How to foster challenging interdisciplinary collaborations: can philosophy support neuroscientists?

Running head or short title: Philosophers can foster interdisciplinarity

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Keywords: biological neuroscience, computational neuroscience, interdisciplinarity, philosophy, reductionism, translational neuroscience.

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Acknowledgements: The authors would like to thank the Région Nouvelle Aquitaine and the PhilInBioMed network for support of this project.

# Abstract

New conceptual and technological developments bring neuroscientists closer to other disciplines, and to other fields in neuroscience with different traditions, despite having overlapping interests. While some neuroscientists may underrate the potential benefits of successful interdisciplinary collaborations, some may be unaware of the typical difficulties of such collaborations or not trained in skills that render them fruitful. Here, we illustrate how interdisciplinary interactions have long been part of neuroscience, although they are often challenging, because neuroscientists may be confronted with concepts, assumptions, and interpretative horizons that differ from their own. This can lead to misunderstanding and little mutual appreciation. Using the historical development of brain imaging techniques, we distinguish different types of interdisciplinary interactions and illustrate some of their benefits. In addition, we present challenges at the interface between traditional laboratory-type approaches and those of clinical or computational neuroscience, and of ecological field experiments. To address these, we invite neuroscientists to consider philosophers as collaboration partners with complementary expertise, which includes special consideration of language use, underlying assumptions and proficiency in conceptual analysis. This expertise can be used by neuroscientists to increase their understanding and to address some difficulties in interdisciplinary interactions more effectively. The benefits of these interactions can be expected to outweigh some challenges in the dialogue with philosophers. Importantly, neuroscientists can choose between reading philosophical literature, participating in joint events with philosophers, and integrating philosophers into neuroscience projects. This may allow neuroscientists to explore unforeseen possibilities to improve or initiate collaborations with scientists from other fields and disciplines.

Abbreviations: *fMRI* functional magnetic resonance imaging; *BOLD* blood oxygen level-dependent, *STED* stimulated emission depletion (microscopy), *ANN* artificial neuronal networks

# Introduction

In the last few decades, important technological and conceptual advances have changed the landscape of neuroscience and extended the range of research questions that can be addressed. This also progressively increased the methodological diversity of neuroscience, with novel observation and intervention techniques contributing to rapid progress in many research fields, such as cellular and molecular neuroscience or cognitive neuroscience. As a result, today´s neuroscience includes different research traditions that can be traced back to the historical developments of scientific investigations of the nervous system. Besides the initial fields of neuroanatomy, neurophysiology, neuroendocrinology and neuropharmacology, and the medical disciplines of neurology and psychiatry, additional fields[[1]](#footnote-1) such as behavioral neuroscience, parts of the cognitive sciences, computational and theoretical neuroscience, and some more are now combined under the umbrella term “neurosciences”[[2]](#footnote-2) (Cowan et al., 2000;Stahnisch, 2016), which is accepted as an independent discipline and encompasses many fields. Thus, in their daily practice neuroscientists can be confronted with collaboration partners educated primarily in other traditions, with different research questions, basic assumptions, methodologies, and interpretative horizons or frameworks. Moreover, neuroscientists are also concerned with interdisciplinarity as broad research questions require collaboration with other scientific disciplines such as physics, psychology or computer science. However, the concrete experience of scientists with interdisciplinary projects seems to show that the expected and advertised advantages of such collaborations are often not achieved. Indeed, misunderstandings, difficult communication and a perceived limited genuine collaboration render interdisciplinary projects challenging (Waldman, 2013;Hall et al., 2018;MacLeod, 2018;Gohar et al., 2019;Mazzocchi, 2019). Moreover, the meaning of “interdisciplinarity” is often ambiguous and it is frequently met with resistance despite incentives to position one’s work as “interdisciplinary” (Ledford, 2015). At the interface between different fields of neuroscience problems may arise that are similar to those encountered between neuroscience and other disciplines, when fields are considered by their social interactions alone instead of well-defined academic structures (Lélé and Norgaard, 2005;Contreras Kallens et al., 2022). Such pitfalls are often underestimated by academic institutions or funding agencies that promote or support interdisciplinary projects without providing accompanying support.

In this manuscript, we highlight that interdisciplinarity in different forms (section-2) has been an inherent part of neuroscience and has contributed to its advances. However, despite successful interdisciplinary collaborations many challenges occur as well. Drawing from general descriptions and concrete examples from neuroscience, we indicate several factors that contribute to these complications (section-3). In practice, low awareness of typical problems and insufficient training in capabilities beneficial for interdisciplinary exchange may play a widely underestimated role. Next, we suggest that, because of their complementary skill repertoire, philosophers would be well-suited to support neuroscientists in challenging interdisciplinary collaborations (section-4). Importantly, different modes of interaction with philosophers are available through which neuroscientists can initiate and pursue this exchange according to their needs (section-5).

# Different forms of interdisciplinarity in neuroscience

## Definition of interdisciplinarity

Without a doubt, many neuroscientists already interact with scientists from other fields or disciplines, for example, when they interact with members of the statistics department to take advice, to find the most appropriate approach, or to implement new kinds of data analysis. In such cases, the neuroscientist will typically accept the domain-specific ‘authority’ of the statistician and the proposed solution regarding the analysis. So, in this case, there is a rather unidirectional exchange between neuroscientist and statistician. Sometimes, neuroscientists also participate in teams composed of scientists from different fields or disciplines, who jointly address research questions for which no discipline alone has sufficient expertise and, in which, all parties benefit from mutual exchange and interactions. Only this type of interactive collaboration is considered ‘interdisciplinary’ here. Even though, the underlying concept of interdisciplinarity is often not made clear (Gozzer, 1982;Choi and Pak, 2006;Alvargonzalez, 2011), the supposed relevance and expected benefits of interdisciplinarity are widely advertised (Jacobs and Frickel, 2009;MacLeod et al., 2019). Much has already been written about interdisciplinarity in general (for summary, see (Huutoniemi et al., 2010)), but in this article we restrict the use of the term “interdisciplinary” to projects or collaborative activities that involve scientists from different fields or disciplines that include neuroscientists and exceed mere service-providing. These collaborations may be driven by a common interest in a technological application or research question, or by a better understanding of a complex phenomenon through mutual exchange between fields or disciplines, as has been the case for the cognitive sciences (Choi and Pak, 2006;Mazzocchi, 2019). Accordingly, in interdisciplinary approaches as we understand them, scientists from different disciplines or fields join their domain-specific skills and knowledge to advance the shared understanding of a phenomenon by interaction and exchange, which, in turn, can reveal misconceptions and biases in respective disciplinary perspectives.In this sense *interdisciplinary* approaches differ from *multidisciplinary* and *transdisciplinary*[[3]](#footnote-3) approaches. Thus, the distinguishing properties of interdisciplinarity are prolonged and active interactions, along with complementarity of approaches.

## Different forms of interdisciplinarity

To illustrate that neuroscience has long been interdisciplinary, we take the establishment of brain imaging techniques for neuroscientific research as a historical example. These methods are well-established tools today, but their implementation in neuroscience required important technical and conceptual developments. Moreover, these examples illustrate different types of interdisciplinary interactions and can thus help neuroscientists to recognize similar examples in their own research fields.

### Methodological interdisciplinarity

The development of magnetic resonance imaging (MRI) from nuclear magnetic resonance was, in hindsight, a masterpiece of cooperation between physicists, chemists, engineers, and physicians to repurpose and further develop a technique that originated in analytical chemistry for advanced medical diagnosis and research (Leach, 2004;Wehrli, 2004). Following general distinctions of different forms of interdisciplinarity suggested before (Huutoniemi et al., 2010) this type of collaboration can be described as *methodological interdisciplinarity*,because different methods or approaches “are combined in a novel, integrated manner,” rather than being merely juxtaposed (Huutoniemi et al., 2010, p. 84; Table 1). The aim of this form of interdisciplinarity can be to progressively develop methods for novel purposes (e.g., for medical diagnosis and research) and typically requires interactions between developers and users for optimal implementation. Methods converting nuclear magnetic resonance signals into images of the structural properties of a brain in a living organism were initially validated by comparison to *postmortem* anatomical planes. A subset of these techniques has been labelled functional magnetic resonance imaging (fMRI) as the signals reflect localized changes in brain physiology during neuronal activation (Raichle, 2009). This subsequent application of MRI to study the functioning brain was also made possible by a joint effort between engineers, radiologists, and cognitive psychologists (Bandettini et al., 1992;Kwong et al., 1992). Thus, methodological interdisciplinarity develops novel methods, which allow for the exploration of domains in previously impossible ways (e.g., having a means to assess activation of brain structures in a non-invasive way in humans) and may initiate new collaborations.

### Empirical interdisciplinarity

The technological progress obtained with fMRI techniques allowed measurements with reasonable temporal and spatial resolution for the study of brain correlates of cognitive and other processes (physiological, pharmacological and diagnostic uses (Matthews et al., 2006)) and fostered interactions between neuroscientists and cognitive scientists. In these interactions, the research question (e.g., correlations between brain activity and mental processes) is jointly approached by several disciplines, and progress in understanding is achieved at the interface requiring different contributions. This kind of interdisciplinarity is close in spirit to *empirical interdisciplinarity* in which different types of empirical findings are integrated to gain more insight into how phenomena observed in different fields can be linked ((Huutoniemi et al., 2010), Table 1). The expected benefit of empirical interdisciplinarity is gained from integrating and relating different types of factors (e.g., mental processes and increased activity of brain areas during a task). This should allow a broader consideration of the phenomenon of interest and increased understanding.

### Conceptual interdisciplinarity

Finally, the advancement in imaging techniques was accompanied by progressive changes in conceptual frameworks presupposed in the application of advanced fMRI techniques for specific scientific and medical purposes. This form of interdisciplinarity has been termed *conceptual*or*theoretical interdisciplinarity* and can include a comparison of concepts, models, or theories across fields ((Huutoniemi et al., 2010), Table 1). This can result in mutual correction, cross-fertilization or the establishment of new relationships between fields and new research strategies. Conceptual changes are often essential for employing new technologies and to repurpose applications established for one research question to other types of scientific investigations[[4]](#footnote-4). The reinterpretation of spontaneous low-frequency fluctuations in the absence of explicit tasks or stimuli as ‘background activity’ instead of ‘noise’ led to the systematic investigation of functional connectivity of parts of the brain by resting state fMRI (Wei et al., 2024). Thus, another benefit of conceptual interdisciplinarity is to challenge or modify categories, concepts or notions, or the relationships between those, which can then be explored experimentally.

Altogether, these different forms of interdisciplinarity focus on developing novel methods, a multi-perspectival view on a phenomenon, or the integration of different types of concepts, theories or explanations, even though a clear-cut separation between the types is often not possible.

### Joint interdisciplinary contributions to the study of human cognitive abilities by fMRI

To underpin our claim that interdisciplinary interactions may give rise to interesting novel questions or challenge even well-established methods or concepts, we describe concrete contributions relative to the use of fMRI as a tool to study the relation between brain activities and complex cognitive functions. When scientists realized the possibility to observe brain activity by fMRI while cognitive functions are being exerted, this inspired some changes in the research questions being investigated, putting more emphasis on “thinking, consciousness, and social cognition” and complementing the cognitive-centered perspective by a brain-centered one (Sutterer and Tranel, 2017). However, neuroscientists, like other experimental scientists, have often been attracted by the power of new tools and have tended to mostly see their advantages. In the early phase, less effort has been dedicated to the critical interpretation of the relation between the newly implemented output (e.g., local glucose or oxygen accumulation in brain tissue) used as a proxy for or read-out of the processes of interest (such as high-level cognition). However, the high expectations were also confronted with reservations and resistance, and challenges often originated from different background assumptions regarding the concept of how the brain functions and what kind of properties of the brain correlate with properties of cognitive functions (2.3.1) and whether and how the output of fMRI measurements reflect and relate to the underlying processes in the brain (2.3.2). The chosen examples thus illustrate that in the development of brain imaging techniques in general, and fMRI in particular, external critiques had their fair share in challenging strategies and concepts (Thagard, 2009), and interdisciplinary exchange allowed the identification of potential technical or conceptual problems, which, in turn, resulted in some clarifications and improvements of the method.

