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PAPER

Is biorobotics science? Some theoretical reflections

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Abstract

In this paper, we ask one fairly simple question: to what extent can biorobotics be sensibly qualified as science? The answer clearly depends on what 'science' means and whether what is actually done in biorobotics corresponds to this meaning. To respond to this question, we will deploy the distinction between science and so-called technoscience, and isolate different kinds of objects of inquiry in biorobotics research. Capitalising on the distinction between 'proximal' and 'distal' biorobotic hypotheses, we will argue that technoscientific biorobotic studies address proximal hypotheses, whilst scientific biorobotic studies address distal hypotheses. As a result, we argue that biroboticians can be both considered as scientists and technoscientists and that this is one of the main payoffs of biorobotics. Indeed, technoscientists play an extremely important role in 21st-century culture and in the current critical production of knowledge. Today's world is increasingly technological, or rather, it is a bio-hybrid system in which the biological and the technological are mixed. Therefore, studying the behaviour of robotic systems and the phenomena of animal-robot interaction means analysing, understanding, and shaping our world. Indeed, in the conclusion of the paper, we broadly reflect on the philosophical and disciplinary payoff of seeing biorobotics as a science and/or technoscience for the increasingly bio-hybrid and technical world of the 21st century.

1. Introduction

Throughout its history, robotics has frequently interacted with research fields devoted to the study of the morphology, behaviour, and cognition of living systems. This interaction has often been characterized as bi-directional. On the one hand, robotics has often drawn inspiration from behavioural, cognitive, and neuroscience in order to build robots that are more reactive, efficient, flexible, and adaptable. The product of this approach has frequently been called 'biologically inspired robotics', which has been thoroughly discussed in the scientific and methodological literature (e.g. Beer *et al* 1997, 1998, Trullier *et al* 1997, Pfeifer *et al* 2007, Meyer and Guillot 2008, Quinn *et al* 2002, Krichmar 2012). On the other hand, occasionally, the claim has been made that robotics can contribute to the study of the adaptive and intelligent behaviour of living systems. This field has been called 'biorobotics' (for methodological reviews, see Webb and Consi 2001, Datteri 2017, 2020). Both fields have deep historical roots, as discussed by Tamborini (2021, 2022a).

One might believe that the distinction made between biologically inspired robotics and biorobotics mirrors the distinction between engineering and science. Whereas the first has been conceived as a field devoted to the development of efficient technological artifacts, the second seems to be devoted to the study and the understanding of natural systems. However, this would be a mistake. There may be good reasons for considering biologically inspired robotics as science. Not only because it heavily relies on science, but also because there are no reasons to deny

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that the results of biologically inspired robotics may somehow contribute to the *scientific* understanding of living systems, perhaps over the long term. Furthermore, the construction of biologically inspired robots involves stages of hypothesizing and testing that are akin to scientific processes (as extensively argued by Poznic 2016, van Eck 2016, Yaghmaie 2021).

Biorobotics, on the other hand, can be regarded as *sui generis* science. Indeed, biorobotics aims to understand adaptive and intelligent behaviour by building technological artifacts, and the experiments that it carries out are mostly on, or crucially involve, robots. A particular branch of biorobotics called interactive biorobotics (Datteri 2020) involves experiments in which one assesses how animals react to stimuli delivered by robots. Even though biorobotics is often thought of as a field devoted to the study of *living* systems, it involves experiments on technological artefacts or on the behaviour of living systems in technologically mediated environments.

It was precisely these considerations that motivated the apparently simple question addressed in this article: to what extent can biorobotics be sensibly qualified as science? The answer will clearly depend on how 'science' is defined, and on whether what is done in biorobotics conforms to that meaning. By leveraging the distinction between 'science' and so-called 'technoscience' (Bensaude-Vincent 2008, Nordmann *et al* 2011), this paper's primary focus is on this question.

In the discussion that follows, it will be argued that, within biorobotics, one can distinguish between two broad kinds of endeavours, with one characterized as *technoscientific*, and the other as *scientific*. The distinction rests on the content of the scientific question that is validly addressed in the study: in other words, any given biorobotic study can be sensibly qualified as scientific if it leads one to validly sustain theoretical hypotheses of a certain kind, otherwise it should be viewed as technoscientific. This paper will spell out in detail how this distinction can be made. Note that, in both cases, it is assumed that biorobotic experiments *validly* support the conclusion (whatever validity may consist in). Therefore, we are not claiming that technoscientific results are less 'sound', or less theoretically significant, than scientific ones.

