coma/DoCs (pathological, irreversible).

The project will conduct coordinated, multi-centric research on (1) sleeping healthy participants in the sleep lab (CNRS), (2) non-neurological patients during general anesthesia in the context of ambulatory orthopedic surgery (Anesthesia Dept., Hôpital Lariboisière, Paris) and (3) comatose patients admitted to the ICU for ischemic/hemorrhagic stroke or cardiac/respiratory failure and who haven't recovered awareness 5 days after withdrawal from sedation (ICU, Hôpital Sainte-Anne, Paris).

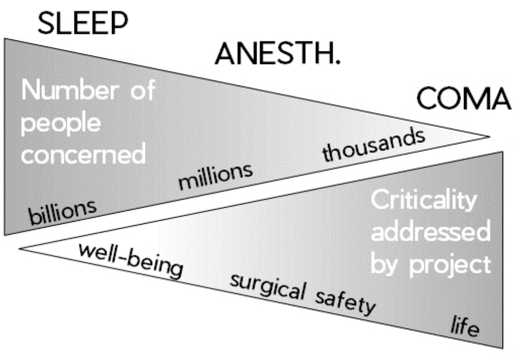
Behavioural and electrophysiological similarities between the various stages of sleep, anesthesia with propofol and coma have been often noted in the literature (Brown, Lydic & Schiff, 2010; Chennu &

Bekinshtein, 2012), but translational research efforts that bridge these three states have been few and far-between (see e.g., Perrin et al., 1999 and 2006 for own-name protocols in sleep, then in DoCs). Yet, using sleep and sedation as models for DoCs and pooling the development of experimental and computational procedures across these three states yield several critical advantages, which the project intends to fully exploit:

- **Experimental control**: contrary to coma, both sleep and anesthesia make it possible to causally induce changes between levels of consciousness in healthy participants (Chennu & Bekinshtein, 2012). Sleep stages can be scored with polysomnography (Berry et al. 2012), and depth of sedation can be controlled with concentrations of hypnotic agents and monitored with the EEG bispectral index (BIS, Kearse et al. 1998).

- **Pre- and post-tests**: with sleep and anesthesia, participants can be be tested with active auditory tasks before induction, and then electrophysiological markers of information processing can continue to be traced throughout loss of consciousness (Kouider et al., 2014; Krom et al., 2019). Similarly, participants can be presented with stimuli during unconsciousness, and then tested with active tasks upon awakening (Davis et al., 2007; Andrillon et al., 2017).

- **Ease of recruitment and ethical aspects**: Sleep research allows the project to recruit appropriately large numbers of non-clinical participants in the sleep lab, while requiring only light ethical procedures. Similarly, our experimental context for general anesthesia (ambulatory orthopedic surgery, flow of ca. 10 patients per day), while requiring clinical-level ethical clearance, warrants conveniently high numbers of patient inclusions. In contrast, experimental research on DoC patients, with their limited recruitment, variety of individual etiologies and paths of recovery, and high ethical criticity, will be reserved for protocols previously validated on sleep and anesthesia.



Besides providing a stepping stone to understand neurological dysfunction in coma, working on sleep and sedation also largely mitigates scientific risk for the project, because results in these two contexts will entirely stand on their own. Humans spend one third of their lives asleep and, each day, an estimated 60,000 patients receive general anesthesia for surgery in the US only (Brown, Lydic & Schiff, 2010). Findings in these two aspects of the project alone will therefore impact potentially billions of people around the world, giving them access to healthier sleep, more effective alarms, and more safely monitored surgical procedures.

In summary, by pooling its research efforts across the three models of sleep, general anesthesia and coma, SOUNDS4COMA is not only methodologically equipped for a critical breakthrough in the study of disorders of consciousness, but also amplifies its impact many-fold with important findings and applications in the domains of sleep and anesthesia.