#### The relative importance of regional and global brain activity to specific abilities

Most fMRI approaches seem to assume that some regions of the brain are particularly important for a cognitive ability of interest and thus show strong changes of regional brain activity when the exertion of the capability is compared to a control condition. The underlying hypothesis is that capacities and cognitive functions are exerted by specific and restricted brain regions can be traced back to the turn of the 19th century, and the results of fMRI studies can be interpreted to support such *brain localizationist theories*. However, another tradition, known as *distributionist or connectionist* theories[[5]](#footnote-5), appealing to holism and equipotentiationism, emphasizes the relevance of widespread activation across the brain or, more recently, of far-reaching brain-networks during the performance of certain cognitive functions. Scientists in the latter tradition have argued that the conclusion that a brain structure is sufficient for a function cannot be drawn from temporal correlations between some cognitive processes and local increases in brain activity, but that such claims require invoking other types of findings (such as the functional consequences of lesions of that brain structure) (Sutterer and Tranel, 2017;Duffau, 2018). Interestingly, this debate in neuroscience was accompanied by a similar debate in philosophy with some parties postulating that the mind itself is modular, at least for some functions (e.g., (Fodor, 1983)). This appeared to further support brain localizationist theories from another, more conceptual, point of view. In a later phase, the idea that widespread activation of brain networks across the entire brain are highly relevant (‘*connectionists*’) for the performance of certain cognitive functions has gained some traction (Sutterer and Tranel, 2017;Duffau, 2018;Arshavsky, 2023). Concurrently, the philosophers’ debate on the mind´s modularity has changed as well and has criticized the modularity hypothesis either for being not convincing in case of some individual abilities (Sutton and Schier, 2014) or for epistemological reasons because it cannot sufficiently explain the convergence of different cognitive modules (Mason et al., 2008). Nonetheless, the localizationist theory is still considered relevant for studying language processing, face recognition or spatial navigation (see for example Zhang et al., 2024). This mutual influence of neuroscience and philosophy can be considered conceptual interdisciplinarity, because the results of one discipline (or field) affected the interpretation in another discipline or field.

#### Interpretation of results obtained by in vivo brain images

The second example is the relationship between fMRI-signals obtained by blood oxygen level-dependent (BOLD) nuclear magnetic resonance measurements and images of brain activity, which were generated as output of functional brain imaging experiments. The interpretation of the relation between neuronal activity and fMRI signal has not been straightforward to establish. An early misconception of a direct relation was based on the relationship between neural activity and either increased cerebral blood flow or glucose binding (critically discussed already in (Roy and Sherrington, 1890) and in (Sokoloff, 1977)). However, a better understanding of the relation between raw data and their interpretation was made possible by contributions in which methodological interdisciplinarity played an important role. Over time it has indeed become clear that changes in the oxygen consumption reflected by the BOLD signal cannot be used as a direct proxy for neuronal activity, because no linear relationship exists with electrophysiological activity and because the course of temporal and spatial changes of the BOLD signal does not always reflect electrophysiological processes alone (Lauritzen, 2005;Logothetis, 2008;Theriault et al., 2023). These systematic investigations revealed that the simple hypothesis underlying BOLD brain imaging needed to be nuanced and gave rise to the development of approaches to distinguish neuronal from vascular effects (Tsvetanov et al., 2021), and to statistical and conceptual improvements (Elliott et al., 2021) of measurements. Moreover, it became increasingly clear how difficult it is to establish whether an fMRI signal reflects function-specific processing or neuromodulatory changes (Gusnard et al., 2001;Szameitat et al., 2011), and how challenging it is to relate an fMRI signal to excitatory or inhibitory processes (Logothetis, 2008). These developments changed the application of fMRI measurements in cognitive science, in which fMRI signals have traditionally been interpreted as representing activation of cognitive task-specific or stimulus-specific neuronal processing. Thus, the early assumption of a direct relation between fMRI signals, brain activity and cognitive processes had to be modified, and more advanced approaches had to be used. On the one hand, this was an important methodical refinement but on the other hand it also changed the underlying assumption of these measurements, which, in turn, changed the interpretation of results.

#### Consequences for fMRI measurements

These lines of critique led some even to doubt that real progress has been made by this type of fMRI measurements. Indeed, some authors argued that the complexity of the relationships between mind and brain is too complex to be addressed by formulating questions from a single perspective (Cooper and Shallice, 2010). However, from another perspective, these challenges were advantageous in that they urged neuroscientists and cognitive scientists (i) to specify the questions more clearly so that they can be addressed by fMRI in the context of cognitive neuroscience (Coltheart, 2013;Mather et al., 2013) and (ii) to use fMRI more specifically to discriminate between alternative cognitive models by formulating hypotheses about the expected outcomes (Price, 2018). Moreover, these discussions led to an increased attention to the corroboration of results by inclusion of additional controls (e.g., comparison with patients with an informative set of deficiencies), by comparison with results of other methods, or the investigation of large datasets obtained by multi-center collaborations for which multi-variant pattern analyses and machine learning approaches can be used (Poldrack et al., 2017;Elliott et al., 2021;Peelen and Downing, 2023). However, these findings also changed the perspective for fMRI analysis of patients, because a conceptual analysis for the interaction between symptoms (cognitive deficits), structural lesions (brain damage) and functional changes (cognitive impairment) (Price, 2018) has been suggested that is driven by the idea of triangulation.In summary, the establishment and further developments in brain imaging techniques have been slow and long-lasting processes and have only been possible due to the contribution of many scientists from diverse disciplinary origins and research fields (Bandettini, 2012).

In a similar manner, the development of other important methods of neuroscience and their establishment took advantage from interdisciplinary collaborations as well, such as the developments of electrophysiology and patch-clamp recordings (Verkhratsky and Parpura, 2014). Some of these developments were more multi-disciplinary whereas others turned out to be truly interdisciplinary.[[6]](#footnote-6) Altogether, interdisciplinarity can aid the spread of better methods between scientific communities (Smaldino and O’Connor, 2022), but interdisciplinary projects can also provide a more complete picture of “real-world situations”, because the diverging perspectives of the different disciplines or fields can complement each other (Brignol et al., 2024).

# Difficulties in interdisciplinary and inter-field exchange as an obstacle for information transfer and the establishment of practical collaborations in today´s neuroscience

## Interdisciplinary and inter-field exchange in current neuroscience

Today´s neuroscience is widely interconnected with other disciplines, rendering awareness of the advantages and challenges of interdisciplinary collaborations highly relevant. For example, many neuroscientists may have collaboration partners belonging to other disciplines with different background assumptions, approaches or interpretations. While neuroscience shares many assumptions with other disciplines of the natural sciences (e.g., physics and chemistry) and still has similarities with the social sciences regarding empirical approaches (e.g., interventions or systematic investigation of cohorts), its closeness to some disciplines of the humanities (e.g., philosophy) appears rather low. Thus, it is not surprising that methodological and empirical collaborations between neuroscientists and natural scientists occur more regularly. Some of these were irreplaceable for the invention of novel technologies that are highly important for neuroscience today, such as stimulated emission depletion (STED) microscopy (Muller et al., 2012;Vicidomini et al., 2018), single cell sequencing (Boulgakov et al., 2020;Piwecka et al., 2023), modern brain imaging techniques (Philiastides et al., 2021;Vizioli et al., 2021;Stangl et al., 2023), advanced multi-electrode recordings (Chen et al., 2021;Urai et al., 2022), or advanced mass-spectrometric analyses (e.g., of the lipid compositions of brain parts) (Xu and Li, 2019;Yoon et al., 2022). Nonetheless, for many practically working neuroscientists the relative ease of such collaborations and the benefits of interdisciplinarity described above may be less intuitive, because (i) in their own collaborations or when establishing a new technology in the lab, their interactions with scientists from other disciplines often remain a sort of service-providing in which the benefits of long-standing and mutually fertilizing interactions cannot be accessed (e.g., mutual corrections by complementary approaches), and; (ii) the gap to distantly related disciplines from the social sciences or the humanities often appears so wide that scholars from the respective fields are reluctant to enter discussions, exchange or active collaborations with representatives of these disciplines, even though this may reveal interesting aspects by informing about relevant context (e.g., in social neuroscience) or by adding further factors to already complex research questions (e.g., in the relation between the scientific investigation of volition and discussions about the ‘free will’). Moreover, (iii) neuroscientists may be confronted with interdisciplinarity-type collaborations even within their own discipline, because their interaction with scientists from other fields of neuroscience with different educational backgrounds and diverging research traditions may suffer from complications similar to those of interdisciplinary collaboration[[7]](#footnote-7). Partially, this can be retraced to the roots of today´s neuroscience in very different disciplines that were formally unified under the umbrella term neuroscience (cf. section-2) without being able to fully remove the barriers between these rather diverse fields. Partially, the differences can be explained by the complexity of some research questions, which require collaboration in large and heterogeneous teams including scientists from various other disciplines. The first type can be considered as occasional interdisciplinary collaboration between fields of the same discipline, whereas the second type can occur even between individuals of the same team on a more continuous basis. However, here we use the term *inter-field type of interdisciplinarity* to refer to both types of interactions, because also the latter involves interlocutors that work as neuroscientists despite their origin in other disciplines. Thus, even collaborations between neuroscientists may be complicated by different backgrounds and thus share problems usually attributed to interdisciplinary collaborations and that might be more challenging than expected. Some of these complications and the occasional experience of dissatisfaction have been described recently (Wudarczyk et al., 2021;Brignol et al., 2024). To demonstrate some of these problems more specifically, we first summarize typical general problems observed in interdisciplinary collaborations from the literature (3.2), then illustrate underlying differences between scientific fields of neuroscience that may render inter-field collaborations difficult from a practice-oriented perspective (3.3)[[8]](#footnote-8), and, finally, expand to and emphasize some additional aspects that may be relevant, or even critical, for interdisciplinary and inter-field collaborations (3.4).

## Problems observed in interdisciplinary collaborations

### Social separations of research traditions can exacerbate differences in underlying assumptions

The beneficial effects of a cooperation between scientists from different disciplines or research fields are often explained by the complementarity of approaches, which compensate to some extent the limitations and biases of individual fields or disciplines (Darden and Maull, 1977). However, such complementing approaches are often embedded in different research traditions of disciplines or fields from which they often cannot easily be disentangled. Supposedly, this can be an obstacle for interdisciplinary collaborations, because these traditions typically correspond to different and partially isolated scientific communities. However, these communities often also have a diverging understanding of what constitutes a meaningful framework, which assumptions are justified, and why some experimental approaches are considered more reliable than others. Moreover, this separation is often reflected by specific terms and phrases used in the respective research tradition. The term ‘epistemic cultures’ has been coined for such differences between groups in science (Knorr-Cetina, 1999), and differences between ‘epistemic cultures’ may contribute to a separation of fields and may cause problems in cooperation. Accordingly, individual neuroscientists and their collaboration partners may actually belong to rather independent communities with different thinking traditions and styles although they consider themselves as part of the same broad community.

### General problems of interdisciplinarity also relevant for neuroscience

Various practical problems for interdisciplinary exchange and collaborations in the life-sciences have already been described in the literature, some of which can also be linked to the separation of groups of scientists into disciplines and fields, and thus allow a first orientation for interdisciplinary and inter-field collaborations. Lélé and Norgaard list the following challenges for interdisciplinary collaborations (Lélé and Norgaard, 2005) (to which we add illustrative examples from neuroscience between brackets): (1) differences in values that are – often unrecognized – associated with a particular study, such as the choice of questions, theoretical positions, variables and the styles of research (e.g., fundamental understanding vs real-world application; using fMRI either for studying brain processes or applying them for the diagnosis of patients; a preference either for the direct study of human individuals or for more indirect, but possibly more invasive investigations in model organisms), (2) differences in theories or explanatory models including their underlying assumptions when studying the same phenomenon (e.g.,different interpretations of similarities and differences between brains and computers; prioritizing biological or social contributions in the explanation of psychiatric disorders; different estimations of the explanatory power of animal experiments for psychiatric disorders between communities of investigators), (3) epistemic differences including differences in methods, notions of adequate proof and other fundamental assumptions (e.g.,in neuroscience different estimations of value and reliability of correlations, which are usually more accepted in disciplines and fields in which interventions are less possible; preference for direct and detailed investigations of individual patients or for large scale comparison together with statistical analyses), and (4) difficulties that are external to science and find their origin the way in which society interacts with and organizes academia and that affect the production of interdisciplinary research (e.g., emphasizing one discipline such as neuroscience with the ‘decade of the brain’ (1990) or important funding such as for the ‘Blue brain project’ (2005) can have detrimental side-effects on interdisciplinary projects by fostering a feeling of unjust preferential treatment or of superiority).

