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Overcoming Boundaries: Interdisciplinary Challenges and Opportunities in Cognitive Neuroscience

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ABSTRACT

Cognitive neuroscience has considerable untapped potential to translate our understanding of brain function into applications that maintain, restore, or enhance human cognition. Complex, real-world phenomena encountered in daily life, professional contexts, and in the arts, can also be a rich source of information for better understanding cognition, which in turn can lead to advances in knowledge and health outcomes. Interdisciplinary work is needed for these bi-direction benefits to be realized. Our cognitive neuroscience team has been collaborating on several interdisciplinary projects: hardware and software development for brain stimulation, measuring human operator state safety-critical robotics environments, and exploring emotional regulation in actors who perform traumatic narratives. Our approach is to study research questions of mutual interest in the contexts of domain-specific applications, using (and sometimes improving) the experimental tools and techniques of cognitive neuroscience. These interdisciplinary attempts are described as case studies in the present work to illustrate non-trivial challenges that come from working across traditional disciplinary boundaries. We reflect on how obstacles to interdisciplinary work can be overcome, with the goals of enriching our understanding of human cognition and amplifying the positive effects cognitive neuroscientists have on society and innovation.

Introduction

Cognitive neuroscience studies cognitive and emotional processes with an array of self-report, behavioural, and physiological tools. In principle, cognitive neuroscience has great potential to translate our understanding of brain function into applications that maintain, restore, or enhance human cognition (Gabrieli et al., 2015; Koen and Rugg, 2019). However, outside of some specific and usually clinical contexts (e.g., Jansen et al., 2022), its record translating fundamental science effectively into practical, 'real-world' applications is arguably thin. In the reverse direction, complex, real-world phenomena encountered in daily life, professional contexts, and in the arts, can be a rich source of information for developing a better understanding of cognition, which in turn can lead to advances in knowledge and health outcomes.

Interdisciplinary work is becoming a necessity to solve complex problems in a variety of disciplines, including in management (Roy and Roy, 2021), business (Razmak and Bélanger, 2016), healthcare (Dzau and Balatbat, 2018; Sharp and Hockfield, 2017), and global challenges (Dzau et al., 2022; Sixt et al., 2022). At the largest scale, 'implementation science' (Bauer and Kirchner, 2020) deals with the scientific investigation of factors associated with effective implementation of interdisciplinary approaches relevant for large-scale organizational problems, for example global health problems (Bammer, 2013; Ridde et al., 2020). On the meso-scale, 'convergence science' is an emerging interdisciplinary framework defined as 'an approach to problem solving that integrates expertise from life sciences with physical, mathematical, and computational sciences as well as engineering to form comprehensive frameworks that merge areas of knowledge from multiple fields to address specific challenges' (Sharp and Hockfield, 2017). Finally at the smaller-scale, individuals and groups must contend with interdisciplinary differences. While many of the challenges of interdisciplinary work are common across problems in an abstract sense (e.g., differences in training and goals create communication challenges), it is not straightforward to find a strategy that works best in a specific interdisciplinary context and an understanding of the most relevant problems and useful solutions is left to practitioners.

The goal of this paper is to address the specific challenges and opportunities encountered in interdisciplinary work involving cognitive neuroscientists interacting with colleagues from other disciplines, working on shared objectives at relatively small scales (i.e., project-based collaborations). Our interdisciplinary framework involves a bi-directional transfer: translating cognitive neuroscience knowledge into real-world applications, and gaining cognitive neuroscience knowledge from real-world applications. Among the authors of this work are representatives from three disciplines. Our teams have been working at several disciplinary interfaces between cognitive neuroscience, robotics engineering, and the performing arts. In the process of these preliminary forays, we have been learning how to incorporate not only domain-specific knowledge, but also

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new tools, and ways of thinking and interacting, into our work. We have come to better appreciate the contributions that cognitive neuroscientists can make to interdisciplinary teams through our knowledge and training, and where the limitations lie. We have also identified some specific challenges and points of friction, including mismatches in goals, differences in teamwork and communication approaches, concerns for training and career advancement, and for sharing the results of interdisciplinary projects. In hindsight, the best way to address these challenges is to know beforehand what to expect and plan the project accordingly to mitigate them. By sharing our experience, we hope that cognitive scientists who are tempted by the idea of venturing beyond their field, but may still be reluctant to embark on interdisciplinary projects, will be better equipped to deal with the challenges and appreciate the opportunities typically encountered in such an undertaking.

In the following sections, we first elaborate on the impediments to bi-directional transfer. Next, we define the key concepts of interdisciplinarity and intersectoriality, before delving into three case studies: development of a closed-loop brain stimulation device, measuring cognitive workload and brain state in complex situations, and biosignals during emotional experiences and as input to artistic production. To better understand the nature of the challenges encountered in these cases studies, we then asked co-authors to reflect on their experience working with their partner disciplines. Finally, we address these challenges more specifically with respect to goals, timelines and products, teamwork and communication, recruiting, training and supporting highly qualified personnel, and dissemination.

Impediments to bi-directional transfer

Returning to the matter of how cognitive science can more productively interact with the wider research world, we suggest that three factors have contributed to limited transfer. The first is of practicality: most of the research equipment that has done the heavy lifting in cognitive neuroscience in the last decades (e.g., electroencephalography, EEG; functional magnetic resonance imaging, fMRI) was too big, expensive, or fragile to use anywhere but the laboratory. This limitation is dissolving. Enabled by technological advances such as dry electrodes and increasing availability of inexpensive electronics, tools have been miniaturized and made more economical (Adams et al., 2017; Gatzoulis and Iakovidis, 2007). Many wearable devices have been validated against standard, high-quality laboratory equipment (e.g., for estimating sleep, heart rate and heart rate variability Miller et al., 2022). Electroencephalographs (EEG), pupillometers, and functional near-infrared spectroscopy systems (which approximates fMRI in that it measures hemodynamic correlates of brain activity) are no longer confined to the lab (Calandra et al., 2017; Krampe et al., 2018; Mikkelsen et al., 2015). Lightweight, inexpensive systems can index autonomic nervous system function via skin conductance response and simple cardiac measures obtained using consumer-grade athletic monitors (Nogueira et al., 2018). People have found clever ways to use smart phone applications to collect behavioural and survey data 'in the wild', and from large numbers of people (Harari et al., 2016). These tools can be combined, exemplified by the simultaneous recording of heart rate, respiration rate, and skin conductance response on whole audiences who attended a musical performance (Tschacher et al., 2023). In sum, equipment-based challenges to studying a wide-range of cognitive phenomena in naturalistic environments, objectively and with high precision, are shrinking.