A background, environment and network of collaborations that puts it within reach

The project builds on the PI’s unique bi-disciplinary career, which combines expertise in both acoustic signal processing and auditory cognitive neuroscience :

- Our work on acoustic signal processing has lead us, over the years, to introduce several influential computational models for the analysis and synthesis of music (Aucouturier & Pachet, 2004 – 463 citations), environmental sounds (Aucouturier, Defreville & Pachet, 2007 – 249 citations) and, in the context of ERC StG project CREAM (2014-2019), the human voice (Aucouturier et al., 2016; Arias, Belin & Aucouturier, 2018). As an unforeseen outcome of project CREAM, our team pioneered the use of data-driven methods for the study of speech perception (Ponsot et al, PNAS 2018; Burred et al., 2019), which opened vast avenues of research into how brain systems process auditory information in general (Schyns & Ince, 2019). The present proposal builds on this incidental finding, proposing a novel application of these methodologies to the critical question of disorders of consciousness.

- All the neuroscientific methodologies to be used in the project are those for which I became established as a PI in cognitive neuroscience: MMN ERP paradigms (Rachman, Dubal & Aucouturier, 2019), EEG spectral analysis (Mercadié et al., 2014; Wollman et al., 2019), facial EMG (Arias, Belin & Aucouturier, 2018), autonomic measures (Aucouturier et al., 2016) and sound localization/psychophysics (Ollivier et al., 2019; Ponsot, Arias & Aucouturier, 2018). There too, the current project is a novel extension of these methodologies to a new, critical research question.

In addition to my direct expertise, I will surround myself and my team with a scientific, technological and clinical environment closely tailored to the need of the present research:

- the project's research on awake and sleep participants will be conducted at the PI's own laboratory at the Institute of Research and Coordination in Music and Acoustics (IRCAM) in Paris (http://www.ircam.fr). IRCAM is the world-leading research center for music informatics, and provides facilities and support for audio engineering, psychoacoustics, as well as a complete EEG lab appropriate for sleep research.
- Research in general anesthesia will be conducted in partnership with surgical anesthesia departments at several hospitals in France, including that of Hôpital Lariboisière, Paris (Fabrice Vallée, PhD., MD., http://ghparis10.aphp.fr/), which staff has an active record of research in EEG/patient monitoring (Touchard et al. 2019). These sites will provide adequate support for ethics and patient management.
- Research in coma/DoCs will be conducted in partnership with intensive care units at several hospitals in France, including that of Hôpital Sainte-Anne (Prof. Tarek Sharshar and Prof. Martine Gavaret, PhD, MD, http://www.ch-sainte-anne.fr/), which staff has an active record of research in EEG monitoring of DoC patients (Martinelli et al., 2019; Azabou et al. 2018), and will provide adequate support for ethics and DoC patient management.

Because of its unique positioning on sound stimulation, SOUNDS4COMA will also be in an ideal position to interact with a growing network of coma research in Europe, incl. groups in Paris (L. Naccache, S. Dehaene), Lyon (H. Bastuji, F. Perrin), Liège (S. Laureys, A. Demertzi), Milano (M. Massimini), Salzburg (M. Schabus), Cambridge (S. Chennu, T. Bekinschtein) and Birmingham (D. Cruse).

The Sainte-Anne/IRCAM ICU: a unique technological platform

The final key asset of the project is to build on the unique opportunity of the construction of a new Neurology and Critical-care building in Hôpital Sainte-Anne, Paris (Neuro-Sainte-Anne, cost: 82,773M€), for which a partnership was made with the PI's own laboratory (IRCAM, specialized in sound/acoustics) to build two pilot ICU rooms with very high acoustic performance (average level inside the room < 23 dBA, room reverberation equivalent to that of an auditorium) and entirely fitted for sound diffusion (3D multi-loudspeaker system embedded in walls, ceiling and supply-unit arm, separated 15sqm control room).

