Robots communicating with fish: Integration requires reciprocal interaction

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Abstract

Animals that live in social groups must interact in order to stay together and move collectively. By socializing a robot with a group of weakly electric fish, we aim at answering fundamental biological questions about the rules that govern social interactions and cause group members to coordinate their movements and come to joint decisions. African weakly electric fish communicate at night by emitting and perceiving short electrical current pulses, a process called electro-communication. Our experiments have shown that it is only possible to integrate a robotic agent into a group of electric fish if it emits electric signals and engages in electro-communication. All other sensory cues, like visual appearance, can be neglected. For full acceptance as a conspecific by live fish, the robot must be able to interact with the animals. We hypothesize that the integration of fish and robot into a mixed society can succeed when the robot's electric signaling interaction is matched by locomotor interactions that are congruent with the behavioral relevance of electro-communication.

Background

Many animals are social and live in groups of different sizes and different degrees of complexity, communicating with group members in a variety of ways (Cafazzo et al., 2016; Couzin, 2006). Many fish form shoals, which according to Pitcher and Parrish (1993), are groups that stay together due to social attraction. How do the individuals in shoals coordinate their movements and come to joint decisions? Understanding these group dynamics and coordination has recently attracted significant attention in scientific research. Here we study these questions by introducing a robotic agent into a group of fish to form a mixed society of fish and robot.

Weakly electric fish of the family Mormyridae are of particular interest as model organisms for studying social coordination in groups. Different species display different types of highly complex social behaviors ranging from territorial and aggressive interactions to nocturnal hunting associations (Arnegard and Carlson, 2005), and the formation of large diurnal shoals (Carlson, 2016).

Mormyrids are nocturnally active and rather independent of visible light. Instead of using visual signals, these fish have a special 'electric organ' with which they generate brief electrical pulses, called electric organ discharges (EODs), to probe their environment ("active electrolocation", von der Emde et al., 2010) and communicate with conspecifics (Gebhardt et al 2012). Experiments with *Mormyrus rume* revealed that these mormyrids rely on their electro-sensory modality for social coherence and shoal formation (Donati et al 2016; Worm et al 2017). Mormyrids use information contained in a conspecific's EOD to localize and approach another individual (Hopkins, 2005), and can even track an artificial, bodiless EOD signal source that is moving along a trajectory (Worm et al., 2018a).

However, electrical signaling does more than just keep the group together. During electro-communication, mormyrids can exchange identity information based on the waveform of their EOD (Carlson, 2016), as well as contextual information through the modification of the inter-discharge intervals (IDI) (Gebhardt et al., 2012; Baker et al, 2016). Besides emitting context-specific IDI patterns, the analysis of electric signalling in grouping mormyrids revealed that these animals frequently engage in episodes of interactive signalling by synchronizing their EODs to each other at very short latencies of only a few milliseconds. This synchronization is afforded by a unique behavioural mechanism known as the mormyrid echo response (Russel et al., 1974 Gebhardt et al., 2012).

Weakly electric fish are particularly well suited for studying social behaviour using robotic approaches since a central feature of their communication — the emission of electrical signals — is easily reproduced and manipulated by electrical playback experiments.

Integrating robots into fish groups

In this project, we aimed to address these questions using biomimetic fish robots that serve as communication partners in a shoal of electric fish. Our robotic agents infiltrate the natural group with the aim to be accepted as a conspecific. Using these artificial fish, we can test different hypotheses to decipher the communicative value of different EOD patterns as well as interactive EOD synchronizations. Much work on robots replacing conspecifics to elucidate the rules governing social interactions has been put forward in the last decade for a variety of species (Romano et al. 2019, Mondada et al., 2013). With biomimetic robots we have full control over the cues we place in a social system (Krause et al. 2011). This permits us to disentangle complex behavioural displays and ask which cues are actual signals, which are by-products? We can implement our current understanding into robots and test our models in the real world.

In this project, we want to investigate the basic processes that support social interactions in shoals of weakly electric fish by developing a biomimetic electric fish robot that communicates with the fish in the group. Thus, we can investigate which

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robotic features are necessary for forming a mixed society of robots and live fish (Aguilar et al 2014). How realistic does the robot have to be and which sensory signals are required to achieve this goal?

Results

The necessary realism of the robot's appearance mainly applies to its electrical behaviour: In consecutive studies (Donati et al., 2016; Worm et al. 2018b), we could show that in a group of electric fish electro-perception is used to perceive both the locomotor behaviour and the electro-communication signals of another fish or a robot. Visual cues or short-distance cues sensed through the lateral line were not found to be relevant, since a moving, but invisible and body-less electrical signal source was also sufficient to evoke the full spectrum of social behaviour in the fish (Worm et al 2018b).