Another impediment to real-world transfer arises because when moving towards naturalistic fieldwork some degree of experimental control and investigative depth must be relinquished. In effect, there is a trade-off between the complexity and sophistication of the measurement tools that we use, and that of the cognition we can get at when abiding by their constraints. Focused mechanistic questions concerning how the brain gives rise to behaviour require extreme precision, and spatially- and temporally-resolved imaging of neural activity is unlikely to ever be better measured on a bicycle than when a participant is immobilized and undisturbed in an acoustically-shielded room. However, concentrating on simpler paradigms and fancier tools also has its limitations for getting at complex human cognition. There is much to be gained by exploring the full range of possible trade-offs (Nastase et al., 2020). In the lab, researchers have devised experimental and analytic means of studying a broad collection of naturalistic stimuli and phenomena, despite constraints imposed by their tools. Narratives and film can be used to induce various emotions (Hanke et al., 2014). Decision-making can be made the more real and salient by attaching real monetary or food rewards to the outcomes of computerized tasks (Krawczyk, 2002). In the opposite direction, careful study designs (and large sample sizes or numbers of samples) can make the most of signals present in noisy, real-world data (Scanlon et al., 2019; Tschacher et al., 2023). Thus the second challenge is also being overcome.

A third reason for poor transfer, which we focus on for the balance of this work, is that it is not obvious *how* to conduct rigorous interdisciplinary research that has one foot in cognitive neuroscience. We believe this discussion is timely. Cognitive neuroscience tools like EEG, traditionally the purview of fundamental researchers, have been creeping into new and unexpected places: in business and technology sectors, in sports, to gauge consumer experience, directly marketed to consumers to monitor their sleep and health, and to maximize emotional responses to (and presumably thus the return on) advertising (i.e., 'neuromarketing' or 'neuroeconomics') - sometimes with dubious designs and interpretations.

In the explosion of possibilities and a drastic change in the landscape of potential users and applications, we believe it is worth reflecting on the roles and skillsets of cognitive scientists contrasted against those of other disciplines, and to ask questions like 'how can we work with and learn from disciplines who have questions to which cognitive science approaches might be usefully applied?'

Such ideas become even more relevant as methods and tools development allows us to explore topics that are progressively further from the origins of our field. These newer areas may have the most untapped scientific and translational potential. Music neuroscience is a good example of an interdisciplinary idea that can come to fruition. When the field was in its infancy in the 1990s, it was not taken very seriously by the scientific community, yet unravelling the problem of how music is perceived, produced, and enjoyed has enhanced our understanding of nearly every brain function from basic elements of perception to high-level ones including language, reward, pleasure and motivation (Herholz and Zatorre, 2012; Tervaniemi, 2023; Zatorre, 2023). It is one of the best models for studying human neuroplasticity (Herholz and Zatorre, 2012), and is now pushing into new territory with increasingly naturalistic paradigms (Tervaniemi, 2023) and promising applications in health such as music therapy (Brancatisano et al., 2020; Thaut et al., 2014). Many other forms of artistic expression and complex human behaviour likely can be exploited to scientific and practical advantage, as can close collaboration with those who can advance methods. Before considering three case studies in interdisciplinary cognitive science research, we define two key concepts: interdisciplinarity and intersectorality.

What are interdisciplinarity and intersectoriality?

Cognitive neuroscience is inherently somewhat interdisciplinary. For example, studying cognition in a particular group of people like patients with Parkinson's or athletes may require specialized physiological knowledge, and frequently benefits from collaboration with professionals with focused experience; however, in these examples both groups would have a natural sciences background, ensuring a certain amount of common ground. Intersectoriality is a less commonly-used term that refers to the collaboration of different sectors of research (health, social sciences, natural sciences and engineering) or society (academia, industry, government, non-profit organizations, and the public). In the context of research and innovation, intersectoriality can involve partnerships between, as an example, artists and engineers, or academia and industry. It can also involve collaborations between different government agencies or the public to address social, economic, or environmental challenges (Selsky and Parker, 2005).

Many funding opportunities, which drive the direction of research, strongly encourage interdisciplinarity and/or intersectoriality through their evaluation criteria. For cognitive neuroscientists, the incorporation of interdisciplinary elements is often a natural aspect of their work, to varying degrees. We focus here on the more distant end of a continuum of interdisciplinarity, in which team members come from very different training backgrounds, and both perspectives and training are necessary to the project's goals (MacLeod et al., 2019). These cases are generally high-risk as they require an extra investment in time and resources (discussed in more detail below) as researchers must figure out how to productively bridge the gaps between fields, but may also offer completely new ways of thinking and working, potentially advancing our understanding of human thinking and behaviour. A key advantage of such collaborations lies in their ability to foster intersectoriality, enabling cognitive neuroscience to extend beyond academic circles and make a broader impact. We observe an increasing number of new companies marketing products rooted in cognitive neuroscience principles (Peake et al., 2018; Sebastian, 2014), while cognitive neuroscience itself aspires to address societal challenges through meaningful engagement with the public at large.

To accompany our discussion, we next describe three case studies from recent projects between the authors. The timing and extent of contributions from each discipline, and the resulting products for our case studies are schematically represented in Figure 1. In the context of our collaborations, we have gradually come to understand and appreciate the strengths of our collaborators' disciplines, across many small interactions. Our view on strengths, outcomes and interactions between disciplines are illustrated in Figure 2.

Case study 1: Development of a closed-loop brain stimulation device

Closed-loop brain stimulation is an approach that offers the possibility of evaluating causal research questions non-invasively (Zrenner et al., 2016). Non-invasive stimulation techniques such as electrical or magnetic stimulation have raised considerable interest, as they make it possible to generate, enhance, or disrupt neural events in healthy human subjects, and thus explore their functions. In brief, a continuous physiological signal, usually from electroencephalography (EEG), is recorded and monitored by a computer, which detects specific neural patterns of interest and quickly outputs a stimulus or activates a brain stimulation device. In a seminal paper, Ngo, et al. (2013) demonstrated that a sleep-specific neural event known as a slow oscillation could be enhanced by playing a soft sound to study participants during the slow oscillations 'up-phase', when neural tissue is more excitable. As compared with sham (i.e., no stimulation), sound stimulation resulted in a train of additional slow oscillations, an increase in other neural events called sleep spindles. Most interestingly, people who received stimulation performed better on a memory test involving a list of word pairs which they had learned prior to falling asleep (Ngo et al., 2013). Slow oscillations are clear, high-amplitude neural events with low frequencies (0.5 - 1.5 Hz); these represent the lower end of frequencies of interest for cognition and behaviour, which can go up to a few hundred hertz. Higher frequency brain oscillations generally have lower amplitudes, meaning that it is more difficult to separate their patterns from other background activity. Faster and less distinct neural patterns require faster computer systems and more sophisticated detection algorithms; however,