This technical platform, a structural investment estimated at 150k€ (3,250€/sqm), will be, to the best of our knowledge, the only one of its kind in the world. With the building expected to be operational in Jan. 2023, the platform will constitute a timely and ideal testing-bed for the novel methodologies developed in the project. Support from the ERC will provide the means to:

- equip the rooms with the sound technology needed for the diffusion of customized sound alarms, 3D moving sound sources and full ambisonic virtual reality with unprecedented levels of patient comfort and realism,

- staff the platform with a full time audio engineer/technician supporting its operation during normal medical practice for the project's clinical studies, and

- establish an appropriately-ambitious fundamental and translational research program for this unique venture, which has the ambition to radically transform how sound is used in ICUs in France, Europe and beyond.

Section b: Curriculum vitae

PERSONAL INFORMATION

Aucouturier, Jean-Julien
Born 14th June 1979 (40 years old), married, 5 children.
French Nationality
ORCID: 0000-0002-4477-4812
Profile: https://scholar.google.com/citations?user=jnST06UAAAAJ&hl=en
Research team: http://cream.ircam.fr

EDUCATION

I have a radically bi-disciplinary career with a unique combination of skills spanning both computer science and cognitive neuroscience. A 'native' of the former field (signal-processing engineer, computer-science PhD), I became fully proficient in experimental methods though postdoctoral experiences in neuroscience laboratories (RIKEN, Japan) and, recently, continuing medical education (neuroanatomy & neurophysiology).

2019 -	**Postgraduate certification in Clinical Neurophysiology** (ongoing) School of Medical Sciences, University of Lille (France)
2017	**Habilitation**, *"Audio signal processing for cognitive science research"*, School of Engineering, University of Paris VI (France)
2014	**Postgraduate certification in Neuroanatomy** Neurocourses, King's College University of London (London, UK).
2006	**PhD Computer Science,** *"Ten Experiments on the computer modeling of musical timbre"* School of Engineering, University of Paris VI (France)
2000-2001	**MSc. Audio and Music Processing**, Dept. of Electrical and Electronic Engineering, King's College University of London (London, UK).

CURRENT POSITION

I'm currently a permanent researcher in Cognitive Science for CNRS (Centre National de la Recherche Scientifique) in Paris, France.

2012 -	**Senior CNRS Researcher**, STMS Lab. (Science & Technology of Music & Sound) Institute for Research and Coordination in Acoustics and Music (IRCAM), Paris (FR)

PREVIOUS POSITIONS

Before my tenure with CNRS, I have held research and faculty positions in both computer science and neuroscience institutions in France and Japan (where my family and I have lived for 5 years).

2011-2012	**Research Scientist**, LEAD Lab. (Lab. d'Etude de l'Apprentissage et du Développement) University of Burgundy, Dijon (France)
2008-2011	**Assistant Professor (Tenure-track),** Dept. Computer & Information Sciences Temple University, Tokyo (Japan)
2008-2011	**Research consultant,** Biolinguistics laboratory, RIKEN Brain Science Institute, Wako (Japan).
2006-2008	**JSPS Postdoctoral Fellow**, Institute of Physics University of Tokyo, Tokyo (Japan)
2002-2006	**Assistant Researcher**, SONY Computer Science Laboratory, Paris (France)

FELLOWSHIPS AND AWARDS

2018	**Early Career Prize** for Fundamental Research, Fondation pour l'Audition, France.
2018	**Best paper award**, Int. Computer Music Conference (ICMC'18).
2014	**Science Communication Fellowship**, French Science Journalism Society (AJSPI), France
2012	**Best paper award**, International Conference on Music Information Retrieval (ISMIR'12)
2007	**Best paper award**, European Conference on Artificial Life (ECAL'07)
2006	**Postdoctoral Fellowship**, Japanese Society for the Promotion of Science (JSPS), Japan
2006	**First prize,** MIREX Software Competition, Int. Conf. Music Inform. Retrieval (ISMIR)
2005	**Postdoctoral Fellowship**, Arts & Humanities Research Council (AHRC), UK
2002	**Doctoral Scholarship**, Agence Nationale de la Recherche et Technologie (ANRT), France
2001	**Graduate Scholarship**, British Council, UK