This article, as such, neither presents novel empirical results nor novel robotic technologies. Instead, it offers a plain and simple philosophical analysis—which is necessarily partial and biased—of the role that biorobotics can play in the advancement of knowledge. Why should biroboticists pay attention to it? More generally, why should roboticists working at the interface between robotics, biology, and cognitive science, pay attention to what philosophy of science and history of science have to say about their discipline? Arguably, they do not need to. However, roboticists quite often make claims that are philosophically, and specifically *epistemologically*, loaded, without justifying them with the same rigour they use to justify their empirical or technological assertions. Consider, for example, the claim that humanoid robotics can 'provide insightful information regarding social cognitive mechanisms in the human brain' (made by Wykowska *et al* 2016). Or the claim that animal-like robots 'have the potential to revolutionize the study of social behaviour' (made by Krause *et al* 2011) and constitute 'a novel method for studying collective animal behaviour' (Faria *et al* 2010). These are neither empirical nor technological claims (as they, *per se*, do not have any empirical or technological content): instead, they are *epistemological* (thus, philosophical) claims, because they suggest that some technological artefacts can be used as tools to acquire knowledge about the natural world.

Offering examples of these epistemic usages (as is done in the works cited in this section) will not suffice to justify these claims—e.g. showing that a robot has been used to study human cognition cannot justify the general claim that robots can be *validly* used to study human cognition. If biorobotics can be sensibly regarded as science, as many contemporary roboticists tend to claim, i.e. if biorobots can be regarded as valid epistemic tools to acquire robust knowledge about the world, is a question that cannot be solved without the contribution of philosophers and historians of science. Building on previous epistemological and historical analyses of biorobotics (Datteri 2020, 2021a, Tamborini 2020b, 2021, Datteri *et al* 2022), this article is meant to take stock of the question and, hopefully, to contribute to the debate on the philosophical and historical foundations of biorobotics in the scientific community.

To pave the way for the ensuing analysis, the next section will explore the distinction between science and technoscience, as it has been made in the history of science and technology literature.

2. Science and technoscience

In recent decades, philosophers and historians of science have shown particular interest in participating in a game that has shaped much of the history and philosophy of science of the 20th century. The game comprises defining what science is and what different types of scientific endeavours can be said to exist. In the late 20th and early 21st centuries, various philosophers have pitted the categories of natural sciences against those of technosciences, on the one hand, and science 1.0 against science 2.0,[3] on the other. According to these scholars, the technoscientific mode of knowledge production as well as science 2.0 characterize today's time (Carrier 2011, 2019, Nordmann *et al* 2011, Tamborini 2020).

The term 'technoscience' has at least three different but intertwined origins (Bensaude-Vincent *et al* 2017, Channell 2017). First, the term was coined to promote a shift from a philosophy of science focused on the analysis of language to one in which technology was to be considered as a co-participating factor in the production of knowledge. Second, Bruno Latour coined and popularized the term 'technoscience' in his *Science in Action* (1987) to indicate that science is never ready-made, since scientific production is a continuously ongoing activity, governed by practices that are always impure, hybrid, contingent, and mixed with different societies and cultures. Third, technoscience has been used to suggest that the boundaries between science, technology and various economic interests are blurred. As historian of science and technology David F. Channell summarized it concisely, 'While some use the term technoscience to refer to a transformation of science into something that is closer to technology, others use the term to refer to changes in which technology is no longer simply focused on the artificial but provides and opens up a new understanding of the natural world […]. Still others see the term technoscience as not just referring to a new view of science or a new view of technology, but see it as representing an epochal break with the past' (Channell 2017, p 21).

A central stance is shared by all these different meanings and uses of the word 'technoscience'. All proponents of technoscience share the idea that the division between science and technology should be reconsidered—by doing so, they are opposing a long-standing philosophical tradition that has seen technology as a mere auxiliary instrument (see for example the classical works of Arnold Gehlen or Martin Heidegger on technology). Conversely, these supporters claim that scientific knowledge production is necessarily an impure enterprise as it merges and hybridizes science and technology—it is indeed *techno*science. A number of disciplines including synthetic biology, chemistry, nanotechnology, and palaeontology can be considered technosciences. Notwithstanding their diversity, these disciplines converge on one crucial point: the formulation of scientific theories is closely and inextricably linked to the use of various technologies. Or, to put it differently, technology is not merely an auxiliary tool for knowledge production, but rather it is involved in all steps of theory and knowledge production.