## Practical examples from complicated inter-field relations in neuroscience

But how do the problems described here in general terms apply to neuroscientists in daily practice, when they are involved either in interdisciplinary or inter-field collaborations? To illustrate this, we consider different fields of neuroscience, between which interaction, communication and collaboration can be challenging, and feelings of superiority of members of one field regarding another field occur frequently.

### Challenging relations between fields applying laboratory-type investigations and those performing ecological field experiments or developing clinical applications

Even among empirically oriented fields of neuroscience such as laboratory-type neuroscience, clinical neuroscience, and the neuroscience of wild-living animals, surprisingly different assumptions, methodological preferences and interpretative horizons seem to exist. This complicates exchange and collaboration, even though the complementary expertise of scientists working in these fields can be expected to compensate for the one-sidedness of each approach. Without a doubt, working in a ‘wet lab’ context is often linked to a special framework with assumptions and priorities that are not always easy to reconcile with those of studies emphasizing the importance of a complex ecological environment and clinical practice. To illustrate this, we first describe characteristics of laboratory-type experiments and the two other, more ecologically oriented, fields of investigation to next pinpoint important differences[[9]](#footnote-9). Thus, these fields can illustrate some of the above-mentioned differences for neuroscience. Keeping these in mind, some possible collaborative interactions are sketched.

#### Laboratory-type investigations to reduce various sources of variability

At the turn of the 21st century, mainstream neuroscience widely studied cultured cells (e.g., neurons), brain slices and model organisms under well-defined conditions and with standardized tests. This type of approach, which has been termed “biological neuroscience” (Gold and Stoljar, 1999), aims at identifying parts, activities and mechanisms (e.g., proteins, their enzymatic activities or processes involving many of these entities) to obtain a better understanding of their role in brain function and behavior. The power of this approach is related to reducing complexity by investigating parts (cells and brain slices), minimizing inter-individual differences by lowering the influence of genetic background and environmental variability, and obtaining higher reproducibility by tightly controlling experimental conditions. Altogether, this approach can thus reach a high level of internal validity or of the validity of a causal claim in a controlled setting. These approaches can be summarized by the reduction of complexity and variability, and the undeniable success of such ‘reductionistic approaches’ has occasionally led to its equation with the scientific method (Glasgow, 2008). However, these approaches primarily reflect a set of underlying assumptions, preferences and interpretations, which have obvious strengths but sometimes overestimate the generalizability of research findings obtained in tightly-controlled settings for subpopulations living under different conditions (Campbell, 1957;Jimenez-Buedo and Miller, 2010;Dirnagl et al., 2022). Consequently, a certain disregard of, and lower appreciation for, other types of investigations may prevail in these fields despite the merits of the latter. Thus, fields favoring this ‘reductionistic approach’ research style may be considered typical for a group with its own framework (e.g., concept or methods), which demarcates it from other disciplines or fields and, hence, resemble an epistemic culture (Knorr-Cetina, 1999).

#### Ecological field experiments

Other approaches emphasize the importance of studying an organism’s behavior and related brain processes in the environmental context in which an animal lives to investigate specific research questions (e.g., in ecological field experiments (Costa and Sinervo, 2004;Kihlstrom, 2021)). This approach focusses on the modulatory role of complex and ecologically-relevant environments, and on the correspondence between ecologically-relevant phenotypes and the living conditions of the species. For example, the physiological response to hypoxia can be investigated by studying specific human populations, such as Tibetans, living in high altitude for millennia, or animal species, such as elephant seals that dive deep and can thus be expected to have developed evolutionary adaptations to the hypoxic conditions upon exploring parts of their natural habitat (Murray et al., 2018;Piot et al., 2023). Obviously, such approaches differ from studies of the detrimental effects of hypoxia on mammalian brains in laboratory environments, which are often investigated in rodents by triggering hypoxia artificially to mimic disease states (e.g., arterial occlusion or stroke models), by inactivating specific genes of interest or by the application of certain drugs. Ecological field experiments allow for a better understanding of mechanisms that may have evolved in species or populations of a given niche and can obviously not be explored in model organisms in laboratory settings. The study of physiologically effective protection systems in organisms living in their natural environments adds very different, but highly valuable information. Such ethological approaches cannot take advantage of the typical tools used in ‘reductionistic approaches’ and thus, they are often limited by the variability of different study objects and the lack of internal controls. However, scientists of this tradition often weigh these limitations less, and tend to have a low appreciation for studies that were performed outside the normal habitat of the species of interest. Although these approaches address very different aspects, the establishment of joint research projects could implement different forms of interdisciplinarity. On the one hand, drawing on the experience from traditional laboratory research, new tools to investigate free-living animals (e.g., elephant seals (Kendall-Bar et al., 2022) or monkeys (Testard et al., 2024)) could be developed as a form of methodological interdisciplinarity. On the other hand, the results obtained in animals living in their natural habitat, which may be too extreme for other organisms to live in, might compensate for the limitations of studies in lab-raised model organisms (Piot et al., 2023) and foster empirical interdisciplinarity. However, a lack of mutual respect that cannot acknowledge the respective strengths of different approaches will favor a disregard of relevant results due to a focus on the possible shortcomings of the other disciplines.

#### Clinical neuroscience

Experiments in translational neuroscience aim at a better understanding of pathophysiological processes and at improving patient care. However, in this research domain the generalizability of results obtained in model organisms or relatively small groups of patients need not hold up under conditions encountered in the general population (Fernandez, 2013;Kympouropoulos, 2023). Moreover, findings considered relevant for humans in general may come into tension with the application to individual patients and the priority of their successful therapy may question advice exclusively based on ‘reductionistic approaches’ that aim at reducing inter-individual variability. In this respect, beneficial therapeutic options for a relatively small (sub)group of patients can be considered real and valuable progress (see for example (Villéga et al., 2024)). Such observations may depend on specific environmental conditions, a specific subpopulation of patients, or a combination of different factors that may be difficult to come across in clinical trials or laboratory conditions. Hence, it may be harder for such approaches to meet the gold standards of a randomized clinical trial or a meta-analysis of evidence-based medicine, although in some domains of clinical neuroscience (e.g., psychiatry) this problem is occasionally addressed by stratification methods (Hampel et al., 2023). Nonetheless, considering and incorporating such clinical observations into laboratory practice and corroborating such results in model organisms should have the potential to further improve ‘bench-to-bedside’ research by also transferring information from ‘bedside-to-bench’ (van der Laan and Boenink, 2015). This type of interdisciplinarity could excel in empirical interdisciplinarity between clinicians (e.g., neurologists or psychiatrists) and experimental neuroscientists but could also give rise to theoretical interdisciplinarity. However, combining the strengths of both approaches can be a demanding task due to the different goals of the respective traditions, particularly when differences in background assumptions are not acknowledged. Altogether, these examples illustrate that these fields have rather different perspectives and that interdisciplinarity should come with the acknowledgement that different disciplines and fields are all well-justified to use different methods. Thus, even an inter-field collaboration between these empirical traditions may benefit from a mediator that bridges different perspectives.

### Complicated relations between experimental and computational neuroscience

When studying complex processes of the brain and their progression over time, the methods of experimentally working and computational neuroscientists are obviously very different. In addition, underlying assumptions may also differ more than often realized by the scientists of these fields. As a consequence, these differences can render collaborations sometimes difficult in practice, hinder interactions and contribute to keeping parts of these fields separated. Some of the differences are more specifically related to underlying assumptions about how processing of information in the brain occurs. Parts of these assumptions are based on perceived and postulated similarities and dissimilarities between brains and computers[[10]](#footnote-10), which have already been amply discussed in the development of computational neuroscience. Other differences relate to the interpretation of the results of analyses and the status of mathematical solutions and computational algorithms. The latter can either be considered as: (i) summarizing descriptions of phenomena of interest that were observed by experiments studying the brain (e.g., changing activity patterns over time), (ii) as inherent properties of brain activities that can be described independently of their material basis (e.g., at the level of complex firing patterns and their mutual interdependencies without considering properties of the material basis), or (iii) as independent mathematical equivalents of physical processes that are underlying empirically observed phenomena. Thus, these interpretations can be considered as different possible answers to the question of whether or not the results of such approaches are ‘real representations’ of the signaling mechanisms in the brain. It is important to note that parts of the interaction between empirical and computational neuroscientists are truly interdisciplinary, because the latter has attracted many scientists from other disciplines, such as physics, mathematics or engineering. However, other parts are interdisciplinary-type interactions between members of different fields of neuroscience. These fields typically have different historical origins and the roots of the field of computational neuroscience in computer science may still be influential. Indeed, the latter has its own traditions, which reflect the development of a field that grew independently, and these traditions may still be influential today in some of the underlying concepts that are at work. To illustrate the complexity in the relation between empirically working and computational neuroscientists, we first describe the roots of computational neuroscience (3.3.2.1) and then describe some typical types of application of computation in today´s neuroscience (3.3.2.2).

#### ***Multiple interpretations of the relationship between brain activity and computation***

Many decades ago, Warren McCulloch claimed that relations in the central nervous system “can be treated by means of propositional logic” (McCulloch and Pitts, 1943, p. 115) and that “brains are a very ill-understood variety of computing machines” (McCulloch, 1965, p. 163). However, in the early 1980s, David Marr concluded that electrophysiological recordings along with microanatomy cannot sufficiently explain perception and cognition and proposed that full explanations require separate analyses at the computational level and the neuronal implementation level (Marr, 1982). Based on new insights provided by neuronal network models some authors subsequently proposed that “explain[ing] how electrical and chemical signals are used in the brain to represent and process information” may be within reach of computational neuroscience (Sejnowski et al., 1988, p. 1299). Indeed, computational neuroscience is expected to play an essential role in simulating and predicting the behavior of nervous systems when “experimental systems are [judged] too complex to allow collection of all the data” (Stern and Travis, 2006, p. 75). But unlike the use of computational approaches in other domains of science, “computational neuroscientists often assume that nervous systems … perform computations and process information” (Piccinini and Shagrir, 2014). Moreover, the idea that the brain can be compared to a computer has led to the metaphor of brains as computers and the invitation to model brain function through computation (Miłkowski, 2018). Since the beginning of the 21st century, with the increased power of computational analyses, predictions and reconstructions, the underlying assumption of ’computational neuroscience´ has broadened from a metaphor with heuristic potential, to the name of an entire field of neuroscience that uses computer models to perform analyses and develop novel concepts about neuronal functions and circuits (Miłkowski, 2018;Brette, 2022). Nevertheless, some authors continue to be of the opinion that we should view computation metaphorically and study brains using computation as a model or as a different level of abstraction (Ballard, 2015, Chirimuuta, 2024, Ch. 4). However, in these views the idea that neuronal circuits can be recapitulated in computational models is often based on the assumption that neurons display all-or-nothing binary activities which determine network activity (‘computation’). But this assumption has to be nuanced in view of the regulatory role of neurons secreting neuromodulators and neuropeptides, which ‘fine-tune’ neuronal networks by modulating synaptic and neuronal function (LeBeau et al., 2005;van den Pol, 2012). These findings seem to question one of the underlying assumptions of neural network modeling approaches but also illustrate that some background assumptions of computational neuroscience may differ from the working models of biological neuroscientists.

Computational neuroscientists often have different training than biological neuroscientists. Thus, their concepts of the brain and its functions may also be different. This renders the understanding of the actual study object (e.g., the underlying algorithm or its material realization) and the exchange about what is represented by computational models or what are the most promising approaches difficult between these fields. Hence, the interactions between computational and biological neuroscientists are an obvious field of interest when considering interdisciplinarity (e.g., by the ability to learn and improve from the results obtained by the other field). However, in practice the exchange can be complicated, not only by domain-specific assumptions and terminological differences, but also by a low awareness of differences in the conceptual framework in which a specific approach is performed.