GRANTS (PAST 5-YEARS)

2019-2024 Agence Nationale de la Recherche (co-PI), Sensory and Emotional Processing in Autism Spectrum Disorder. 349,000€

2019-2022 Fondation pour l'Audition (PI), Data-driven techniques for the diagnosis and prognosis of impairments of prosodic perception in brain-stroke survivors. 120,000€

2019-2010 **ERC Proof of Concept (PI)**, Augmenting the Value of Conversations with Voice Transformations. 150,000€

2017-2020 Agence Nationale de la Recherche (co-PI), Facial and Vocal Feedback and Post-Traumatic Stress Disorders. 660,000€

2017-2020 Agence Nationale de la Recherche (co-PI), Musical Interaction and Collective Action. 430,000€

2014-2019 **ERC Starting Grant (PI)**, Cracking the Emotional Code of Music. 1,492,000€

2014-2015 Fyssen Foundation (co-PI), Behavioural platform for mouse cognition. 35,000€

SUPERVISION OF GRADUATE STUDENTS AND POSTDOCTORAL FELLOWS

Students & fellows supervised come from the fields of audio signal processing, speech and music neurosciences and, starting recently, clinical medicine (neurophysiology, language disorders).

2014 – 2019 **Five postdocs** – two now hold faculty positions, two hold Marie-Curie Fellowships abroad
Four PhD students – two ongoing, two have obtained postdoctoral positions abroad
Seven master students – four have obtained PhD Scholarships in French universities
Brain, Cognition & Behaviour Graduate School, Sorbonne Université, Paris (France)

TEACHING ACTIVITIES

2013 **Invited** professor, signal processing (MSc course), Université de Franche-Comté (France)

2012 **Invited** professor, psychoacoustics (BSc course), Université de Bourgogne (France)

2010-2011 **Assistant professor**, computer science & psychology (6 BSc courses, 350hrs), Temple University, Tokyo (Japan)

ORGANISATION OF SCIENTIFIC MEETINGS

2018 **Session chair**, Europ. Soc. Cogn. Affect. Neurosciences (ESCAN), Leiden (Netherlands).

2017 **General chair**, Int. Workshop "Reverse-correlation for audio cognition", Paris (France).
Session chair, Consortium for European Research on Emotions (CERE), Glasgow (UK).

2016 **General co-chair**, Int. Workshop "Music cognition and audio technology in Tokyo" (Japan).
General chair, Int. Workshop "Emotional Archetypes: Music and Neuroscience", Paris (Fr).

2012 **'Demos track' chair**, Int. Conf. Music Inf. Retrieval (ISMIR), Porto (Portugal)

INSTITUTIONAL RESPONSIBILITIES

I became an ERC StG PI in 2014 and have since then directed the Music Neuroscience team in IRCAM (http://cream.ircam.fr). In 2019, I co-founded Altavoce, a start-up company offshoot from our research.

2019 **Co-founder**, Altavoce Inc. (voice transformation start-up), Paris (France)

2018-2019 **Scientific Advisory Board,** Fondation pour l'Audition, Paris (France)

2013 – 2019 **Team leader**, Music Neuroscience Team, IRCAM, Paris (France)

2014 – 2019 **Member of Departmental Board** (*Conseil de Laboratoire*), IRCAM, Paris (France)

2013 – 2019 **Advisor** to ERC applicants, ERC National contact point, Paris (France).

2014 – 2016 **Founding Member**, Institute for Health and Engineering, Sorbonne Université, Paris (Fr)

2010 – 2011 **Directorship of the Science undergraduate program**, Temple University, Tokyo (Japan)

2010 – 2011 **Campus representative**, Teaching Technology Committee, Temple University, Tokyo (JP)

REVIEWING ACTIVITIES

2015 - 2019 **Editorial Board**, Music & Science; Musicae Scientiae

2016 - 2019 **Scientific Evaluator**, Funding agencies: European Research Council, Agence Nationale de la Recherche (France), VIDI/VICI (Netherlands), Science Fund FWF (Austria), Engineering and Physical Science Research Council (UK), Levenhulme Trust (UK).