Consider, for example, Donna Haraway's discussion on the OncoMouse, a genetically modified animal derived from a transplanted human tumour-producing gene, which was developed for biomedical research. What makes the OncoMouse special is that it is an impure organism: it is *both alive and artificial*. It is an invented, created, and patented creature, but it is also a living animal. In this way, the OncoMouse blurs the distinction between the natural and the artificial. In a sense, the phenomena under study in palaeontology, nanobiotechnology, or, as we shall see, in some areas of biorobotics, often share several fundamental features with the phenomena under investigation in other highly technologically oriented disciplines, such as bioengineering or synthetic biology: they are all 'impure' phenomena, 'not in need of purification' (Bensaude-Vincent *et al* 2017, p 6). Technoscientists do not use these impure phenomena only as means to understand non-human-made systems: their very purpose is to study and control the behaviour of human-made objects (Haraway and Goodeve 2018).

Moreover, by addressing technologically recreated phenomena *per se*, technoscience offers us a new ontological attitude: 'the scientific enterprise and the regime of techno-science came into the world united; they were born as twins. More precisely, the scientific enterprise always had a technoscience commitment at its core […]. What is novel, instead, is that the techno-scientific mode has become dominant over the past decades' (Carrier 2011, p 52). The technoscientific mode is rooted in the indissoluble bond between technology and theory. This intertwinement allows for the presentation and control of objects and phenomena which are no longer part of untamed nature. This is the so-called 'technoscientific turn' in knowledge production, which is massively affecting the bio-hybrid world of the 21st century (Daston and Galison 2007, Friedman and Krauthausen 2021, Tamborini 2022a).

Within this broader characterization of technoscience, one aspect that philosophers have explored in depth is the possibility of formulating clear and precise criteria for distinguishing the 'classical' sciences, such as physics or evolutionary biology, from the technosciences. Many attempts have been made by philosophers and historians, analysing the practices found in putative examples of technosciences and

[3] The 16th and 17th centuries are the prototype for Science 1.0. In moving from the distinction between religious faith and scientific knowledge, autonomous scientific institutions and disciplines emerged. Scientists of this period aimed to discover the true laws of nature with the help of experiments, as aptly described by Bacon in his *Novum Organum* (1620). Science 2.0, which emerged in the second half of the 20th century, seeks to generate hypotheses rather than to explore the deep truth of the world. Moreover, it is not characterized by disciplinary formation and a clear boundary between science and the public, but by the collaboration of laypeople and scientists. In addition, science itself becomes an economic product, as does its data. Thus, philosopher Martin Carrier summarizes the transition from Science 1.0 to 2.0 as follows: 'In sum, the thesis states that science has moved from the seclusion of the academic laboratory into the social arena, operating under novel constraints and undergoing a profound institutional and methodological reorientation' (Carrier 2019, p 156). See also (Tamborini 2022a).

comparing them to the practices adopted in putative examples of 'classical' natural sciences. These analyses have led many scholars to conclude that a clear-cut line of demarcation between these two different approaches is hard to draw (see Klein 2003, Gorokhov 2015, Tamborini 2020). As many philosophers have pointed out, however, at least *paradigmatic* examples of scientific and technoscientific research endeavours can be found, where the distinction hinges on the nature of their object of inquiry. In typical cases of technoscience, the object of inquiry is a technological artefact, whilst in typical cases of science, the object of inquiry is a non-technological artefact. This provisional criterion will be explored and deployed in this paper to argue that contemporary biorobotics has both a scientific and a technoscientific side.

3. Biorobotics: science or technoscience?

3.1. Classical and interactive biorobotics

As discussed in the previous section, the distinction between science and technoscience can be made along several dimensions. However, just one of these is particularly useful for addressing the question approached in this article—i.e. to understand whether, and under what conditions, biorobotics can be properly conceived as a science. The dimension of interest concerns the object of inquiry. In some research endeavours—which will be called technoscientific—the object of inquiry is a technological artefact or a phenomenon that is significantly influenced by technical artefacts. In other cases—i.e. in science as typically conceived—the object of inquiry is not a technological artefact, or it is a phenomenon not significantly influenced by technical artefacts. This distinction is not devoid of problems, one of them being the following. If one stretches the concept of technological artefact to a sufficient degree, all scientific endeavours turn out to be technoscientific. As discussed by several philosophers of science (chiefly among these is Hacking 1983), technological artefacts always shape the contexts in which natural phenomena are observed and studied[4].

This problem will be partially sidestepped here, as the focus of the following discussion is restricted to a particular class of technological artefacts, namely, robotic systems. This restriction may enable one to formulate a reasonable distinction between research endeavours that qualify as technoscientific—where the object of inquiry is a robotic system or a phenomenon significantly influenced by robotic systems—and scientific endeavours whose object of inquiry is non-robotic or a system that is not significantly influenced by robotic systems. Both kinds of research endeavours can be found in biorobotics, leading to the tentative conclusion that some biorobotic studies, but not all, can be properly understood as scientific. This section is devoted to elaborating on this idea.