In Worm et al. (2017) we found that animals are attracted to the robot when it emitted EODs, but attraction was largely independent of the particular playback pattern that was emitted by the replica. However, whether fish responded with electrical double pulses or regularization displays – two temporal patterns of EOD which probably bear communicative meaning for the fish - varied depending on the robot-emitted playback pattern. These findings support the idea that certain IDI-patterns convey information while the EOD itself could play a role in mediating spatial interactions and social cohesion of individuals within groups of weakly electric fish.

When comparing following-behaviour of fish in mixed groups (two fish following one robot) with the behaviour of natural groups (two fish following another fish), we found no differences in most spatial observables (Pannhausen et al. 2018). Also, the electrical behaviour (e.g. regularization, double-pulses) and interactive electro-communication patterns directed towards the replica were similar in both groups. However, some important differences were observed: the fish swam closer to the robot than to their living companion, they showed more attempts of synchronizing their EODs with the dummy and they swam longer in its proximity. These differences in the fish´s interactions with the robot could have been due to its "abnormal" locomotor behaviour and the lack of interactive electric signalling of the robot, which was unable to respond to their synchronization attempts because of the open-loop design of these experiments.

Our first attempt to design a closed-loop experiment with a mixed pair of a live electric fish and a robot was made by Worm et al. (2018a). In this study, a freely moving replica was used, whose position could not be controlled as a function of the other fish but it was able to produce echo responses to the fish's EOD, i.e. the dummy could synchronize electrically with the fish. It turned out that back-synchronizations of EOD-sequences of *M. rume* with the mobile robot were strongly enhanced (in frequency and duration) when the robot synchronized itself. An animal that received echoes reacted by responding with more echoes of its own - more than it produced when the robot did not echo. The onset of strong synchronization by the fish was frequently associated with an approach configuration, i.e., the fish approached the replica in a stereotyped manner by coming from behind and then catching up into a more lateral position. Mutual synchronization in mormyrids may thus serve a communicative function in integrative behavioural contexts. Based on these observations we suggested that echoing provides a relatively simple electromotor mechanism to address a particular individual electrically and forms a strategy for the mutual allocation of social attention (Worm et al., 2018b).

Discussion

In our experiments, we showed that in order to be followed by the fish, a robot could be reduced to just a disembodied dummy electrode moving in the ground. The behaviour of living fish when following the disembodied dummy electrode closely resembled the behaviour of single animals following an EOD-emitting fish replica moving through the water (Worm et al., 2017). Our results support the hypothesis that it is only electro-communication mediated through the electric sense that is used to evoke spatial interactions between individuals and thus also between a robotic agent and living fish.

Such findings have interesting implications regarding socially and cognitively complex behaviours of mormyrids, which are increasingly recognized to exist among different species of fish (Bshary et al., 2014). In particular, we hypothesized that mormyrids could address another fish by matching its signalling sequences with high temporal precision and thus addressing it individually in a manner that will be perceived as an intent to communicate. This echoing behaviour, if reciprocated, then leads to a mutual synchronization of IDI sequences and could establish a communication framework that facilitates the exchange of signalling information contained in the EOD between two fish for the duration of synchronization. This may enable communication in the electrically noisy environment of a group of mormyrids. Combined with the proven capability to recognize individuals and their social status based on the waveform of their EOD (Paintner and Kramer, 2003; Terleph and Moller, 2003), synchronization may thus have served as a foundation for the evolution of relatively advanced cognitive capacities in mormyrids.

In our previous studies we could not find an effect of the robot's electrical synchronization behaviour on inter-individual distances or the spatial distribution of the shoal in comparison to random sequences of EODs. On the other hand, the lack of an effect of electrical synchronization alone on quantifiable motor behaviour of the fish is not surprising, since, according to our hypothesis, EOD synchronization establishes a social attention framework rather than carrying a particular message. In a follow-up project, we will test whether an appropriate post-sync behaviour of the robot will have an effect on fish behaviour. Additionally, the reason why synchronization alone did not elicit distinct responses reflected in the fish's locomotor behaviour towards the robot could have been because our robot was not moving in accordance with what would have been appropriate behaviour based on the signalling information exchanged during synchronization. This means that the robot was not operating fully in closed-loop with respect to locomotor responses and thus could not respond to the fish on this level. In both cases, the robot would not reciprocate appropriately from the perspective of the fish, which could lead to a premature termination of interactive behaviour patterns. In a future project, we want to overcome these problems by designing a fully interactive robot, which operates in closed loop both electrically and locomotory.

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