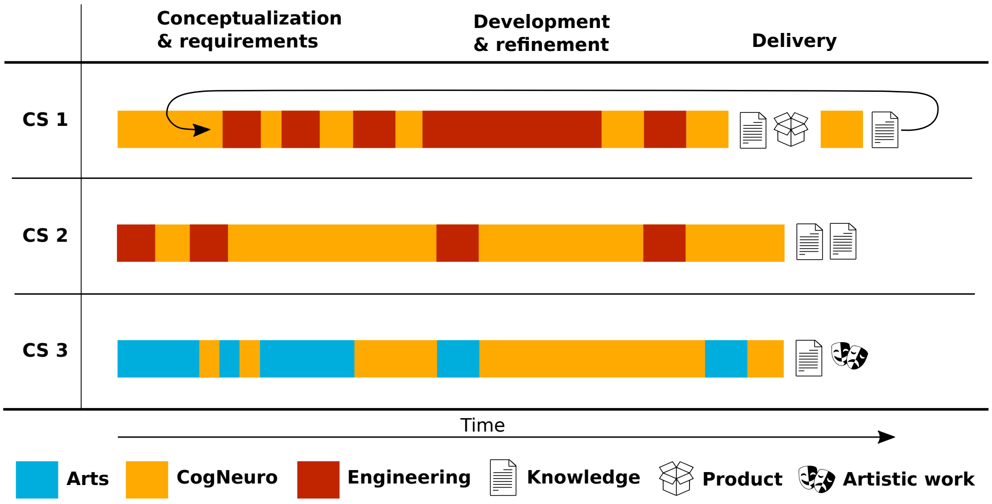


Figure 1: Timeline of disciplinary contributions and products in three case studies (CS). In CS1, limitations in existing scientific equipment prompted a collaboration between cognitive scientists and engineers. The scientists outlined the requirements of a flexible, portable, closed-loop brain stimulation device, which was developed and built by the engineering team. Both teams tested and validated the product, which resulted in a technically-focused paper in a general journal. The scientists went on to use the tool and produce a scientific paper, which led to requests for new features, continuing the collaboration. In CS2, engineers working in human-computer interaction outlined the need for more accurate cognitive workload measurements. Cognitive scientists helped to design, run, and analyze a human study. Research questions addressing technical and basic research topics were published separately in domain-specific journals. In CS3, performing artists identified the need to better understand how performing traumatic narratives impacts emotional reactions and mental health of actors. Cognitive scientists designed a human study that measured emotional responses and the effects of director instructions on them, and after cross-training, collaboratively collected data. The resulting knowledge is disseminated in a scientific journal, and in the form of workshops/information sessions to theatre practitioners.

extent equipment was too expensive, cumbersome, slow and inflexible to be used easily in most research contexts.

A casual discussion with an engineer with a background in real-time and embedded systems (Beltrame) suggested a means of creating a new, flexible, portable, and low-cost closed-loop brain stimulation device, using newly available electrical components and taking advantage of the latest innovations in real-time computing, machine learning, and optimization. Members of Beltrame's group have since worked closely with cognitive neuroscientists in Coffey's group to design, test, and validate such a device (the 'Portiloop', Valenchon et al., 2022).

The Portiloop project is interdisciplinary in that two completely different training backgrounds are essential (illustrated in Figure 1, 'CS1'). The cognitive neuroscientists defined the requirements and contributed knowledge of the brain processes and signals. The computer engineers designed, built, and tested the hardware, and wrote the software that detects stimuli. The cognitive neuroscientists obtained access to a training dataset, and tested and validated the physiological effects on human participants. Their work continues past the initial publication and product delivery, as they are the first to exploit the device's unique features to explore the effects of brain stimulation on cognitive processes. As the field advances, new research questions about brain-behaviour relationships generate new feature requests, which in turn provoke the engineering team to innovate.

Case study 2: Measuring cognitive workload and brain state in complex situations

Cognitive workload (i.e., the mental capacity it takes to perform a task) is an important factor of human performance. Performance is negatively affected when cognitive load is too high (overload) or too low (underload), leading to decreased efficiency, decreased productivity, increased errors, and increased fatigue and stress on the operator/performer (McWilliams and Ward, 2021). While workload has long been used to study basic processes of cognitive function and dysfunction, it is now predominantly used to study and predict human performance in safety-critical settings (e.g., during robot-assisted surgery (Zhou et al., 2020)).

One such application is in human-robot interactions, and particularly in multi-robot systems. Rapid advances in artificial intelligence are driving the adoption of robotics and automation in many areas including transport and logistics, in which new solutions to highway systems (Shladover, 2018), last-mile delivery (Grippa et al., 2019), and automated warehouses (Enright and Wurman, 2011) are becoming possible. For the foreseeable future, humans will remain indispensable to supervise and manage such robotic fleets because we are transitioning from systems that are generally already in use; technology gaps prevent us from performing all of the required functions autonomously; and particularly in visible, safety-critical applications, society's trust in AI technology will be earned gradually. However, integrating increasingly sophisticated AI techniques leads to increasingly opaque control programs. Furthermore, human supervisors' cognitive capacities are challenged (and eventually exceeded) as the size and complexity of these systems grow. The difficulty of ensuring operational performance is compounded when incoming information is scattered, delayed, asynchronous, or unreliable. These factors lead to increased pressure on human supervisors' cognitive resources and their ability to maintain situational awareness, detect problems, and make successful decisions. By introducing new portable equipment capable of measuring human workload and stress, we can assess human-machine interaction more effectively. This approach connects to existing research on human cognition and performance, allowing us to allocate system resources adaptively (Lindlbauer et al., 2019). This, in turn, ensures optimal operator performance and safety.