To prepare the ground for the ensuing discussion, it is worth stating how the term 'biorobotics' is used here. Biorobotics is the use of robots as experimental tools to investigate the adaptive and intelligent behaviour of living systems. As such, it does not refer to a single discipline but to a methodological approach which, as we shall see, is multifaceted. A biorobotic approach can be pursued in disciplines as diverse as palaeontology and neuroscience, to investigate the behaviour of extinct animals or the motor responses of neural tissues in the human brain. What characterises a biorobotic study is the use of one or more robots as experimental tools to investigate the intelligent and adaptive behaviour of a living system. Even though some authors use the term 'biorobotics' to refer to what is more commonly called 'biologically inspired robotics' (see, for example, Ijspeert 2014), the definition offered here is in line with the use of the term made in (Webb and Consi 2001), which is generally recognized as the text that laid the foundations for this approach.

In recent methodological analyses of the field, it has been suggested that two broad kinds of biorobotics can be identified, which have been dubbed classical and interactive (Datteri 2020, 2021b). In classical biorobotics, the robot implements a theoretical hypothesis on the mechanism governing the behaviour of the target living system. By observing whether it reproduces the behaviour of the living system to a sufficient degree, one provisionally corroborates or discards the hypothesis that the implemented mechanism governs the behaviour of the target system too. Classical biorobotics is non-interactive: the robot does not interact with the target living system, but in a certain sense it simulates it (Datteri and Schiaffonati 2019).

One paradigmatic example of classical biorobotics can be found in (Mansour *et al* 2019). In environments full of obstacles, the sonar system of bats receives many interfering and overlapping echoes. How can bats swiftly fly through these habitats avoiding obstacles? According to one hypothesis formulated by Mansour *et al*, bats can 'compare the intensity of the echo onset in the left and the right ear. If the onset of the echo train is louder in the left (right) ear, the bat turns right (left)' (p 2). This hypothesis worked well in simulation. However, the literature suggests that bats also perform acoustic gaze scanning, i.e. they move their head (thus, their sonar system) relative to their body axis according to interaural level differences. Does gaze scanning

[4] The distinction made above is also blurred by the vagueness of the term 'significantly'. Admittedly, this paper does not offer criteria for a clear-cut distinction. However, the argument made here can be useful at least to identify biorobotic studies that are situated at the two extremes of the science-technoscience spectrum.

contribute to efficient obstacle avoidance? To address this question, the authors implemented two hypothetical mechanisms on a mobile robot. The first was solely based on interaural comparison: the head was always aligned with the body axis (fixed head strategy). The other hypothesis combined acoustic gaze scanning with interaural comparison (acoustic gaze scanning strategy). The choice of a robotic implementation instead of a computer simulation was justified as follows: 'compared to computational models, robotic models are especially helpful when modelling the physics and dynamics of the animal's interaction with the environment is difficult […]. In this case, computational models often have to resort to simplifications, which may limit the validity of the results' (p 3).

The two control strategies were tested in real-world environments that returned many interfering echoes to the robot's sensors. In the experimental trials, the fixed head strategy performed better than acoustic gaze scanning in terms of number of collisions. This result was interpreted, on the one hand, as speaking to the performance of the robotic system: 'the results confirm that the robust interaural difference based obstacle avoidance strategy, previously proposed in simulation […], steers the robot away from obstacles, even under very demanding conditions' (p 13). On the other hand, the behaviour of the robot was taken as empirical evidence to support a theoretical hypothesis about bat navigation: 'if the complexity of the environment prevents the bat from inferring the spatial layout of the environment, gaze scanning is disadvantageous' (p 14). Indeed, 'the limited spatial information provided by the interaural differences might not be sufficient to guide the gaze to informative directions. In particular, under these conditions, the cost of not looking where you are going might outweigh the limited benefit of looking around' (p 14).

To sum up, this study is a paradigmatic example of classical biorobotics, as characterized above. The robot implemented a theoretical hypothesis (actually, two competing hypotheses in different sessions) on the mechanism governing the behaviour of the target living system (navigation of bats). By observing whether the robot reproduced the behaviour of the living system to a sufficient degree (i.e. if it could swiftly navigate through cluttered environments), the hypothesis that one of the two implemented hypotheses (the fixed head strategy) governs bat navigation was provisionally corroborated. This study was non-interactive as it included no interaction between the robot and the bats whatsoever. Other examples of classical biorobotics studies can be found in (Grasso *et al* 2000, Lambrinos *et al* 2000, Reeve *et al* 2005). For a comprehensive review, see (Webb 2002, Gravish and Lauder 2018).