#### Different perspectives on the power of computational tools in neuroscience

From a pragmatic perspective the potential of computational approaches is often used as a heuristic or strategic tool to extract information from complex and poorly understood data sets, without the need to understand the underlying biological mechanisms in detail. A relatively simple illustration of the latter, albeit not limited to neuroscience, is the prediction of functional elements in nucleic acid or protein sequences that act as binding sites for proteins (e.g., transcription factors) or nucleic acids (e.g., microRNAs) or harboring specific information (e.g. targeting signals (Kunze, 2018)). In these cases, key properties of such motifs are extracted from compilations of known binding sites, but the actual rules for such motif binding may remain obscure. Similarly, complex data sets obtained by multi-electrode brain recordings can be analyzed to identify several single unit activities, considered as individual neurons, and based on this, characteristic and repetitive pattern of neuronal activity can be described, for example as oscillations. In addition, computational approaches can be used to analyze large data sets and extract proxies of causal relations (Kanwisher et al., 2023), which can be interpreted as potential targets of interventionist approaches using optogenetic or chemogenetic methods (Jennings and Stuber, 2014;Buzsaki et al., 2015). These causal inferences are often motivated by a scarcity of interventional data and partially driven by the conviction that mathematical models can reveal critical variables and relations (Weichwald, 2021). Accordingly, computational neuroscientists sometimes treat algorithms, mathematical processes, and results of computational predictions as if they are implemented in neurons or brain circuits, which is often not easy to reconcile with the framework of biological neuroscience (Kanwisher et al., 2023). However, it often remains unclear, whether modelling presumes just a similarity in input-output relations, which can be mimicked by a computational algorithm, or whether the structural properties of neurons, networks and brains actually allow the realization of processes, which are very similar to computational processing and take place in the brain (Kanwisher et al., 2023). Accordingly, some approaches try to extract characteristic input-output relations from data sets obtained in living animals and employ mathematical models to narrow down these relations, whereas others reconstruct and mimic structural properties of neurons or brain areas and identify mathematical representations or algorithmic elements that are sufficient to generate the pattern. Still others use established models for some properties of neurons or brain regions to predict the expected input-output relations and to test the relevance of such structural or functional properties, which cannot be addressed empirically (e.g., reconstruction of dendritic information processing (Poirazi and Papoutsi, 2020)).

In these cases, consistent outcomes of computational predictions along with *post-hoc* experimental corroboration can be thought to represent another form of empirical interdisciplinarity. The spread of these approaches and the interpretation of recent computational analyses of results obtained by advanced functional MRI techniques have re-ignited a debate on the relation between correlation and causation in computational inferences and on criteria for the evaluation of their results (Moreau and Dumas, 2021;Novembre and Iannetti, 2021). In these debates some contributions from outside the community may lead to a new form of theoretical interdisciplinarity in the future (Dijkstra and de Bruin, 2016;Reid et al., 2019;Chirimuuta, 2021). In the context of interdisciplinary projects, a lack of clarity about the extent to which algorithms correspond to real processes in the brain or are ‘merely’ mathematical representations of the material processes in the brain may render collaboration with biological neuroscientists challenging. Particularly, diverging assessments of the specific contribution of computational analyses and the type of information that can be obtained by such approaches affects the evaluation of the explanatory power of results (Teufel and Fletcher, 2016;Chirimuuta, 2018;Chirimuuta, 2021). These examples show how concepts can be understood differently and how they can be mobilized in different stages of a research project (conceptualization, experimentation, interpretation). This illustrates that the interaction between experimental and computational neuroscientists or with scientists of different backgrounds can be more complicated than expected and, thus, it should not be too surprising that these groups often remain separated. In addition, it stresses that the reading and interpretation of publications from the other discipline or field requires caution.

Altogether, these examples illustrate that inter-field interactions in neuroscience can be negatively affected by very similar phenomena, factors or processes as interactions between disciplines (cf. 3.2.1). Moreover, they make it plausible that a lack of awareness for underlying differences can effectively foster misunderstandings, a low awareness for the need for complementary approaches, and an underestimation of potential benefits of inter-field exchange or collaborations.

### Practical problems in interdisciplinary and inter-field collaborations and critical elements

Problems in interdisciplinarity and inter-field collaborations, such as those illustrated above, can be considered as by-products of a low awareness of differences in the underlying conceptual frameworks of different disciplines or fields, and of the difficulties of communication between individuals and groups with diverging backgrounds. Conceptually, these problems become detrimental for collaborations, when they (i) complicate communication and hinder information transfer (e.g., because of conceptual or terminological differences); (ii) hinder scientific collaboration because of different conceptual frameworks, which include underlying assumptions, methodology, and interpretative horizon; (iii) make a commonly accepted interpretation of the phenomenon of interest difficult, because perspectives and preferences are too different, or (iv) jeopardize equal partnership, because some scientists have littler appreciation for the methods and approaches of the other fields or disciplines, or consider the understanding or perspective of their own field or discipline more valid, reliable or justified than those of others. The latter can cause a lack of respect, but also implicit or even subconscious feelings of superiority for their own discipline or field and assign the others a subordinate or service providing role in a joint project. This has been described by the philosopher Nancy Nersessian based on a study on the interaction between modelers and experimental scientists as follows: “… what we witnessed in the labs we investigated … is that modelers have little understanding of the possibilitiesand constraints of experimental practices, and experimentalists have little understanding of the nature and requirements of model-building— and, I would add, neither has an understanding of the epistemic norms and values of the other.”(Nersessian, 2022, p. 306). A little further, she insists that “… often each side positions the other as a service provider rather than a collaborator” and that “[t]he experimentalist requests the modeler to *“model my data,”* and in turn the modeler, as we frequently heard, *“order[s] my experiments” from the*m” (Nersessian, 2022, p. 309). Similar problems might appear between clinicians and computational neuroscientists and have been described between the fields of computational neuroscience and systems biology, which apparently have so little in common that the fields have been described as separated in spite of some superficial similarity (De Schutter, 2008).

We want to propose that some of the problems rendering such collaborations infrequent and complicated have common underlying causes, which are favored by insufficient education and training of neuroscientists in approaches not directly related to their scientific practice. This encompasses low appreciation for reflections on and specification of the underlying assumptions of research programs, methods and interpretations, and for questions of language and concepts that underlie communications. It has been suggested previously that some of the problems in interdisciplinary exchange are related to differences between fields and the way in which their scientific activities are structured around conceptual and methodological frameworks (MacLeod, 2018). However, in many cases, field-specific practices remain opaque to outsiders (Brown et al., 2015;MacLeod, 2018), which also can include members of other fields (e.g., between different fields of neuroscience), and would require explanations and specification. Researchers will most likely benefit from increased awareness of the existence of different research traditions and the ability to communicate, both, the advantages and limitations of their own methods. This requires that specific assumptions, preferences, and limitations of one’s field are made explicit in order to prevent perspectival narrowing. Better understanding of disciplinary characteristics should raise mutual respect for different traditions without fearing to compromise the value of one´s own research and facilitate the exploration of joint research strategies to integrate the specific advantages of different research fields.

Another challenge is to deal with *terminological differences or ambiguities* between disciplines or fields and to work out differences in the meaning of some terms and the underlying concepts. Sometimes different terms seem to be used for a similar construct or notion with nuances (e.g., the distinction between “state anxiety” and “trait anxiety” and between fear and anxiety, made in psychology, are widely disregarded in many fields of neuroscience using animal behavioral experiments) whereas in other cases scientists employ the same term for different things (e.g., biologically-oriented or computational neuroscientists using the term ‘model’ may refer to a computational program, a graphical illustration or an organism (Frigg and Hartmann Stephan, 2020)). But it can also happen that when the same words are being used in two or more fields or disciplines, they may either have overlapping but somewhat different meanings for the parties involved (for example ’stress‘, ‘coding’ or ‘computation’) or even refer to different concepts such as that of ‘causality’, which has presumably different meanings in biological neuroscience, computational neuroscience and cognitive neuroscience, respectively (Rolls, 2021;Barack et al., 2022). In the latter case, causality can either mean a concept about reality that is used to explain experimental results, a basic assumption necessary for a certain type of analysis (methodological, e.g., Granger causality) or a mechanistic assumption, for which the mathematical correlate is to be identified (cf. Lélé and Norgaard, 2005 point 3) above). The ‘language problem’ has been mentioned in the context of the Human Brain Project (Aicardi and Mahfoud, 2024) but, not surprisingly, problems of common language use have also been acknowledged in the exchange with other disciplines such as neuroscience and law (Buckholtz and Faigman, 2014) and neuroscience and psychoanalysis (Scalzone, 2005). Thus, being aware of and becoming more sensitive in practice to differences in terminology and the concepts underlying specific terms should be a first step in promoting interdisciplinarity. Moreover, clarification and the development of a common language and the reference to shared concepts can be expected to facilitate interdisciplinary exchange and collaborations involving neuroscientists. At first glance, achieving a sort of *lingua franca* or ‘mediation language’ that is valid in all neuroscientific fields and widely shared with other disciplines may appear necessary. However, concepts and terms are often so intertwined with the methodology and theory of fields or disciplines that finding common ground might require accepting the use of more loose or vague concepts. Accordingly, the corresponding terms may even appear inherently imprecise (e.g., ’self‘, ’stress,’ and ’computation’, because they play various heuristic roles in different fields). Indeed, some concepts may even seem to have little common measures between disciplines (e.g., resilience between ecology and the social sciences) and become close to incommensurable in interdisciplinary projects and render them very difficult to use in such projects (for example (Annerstedt, 2010;Olsson et al., 2015)). However, these ambiguities can also occasionally be utilized intentionally as loose or vague concepts at the boundaries of fields or disciplines and serve as so-called boundary objects (Star, 1989a;Star, 1989b), which facilitate converging developments as common long-term research strategies between different communities (Löwy, 1992;Neto, 2020). In this context, it might be more helpful to consider a widely accepted *lingua franca* as some kind of parlance with common core vocabulary reflecting shared ideas that support communication between different communities, similar to the situation in ancient Mediterranean communities, or as a “creole” (Galison, 1997;Thagard, 2009;Mazzocchi, 2019). Finally, it may be important to understand that some arguments may be well-established in one discipline or field but less accepted in another, which may render their evaluation less clear in the context of interdisciplinary-type exchange.

In summary, it would be helpful to recognize the diversity of scientific cultures in different disciplines and fields, which render mutual understanding between these research traditions difficult and interdisciplinary collaborations a challenging task. Some of these problems can be addressed by an increased awareness of the problem and more time devoted to further clarifications alone, but others might require support from outside by individuals with complementary training.[[11]](#footnote-11)

# Interactions with philosophers to improve interdisciplinarity in neuroscience

The description so far may convince the reader that interdisciplinary or inter-field exchange and collaborations are often more challenging than anticipated and can complicate otherwise exciting and promising projects. Thus, identifying causes for misunderstandings, addressing critical points or searching for common ground in joint projects may be essential to promote, foster or improve these types of collaboration. In such challenging situations, progress may require that all partners collaborate to recognize and highlight differences in the orientation of research questions, the underlying assumptions, or the interpretative horizon. Moreover, they may need to specify their own conceptual framework and explain terms and concepts that are well-established within their own community. However, in academic education the awareness of the need to develop these skills is surprisingly low, given the frequent posting of institutional incentives for interdisciplinary projects. To address this problem, neuroscientists could either try to acquire the necessary skills themselves or to obtain support of experts with proficiency in these skills. Here, we want to propose that part of the typical skill set of philosophers could support neuroscientists in their interdisciplinary activities, because they are complementary to those of neuroscientists. In the course of their training, philosophers usually acquire a set of skills, a ‘philosophers´ toolbox’, which should enable them to facilitate interdisciplinary or inter-field collaborations involving neuroscientists. While basal philosophical education should render *philosophers* proficient in the analysis of arguments and concepts, *philosophers of science* bring to the table a large body of information about scientific practice, concepts and argumentations. This understanding has been developed by observation of scientific practice, text analyses, and exchange or collaborative interactions with scientists (Kaiser et al., 2014), which may even encompass the long-term participation in scientific projects for which the term ‘philosophy *in* science’ has been coined (Pradeu et al., 2024). Moreover, some subfields of philosophy of science such as the philosophy of biology and the philosophy of neuroscience offer a wide variety of contributions, which address similar topics as neuroscientists but from a different perspective and under different assumptions. Of note, and in contrast, the field of *neurophilosophy* is concerned more with the implementation and application of neuroscientific understanding to questions traditionally linked to philosophy (Churchland, 2007). This illustrates that the interaction between neuroscientists and philosophers is interdisciplinary by itself.