Contrary to Case Study 1, in which the engineers built a tool for use in cognitive neuroscience research applications, in Case Study 2 it is the engineers who raised the need to measure the state of human operators to advance their own objectives. The labs of Beltrame, Coffey and St-Onge are currently working on measuring cognitive workload in real-world, operational conditions. In a first feasibility study, they measured pupillometry and heart rate variability while astronauts controlled swarms of flying robots on an exploration mission in Mars analogue (St-Onge et al., 2019b). This led to subsequent studies to better understand the results in a more controlled laboratory setting, using a similar task and assessing an additional control interface for the swarm of drones (Paas et al., 2022), and focusing on the tools and methods to increase the reliability of data collection and processing (Duval et al., 2022). In a second feasibility study, they measured cognitive workload and emotional arousal during a speleological expedition [biorxiv], an operational environment which has many of stressors experienced in isolated, confined environments including spaceflight (Mogilever et al., 2018; Sauro et al., 2021).

The workload project is interdisciplinary in that the engineers designed and built the robots and their control algorithms. Accomplishing exploration objectives given the available technology defines and constrains the human operator's tasks and gives rise to specific cognitive bottlenecks. For example, directly controlling each robot (i.e., teleoperation) is more difficult than providing higher-level instructions to a self-organizing fleet, but may lead to inattention and distraction (Paas et al., 2022). The technology also raises specific research questions of a cognitive nature, for example, whether or not the human operator's tasks lead to boredom or overload, and inattention errors. The neuroscientists contributed knowledge of appropriate cognitive constructs (e.g., workload, attention, etc.), means of measuring them, human study design, ethics considerations and protocols, and analyzing and interpreting highly variable physiological responses, with regular coordinating and input from the engineering teams to ensure that, as the study paradigm is refined to maximize sensitivity to research questions, it remains relevant to eventual use cases.

Case study 3: Biosignals during emotional experiences and as input to artistic production

Cognitive neuroscientists have the tools and expertise to measure biosignals which provide indirect information about the autonomic nervous system, changes which correlate with emotional experiences. One of the roles of the arts is to produce emotional responses in an audience for a variety of reasons; for example, to share awareness of experiences, to encourage reflection or action, to facilitate the resolution of conflicts and injustice (Castro, 2023; Sotelo Castro, 2020), or for entertainment. It can therefore be valuable to both areas to measure physiological responses to artists' creations and artistic experiences.

It is typically expected that actors are able to affect their audiences through their delivery of emotionally-charged narratives. An area of acting in which this often happens is when actors perform real-life stories by people impacted by violence or by an armed conflict. This type of acting is present in documentary and verbatim theatre, oral history performance, autobiographical performance within both dance and theatre, documentary films, and even in what streaming services present as films 'based on real life-stories'. The appeal of this kind of work has to do with its power to engage audiences with disclosures. However, there are health risks for the performers (Krans et al., 2010). Sotelo-Castro's lab is using 'headphones verbatim', a performance method in which actors are asked to hear through headphones fragments of pre-recorded interviews or real-life conversations and to deliver the words that they hear live for an audience. The performer's work resembles what simultaneous interpreters do: they serve as a vehicle for someone else's words to reach a target audience. Sotelo-Castro has observed that while some trainees execute the task of delivering traumatic texts (for instance narratives by a victim of sexual violence) without feeling affected by the traumatic nature of the words that they hear and articulate, others seem to have stronger emotional responses to what they hear and enact, and may feel disturbed afterwards.

To answer the question of whether a director's instructions to the actors and the actors' ability to modulate their own emotional experiences can mitigate the negative effects of working with traumatic material, he partnered with cognitive neuroscientists from Coffey's group. In an experiment conducted in a theatre environment, the team measured autonomic nervous system responses (using pupillometry, skin conductance response, and heart rate variability) as actors performed neutral and emotional narratives while following instructions either to focus on accurately delivering the narrative (i.e., intonation, rhythm, volume, and tempo), or imagined being the narrator and letting their own thoughts and emotions arise during their performance (Mooren et al., 2016).

This project is interdisciplinary in that actors and directors contributed a topic and research question, and knowledge about the headphones verbatim technique and working with traumatic material. By examining the effects of these different instructions on emotional arousal and memory for narratives, the theatre personnel hoped to identify effective strategies for minimizing mental health risks among performers. The cognitive scientists refined the concepts and definitions provided by the artists' and made them measurable. The paradigm is interesting for exploring how cognitive strategies like selectively attending to different aspects of a narrative can be used to modulate emotional experiences. This research direction might find further application in a broader set of situations and careers in which people are confronted with narratives of traumatic events, for example, first responders, emergency room staff, police, and psychologists.

To better understand the context in which interdisciplinary challenges occurred, we asked co-authors to reflect informally on what they have learned about working with other disciplines. In particular, we asked about the strengths and weaknesses of theirs and others' disciplines and what value interdisciplinarity brings to their work. The responses are summarized in Figure 2, and described in the next section.

Know thyself

Three ways

Cognitive neuroscientists study relationships between behaviour and cognition, and the biological processes that underlie them. The expected outcome of their work is scientific knowledge, which is generally shared in the form of journal publications and presentations at conferences. The strengths of cognitive neuroscientists (who study humans) are their ability to design a study that addresses a given research question, meticulously taking into account potential confounds (e.g., recruiting bias, environmental conditions, nature of instructions). This process can take considerable time and thought, often with multiple iterations of piloting and refinement before data are collected. They are also adept at computational and statistical methods for analyzing biological signals, and interpreting the results in a wider context. Cognitive neuroscientists are typically trained in some combination of psychology and neuroscience. They are able to refine and operationalize ideas, making intuitions about internal and external phenomena measurable. Many have achieved a high level of expertise in the technical tools used in their areas (e.g., coding computerized tasks, brain image analysis), though may lack a broader technical background. When working with engineers, cognitive neuroscientists benefit from the groups' greater technical knowledge, which can be critical for activities like extending a tool's capabilities beyond its design specifications, or setting up complicated study equipment efficiently. For example, figuring out how to precisely synchronize and stream data from multiple measurement tools that use different communication protocols, data formats and sampling frequencies would take most engineering colleagues less time. When working with artists, cognitive neuroscientists benefit from a new and unfamiliar perspective and set of observations about human behaviour and experience, which can motivate new areas or methods of study. As master communicators, artists can also help scientists disseminate ideas and attitudes in ways that are accessible and engaging to the general public.