2006 – 2019 **Reviewer**: PNAS, Scientific Reports, British Medical Journal, PLOS One, J. Acoustical Society of America, Music Perception, Psychology of Music, Behavior Research Methods, IEEE Multimedia Magazine, IEEE Trans. on Audio, Speech and Language Processing, etc.

MEMBERSHIPS OF SCIENTIFIC SOCIETIES

2016 - 2019 **Member**, Europ. Soc. for Social, Cognitive and Affective Neurosciences (ESCAN); Assoc. for the Scientific Study of Consciousness (ASSC); Europ. Soc. Music Cognition (ESCOM)

Appendix: All ongoing and submitted grants and funding of the PI (Funding ID)
Mandatory information (not counted towards page limits)

On-going Grants :

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*
SEPIA (*Sensory and Emotional Processing in Autism Spectrum Disorder*)	Agence Nationale de la Recherche (ANR, France)	349,000€	Jan. 2020 - Dec. 2024.	Co-PI	Applies reverse-correlation to understand prosodic perception in autism. No overlap with the objectives of the current proposal.
ACTIVATE (*Augmenting the Value of Conversations with Voice Transformations*)	ERC Proof of Concept	150,000€	Jan. 2020 – Dec. 2020	PI	Measures the commercial value of using real-time voice transformation technologies in the context of telephone conversations, vocal assistants and augmentative communication devices. No overlap with the objectives of the current proposal.
PROSAVC *(Data-driven techniques for the diagnosis and prognosis of impairments of prosodic perception in brain-stroke survivors)*	Fondation pour l'Audition	120,000€	Dec. 2019-Dec 2022	PI	Applies reverse-correlation to understand prosodic perception in brain-stroke survivors with aphasia. No overlap with the objectives of the current proposal.
REFLETS (*Facial and Vocal Feedback and Post-Traumatic Stress Disorders*)	Agence Nationale de la Recherche (ANR, France)	660,000	Oct. 2017 – April 2021	Co-PI	Applies voice transformation technologies to rehabilitate patients with post-traumatic stress disorders. No overlap with the objectives of the current proposal.

Grant applications: No other ongoing applications.

Section c: Ten years track-record

- Over **40 journal articles** in computer science and neuroscience, incl. 3x**PNAS** and **Current Biology**
- Over 3300 citations, **H-index = 26** (source: Google Scholar)
- **Second most-cited** MIR article of all times (368 cit., source: Lee, Jones & Downie, 2009)
- Recipient of the Fondation pour l'Audition **Early Career Prize for Fundamental Research**, 2018.

I am a 40-year-old cognitive scientist interested in **how sound and music impact the human brain** in health and disease. Over the 13 years since my PhD, I have studied this question with a **radically bi-disciplinary approach** which has had **equally-high impact in the fields of computer science and cognitive neuroscience**. As head of the music neuroscience team in IRCAM (Paris) and PI of ERC StG project CREAM since 2014, I have created an original research program combining state-of-art **signal processing techniques for manipulating speech and musical sounds** with modern psychoacoustical and **electrophysiological methods to characterize the auditory systems** involved in their processing. This approach has been well-received in the scientific community, with publications in top-tier journals such as PNAS (2016, 2018) and Current Biology (2018) and the award of an Early Career Prize.

Three examples from my current research lines:

Automated acoustical analysis of speech and music: My initial work is rooted in the emergence, in the early 2000s, of the field of Music Information Retrieval (MIR). In a series of articles notably published in JASA (2007, 2009, 2015), I established a computational paradigm to compute similarities between audio signals, the bag-of-frames, which became foundational to a large part of the field: the task of music similarity as we defined it has been part of the annual **MIR algorithm evaluation campaign** (MIREX) since 2006 (our algorithm won **first prize** that same year); our 2002 princeps paper is the **2nd most-cited article in the field** (source: Lee, Jones & Downie, 2009) and, on Google scholar, the expression "bag-of-frames" now appears in more than **700 publications**. In my recent work, I have adapted these techniques to analyse large corpora of baby cries (JASA, 2011), social interactions (Cognition, 2017) and biomarkers of anxiety in patient voices (Brit. J. Anesth., 2019).