Some expected benefits of philosophical contributions on the use of language and underlying concepts in neuroscience have been described by Max Bennett and Peter Hacker in their book “Philosophical foundations of neuroscience”. The authors argue that the “province [of analytic philosophy] is not the domain of empirical truth or falsehood, but the domain of sense and nonsense” and that “[t]he solution proposed may be philosophical clarifications on the one hand, or empirical discoveries and scientific theories, on the other.” (Bennett and Hacker, 2005, p. 399). Thus, the contribution of philosophers to neuroscience does not necessarily depend on their scientific excellence but rather on expertise to clarify or work out problems and ambiguities. Becoming aware of terminological inaccuracies and conceptual inconsistencies can be enlightening for neuroscientists and can help improving their own thinking and, hence, foster interdisciplinary activities. Moreover, philosophers of science can also contribute to the identification of sources and potentials for and limitations of interdisciplinary collaborations because of their long-standing study of scientific practice (MacLeod, 2018). Indeed, when some neuroscientists and philosophers realized that there were problems in the use of the terms, such as ’representation’”, ‘code’ and ’computation’, they identified different forms of use and suggested clarification while acknowledging input from philosophy (Barack and Krakauer, 2021;Baker et al., 2022).

Finally, philosophers cannot only address concepts and topics that are concomitantly very close to scientific practice, but also reflect on important ‘meta-scientific’ or epistemic questions (e.g., causality, scientific realism, or the relation between regularity and necessity). This approach has a long-standing tradition in the general philosophy of science but has recently been applied to neuroscience (Bassett et al., 2018;Chirimuuta, 2018;Chirimuuta, 2021;Ross and Bassett, 2024). Accordingly, a request for better clarification of different causal concepts at work in neuroscience has recently been stated in an article co-authored by a philosopher and a neuroscientist (Ross and Bassett, 2024). The authors argue that the understanding of causality in general is naturally relevant for neuroscience and for the interpretation of results obtained, but differs across fields of neuroscience (e.g., computational neuroscience, pharmacology & therapy of neuroscientific diseases, neurobiology, or psychiatric diseases) (Barack et al., 2022). Indeed, distinct concepts of causality can be related to different fields and these assumptions have been addressed for computational neuroscience regarding the understanding of the mind (Rolls, 2021), the role it plays in explanations at the interface between computational and empirical neuroscience (Chirimuuta, 2018), or the difference between causation and correlation to problematize this dichotomy (Moreau and Dumas, 2021). Bringing forth perceived differences in the strength of causal claims, the understanding of the relation between observation and testing of hypotheses, and in the burden of proof should help to reduce communication barriers in joint scientific endeavors. In general, interdisciplinary research projects can be expected to benefit greatly from time dedicated to discussing the use of terms and the establishment of assumptions. Consequently, it is important to develop new tools to facilitate exchange between individuals or groups and to foster the implementation of interdisciplinary collaborations (Nancarrow et al., 2013;O’Rourke and Crowley, 2013). Altogether, philosophers can contribute to some of the most critical aspects of interdisciplinary or inter-field collaborations that are underlying the problems described by Lele and Norgard and by our examples above.

# Different forms of collaboration of neuroscientists with philosophers

As described, in interdisciplinary collaborations problems are often linked to differences in assumptions, methods, and conceptual frameworks, which can be further exacerbated by a low awareness of the potentially detrimental consequences of unclear or only seemingly shared terminology. Intensifying the collaboration between neuroscientists and philosophers might, therefore, be a promising strategy to support various forms of interdisciplinary-type research. Because of their training in the analysis of problems of terminology and the rigor of argumentation, philosophers are in a privileged position to identify sources of misunderstanding between the collaborating fields and, hence, to support interdisciplinary activities (Kaiser et al., 2014;Laplane et al., 2019a). Moreover, philosophers have also addressed problems of interdisciplinary research themselves and emphasized the importance of conceptual clarification and rigorous argumentation to facilitate interdisciplinary dialogue (Hoffmann et al., 2013;Holbrook, 2013;O'Rourke and Crowley, 2013).

However, the collaboration between neuroscientists and philosophers is interdisciplinary in itself with different ways of approaching questions and argumentation, and thus this exchange can come with some of the problems discussed before. However, in philosophy the recent switch to a more practice-oriented philosophy of science (philosophy of science in practice; (Boumans and Leonelli, 2013)) has led to more reflection of philosophers on their role in exchange and participation in collaborations with scientists. An overview suggested to distinguish reflective approaches in philosophy of science from more collaborative ones, which require regular interactions between philosophers and scientists around a common problem (Kaiser et al., 2014). In the latter, the exchange is also in the interest of the philosophers, because they want to learn about processes in science and understand the phenomena better. In this context, the interactions between neuroscientists and philosophers can thus be beneficial for both sides and philosophers with this perspective might be particularly interesting interaction partners. However, neuroscientists must not forget that the interaction with philosophers is inherently interdisciplinary. Thus, neuroscientists may be confronted with different styles of argumentation and critique that appear less concrete or even picky and may reflect different academic cultures. Consequently, these interactions may benefit from personal acquaintance, long-standing interactions fostering trust and the continuous learning about the other’s language and thinking tradition (O'Rourke and Crowley, 2013) (famous pairs of philosophers and neuroscientist are John Bickle & Alcino Silva, Max Bennett & Peter Hacker, Carl Craver & Shayna Rosenbaum). However, these personal long-lasting interactions are not always possible. Nevertheless, neuroscientists can consider other forms of interactions with philosophers which differ in intensity and duration of interaction, to the extent of active practice in specific skills, and thus in the expected insights and effects on the interdisciplinary skills of neuroscientists[[12]](#footnote-12).

## Philosophy of science applied to neuroscience

This approach emphasizes the wealth of knowledge about scientific methods, approaches and concepts that has accumulated in philosophy of science and that is available to neuroscientists in the form of literature and qualified individuals (Fig. 1A). From the early 20th century and the positivism of the Vienna circle, philosophy of science has dealt with formalizing scientific methodology and establishing criteria, such as empirical confirmability, to distinguish meaningful scientific statements from metaphysical or non-scientific ones (Neurath et al., 1996). However, in its present-day form, philosophy of science often provides detailed analyses of scientific practice, and reflects on models and explanations used in knowledge acquisition in neuroscience, but from a philosophical point of view (Bechtel and Huang, 2022). This modern-day approach remains mainly in an external position of describing and commenting on scientific processes without attempting to intervene in or prescribe scientific practice (Kaiser et al., 2014) and thus differs from work by early 20th century philosophers of science who often tried to prescribe idealized forms of scientific investigations. Awareness of the internal workings of scientific research and different modes of knowledge production in general can help neuroscientists to recognize similar processes in their own interdisciplinary practice. Moreover, philosophers of science have reflected on various topics relevant for (neuro)scientific practice, some of which have been mentioned above, such as “models in science”, “causality” or “reductionism”. These contributions reflect on concepts fundamental to (neuro)science on which scientists can then build further. Neuroscientists can take advantage of this external general perspective to recognize and avoid typical types of errors made in the past and to respond to constructive criticism of their actual practice. Importantly, this type of information transfer between philosophers and neuroscientists regarding philosophy of science does not require direct exchange and can be achieved by the effort of the neuroscientist to read the existing literature in philosophy of science. For example, two recent papers published in high-impact factor journals that were written by neuroscientists contain many references to publications by philosophers of science, which the authors considered valuable (Rolls, 2021;Levenstein et al., 2023).

## Philosophy for neuroscientists

Another approach is to focus on the direct exchange between scientists and philosophers when they share an interest in a topic or a research question, and the latter present their points of view to the former on certain occasions (Fig. 1B). This can raise the interest of scientists for philosophical methods when they are applied directly to specific research questions. By this means, scientists become familiar with the thinking style(s), frameworks and methods philosophers utilize in practice. In addition, observing different approaches and comparing various tools should enable neuroscientists to become more aware of some of the characteristic hurdles to interdisciplinary practice. Such exchanges between neuroscientists and philosophers can occur in courses or interdisciplinary exchange events (for example through networking events at neuroscience conferences[[13]](#footnote-13)), in part because their expertise allows philosophers to mediate between scientists and the positions of philosophy of science reflecting on this practice (Kaiser et al., 2014). Moreover, philosophers can make some scientific assumptions and terms explicit, propose how they may be articulated better when they are used in different scientific disciplines or fields, and indicate standards for good scientific methods and theories (De Haro, 2020). For this purpose, philosophers need to “study the heuristic techniques that scientists use to explore, model and analyze complex systems” instead of starting with particular idealizations (Wimsatt, 2007, p. 8). Thus, a philosopher like Bill Wimsatt, who has been proposed to do “philosophy for science” (Griesemer, 2008; 2011), has also engaged in debates with neuroscientists. Such local and limited interaction processes do not require a constant investment of time and energy, but can provide a wealth of information in workshop-like events. This type of interaction may result in joint papers reflecting a personal interaction between neuroscientists and philosophers based on meetings at different levels (Barack et al., 2022;Ross and Bassett, 2024).

## Philosophy in neuroscience

Finally, scientists can benefit from direct participation of philosophers in their research projects (Fig. 1C). This approach includes philosophers structurally in long-term projects, in which they continuously participate and either make their own thematic contributions (e.g., theories or suggestions for experiments) that are directed to and can be used by scientists (Laplane et al., 2019b;Pradeu et al., 2021) or foster interdisciplinary interactions of neuroscientists with scientists from other fields (*cf*.4). In this context, getting to know each other progressively better can improve the mutual learning process and facilitate the acquisition of important interdisciplinary skills. Moreover, such research projects can be expected to benefit from the intellectual contributions of philosophers because the latter can broaden the perspective of neuroscientists and might even reveal aspects that were previously unnoticed by the internal perspective of the neuroscientific community. As such, it attempts to avoid a merely unilateral relationship between philosophy and the sciences (Kaiser et al., 2014;Pradeu et al., 2021). This can be mitigated either by publications written by philosophers for neuroscientists (Van Gelder, 1998;Thagard, 2009;Barwich, 2019) or by joint publications between neuroscientists and philosophers (Rosenbaum et al., 2016;Barwich, 2019;Mok et al., 2021;Bickle et al., 2022;Barwich and Severino, 2023).

Whereas the first approach (philosophy of science) primarily tries to extract relevant information from philosophical literature without necessarily exchanging with philosophers, the second approach (philosophy for neuroscientists) aims at taking advantage of occasionally organized interactions between scientists and philosophers and the third approach (philosophy in science) counts on a more long-term involvement of philosophers in neuroscientific practice. Neuroscientists may need to consider which format is best suited to expand their horizon or to address the problems of their current interdisciplinary research project. From the perspective of a neuroscientist interested in interdisciplinary research ‘philosophers *of* neuroscience’ have potentially interesting things to say, but these may be obscured by formulations (terms, phrases, or metaphors) not familiar to neuroscientists. However, efforts of neuroscientists to familiarize themselves with these traditions can be expected to pay off with exposure to and practice with the philosophy of science literature. Given that ‘philosophers *for* science’ share an interest with neuroscientists and take inspiration from their approaches, it should be easier for neuroscientists to engage in productive exchange with these philosophers. ‘Philosophy *in* neuroscience’ seems like a promising, but highly challenging, approach, as philosophers take scientific problems as a starting point to mobilize their own ‘toolkit’ to propose improvements and alternative solutions to neuroscientists. In the long run, this approach may be highly rewarding but requires more continuous collaboration and mutual understanding. Some neuroscientists may have philosophical training or philosophical inclinations, or may already be engaged in exchanges with philosophers, but for others this particular opportunity may be of help to develop specific skills and thus foster interdisciplinarity. Obviously, all forms of collaborative integration of philosophers in neuroscience teaching and research should ensure equal partnership and, thus, occur in a way in which neither party claims a dominant role nor requests to fully master the other party’s discipline.

# Outlook

Neuroscience is inherently interdisciplinary, and this characteristic can be expected to last, because it enables researchers to address complex study objects at different levels using new methods. Thus, a lack of such interdisciplinarity would generate disciplinary or field-specific islands of knowledge with very limited interconnections, and, hence, limit the power of corroboration by different methods to increase the robustness of analysis (Wimsatt, 2007). Neuroscientists, along with their national and international scientific societies, as well as educational programs promoting and calling for interdisciplinarity should be aware of and acknowledge the opportunities, but also of the difficulties of interdisciplinary research endeavors. These institutions should help neuroscientists to develop the proper skills not only to submit interdisciplinary projects, but also to effectively conduct them. Personal experience of fruitful and satisfying interdisciplinary interactions is obviously important (Brown et al., 2015) but to provide neuroscientists with skills to collaborate better and more effectively is also essential.