Engineers invent, design, analyze, build and test machines and other complex systems to fulfill functional objectives and requirements, while considering the limitations imposed by practicality, regulation, safety and cost. Their main output consists of devices, processes, and procedures. Engineers are used to solving problems in a straightforward manner, leading to a definite answer about what works or not. Their ability to dissect a problem in a very systematic way is one of their main strengths. They are good at troubleshooting issues and generally finding out why things do not work. In addition, they can turn abstract ideas into concrete applications relying on a design flow that starts from models and proceeds to implementation. Engineers undergo comprehensive training in mathematics, physics, project management, and design, starting with a broad foundation and gradually honing their expertise as they advance in their studies. Engineers are generally quite capable of creating and using models to design new devices or procedures, refining their designs into prototypes and into final products. However, engineers often have very little experience with human experimentation as well as the statistical methods that are necessary because of high variability when working with human datasets. Engineers looking at human data for the first time are frequently surprised by the inter-individual differences. For example, when measuring a correlation in some physical relationship, engineers might expect data points to align nicely; instead in human behavioural and physiological data, relationships are rarely clean, and are influenced by many factors. Engineers benefit from cognitive neuroscientists' understanding of human behaviour and cognitive principles, and experience measuring and interpreting data from these particular complex systems. When working with artists, engineers are challenged and stimulated by the technical requirements of implementing their ideas, and can learn more about how the public perceives and can interact with technology through dedicated studies and also public performances (e.g., Côté-Allard et al., 2017; St-Onge et al., 2019a,c).

Artists see art not only as entertainment, but as an integral part of everyday life. For performing artists, a performance is a dynamic co-creation between them and their audience, in alignment with the flow of the moment. They facilitate this two-way communication using different skills from different sub-disciplines, including acting, performance studies, oral history listening and interviewing, and listening studies (Hall, 2017). The use of different acting techniques enable them to have a direct emotional and cognitive impact on their audiences, which can be used to express ideas, to educate and inform, to challenge norms and change attitudes, and to reflect on the state and direction of societal trends. Visual arts can achieve similar aims through different media in a less direct (though also more lasting) way, as the artists themselves are usually not the objects of attention. Artists' discipline-specific training often begins at a young age when children take classes or are involved in school performances. Some artists gain experience in a self-directed fashion. For those who study their craft formally, they cover more theoretical aspects, learn about the history of their art, and may take studio-based classes and workshops with experts to learn specific skills. A lot of the training is hands-on, learning-by-doing, with feedback from teachers and/or directly from the public. Artists can benefit from working with cognitive scientists, particularly when they have questions from their practice that can be addressed using human measurement tools, including subjective, emotional, and cognitive experiences of artists and their audiences. Engineers instead can contribute new opportunities for artistic expression; every technology from three-dimensional printing to swarms of flying robots to electroencephalograph signals are explored in the arts.

Walking together

To promote successful interdisciplinary collaborations, recognizing that each discipline views humans from different but complementary perspectives can be highly useful. Engineers dissect a problem in a very systematic way and model physical phenomena. They tend to see humans as a mechanistic system with many variables. Artists see humans in a holistic way, taking into account less tangible phenomena such as emotions and group dynamics. At one extreme, engineers would find it easier if humans could be studied as a predictable system in very controlled conditions. On the other, artists rely on their intuitive understanding of people to facilitate a spontaneous exchange with their audience during live performances. Cognitive scientists can be seen as mediators between these extremes. They design and implement studies to understand why humans behave in a certain way by measuring physiology, behaviour, and subjective experiences. Human experimental design may seem elusive to engineers, as doing it effectively requires years of training in human behaviour and cognition. Collaborations with cognitive scientists is an important step towards the next technological leap, in which humans are fully integrated in the engineering development. For example, as robots are becoming ubiquitous in society, seamless integration of machines with humans will be essential to ensure safe and trustworthy systems. As for artists, repeating the same performance under the same conditions may seem nonsensical as the spontaneous flow of the performance would be negated by doing so. However, it could also help artists to better quantify the impact of their performance on their audience and learn more about phenomena they observe in their practice.

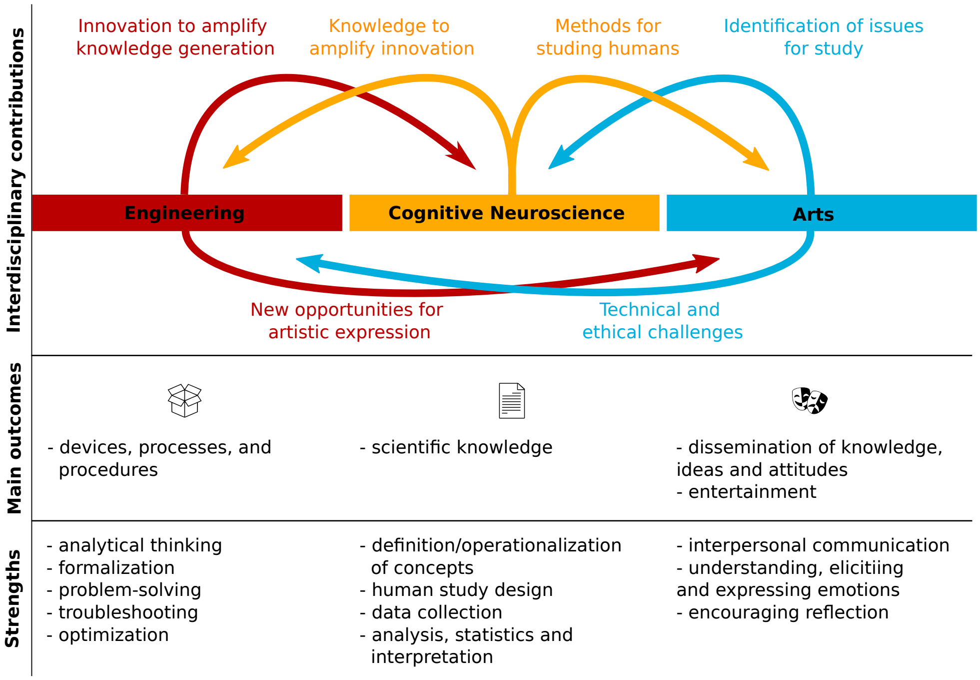
Recognizing that each discipline has a different realm of influence as regards shaping the future of our society is also helpful. Engineers are eager to push technological boundaries, but may not always be as focused on the effects on humans, nor on long-term consequences of the changes they instigate. Even technology intended to improve human well-being can have negative effects. An example is 'smart-watches' (wearable computing devices), which can measure biometrics yielding information about one's sleep quality and energy levels throughout the day. They can be helpful to encourage people to avoid driving and prioritize rest when overtired, but overly relying on such metrics may lead people to become disconnected from their body's inbuilt feedback systems, and can unnecessarily raise anxiety in people who have physiological needs that differ from the population mean (Roomkham et al., 2018; Trabelsi et al., 2023). Some technologies like smartphones have changed how we spend much of our time, and thus changed the way our brains function and grow (e.g. screen habits in children affect their cognition, Guellai et al. 2022). Artists shape and reflect society's culture and values, and can stimulate valuable reflection on society's direction (e.g, the British television series 'Black Mirror', which explored dystopian scenarios concerning our relationship with technology, Blanco-Herrero and Rodríguez-Contreras 2019). Cognitive neuroscience could be seen as a mediating factor between technological change and potential futures. By measuring and understanding naturalistic human behaviour in all its complexity, we can provide knowledge on which to base individual and societal decisions, and to shape technology that is better suited to human needs. While interdisciplinary work offers many opportunities to combine the best of several disciplines into something greater than any single discipline can achieve, differences in expectations for goals, timelines and products, and differences in teamwork and communication styles, can create friction and inefficiencies. In the next section, we discuss some of the potential issues and suggest how to avoid them.