Interactive biorobotics adopts a different approach. The role of the robot is not to simulate the system under investigation, but to *stimulate* it. Theoretical conclusions about the behaviour of the living system—typically called a *focal system* in the literature—flow from the analysis of its reactions to the robot. Interactive biorobotics has been adopted to study the behaviour of fish (Phamduy *et al* 2014), locusts (Romano *et al* 2019a), starlings (Butler and Fernández-Juricic 2014), quail chicks (de Margerie *et al* 2011), bees (Michelsen *et al* 1992) and other living species (for a comprehensive review, see Romano *et al* 2019b). The interactive biorobotics approach has also been adopted in contemporary ethorobotics and social cognitive neuroscience (Datteri *et al* 2022). Interactive biorobotics will be illustrated here in a cursory review of two studies, that will be called proximal and distal in section 3.2.

The first study concerns zebrafish shoaling (Ruberto *et al* 2016). What are the determinants of the phenomenon of shoaling in zebrafish? More specifically, what behavioural and physical features must zebrafish A possess to 'attract' another individual zebrafish B swimming nearby? The authors tested the role of two factors: realistic vs. non-realistic appearance, and type of motion (three-dimensional realistic motion, two-dimensional motion, and no motion at all). To this end, they set up an experimental platform in which the role of zebrafish A was played by a robot that could have a realistic or non-realistic appearance, and generated one of the three kinds of motions listed before. Zebrafish B—the focal system—was a real-life zebrafish, swimming in the same pool as A. The behaviour of zebrafish B was analysed in terms of speed and acceleration, distance from the robot, time budgeting along the water column and shoaling tendency, under conditions differing from the characteristics of A. In the experiments, the focal fish B was attracted neither by the static realistic replica nor by the moving non-realistic robot. Instead, it was 'attracted toward the three-dimensional moving replica, and this attraction was lost when either its visual appearance or motion was controlled' (p 11).

Note that this provisional conclusion—representing the main output of the study—specifically concerns the factors determining zebrafish attraction towards *robotic* fish. It is reasonable to suppose that the authors' interest was towards shoaling phenomena in real-life fish, i.e. towards phenomena that are not significantly influenced by robotic systems. However, the authors carefully pointed out that they 'studied the behavioural response of zebrafish to a biologically inspired three-dimensional printed replica'. They also discussed some limiting factors of the robotic set-up, including 'the partial smoothness of the motion imparted to the rod [connecting the replica to the actuator system], the mechanical rigidity of the replica and the rudimentary control of its orientation'. Another potentially limiting factor signalled by the authors was that the interaction between the robot and the focal fish was unidirectional: the motion of the robot was not influenced by the concurrent motion of the focal fish, making the interaction scenario quite different from real-life contexts. The point here was not that the experimental environment displayed limiting factors, which are always present in scientific experimentation. The important aspect worth noting was that the authors of this study carefully avoided making hazardous generalisations from results concerning robot-animal interaction to results concerning animal-animal interaction. In other words, they brought their experimental results to bear on theoretical conclusions concerning how zebrafish interact with *robots*, without making further inferences on how zebrafish interact with one another. This consideration will be expanded on in section 3.2.

The second interactive biorobotics study considered here concerns gaze following in starlings (Butler and Fernández-Juricic 2014). Gaze following occurs when individual B directs its attention to the location of A's gaze. This is a pervasive phenomenon among humans. Does gaze following occur in starlings too? To address this question, the authors of the study proceeded with the same approach adopted in the zebrafish study. They built two robots to play the role of A, replicating the shape and appearance of a male and a female starling. The robots could rotate the whole body and perform head-down and head-up movements[5]. Each experimental session involved the robot and one real-life starling, playing the role of B. The robot could gaze towards the focal starling, or towards a different point P. The experimenters measured B's gaze location and head movement rate (in some bird species, fixation leads to an increase in head movement rate). The results suggested that the robot was able to direct the focal starling's attention: more specifically, the probability that B would look at point P was significantly higher when the robot gazed at P, compared with when the robot gazed at the starling. Note that this consideration concerns how starling B reacts to starling-like robots. It is a theoretical conclusion on animal-*robot* interaction. However, unlike the zebrafish study, the authors bring these results to bear on the dynamics of animal–animal interaction, when they state that 'to our knowledge, this is the first report of a non-mammal reorienting its attention geometrically in response to the orientation behaviour of *conspecifics* in a species with laterally placed eyes. This suggests that starlings recognize the location of conspecific attention' (p 4). The authors of this study make an inferential jump that is missing in the zebrafish study.