We are convinced that the progress in neuroscientific understanding will increasingly require the ability to work interdisciplinarily. However, such endeavors require properly trained neuroscientists as well as mediators to facilitate such interactions. Philosophers are certainly not the solution for all problems, but their specific sets of skills and methods can make them valuable partners in these endeavors. Increased interactions with philosophers could be achieved by re-introducing or fostering philosophy of science courses in neuroscience *curricula* and specific funding opportunities for interdisciplinary sessions in both neuroscience and philosophy conferences.

# Figure and table legends

**Table 1: Different forms of interdisciplinarity** with a short description (column 2) and illustrated using the development of brain imaging techniques as an example (column 3). Please note that the list of scientists participating in these different forms of interdisciplinarity is only suggestive and linked to the example (column 4).

**Figure 1**: **Different opportunities for neuroscientists to engage in interactions with philosophers**: (A) Philosophy *of* science applied to neuroscience: scientists can take advantage of the available ideas provided by philosophers of science, who observe, conceptualize and reflect on scientific practice to develop descriptions, criteria, and suggestions for improvement. (B) Philosophy *for* neuroscientists: neuroscientists and philosophers sharing interests in similar broad research questions can exchange and discuss topics of interest at interdisciplinary events or in special issues of neuroscientific journals, to experience the benefits of the complementary skills of these two disciplines. (C) Philosophy *in* neuroscience: neuroscientists involve philosophers directly in their specific research projects, in which philosophers can clarify assumptions, discuss concepts and develop novel frameworks. Dashed arrows indicate activities of the neuroscientist (reading in A, discussing in B and involving in projects C), grey borders highlight communities in B & C.

Conflict of interest statement: The authors have no conflict of interest to declare.

Author contribution: **MK**: Conceptualization (joint lead), Writing – Original Draft Preparation, Writing – Review & Editing **CB**: Writing – Review & Editing; **JB**: Writing – Review & Editing; **MD**: Writing – Review & Editing; **FG**: Writing – Review & Editing; **LP**: Writing – Review & Editing; **TP**: Writing – Review & Editing; **ISJ**: Writing – Review & Editing; **JPK**: Conceptualization (joint lead), Writing – Original Draft Preparation, Writing – Review & Editing

Data sharing statement: Given that this is an opinion/review paper, no data were generated as part of the present manuscript.

# References

Aicardi, C., and Mahfoud, T. (2024). Formal and Informal Infrastructures of Collaboration in the Human Brain Project. *Science Technology & Human Values* 49**,** 403-430.

Alvargonzalez, D. (2011). Multidisciplinarity, Interdisciplinarity, Transdisciplinarity, and the Sciences. *International Studies in the Philosophy of Science* 25**,** 387-403.

Amemiya, S., Takao, H., and Abe, O. (2024). Resting-State fMRI: Emerging Concepts for Future Clinical Application. *J Magn Reson Imaging* 59**,** 1135-1148.

Annerstedt, M. (2010). Transdisciplinarity as an inference technique to achieve a better understanding in the health and environmental sciences. *Int J Environ Res Public Health* 7**,** 2692-2707.

Arshavsky, Y.I. (2023). Brain energetics and the connectionist concept in cognitive neuroscience. *Journal of Neurophysiology* 130**,** 61-68.

Baker, B., Lansdell, B., and Kording, K.P. (2022). Three aspects of representation in neuroscience. *Trends Cogn Sci* 26**,** 942-958.

Ballard, D.H. (2015). *Brain Computation as Hierarchical Abstraction* Cambridge, MA The MIT Press.

Bandettini, P.A. (2012). Twenty years of functional MRI: the science and the stories. *Neuroimage* 62**,** 575-588.

Bandettini, P.A., Wong, E.C., Hinks, R.S., Tikofsky, R.S., and Hyde, J.S. (1992). Time course EPI of human brain function during task activation. *Magn Reson Med* 25**,** 390-397.

Barack, D.L., and Krakauer, J.W. (2021). Two views on the cognitive brain. *Nature reviews Neuroscience* 22**,** 359-371.

Barack, D.L., Miller, E.K., Moore, C.I., Packer, A.M., Pessoa, L., Ross, L.N., and Rust, N.C. (2022). A call for more clarity around causality in neuroscience. *Trends in Neurosciences* 45**,** 654-655.

Barwich, A.S. (2019). A Critique of Olfactory Objects. *Front Psychol* 10**,** 1337.

Barwich, A.S., and Severino, G.J. (2023). The Wire Is Not the Territory: Understanding Representational Drift in Olfaction With Dynamical Systems Theory. *Top Cogn Sci*.

Bassett, D.S., Zurn, P., and Gold, J.I. (2018). On the nature and use of models in network neuroscience. *Nature reviews Neuroscience* 19**,** 566-578.

Bechtel, W., and Huang, L.T.-L. (2022). *Philosophy of Neuroscience.* Cambridge University Press.

Bennett, M.R., and Hacker, P.M.S. (2005). *Philosophical Foundations of Neuroscience.* Wiley-Blackwell.

Bickle, J., De Sousa, A.F., and Silva, A.J. (2022). New research tools suggest a "levels-less" image of the behaving organism and dissolution of the reduction vs. anti-reduction dispute. *Front Psychol* 13**,** 990316.

Boulgakov, A.A., Ellington, A.D., and Marcotte, E.M. (2020). Bringing Microscopy-By-Sequencing into View. *Trends Biotechnol* 38**,** 154-162.

Boumans, M., and Leonelli, S. (2013). Introduction: On the Philosophy of Science in Practice. *Journal for General Philosophy of Science* 44**,** 259-261.

Brette, R. (2022). Brains as Computers: Metaphor, Analogy, Theory or Fact? *Frontiers in Ecology and Evolution* 10.

Brignol, A., Paas, A., Sotelo-Castro, L., St-Onge, D., Beltrame, G., and Coffey, E.B.J. (2024). Overcoming boundaries: Interdisciplinary challenges and opportunities in cognitive neuroscience. *Neuropsychologia* 200.

Brown, R.R., Deletic, A., and Wong, T.H.F. (2015). Interdisciplinarity: How to catalyse collaboration. *Nature* 525**,** 315-317.

Buckholtz, J.W., and Faigman, D.L. (2014). Promises, promises for neuroscience and law. *Current Biology* 24**,** R861-R867.

Buzsaki, G., Stark, E., Berenyi, A., Khodagholy, D., Kipke, D.R., Yoon, E., and Wise, K.D. (2015). Tools for probing local circuits: high-density silicon probes combined with optogenetics. *Neuron* 86**,** 92-105.

Campbell, D.T. (1957). Factors relevant to the validity of experiments in social settings. *Psychol Bull* 54**,** 297-312.

Chen, Y.H., Rommelfanger, N.J., Mahdi, A.I., Wu, X., Keene, S.T., Obaid, A., Salleo, A., Wang, H.L., and Hong, G.S. (2021). How is flexible electronics advancing neuroscience research? *Biomaterials* 268.

Chirimuuta, M. (2018). Explanation in Computational Neuroscience: Causal and Non-causal. *The British Journal for the Philosophy of Science* 69.

Chirimuuta, M. (2021). Prediction versus understanding in computationally enhanced neuroscience. *Synthese* 199**,** 767–790.

Chirimuuta, M. (2024). *The Brain Abstracted, Simplification in the History and Philosophy of Neuroscience.* Cambridge, MA, USA The MIT Press.

Choi, B.C., and Pak, A.W. (2006). Multidisciplinarity, interdisciplinarity and transdisciplinarity in health research, services, education and policy: 1. Definitions, objectives, and evidence of effectiveness. *Clin Invest Med* 29**,** 351-364.

Churchland, P.S. (2007). Neurophilosophy: the early years and new directions. *Functional Neurology* 22**,** 185-195.

Coltheart, M. (2013). How Can Functional Neuroimaging Inform Cognitive Theories? *Perspectives on psychological science : a journal of the Association for Psychological Science* 8**,** 98-103.

Contreras Kallens, P., Dale, R., and Christiansen, M.H. (2022). Quantifying Interdisciplinarity in Cognitive Science and Beyond. *Top Cogn Sci* 14**,** 634-645.

Costa, D.P., and Sinervo, B. (2004). Field physiology: physiological insights from animals in nature. *Annu Rev Physiol* 66**,** 209-238.

Cowan, W.M., Harter, D.H., and Kandel, E.R. (2000). The emergence of modern neuroscience: some implications for neurology and psychiatry. *Annual review of neuroscience* 23**,** 343-391.

Darden, L., and Maull, N. (1977). Interfield Theories. *Philosophy of Science* 44**,** 43-64.

De Haro, S. (2020). Science and Philosophy: A Love – Hate Relationship. *Foundations of Science*.

De Schutter, E. (2008). Why are computational neuroscience and systems biology so separate? *PLoS Comput Biol* 4**,** e1000078.

Dijkstra, N., and De Bruin, L. (2016). Cognitive Neuroscience and Causal Inference: Implications for Psychiatry. *Front Psychiatry* 7**,** 129.

Dirnagl, U., Bannach-Brown, A., and Mccann, S. (2022). External validity in translational biomedicine: understanding the conditions enabling the cause to have an effect. *EMBO Mol Med* 14**,** e14334.

Duffau, H. (2018). The error of Broca: From the traditional localizationist concept to a connectomal anatomy of human brain. *J Chem Neuroanat* 89**,** 73-81.

Elliott, M.L., Knodt, A.R., and Hariri, A.R. (2021). Striving toward translation: strategies for reliable fMRI measurement. *Trends Cogn Sci* 25**,** 776-787.

Fernandez, O. (2013). Best practice in the use of natalizumab in multiple sclerosis. *Ther Adv Neurol Disord* 6**,** 69-79.

Fodor, J.a.A. (1983). *The Modularity of Mind: An Essay on Faculty Psychology.* A Bradford Book / MIT Press.

Frigg, R., and Hartmann Stephan. 2020. Models in Science. *Stanford Encyclopedia of Philosophy* [Online].

Galison, P. (1997). Three Laboratories. *Technology and the rest of culture* 64**,** 1127-1155.

Glasgow, R.E. (2008). What types of evidence are most needed to advance behavioral medicine? *Ann Behav Med* 35**,** 19-25.

Gohar, F., Maschmeyer, P., Mfarrej, B., Lemaire, M., Wedderburn, L.R., Roncarolo, M.G., and Van Royen-Kerkhof, A. (2019). Driving Medical Innovation Through Interdisciplinarity: Unique Opportunities and Challenges. *Front Med (Lausanne)* 6**,** 35.

Gold, I., and Stoljar, D. (1999). A neuron doctrine in the philosophy of neuroscience. *Behav Brain Sci* 22**,** 809-830; discussion 831-869.

Gozzer, G. (1982). Interdisciplinarity: a concept still unclear. *Prospects* 12**,** 281-292.

Griesemer, J. (2008). "Origins of Life Studies," in *Oxford Handbooks Online.* .), 263–290.

Griesemer, J. (2011). Philosophy and tinkering. *Biology & Philosophy* 26**,** 269–279.

Gusnard, D.A., Raichle, M.E., and Raichle, M.E. (2001). Searching for a baseline: functional imaging and the resting human brain. *Nat Rev Neurosci* 2**,** 685-694.

Hall, K.L., Vogel, A.L., Huang, G.C., Serrano, K.J., Rice, E.L., Tsakraklides, S.P., and Fiore, S.M. (2018). The science of team science: A review of the empirical evidence and research gaps on collaboration in science. *Am Psychol* 73**,** 532-548.

Hampel, H., Gao, P., Cummings, J., Toschi, N., Thompson, P.M., Hu, Y., Cho, M., and Vergallo, A. (2023). The foundation and architecture of precision medicine in neurology and psychiatry. *Trends Neurosci* 46**,** 176-198.

Hoffmann, M.H.G., Schmidt, J.C., and Nersessian, N.J. (2013). Philosophy of and as interdisciplinarity. *Synthese* 190**,** 1857-1864.