Goals, timelines and products

Engineers vs. cognitive scientists

Engineering is a very fast-moving discipline. The usual workflow starts with an idea and a set of requirements, which are transformed into a model. The model is studied and then implemented in a concrete application which is tested and, if intended for human use, validated through a user study (Kotonya and Sommerville, 1998). Finally, once results demonstrate that it is a meaningful contribution, the work is published, and the tool, product or procedure is released. Usually, the goal is a device or a procedure to achieve a specific objective, with given performance metrics. In other words, the job ends when one can show that the product meets the design requirements.

In cognitive neuroscience, a truth about reality is sought, and the process is incomplete until researchers can be reasonably sure they have answered their question. A lot of time is invested in designing the experiment before setting up the equipment and tasks. The next step is to check that everything is working properly and that preliminary data demonstrate sensitivity to the relevant factors. Finally, the 'real' dataset can be collected. Afterwards, analysis, statistics, and interpretation of the results are still needed before



	Engineering	Cognitive Neuroscience	Arts
Main outcomes	- devices, processes, and procedures	- scientific knowledge	- dissemination of knowledge, ideas and attitudes - entertainment
Strengths	- analytical thinking - formalization - problem-solving - troubleshooting - optimization	- definition/operationalization of concepts - human study design - data collection - analysis, statistics and interpretation	- interpersonal communication - understanding, elicitiing and expressing emotions - encouraging reflection

Figure 2: Schematic of strengths, main outcomes and interactions between disciplines. An appreciation of collaborators' training background, value to interdisciplinary collaborations, and their expectations as regards a successful outcome can maximize efficiency and harmony. Whilst not a focus of this work, arts-engineering relationships are illustrated for completeness.

sharing the work in its final state, usually in the form of a research paper.

In general, tool validation and proof-of-concept testing might be the final steps for engineers, whereas in cognitive neuroscience, they are only the first steps. A human study to confirm a device or procedure is working is a necessary step, but one that does not further the scientist's goal of better understanding the human brain and behaviour. The differences in objectives can cause timeline mismatches in joint projects, for example when the scientists are waiting to start using a tool that is still in development phases. Research and development processes in engineering can proceed unpredictably.

A difficulty in Case Study 1 was that the cognitive neuroscientists could only start their main element, a study using humans, once the prototype device was in a stable, tested and functional state - yet unavoidable delays such as in procuring parts due to global shortages meant that the human studies were also delayed. The two groups' work was therefore sequential rather than parallel, at least in the first cycle; subsequently, the cognitive neuroscientists can use the tool while the engineers develop new versions with more advanced features.

In Case Study 2, awaiting a final implementation of the robotic system before doing human studies would cause the same sequential bottleneck as described above. To avoid this potential problem, we instead defined open questions that are critical to eventual uses, and which can be addressed in parallel. For example, to advance work in measuring robotic operators, we must learn how to reliably measure human workload across different tasks. By using a standard simple task for working memory (N-back task; Urrestilla and St-Onge, 2020) and a more complex, multisensory task (a hearing-in-noise perception task; Coffey et al., 2019), we can evaluate the ability of machine-learning classifiers trained on physiological signals (similar to Albuquerque et al., 2020) to generalize across tasks. Results from this investigation are interesting both as input for the joint project, and separately in auditory cognitive neuroscience (in which we are investigating the role of workload in hearing-in-noise contexts).

Artists vs. cognitive scientists

Theatre practitioners often perform only a few times for a specific audience. This may involve a lot of preparation for a few ephemeral performances, during which successful communication of ideas and emotions to and with the audience (and perhaps critical review) is the measure of success. The work is complete after a production run or show and there is usually limited follow-up activity. The performance or exhibition is the ultimate goal - the art piece must be coherent and follow the creator(s) vision on the exhibition opening or theatre premiere.

Although there are exceptions (e.g., when multiple people's responses are recorded to a single performance; Dikker et al., 2021, 2019), in cognitive neuroscience studies, most data are collected by repeating the experiment on many individuals to obtain a sufficiently large sample size for adequate statistical power, which can take months (or years). To maintain control over extraneous variables, the iterations and thus audience or performer experience must be as similar as possible - stability of the participants' experiences are therefore a more important goal than, say, having the greatest possible audience response. As in engineering collaborations, a large proportion of the work of cognitive scientists is incomplete as the last study participant is measured; analytic and interpretation steps can take a long time.

Although theatre colleagues highly value face-to-face interaction, it is logistically prohibitive to set up an event like a theatre performance for each subject. This problem can be partly overcome by compromise; most experiences can be somewhat simplified and automated, while the artists can help ensure that elements that are key to their experiences are retained. For example, in Case Study 3, participants had to first learn and practice the theatre technique used in the study ('headphones verbatim'), a practice that would normally take place face-to-face. To save time, we were able to do this in groups by videoconference, such that participants could still be instructed by and interact with the theatre experts. We retained in-person warm-up and cool-down exercises from theatre practice, which researchers, actors and participants did together to help establish the context, a trusting environment, and a sense of common purpose.

Three-way interactions

Although we focus on two-way collaborations between cognitive scientists and other disciplines in the present work, three-way collaborations (and two-way collaborations that focus on engineering and the arts, see Figure 2) are also possible. We discuss these briefly to illustrate further extensions to interdisciplinarity in a wider context.