No claim is being made here concerning the validity of the inferences made in the zebrafish and starling studies (an issue that is addressed in Datteri 2020). These considerations are purely descriptive and purport to make a distinction between two possible usages of animal-robot interaction data. As suggested here, in some cases, exemplified by the zebrafish study, experimental results are used to support theoretical conclusions about how animal behaviour is influenced by robots. In other cases, exemplified by the starling study, they are brought to bear on the interactive behaviour that animals display without any robotic influence. In the next section, this distinction will be connected to the main question addressed in this paper.

3.2. The object of inquiry in biorobotics: proximal and distal studies

The review of some biorobotic studies made in the section above paved the way for a more precise characterization of the distinction between scientific and technoscientific research endeavours in biorobotics. As happens in science generally, the experimental results in biorobotics can be directly or indirectly brought to bear on a variety of theoretical hypotheses. This said, a tentative distinction can be made between two circumstances. In some cases, the experimental results are validly brought to bear on a theoretical hypothesis that concerns (in classical biorobotics) the behaviour *of the robotic system*, or (in interactive biorobotics) the behaviour of the focal living system *under robotic stimulation*. In other cases, the experimental results are validly brought to bear on a theoretical hypothesis that concerns (in classical biorobotics) the behaviour *of the modelled living system*, or (in interactive biorobotics) the behaviour of the focal living system under stimulations delivered *by another living system*. In the first case, borrowing from (Datteri 2020), the theoretical hypothesis is called *proximal*, in the second case it is called *distal*. When the hypothesis under scrutiny is proximal, the object of research is a robot, or a living system significantly affected by a robot. In the other case, the object of research is a living system or a phenomenon which is not significantly affected by a robotic system. We propose that the first circumstance exemplifies a case of technoscience, whereas the second case can be properly qualified as a case of science. Let us further explore this distinction.

Some stages of biorobotic experimentation are devoted to examining the behaviour of the robotic system involved in the study, or the behaviour of the focal system under robotic stimulation. In classical biorobotics, where the robot simulates a theoretical

[5] This review contains a number of simplifications. The authors built two robots, one resembling a male and the other a female starling, to neutralise the potential effect of the sex on B's reaction. The experimental setting consisted in a three-compartment enclosure, and some theoretical assumptions were used to infer gaze direction from head position (which is a difficult problem, given that starlings have laterally placed eyes and often perform gaze movements). These details are irrelevant to the present goal, which is to show that robots can be used to stimulate living systems in behavioural research, and to introduce the distal nature of this study. For a more informative methodological discussion, see (Datteri 2020).

model of the living system, one may perform preliminary experiments to verify that the robot is working properly (i.e. as intended and expected by the designers and builders). Preliminary test procedures may be needed to sensibly use the robot to test models of cognition and behaviour. More specifically, in biorobotic experimentation, one must ensure that the robot accurately implements the cognitive, neuroscientific, or behavioural hypothesis under investigation, otherwise it is not clear why its behaviour can be brought to bear on it. Accuracy checks may involve experimental tests which are totally focused on the functioning of the robot, with no interest whatsoever in whether the robot can reproduce the behaviour of the living system (this will be the successive stage of experimentation). Experiments on the robots are carried out to test hypotheses on the robot itself, which is why the hypothesis is called *proximal*.

Proximal hypotheses are tested in interactive biorobotics too: here, one is interested in how the focal living system reacts to the stimuli delivered by the robot. Experiments of this kind are always carried out in interactive biorobotics. In some cases, testing animals' reactions to robots is the primary goal of the researchers, and the proximal theoretical hypothesis is the main hypothesis tested in the study. The zebrafish study reviewed in section 3.1 is a case in point. Another example is discussed in (Abaid *et al* 2012), whose goal was to understand how zebrafish respond to robotic fish depending on the characteristics of the latter (aspect ratio, tail beat frequency, noise, and colour). Jolly *et al* (2016) aimed to study whether gallinaceous birds can become socially 'attached' to a robot. Other examples of proximal studies can be found in (Datteri 2020). Testing proximal hypotheses may be of great importance for the design of robotic systems that are able to interact with living systems socially and efficiently. Over and above this engineering purpose, assessing how living systems react to robots is scientifically interesting *per se*, also considering that the world 'out there' will be more and more pervaded with robotic systems in the future. When biorobotics deals with proximal hypotheses, as defined here, it can be aptly qualified as *technoscience*.