Holbrook, J.B. (2013). What is interdisciplinary communication? Reflections on the very idea of disciplinary integration. *Synthese* 190**,** 1865-1879.

Huutoniemi, K., Thompson Klein, J., Bruun, H., and Hukkinena, J. (2010). Analyzing interdisciplinarity: Typology and indicators. *Research Policy* 39**,** 79-88.

Jacobs, J., and Frickel, S. (2009). Interdisciplinarity: A Critical Assessment. *Annual Review of Sociology* 35**,** 43-65.

Jennings, J.H., and Stuber, G.D. (2014). Tools for resolving functional activity and connectivity within intact neural circuits. *Curr Biol* 24**,** R41-R50.

Jimenez-Buedo, M., and Miller, L.M. (2010). Why a Trade-Off? The Relationship between the External and Internal Validity of Experiments. *THEORIA* 25**,** 301–321.

Kaiser, M.I., Kronfeldner, M., and Meunier, R. (2014). Interdisciplinarity in Philosophy of Science. *Journal for General Philosophy of Science* Journal for General Philosophy of Science pages 59–70.

Kanwisher, N., Khosla, M., and Dobs, K. (2023). Using artificial neural networks to ask 'why' questions of minds and brains. *Trends Neurosci*.

Kendall-Bar, J.M., Mukherji, R., Nichols, J., Lopez, C., Lozano, D.A., Pitman, J.K., Holser, R.R., Beltran, R.S., Schalles, M., Field, C.L., Johnson, S.P., Vyssotski, A.L., Costa, D.P., and Williams, T.M. (2022). Eavesdropping on the brain at sea: development of a surface-mounted system to detect weak electrophysiological signals from wild animals. *Animal Biotelemetry* 10.

Kihlstrom, J.F. (2021). Ecological Validity and "Ecological Validity". *Perspect Psychol Sci* 16**,** 466-471.

Knorr-Cetina, K. (1999). *Epistemic Cultures, How the Sciences Make Knowledge.*

Kringelbach, M.L., Sanz Perl, Y., and Deco, G. (2024). The Thermodynamics of Mind. *Trends Cogn Sci* 28**,** 568-581.

Kunze, M. (2018). Predicting Peroxisomal Targeting Signals to Elucidate the Peroxisomal Proteome of Mammals. *Subcell Biochem* 89**,** 157-199.

Kwong, K.K., Belliveau, J.W., Chesler, D.A., Goldberg, I.E., Weisskoff, R.M., Poncelet, B.P., Kennedy, D.N., Hoppel, B.E., Cohen, M.S., Turner, R., and Et Al. (1992). Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. *Proc Natl Acad Sci U S A* 89**,** 5675-5679.

Kympouropoulos, S. (2023). Real World Evidence: methodological issues and opportunities from the European Health Data Space. *BMC Med Res Methodol* 23**,** 185.

Laplane, L., Duluc, D., Bikfalvi, A., Larmonier, N., and Pradeu, T. (2019a). Beyond the tumour microenvironment. *Int J Cancer* 145**,** 2611-2618.

Laplane, L., Mantovani, P., Adolphs, R., Change, H., Mantovani, A., Mcfall-Ngai, M., Rovelli, C., Sober, E., and Pradeu, T. (2019b). Why science needs philosophy. *Proceedings of the National Academy of Sciences* 116**,** 3948–3952.

Lauritzen, M. (2005). Reading vascular changes in brain imaging: is dendritic calcium the key? *Nat Rev Neurosci* 6**,** 77-85.

Leach, M.O. (2004). Nobel Prize in Physiology or Medicine 2003 awarded to Paul Lauterbur and Peter Mansfield for discoveries concerning magnetic resonance imaging. *Phys Med Biol* 49**,** 2 p preceding R13.

Lebeau, F.E., El Manira, A., and Griller, S. (2005). Tuning the network: modulation of neuronal microcircuits in the spinal cord and hippocampus. *Trends Neurosci* 28**,** 552-561.

Ledford, H. (2015). Team Science. *Nature* 525**,** 308-311.

Lélé, S., and Norgaard, R.B. (2005). Practicing interdisciplinarity. *Bioscience* 55**,** 967-975.

Levenstein, D., Alvarez, V.A., Amarasingham, A., Azab, H., Chen, Z.S., Gerkin, R.C., Hasenstaub, A., Iyer, R., Jolivet, R.B., Marzen, S., Monaco, J.D., Prinz, A.A., Quraishi, S., Santamaria, F., Shivkumar, S., Singh, M.F., Traub, R., Nadim, F., Rotstein, H.G., and Redish, A.D. (2023). On the Role of Theory and Modeling in Neuroscience. *Journal of Neuroscience* 43**,** 1074-1088.

Li, D., Wang, Y., and Liu, Z.-P. (2021). Academic background of Nobel prize laureates reveals the importance of multidisciplinary education in medicine. *Social Sciences & Humanities Open* 3.

Logothetis, N.K. (2008). What we can do and what we cannot do with fMRI. *Nature* 453**,** 869-878.

Löwy, I. (1992). The strength of loose concepts - boundary concepts, federative experimental strategies and disciplinary growth: the case of immunology. *History of Science*.

Macleod, M. (2018). What makes interdisciplinarity difficult? Some consequences of domain specificity in interdisciplinary practice. *Synthese* 195**,** :697-720.

Macleod, M., Merz, M., Mäki, U., and Nagatsu, M. (2019). "Investigating Interdisciplinary Practice: Methodological Challenges (Introduction)," in *Perspectives on Science*. The Massachusetts Institute of Technology), 545-552.

Mason, K., Sripada, C.S., and Stich, S. (2008). "The Philosophy of psychology," in *The Routledge Companion to Twentieth Century Philosophy,* ed. D. Moran.).

Mather, M., Cacioppo, J.T., and Kanwisher, N. (2013). How fMRI Can Inform Cognitive Theories. *Perspect Psychol Sci* 8**,** 108-113.

Matthews, P.M., and Hampshire, A. (2016). Clinical Concepts Emerging from fMRI Functional Connectomics. *Neuron* 91**,** 511-528.

Matthews, P.M., Honey, G.D., and Bullmore, E.T. (2006). Applications of fMRI in translational medicine and clinical practice. *Nature Reviews Neuroscience* 7**,** 732-744.

Mazzocchi, F. (2019). Scientific research across and beyond disciplines: Challenges and opportunities of interdisciplinarity. *EMBO Rep* 20.

Mcculloch, W.S. (1965). *Embodiments of Mind* MIT Press.

Mcculloch, W.S., and Pitts, W. (1943). A logical calculus of the ideas immanent in nervous activity. *Bulletin of mathematical biology* 52**,** 99-115.

Miłkowski, M. (2018). From Computer Metaphor to Computational Modeling: The Evolution of Computationalism. *Minds and Machines* 28**,** 515–541.

Mok, J.N.Y., Green, L., Myerson, J., Kwan, D., Kurczek, J., Ciaramelli, E., Craver, C.F., and Rosenbaum, S.R. (2021). Does Ventromedial Prefrontal Cortex Damage Really Increase Impulsiveness? Delay and Probability Discounting in Patients with Focal Lesions. *J Cogn Neurosci* 33**,** 1-19.

Moreau, Q., and Dumas, G. (2021). Beyond Correlation versus Causation: Multi-brain Neuroscience Needs Explanation. *Trends Cogn Sci* 25**,** 542-543.

Muller, T., Schumann, C., and Kraegeloh, A. (2012). STED microscopy and its applications: new insights into cellular processes on the nanoscale. *Chemphyschem : a European journal of chemical physics and physical chemistry* 13**,** 1986-2000.

Murray, A.J., Montgomery, H.E., Feelisch, M., Grocott, M.P.W., and Martin, D.S. (2018). Metabolic adjustment to high-altitude hypoxia: from genetic signals to physiological implications. *Biochemical Society Transactions* 46**,** 599-607.

Nancarrow, S.A., Booth, A., Ariss, S., Smith, T., Enderby, P., and Roots, A. (2013). Ten principles of good interdisciplinary team work. *Hum Resour Health* 11**,** 19.

Nersessian, N.J. (2022). *Interdisciplinarity in the making.* MIT Press.

Neto, C. (2020). When imprecision is a good thing, or how imprecise concepts facilitate integration in biology. *Biology & Philosophy* 35.

Neurath, O., Schlick, M., and Carnap, R. (1996). *Logical Empiricism at Its Peak.* Taylor and Francis.

Novembre, G., and Iannetti, G.D. (2021). Hyperscanning Alone Cannot Prove Causality. Multibrain Stimulation Can. *Trends Cogn Sci* 25**,** 96-99.

O'rourke, M., and Crowley, S.J. (2013). Philosophical intervention and cross-disciplinary science: the story of the Toolbox Project. *Synthese* 190**,** 1937-1954.

O’rourke, M., and Crowley, S.J. (2013). Philosophical intervention and cross-disciplinary science: the story of the Toolbox Project. *Synthese* 190**,** 1937–1954.

Olsson, L., Jerneck, A., Thoren, H., Persson, J., and O'byrne, D. (2015). Why resilience is unappealing to social science: Theoretical and empirical investigations of the scientific use of resilience. *Sci Adv* 1**,** e1400217.

Peelen, M.V., and Downing, P.E. (2023). Testing cognitive theories with multivariate pattern analysis of neuroimaging data. *Nat Hum Behav* 7**,** 1430-1441.

Philiastides, M.G., Tu, T., and Sajda, P. (2021). Inferring Macroscale Brain Dynamics via Fusion of Simultaneous EEG-

MRI. *Annual Review of Neuroscience, Vol 44, 2021* 44**,** 315-334.

Piccinini, G., and Shagrir, O. (2014). Foundations of computational neuroscience. *Curr Opin Neurobiol* 25**,** 25-30.

Piot, E., Picard, B., Badaut, J., Gilbert, C., and Guinet, C. (2023). Diving behaviour of southern elephant seals: new models of behavioural and ecophysiological adjustments of oxygen store management. *J Exp Biol* 226.

Piwecka, M., Rajewsky, N., and Rybak-Wolf, A. (2023). Single-cell and spatial transcriptomics: deciphering brain complexity in health and disease. *Nature reviews Neurology* 19**,** 346-362.

Poirazi, P., and Papoutsi, A. (2020). Illuminating dendritic function with computational models. *Nat Rev Neurosci* 21**,** 303-321.

Poldrack, R.A., Baker, C.I., Durnez, J., Gorgolewski, K.J., Matthews, P.M., Munafò, M.R., Nichols, T.E., Poline, J.B., Vul, E., and Yarkoni, T. (2017). Scanning the horizon: towards transparent and reproducible neuroimaging research. *Nature Reviews Neuroscience* 18**,** 115-126.

Pradeu, T., Lemoine, M., Khelfaoui, M., and Gingras, Y. (2021). Philosophy in Science: Can philosophers of science permeate through science and produce scientific knowledge?

Pradeu, T., Lemoine, M., Khelfaoui, M., and Gingras, Y. (2024). Philosophy in Science: Can Philosophers of Science Permeate through Science and Produce Scientific Knowledge? *The British Journal for the Philosophy of Science* 75**,** 375-416.

Price, C.J. (2018). The evolution of cognitive models: From neuropsychology to neuroimaging and back. *Cortex* 107**,** 37-49.

Raichle, M.E. (2009). A brief history of human brain mapping. *Trends Neurosci* 32**,** 118-126.

Reid, A.T., Headley, D.B., Mill, R.D., Sanchez-Romero, R., Uddin, L.Q., Marinazzo, D., Lurie, D.J., Valdes-Sosa, P.A., Hanson, S.J., Biswal, B.B., Calhoun, V., Poldrack, R.A., and Cole, M.W. (2019). Advancing functional connectivity research from association to causation. *Nat Neurosci* 22**,** 1751-1760.

Rolls, E.T. (2021). Mind Causality: A Computational Neuroscience Approach. *Front Comput Neurosci* 15**,** 706505.

Rosenbaum, R.S., Kwan, D., Floden, D., Levine, B., Stuss, D.T., and Craver, C.F. (2016). No evidence of risk-taking or impulsive behaviour in a person with episodic amnesia: Implications for the role of the hippocampus in future-regarding decision-making. *Q J Exp Psychol (Hove)* 69**,** 1606-1618.

Rosenfield, P.L. (1992). The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. *Soc Sci Med* 35**,** 1343-1357.