Real-time emotional voice transformations: In a well-received **PNAS 2016** paper, we developed a digital audio platform (available as an open-source toolbox, http://forumnet.ircam.fr/product/david, 2000 downloads) to modify the emotional tone of a spoken voice in real-time, and used it to show that speakers whose voices were manipulated with the tool not only did not detect the change, but saw their own emotions change in congruence with the emotion heard in their voice. This result was said to open the way for **a new generation of "cognitive prosthetics"** able to alter one person's self-image through vocal feedback, and is currently ongoing a clinical trial for application to post-traumatic stress disorder (600k€ **funding by Agence Nationale de la Recherche**, 2017). In the same line, my team and I have created a tool to simulate the acoustic consequences of stretching lips (i.e. smiling) while speaking and, using it, have shown that smiled speech triggered facial imitations in listeners, even when these auditory smiles were not consciously detected (**Current Biology 2018**). This technology was **patented** by CNRS in 2018, and lead to the **creation of a start-up company**, which aims to bring this technology to patients who rely on speech synthesizers for their social life (150k€ **funding by ERC PoC**, 2019).

Data-driven methods in auditory cognitive neuroscience: In a series of recent studies (**PNAS 2018**, JASA 2018, PLOS One 2019), we introduced a novel experimental paradigm that combines voice synthesis algorithms with psychophysical reverse correlation (available as an open-source toolbox, http://forumnet.ircam.fr/product/cleese, 800 downloads) and used it to show that social judgments of dominance and trustworthiness from spoken utterances such as the word 'hello' are driven by robust mental prototypes of pitch contours, using a code that is identical across genders (https://lejournal.cnrs.fr/videos/dis-moi-bonjour-et-je-te-dirai-qui-tu-es). This paradigm brings the power of data-driven methods, so far only used in the visual neurosciences, to the vast domain of speech prosody, a contribution for which I received the 2018 **Early Career Prize for Fundamental Research** (https://www.youtube.com/watch?v=toHbRQMHB-w) of the Fondation de l'Audition. In one particularly promising application, clinical colleagues and I are now using the technique to characterize the raising-pitch 'filters' used to discriminate interrogative and declarative intonations ("really?/really!") in acute brain-stroke patients undergoing speech therapy (120k€ **funding, Fondation pour l'Audition**, 2019). The technique opens a fascinating window into how patients make, or fail to make, such judgements, their plasticity and sensitivity to treatment.

Through these results, I have become a **recognized international research leader** in approaches combining acoustic signal processing with cognitive neuroscience. As an illustration, the research software created in my work has been **downloaded more than 4000 times** and is being used in some of the best-known laboratories in the field, incl. those of Robert Zatorre (Montreal), Philippe Schyns (Glasgow) and Kazuo Okanoya (Tokyo), as well the industry (Microsoft: Costa et al. 2018; Softbank Robotics: Burkhardt et al. 2019). This bi-disciplinary trajectory culminates in the present proposal, SOUNDS4COMA, which mobilizes novel techniques from both fields to completely overhaul how sound is used in the scientific and clinical study of consciousness.

Publications: My complete list of publications includes **41 articles in international peer-reviewed journals** (16 as senior author), almost equally divided among computer science (20, incl. IEEE Intelligent Systems, IEEE Transactions) and cognitive science (21, incl. PNAS, Current Biology, Cognition), **40 articles in international peer-reviewed conferences** (computer science: 19; cognitive sciences: 21), **3 edited journal special issues** (Pattern Recognition Letters, J. New Music Research, IEEE Intelligent Systems), **2 book chapters, 4 audio-technology patents** and **3 open-source research software tools**. I have published with more than **70 co-authors, from over 25 international institutions**, incl. the University of Tokyo, University College London, University of California Los Angeles and University of Lund. Google Scholar profile: https://scholar.google.fr/citations?user=jnST06UAAAAJ.