In other cases, biorobotics aims at reaching theoretical conclusions concerning the behaviour that living systems produce with no influence by any robotic system—hypotheses that are called *distal* here (and in Datteri 2020). This is the chief goal of classical biorobotics: observing the behaviour of a robotic model enables one to test hypotheses about the modelled system. As described before, Bou Mansour *et al* (2019) tested hypotheses on the mechanisms of bat echolocation using a robotic model. Grasso *et al* (2000) rejected an initially plausible model of chemotaxis in lobsters because a robotic implementation of it did not replicate the behaviour of lobsters to a sufficient extent.

Some interactive biorobotic studies aim at reaching distal conclusions too. The authors of the starling study described in section 3.1 used robots to test hypotheses on gaze following in starlings. de Margerie *et al* (2011) investigated the spatial behaviour of quail chicks using robots. In both studies, biomimetic robots interacted with the focal systems under investigation (lobsters, quail chicks). Eventually, the authors reached proximal theoretical conclusions concerning robot-animal interaction. However, in the same studies, they brought these proximal conclusions to bear on distal theoretical hypotheses. The phenomenon of interest did not concern the behaviour of the focal system in its interaction with the robot, but the behaviour of the focal system in interaction with other living systems. Like in the cases that we called technoscientific, here the goal was to model the working of the world 'out there'. But the world of interest, in this case, was not significantly influenced by robotic technologies. These research endeavours may be aptly considered *scientific* (and not technoscientific) according to the distinction that we made before.

One may doubt that distal studies in interactive biorobotics can be called *biorobotics* at all[6]. Distal studies in interactive biorobotics lead to theoretical conclusions on the interactive behaviour of animals under no robotic influence whatsoever: why, then, call them bio*robotic*? The issue clearly hinges on how biorobotics is defined. Here, as pointed out at the beginning of section 3.1, biorobotic studies are characterised by the use of robots as experimental tools to investigate adaptive and intelligent behaviour of living systems. Distal studies like the starling study discussed in section 3.1 deserve to be called biorobotic because, even though they end up supporting hypotheses on animal–animal interaction, this goal is reached through the use of a robot[7]. Thus, an interactive biorobotic study may be at the same time distal and biorobotic.

[6] We thank an anonymous referee for this point.

[7] One may also doubt that proximal classical biorobotic studies may be called *bio*robotic: if they end up testing hypotheses concerning a robotic system, why not simply call them *robotic*? It would be reasonable to claim that what makes a proximal classical biorobotic study biorobotic is the long-term research goal of the experimenter. As pointed out before, the classical biorobotics approach proceeds by building a robotic system that implements a theoretical model of the living system under investigation (recall the study on bat echolocation described in section 3.1). During this implementation process, a number of sub-studies may be needed to test the good functioning of the robotic system, or to ensure that it actually implements the theoretical model under scrutiny. These sub-studies may be aptly called proximal, to the extent that their object of research is a robotic system, and (classically) biorobotic, to the extent that they are an integral part of a research inquiry whose long-term goal is to study the adaptive and intelligent behaviour of living systems.

Note that, as pointed out in the section 1, the distinction between biorobotics as science and biorobotics as technoscience is not based on the methodological validity of the study: it is assumed that all the studies considered here are valid (whatever validity consists in). However, it should also be noted that scientific studies testing distal hypotheses pose serious challenges to validity. As far as classical biorobotics is concerned, one thing is to perform experiments with a robot in order to test a hypothesis concerning that robot, whilst to generalize the results obtained using the robot to achieve theoretical results concerning the modelled living system is altogether something else. Even though proximal studies may pose methodological challenges themselves, in distal studies one must carry out non-trivial chains of inferences from the behaviour of the robot to the characteristics of the target living system. Justifying these inferences may be tricky, as philosophers of science dealing with the validity of so-called model-based science have extensively shown (for a review, see Frigg and Nguyen 2017).

Similarly, justifying the validity of distal studies in interactive biorobotics can be quite challenging. When one observes how the focal system reacts to the behaviour of a robot nearby, what entitles them to conclude that the focal system will react in the same way to the same stimuli when they are delivered by a living system represented by the robot? What authorises one to believe that the factors that modulate robot-animal interactions will similarly modulate animal–animal interaction? In distal studies—the scientific province of interactive biorobotics—one has to fill the epistemic space between the behaviour of a living system in a technologically mediated environment and its behaviour in an environment devoid of robots. Some insights on how to rationally do that have been offered in (Datteri 2020, 2021b).