Ross, L.N., and Bassett, D.S. (2024). Causation in neuroscience: keeping mechanism meaningful. *Nature Reviews Neuroscience* 25**,** 81-90.

Roy, C.S., and Sherrington, C.S. (1890). On the Regulation of the Blood-supply of the Brain. *The Journal of Physiology* 11**,** 85-158.

Scalzone, F. (2005). Notes for a dialogue between psychoanalysis and neuroscience. *International Journal of Psychoanalysis* 86**,** 1405-1423.

Schwiening, C.J. (2012). A brief historical perspective: Hodgkin and Huxley. *J Physiol* 590**,** 2571-2575.

Sejnowski, T.J., Koch, C., and Churchland, P.S. (1988). Computational neuroscience. *Science* 241**,** 1299-1306.

Smaldino, P.E., and O’connor, C. (2022). Interdisciplinarity can aid the spread of better methods between scientific communities. *Collective Intelligence* 0**,** 1–18.

Sokoloff, L. (1977). Relation between physiological function and energy metabolism in the central nervous system. *Journal of neurochemistry* 29**,** 13-26.

Stahnisch, F.W. (2016). "History of the neurosciences", in: *Encyclopedia of life support systems.*).

Stangl, M., Maoz, S.L., and Suthana, N. (2023). Mobile cognition: imaging the human brain in the 'real world'. *Nature reviews Neuroscience* 24**,** 347-362.

Star, S.G., Jr. (1989a). Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science* 19**,** 387-420.

Star, S.L. (1989b). "The Structure of Ill-Structured Solutions: Boundary Objects and Heterogeneous Distributed Problem Solving," in *Distributed Artificial Intelligence*.), 37-54.

Stern, P., and Travis, J. (2006). Of Bytes and Brains. *SCIENCE* 314**,** 75.

Sutterer, M.J., and Tranel, D. (2017). Neuropsychology and cognitive neuroscience in the fMRI era: A recapitulation of localizationist and connectionist views. *Neuropsychology* 31**,** 972-980.

Sutton, J., and Schier, E. (2014). "Philosophy of Mind and Cognitive Science since 1980," in *History of Philosophy in Australia and New Zealand,* eds. G. Oppy & N. Trakakis. Springer).

Szameitat, A.J., Schubert, T., and Müller, H.J. (2011). How to test for dual-task-specific effects in brain imaging studies — An evaluation of potential analysis methods. *NeuroImage2011* 54**,** 1765-1773.

Testard, C., Tremblay, S., Parodi, F., Ditullio, R.W., Acevedo-Ithier, A., Gardiner, K.L., Kording, K., and Platt, M.L. (2024). Neural signatures of natural behaviour in socializing macaques. *Nature* 628.

Teufel, C., and Fletcher, P.C. (2016). The promises and pitfalls of applying computational models to neurological and psychiatric disorders. *Brain* 139**,** 2600-2608.

Thagard, P. (2009). Why cognitive science needs philosophy and vice versa. *Top Cogn Sci* 1**,** 237-254.

Theriault, J.E., Shaffer, C., Dienel, G.A., Sander, C.Y., Hooker, J.M., Dickerson, B.C., Barrett, L.F., and Quigley, K.S. (2023). A functional account of stimulation-based aerobic glycolysis and its role in interpreting BOLD signal intensity increases in neuroimaging experiments. *Neuroscience and Biobehavioral Reviews* 153.

Tsvetanov, K.A., Henson, R.N.A., and Rowe, J.B. (2021). Separating vascular and neuronal effects of age on fMRI BOLD signals. *Philos Trans R Soc Lond B Biol Sci* 376**,** 20190631.

Urai, A.E., Doiron, B., Leifer, A.M., and Churchland, A.K. (2022). Large-scale neural recordings call for new insights to link brain and behavior. *Nat Neurosci* 25**,** 11-19.

Van Den Pol, A.N. (2012). Neuropeptide transmission in brain circuits. *Neuron* 76**,** 98-115.

Van Der Laan, A.L., and Boenink, M. (2015). Beyond bench and bedside: disentangling the concept of translational research. *Health Care Anal* 23**,** 32-49.

Van Gelder, T. (1998). The roles of philosophy in cognitive science. *Philosophical Psychology* 11**,** 117-136

Verkhratsky, A., and Parpura, V. (2014). History of electrophysiology and the patch clamp. *Methods Mol Biol* 1183**,** 1-19.

Vicidomini, G., Bianchini, P., and Diaspro, A. (2018). STED super-resolved microscopy. *Nature methods* 15**,** 173-182.

Villéga, F., Fernandes, A., Jezequel, J., Uyttersprot, F., Benac, N., Zenagui, S., Bastardo, L., Gréa, H., Bouchet, D., Villetelle, L., Nicole, O., Rogemond, V., Honnorat, J., Dupuis, J.P., and Groc, L. (2024). Ketamine alleviates NMDA receptor hypofunction through synaptic trapping. *Neuron* 112.

Vizioli, L., Yacoub, E., and Lewis, L.D. (2021). How pushing the spatiotemporal resolution of fMRI can advance neuroscience. *Progress in Neurobiology* 207.

Waldman, D.A. (2013). Interdisciplinary research is the key. *Front Hum Neurosci* 7**,** 562.

Wehrli, F.W. (2004). On the 2003 Nobel Prize in medicine or physiology awarded to Paul C. Lauterbur and Sir Peter Mansfield. *Magn Reson Med* 51**,** 1-3.

Wei, W.Z., Zhang, K.Y., Chang, J., Zhang, S.Y., Ma, L.J., Wang, H.X., Zhang, M., Zu, Z.Y., Yang, L.X., Chen, F.L., Fan, C., and Li, X.M. (2024). Analyzing 20 years of Resting-State fMRI Research: Trends and collaborative networks revealed. *Brain Research* 1822.

Weichwald, S.P., J. (2021). Causality in cognitive neuroscience: concepts, challenges, and distributional robustness *Journal of Cognitive Neuroscience* 33**,** 226–247.

Wimsatt, W.C. (2007). *Re-Engineering Philosophy for Limited Beings: Piecewise Approximations to Reality.* Harvard University Press.

Wudarczyk, O.A., Kirtay, M., Kuhlen, A.K., Abdel Rahman, R., Haynes, J.D., Hafner, V.V., and Pischedda, D. (2021). Bringing Together Robotics, Neuroscience, and Psychology: Lessons Learned From an Interdisciplinary Project. *Front Hum Neurosci* 15**,** 630789.

Xu, G., and Li, J. (2019). Recent advances in mass spectrometry imaging for multiomics application in neurology. *J Comp Neurol* 527**,** 2158-2169.

Yoon, J.H., Seo, Y., Jo, Y.S., Lee, S., Cho, E., Cazenave-Gassiot, A., Shin, Y.S., Moon, M.H., An, H.J., Wenk, M.R., and Suh, P.G. (2022). Brain lipidomics: From functional landscape to clinical significance. *Sci Adv* 8**,** eadc9317.

1. Although the terms "field" and "discipline" are sometimes used interchangeably, they refer to different areas of academic inquiry. "Field" usually means a particular area of study dealing with a specific subject matter, methodologies, and research questions. Fields can encompass a wide range of topics and subtopics, and they often involve interdisciplinary collaboration. In contrast, "disciplines" are understood as scholarly areas organized around specific academic subjects, often grouping different fields, and characterized by a set of theories, principles, methods, and standards of practice. Disciplines often have well-established structures reflected by university departments and grant university diplomas (Jacobs, In defense of disciplines, 2013). Neuroscience can thus now be considered a discipline, even though it has started as a field in the past. [↑](#footnote-ref-1)
2. Historically the plural of the term “neurosciences” has been used, but for consistency we use the singular “neuroscience” throughout the rest of this manuscript. [↑](#footnote-ref-2)
3. In contrast to interdisciplinary approaches, in multidisciplinary approaches researchers address a common problem only from their own disciplinary perspective. Finally, in transdisciplinary approaches scientists attempt to dissolve their disciplinary boundaries while their collaborating partners try to surpass their own disciplines Rosenfield, P.L. (1992). The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 35**,** 1343-1357, Mazzocchi, F. (2019). Scientific research across and beyond disciplines: Challenges and opportunities of interdisciplinarity. EMBO Rep 20. [↑](#footnote-ref-3)
4. Exemplarily, combining the development of large scale fMRI with theoretical studies on the temporal dynamic of complex brain activity patters allowed the development of functional connectomics measurements based on resting-state fMRI and its clinical applications Matthews, P.M., and Hampshire, A. (2016). Clinical Concepts Emerging from fMRI Functional Connectomics. Neuron 91**,** 511-528, Amemiya, S., Takao, H., and Abe, O. (2024). Resting-State fMRI: Emerging Concepts for Future Clinical Application. J Magn Reson Imaging 59**,** 1135-1148, Kringelbach, M.L., Sanz Perl, Y., and Deco, G. (2024). The Thermodynamics of Mind. Trends Cogn Sci 28**,** 568-581.). Additional: (Bandettini, 2012; Price, 2012; Coltheart, 2013; Mather et al., 2013; Coltheart and Caramazza, 2017; Peelen and Downing, 2023) [↑](#footnote-ref-4)
5. Connectionism is a broader paradigm of modeling of networks (including artificial neuronal networks (ANN)), while distributionism focuses on how information is represented within these networks (in particular in the brain). [↑](#footnote-ref-5)
6. The famous collaboration between Alan Hodgkin and Andrew Huxley (A neurophysiologist and biologist, respectively) took advantage of their technical and engineering skills developed during WW-II. Indeed, Huxley was involved in the development of radar control and anti-aircraft guns while Hodgkin developed radars) Schwiening, C.J. (2012). A brief historical perspective: Hodgkin and Huxley. *J Physiol* 590**,** 2571-2575. This fits with the observation that many Nobel prize laureates for medicine, have an additional educational background, many in physics or chemistry. Li, D., Wang, Y., and Liu, Z.-P. (2021). Academic background of Nobel prize laureates reveals the importance of multidisciplinary education in medicine. *Social Sciences & Humanities Open* 3. [↑](#footnote-ref-6)
7. The term ‘interdisciplinary-type collaboration’ is used here to summarize interdisciplinary and inter-field collaborations. [↑](#footnote-ref-7)
8. The examples of 3.3 are linked to practical experience of some of the authors and may illustrate more general patterns. [↑](#footnote-ref-8)
9. It goes without saying that not all members of these communities share the same attitude. [↑](#footnote-ref-9)
10. This refers to the early phase of neuroscience, in which brain has been compared to computers and neuronal processing to computation, which has been used with different intentions to express similarity, analogy or functional identity. [↑](#footnote-ref-10)
11. These examples illustrate that neuroscientists should benefits from an awareness of typical problems in interdisciplinary and interdisciplinary-type interactions and collaborations with scientists from other disciplines or fields of neuroscience, to recognize and address them specifically (although they are often disregarded because the involved partners believe to share the same framework). [↑](#footnote-ref-11)
12. In a similar approach different forms of engaging with other disciplines have been formulated for the philosophy of science “Interdisciplinarity in Philosophy of Science” by Marie Kaiser, Maria Kronfeldner and Robert Meunier (J Gen Philos Sci (2014) 45:59–70, DOI 10.1007/s10838-014-9269-1). Of note, the three modes of interaction between scientists and philosophers has little in common with the three modes of interaction between neuroscience and philosophy discussed by Bartosz Brożek in Philosophy and Neuroscience - Three Modes of Interaction (<https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2378013> Indeed, the possible relations described by Brozek include isolation, replacement and interplay. It is only within this latter category that our three modes of interaction can be considered. Similarly, the distinction between metaphysics *for* and metaphysics *in* biology has been discussed by Vanesa Triviño (Synthese (2022) 200:428

    https://doi.org/10.1007/s11229-022-03897-3) [↑](#footnote-ref-12)
13. Getting acquainted with long-standing philosophical debates, which overlap in content with actual debates in neuroscience (e.g. consciousness in the FENS-contribution by J.P. Changeux) or share a common topic (e.g. subjectivity and first order perspective as topic in philosophy (qualia), but also as an experimental challenge for neuroscience & psychology as introduced by Ann-Sophie Barwich for the perception of smell at the FENS) might prevent them from the need to rediscover well-known errors or to reinvent conceptual frameworks already established in philosophy. [↑](#footnote-ref-13)