One of the engineers in our group (St-Onge) works regularly with performing and visual artists. In these collaborations, the artists often choose themes that explore and can challenge the direction of rapid technological development and its effects on society. Because intelligent systems and in particular robotics can interact and co-operate with humans, the engineers are also interested to learn from artists and from the public, for example, about how robots can detect social attitudes and express information in ways that are more intuitive to humans (St-Onge et al., 2019c). As their creative process evolves, artists' requirements frequently change and exceed the original design specifications. This process of 'co-creation', in which people from different backgrounds and expertise make creative outputs, is most often conceptualized in industrial contexts as a means of co-opting customer competences to add product value (Durugbo and Pawar, 2014). In a research and development context, co-creating artistic works challenges the engineers to greater innovation, which can lead to theoretical and methodological advances in engineering applications.

By strengthening our interdiscplinary networks and our appreciation for colleagues' skillsets, our work is further inspired and facilitated. For example, a recent performance explored how complex emergent behaviour can come about via many basic units (robots) following simple rules, and interacting with external elements (objects and the audience). A cognitive science observer cannot help but note that the field of robotics is embarking on a fundamental open problem in cognitive neuroscience - that of how the brain's billions of neurons and trillions of synapses produce an incredible range of cortical configurations and behaviours in a flexible manner (Chialvo, 2010). In the future, this problem might benefit from the tools, insights and models of robotics engineering. On a more directly practical level, Case Study 3 was primarily a collaboration between arts and cognitive neuroscience, but in reality, considerable engineering support from Beltrame's team went into making it possible to stream and coordinate data collection within a theatre performance-like context.

Overall, the challenges encountered in three-way and artist-engineer interactions are similar in kind though perhaps more exaggerated as compared with the two-way interactions described above. In the next sections, we outline areas of concern and specific recommendations.

Teamwork and communication

Areas of concern

Having common goals and the right expertise on the team is no guarantee of success or efficiency. Differences in expectations for teamwork and communication styles may negatively affect a collaboration. The very idea of teamwork and when communication is needed may differ between disciplines. For example, a lot of engineering work can be done by splitting the work into packages and tasks to be completed by individuals, which are integrated upon completion. By contrast, cognitive scientists might favour whole-team discussions during study planning phases, such that they can draw from everyone's experience working with human participants as they think through the design choices. Discussions often lead to new questions requiring literature review and additional discussion, until consensus is reached. These steps might seem inefficient to the engineers, yet are of fundamental importance to cognitive scientists, who might instead feel that engineers are inclined to rush to collect data that might prove conceptually flawed. In addition, cognitive scientists adopting new technology (which is not commercially-supported) may feel in a vulnerable and dependent position when it does not work as expected, for example if a technical problem arises partway through a project that causes data loss (as occurred in Case Study 1); this can be stressful for both parties as the issue had to be rapidly solved. The engineers may not be prepared to act as on-call technical support for the scientists' experiments, particularly if they consider their work completed upon prototype delivery.

Shared knowledge, objectives, and norms of practice can mean that disciplines develop sub-cultures with unique communication styles. Additionally, people with certain personality types may self-select into specific fields. For example, we might expect a higher proportion of outgoing, expressive personalities in a group of performing artists than in a group of cognitive scientists. In Case Study 3, some tension arose between cognitive neuroscience trainees and theatre trainees because of different communication expectations. The actors seemed more attuned to interpersonal interactions within the team, and expected greater attention to relationships and playful interactions; the cognitive neuroscientists instead were focused on being efficient, well-organized and direct (the problem was easily resolved by discussion, but could have been avoided). Indeed, a significant challenge in this project was that colleagues from the two fields had quite limited understanding of each other's purposes, tools, approaches, and even vocabulary at the outset. These fields are more different than cognitive science and computer engineering, in which there is some common basis; practitioners in both fields take for granted the notion of collecting data on a representative sample and conducting inferential statistics to evaluate hypotheses.

Consequently, the theatre project required a considerable amount of communication to arrive at an experimental paradigm that was experimentally-controlled reasonably well, yet retained elements that were important for respecting and replicating key elements of theatre practice. For example, the actors preferred to move freely during performances, some feeling that it was distracting or stressful to be still; yet the best way to collect clean physiological signals is by immobilizing participants with a chin rest and fixation point in a laboratory environment (a seated compromise with minimal movement but without constraints was reached). The theatre experts felt that it was important to include warm up and cool-down exercises before and after the experiment, as they would in theatre practice; these were standardized by the researchers and incorporated into the protocol.

By contrast, cognitive neuroscientists may instead seem to engineers to express ideas in ways that are insufficiently formal and too vague. At the beginning of the study described in Case Study 1, the engineers expected a much more precise, numeric definition of requirements (this problem is common in industry and has led to the notion of 'requirements engineering'; Kotonya and Sommerville, 1998). As a consequence, team members had to absorb considerable amounts of technical detail from their counterparts' field to have effective conversations. Staying in close communication ensures that knowledge from cognitive neuroscience is incorporated into the engineers' user interface design, and that knowledge advances in human measurement can then be directly applied once the robotics research and development process is completed. Another interdisciplinary challenge in this work is that there are often three rather than two parties. In addition to the engineers designing systems, technology users (e.g., astronauts and speleologists) also provide practical constraints associated with the mission (e.g., limited sample size, equipment that is robust and does not interrupt or cause safety concerns during concurrent activities). The users' involvement is important as they ultimately define the value of the equipment or procedure for their activities. In the speleological experiment, we worked closely with experts to make sure it was possible to record signals in that extreme environment, and that our methods would be comfortable, safe, and accepted by the expedition team.

Finally, when cognitive neuroscience or artist technology users report a problem to engineers for assistance, they may inadvertently cause frustration by not describing it in sufficient technical detail for the engineers to start a troubleshooting process.

Recommendations

Project leaders from both sides of a collaboration should be aware that forming and maintaining a cohesive interdisciplinary collaboration requires additional time and care. To set the stage for effective collaboration, they can create a project plan that explicitly considers differences in goals, timelines, and products of each discipline, reduces dependencies between interdisciplinary project objectives, and communicates the plan (and any changes) clearly to all team members.

Interdisciplinary teams that are co-developing tools (as in Case Study 1) should be cognizant of the different expected outcomes for each group, and consider the readiness level of the technology and the dependencies between project milestones during planning phases, with adequate buffer for unexpected delays. Splitting and interleaving or running engineering and cognitive science objectives in parallel (Case Study 2) while limiting direct dependencies can improve the overall efficiency of joint projects. Close communication between teams during development will help to avoid unfortunate surprises, for example a design decision that limits scientific functionality.