4. Concluding remarks

In this paper, we analysed the philosophical distinction between science and technoscience and then we applied that distinction to biorobotics to reflect on whether it can be sensibly qualified as science. Our starting point was the features of the objects of inquiry. In technoscientific research, the object of inquiry is a technological artifact or a phenomenon significantly influenced by technical artifacts. In scientific research, on the other hand, the object of investigation is not a technological artifact, nor is it substantially modified by one. Building on this assumption, we isolated different kinds of objects of inquiry in biorobotics and paired them to the distinction between 'proximal' and 'distal' hypotheses. We argued that in proximal studies, the object of inquiry is a robot or a living system that is significantly influenced by a robot (such as in the case of the zebrafish response to a robot, see section 3.1). In a distal hypothesis, the object of inquiry is a living system or a phenomenon that is not significantly influenced by a robotic system (like the robotic model of bat obstacle avoidance, and the starling studies, illustrated in section 3.1). We proposed that the first circumstance illustrates a case of technoscience, whilst the second case can be qualified as a case of science.

By defending this claim, this article intended to pursue several goals. First, since today's biorobotics have emerged from a 'synthetic approach' (as professed by Hull and others during the 1960s, Cordeschi 2002) and strong hybridity (as advocated by the *New Bionics* of the 1980s, Dario *et al* 1993), our work has brought clarity to the different components, approaches, and the role of objects of inquiry that characterize the practices that are clustered under the umbrella term 'biorobotics'. These distinctions are important for understanding the possible different theoretical, philosophical, and conceptual issues that can be locally found in the diverse biorobotic methods and approaches. As shown, it is one thing to use robots for a technoscientific purpose. Using robots for a scientific purpose is something altogether different. Different conceptual and practical issues are at the heart of these two endeavours, as briefly illustrated at the end of the previous section. As a result, this paper has called for a pluralistic philosophical comprehension of biorobotics.

Second, to emphasize that there are strong technoscientific and scientific components in today's biorobotics is to accept and develop further the rationale that was used to coin the term 'technoscience' in recent decades. As noted in section 2, the term technoscience was, among other things, coined to emphasize how knowledge production is fundamentally and strongly connected to economic, technological, and hybrid components. Our paper drew attention to the key role of technology (and other components) in biorobotics, thus opening a possible dialogue between biorobotics and other strongly technological and bio-hybrid disciplines (such as nanotechnology, palaeontology, synthetic biology etc—on this possible dialogue, see Tamborini 2022a, 2022b, 2023).

Third, not only did our paper show how technoscientific and scientific components can coexist to produce knowledge, but also that they must do so. The idea of a supremacy of pure over applied sciences or of a conflict between scientific and engineering cultures is a legacy that has no place in the genuine practice of today's sciences. In biorobotics, as in many disciplines, technoscience and science do coexist, because they inform one another.

Fourth, in asking how biorobotics can be considered a science and by focusing on the features of the objects of inquiry in biorobotics, this paper initiated a possible joint comparative study between the practices of biorobotics, the notion of organism as it emerges from distal and proximal studies, and what happens in other technology-driven disciplines. In a recent paper, Rijssenbeek *et al* (2022) developed some guidelines for an ontology of hybrids based on the analysis of technoscientific production in synthetic biology. One of the major achievements of their analysis was to transcend classical philosophical identities (e.g. the identification of an organism with a more or less complex machine) to highlight new tools and metaphors suitable for capturing scientists' epistemic (and ontological) presuppositions in dealing with hybridity.

But what happens when we widen our viewpoint and question the characteristics of the hybrid object of study?[8] In other words, if, as suggested in this article, we take the epistemological and ontological claims of biorobotics seriously (e.g. by focusing on the objects of inquiry) and analyse how distal and proximal approaches intersect and hybridize in scientific practices, what kinds of new epistemological terms, categories, and claims might we find? By this hybridization we mean not only that the object of inquiry is both natural and technical, like Haraway's OncoMouse, but that scientific and technoscientific practices and approaches intermingle. A primary example of this would be where scientists use a robot to study OncoMouse behaviour or to control the robot-organism relationship in an experimental context of interactive biorobotics. In this case, what new philosophical taxonomies might emerge? What new features would the distinction between technoscience and science take on? What new metaphors might we need to work with and understand hybrid elements?

Last, by showing the technoscientific and scientific components of biorobotics, our work has called for a greater awareness of the role of biorobotics in the biotechnological world of the 21st century. Studying animal-robot interaction in a technological context means entrusting biorobotics with an important role: the possible development of a combination of smooth functioning bio-hybrid systems that will shape 21st-century society, thus the possibility of finding biotechnical solutions to major global problems.

Data availability statement

No new data were created or analysed in this study.

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