Ten top publications. Cognitive Science:

1. Arias, P., Belin, P. & Aucouturier, JJ. (2018) Auditory smiles trigger unconscious facial imitations. Current Biology, vol.28(14), R782-R783. https://www.cell.com/current-biology/fulltext/S0960-9822(18)30752-8

2. Ponsot, E., Burred, JJ., Belin, P. & Aucouturier, JJ. (2018) Cracking the social code of speech prosody using reverse correlation. Proceedings of the National Academy of Sciences, vol. 115 (15), 3972-3977. https://www.pnas.org/content/115/15/3972

3. Aucouturier, JJ. & Canonne, C. (2017) Musical friends and foes: the social cognition of affiliation and control in musical interactions. Cognition, vol. 161, 94-108. https://www.sciencedirect.com/science/article/pii/S0010027717300276

4. Aucouturier, JJ., Johansson, P., Hall, L., Segnini, R., Mercadié, L. & Watanabe, K. (2016) Covert Digital Manipulation of Vocal Emotion Alter Speakers' Emotional State in a Congruent Direction, Proceedings of the National Academy of Science, vol. 113(4), 948-953. https://www.pnas.org/content/early/2016/01/05/1506552113

5. Boidron, L., Boudenia, K., Avena, C., Boucheix, J.M. & Aucouturier, JJ. (2016) Emergency medical triage decisions swayed by manipulated cues of physical dominance in caller's voice, Scientific Reports, 6, 30219. https://www.nature.com/articles/srep30219

Computer Science:

6. Arias, P., Soladié, C., Bouafif, O., Roebel, A., Séguier, R. & Aucouturier, JJ. (2018) Realistic manipulation of facial and vocal smiles in real-world video streams. IEEE Trans. Affective Computing (early access). https://hal.archives-ouvertes.fr/hal-01712834

7. Aucouturier, JJ. & Bigand, E. (2013) Seven problems that keep MIR from attracting the interest of cognition and neuroscience, Journal of Intelligent Information Systems, 41 (3), 483-497. https://hal.archives-ouvertes.fr/hal-01546752

8. Aucouturier, JJ., Defreville, B. & Pachet, F. (2007) The bag-of-frame approach to audio pattern recognition: A sufficient model for urban soundscapes but not for polyphonic music. J. Acoustical Soc. America, 122(2), 881-91. **[250 cit.]**, http://www.academia.edu/download/33280504/aucouturier-07b.pdf

9. Aucouturier, JJ. & Pachet F. (2004) Improving Timbre Similarity: How high's the sky? J. Neg Results in Speech & Audio Sci., 1(1), 1-10. **[463 cit.]** http://www.academia.edu/download/33280566/aucouturier-04b.pdf

10. Aucouturier, JJ. & Pachet, F. (2003) Representing Musical Genre: A State of the Art. Journal of New Music Research, 32(1), 83-93.**[448 cit.]** http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.409.1645

Granted Patents:

Method and Apparatus to modify voice timbre by shifting the formants of spectral envelopes (EP2018/053433); Hybrid Audio-visual Categorization System and Method (US2008/040362); Mapped Meta-data Sound-Reproduction Device and Audio Sample Processing System Usable Therewith (JP2006/106754); A Content Management Interface (WO2006037786).

Plenary invited conferences (last 2 years):

Inaugural conference, Hearing Institute (France, Sept.19); Journées Science et Musique (France, Jun.19); Congrès National des Audioprothesistes (France, Mar.19); ERC Delegation at the World Economic Forum (China, Sept.18); Emotion & Artificial Intelligence Colloquium (France, Sept.18); Royaumont conference on the Evolution of Music (France, Dec.17); Montreux Jazz Artist Foundation (Switzerland, Jul.17); International Workshop in Timbre (Germany, Jan.17)

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