Team formation can be aided by planning kick-off meetings or workshops where each group presents their approach and face-to-face meetings to establish working relationships among team members. Understanding the scope of background knowledge in the collaboration's disciplines can also be beneficial for team members. Sample degree program syllabuses can provide insights into counterparts' background knowledge, especially for disciplines with professional accreditation and shared course bases, such as engineering and psychology. For example, we realized in Case Study 1 that engineers do not typically have access to training in statistical methods that are foundational in human and biological science programs.

To keep the team working well together over time, regular meetings and joint communication channels are essential. Leaders should ensure that critical information is clearly conveyed across disciplinary boundaries. In Case Study 1, Coffey and Beltrame's labs have a shared text-based communication channel. All team members have access to the exchanges, but cognitive neuroscientists may find it challenging to follow detailed technical discussions, and engineers may not always closely follow developments in human testing. The principal investigators from each team keep track of progress in their area and make sure that problems, progress, and next steps are communicated clearly to the other side at an appropriate level of detail. Students or postdoctoral fellows who are explicitly training to become cross-disciplinary experts can serve as 'translators'. Interdisciplinary work forces team members to develop empathy and patience, making it a valuable educational experience for trainees.

Recruiting, training, and supporting highly qualified personnel

Areas of concern

The ideal candidate for an interdisciplinary collaboration would possess a strong foundation in both disciplines. However, there are limited training opportunities at the bachelor and graduate levels for truly interdisciplinary education. Those who attempt to pursue expertise in two disciplines might not receive the same level of recognition as their peers specializing in a single discipline, leading to fewer opportunities for them. As a result, it is more common to recruit students with a strong background in one discipline and, at the very least, an interest in and appreciation for the other which can be developed. In that case, additional training in the secondary discipline should be considered. For instance, trainees with a background in cognitive neuroscience may discover that they need to dedicate additional effort to develop their computer skills. Trainees, supervisors, and granting agencies must recognize that trainees who are cross-training may have reduced output while they catch up on other disciplines that are needed for their interdisciplinary work.

Recommendations

If funding agencies are genuinely committed to fostering interdisciplinary trainees (as they appear to be in their push for interdisciplinary research), it becomes imperative to acknowledge and address the unique challenges they face. Creating a distinct category for funding interdisciplinary candidates, one that is not solely centred around academic publications, but takes into account other forms of engagement, can be a step in the right direction. Principal Investigators (PIs) play a pivotal role in this endeavour: they can support trainees through side projects that encourage interdisciplinary exploration. By considering atypical career paths and facilitating the development of a variety of skills, PIs can create an environment conducive to the growth of well-rounded, interdisciplinary researchers who can bridge the gaps between various fields and contribute significantly to transformative research and innovation.

As these trainees graduate and pursue careers in different sectors (academia, industry, government, or public-related jobs), they bring a unique perspective and a broad range of expertise. Their presence can foster innovation and, more importantly, enable new cross-sector collaborations that address complex challenges at the intersection of science, art, and technology for the benefit of society.

Dissemination

Areas of concern

It can be difficult to find a venue to effectively share interdisciplinary work. For example, Case Study 3, a project which is motivated by better understanding actors' emotional experiences and which uses the tools of cognitive neuroscience, might be seen as a strange curiosity both at a meeting of actors and at a meeting about brain function. While there is a growing interest in how insights gained by neuroscience can inform the art of acting and acting techniques (Kemp, 2012), it may not generate much interest, interaction, and visibility at either venue. There is indeed not yet enough work in this area to warrant a separate, focused meeting. The work risks falling through the cracks.

Sharing interdisciplinary knowledge via written reports can also be complicated. In Case Study 1, we had thought that the best way of sharing the result of the technological development and its validation would be to write an article for a general science journal with a roughly even content split; each group wrote their sections and we worked together to reduce field-specific jargon and integrate the style and ideas for a smooth reading experience. We thought that readers from both disciplines would benefit from a general introduction and conclusions, and then readers from each discipline could be directed to detailed sections where more domain specific details could be found (e.g., methods). However, reviewers of research articles are chosen for their expertise in a single discipline, and might come to opposite recommendations; reviewers from each discipline found the advances and data from the opposing discipline to be less interesting and asked that it be removed (we compromised by moving most of the detailed material to supplementary methods, but the result may be unsatisfying to both groups; Valenchon et al., 2022).

There is also the challenge of understanding what the norms are in a field one is not trained in. Readers and reviewers have strong, field-dependent expectations about style, format, and technical approaches. For example, in engineering publications it is common to have a separate section following the introduction called 'state of the art' which describes current technology level; this is unexpected for cognitive neuroscience readers. In engineering, it is the accepted practice to publish a short conference paper sometimes followed by a longer journal article on the same research (both are considered full publications). In cognitive neuroscience, conference presentations are used to show work at a more preliminary stage for discussion, and are rarely accompanied by a full-text article. They are not given much weight in an individuals' publication record, and written publications with significant overlap are discouraged as any duplication could be considered self-plagiarism.

Recommendations

Without an effective dissemination strategy, knowledge 'products' are not useful and will have little impact on society (Leahey, 2018). Furthermore, if publications are not well-positioned and receive no attention, trainees will have trouble advancing their careers and PIs will have difficulty obtaining support for continued work (Campbell, 2005; Walklate and Richards, 2012). Interdisciplinary researchers should consider where work can be presented during project creation, to establish roles and responsibilities and because tweaks to the presentation can help increase the impact of the research (De Bakker et al., 2019). Viable approaches include targeting general and interdisciplinary journals and attempting to write for both audiences (as we did for Case Study 1), splitting the work such that each of multiple contributions is more targeted to one specialization with smaller contributions from the other (as in Case studies 2 and 3), and seeking or creating structures that gather together similar topic combinations (e.g., special issues or focused symposia).

Conclusions

Cognitive scientists specialize in measuring and understanding human behaviour, including the effects and causes of subjective experience and cognitive performance. Ultimately, we aim to translate knowledge generated by cognitive neuroscience outside of the laboratory to the benefit of society, and to enrich our understanding of the brain and of ourselves through studying cognition in naturalistic environments and during complex, high-performance operations. As in other human endeavours such as in business, healthcare, and global challenges, interdisciplinary collaboration will likely play an increasingly important role in achieving these goals. By bringing together the perspectives of artists, engineers, and cognitive scientists, we can foster technological development that puts humans at the centre and prioritizes responsible innovation. Many challenges are inherent to interdisciplinary collaborations and cannot be avoided, but they can at least be mitigated when anticipated. We hope that by sharing our experience on communication, expectations about goals and timelines, interdisciplinary training and dissemination, we make some progress towards a 'convergence science' that is tailored to cognitive neuroscience.

CRediT author statement

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