Towards Multi-Context Two-Way Communication Between Humans and Common Octopuses: An AI-Assisted Approach

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We document and analyze two-way, multi-context communication between humans and common octopuses *(O. vulgaris)*, using AI technologies and long-term behavioral observations. We show the octopus's capacity for complex, context-dependent interactions, significantly surpassing previously documented cephalopod communication abilities. Our findings challenge traditional views on invertebrate cognition and open new avenues for interspecies communication research.

Cephalopods, particularly octopuses, have long fascinated researchers with their remarkable intelligence and problem-solving abilities[1,2]. The common octopus (*O. vulgaris*) has demonstrated capabilities that have questioned our understanding of invertebrate cognition, including tool use, abstract symbol recognition, play behavior, and observational learning[3].

The interspecies communication from octopuses to other animals presents a unique challenge[4], as they lead a predominantly solitary lifestyle. Their social contacts appear to focus on courtship and mating encounters. However, our recent observations indicate a capacity for spontaneous and complex interactions with humans. This apparent contradiction – between their limited intraspecies communication and their readiness to engage with humans – presents both a challenge and an opportunity for interspecies communication research. Common octopuses possess a neural complexity that rivals or exceeds that of many vertebrates, with approximately 500 million neurons already at early stages of their life, similar in number to those of dogs. This level of neural sophistication suggests the potential for emergent cognitive capabilities, apparent in both the evolution of animal species, but recently also in large language models (LLMs), where increased processing capacity has led to qualitative leaps in functionality[5]. *O. vulgaris* may well have passed a cognitive threshold where their neural complexity allows for advanced communication and problem-solving skills, even if these are not fully utilized in their natural, solitary environments.

The difficulty lies in deciphering and interpreting behaviors that may not have evolved specifically for communication but seem to be repurposed for interaction with humans. As Yovel and Rechavi (2023) point out, interpreting animal communication signals is significantly limited by our human *umwelt*[6]. This anthropocentric bias is particularly challenging when studying a species with such a different evolutionary and social background. We thus aim to be extra vigilant in overcoming the limitations of human interpretation and developing a more objective understanding of octopus behavior and potential communication. Our approach aligns with the growing trend of using AI to study animal behavior, as highlighted by Valletta et al. (2017)[7].

Our study is currently limited to a single male European Atlantic common octopus, observed over a period of 9.5 months in a specially designed 2000-liter laboratory aquarium. The aquarium is equipped with enrichment items and multiple 'dens' for the octopus. A key feature of the setup is an LCD screen on the aquarium wall used to display various visual stimuli. Ten high-resolution 4K cameras with infrared capabilities are continuously monitoring the aquarium. Infrared illumination, which is invisible to octopuses, allows for non-intrusive observation during dark periods. This setup has resulted in over 5000 hours of recorded interactions.

Currently, we have implemented a YOLOv8[8]-based computer vision system for octopus detection and tracking. This system has so far been trained on a dataset of 1900 images containing 1700 octopus instances, achieving an mAP50 of 0.902 and mAP50-95 of 0.613. However, the current implementation is limited to tracking the octopus's position as a moving rectangle, with significant uncertainty due to the octopus's ability to rapidly change its skin color, pattern, and body shape.

We plan to use generative AI to confirm our interpretations of behaviors in differentiating between similar gestures used in different contexts (e.g., 'greeting' vs. 'thank you' gestures). Figure 1 shows the presumed 'thank you' interaction and the 'gratefulness' pulsating skin pattern.

Through manual annotation and preliminary AI-assisted analysis, we have observed several behaviors that suggest potential for complex communication: (1) The octopus has developed a consistent greeting ritual, involving eye contact, arm extensions towards humans, pulling and pushing the arm, as well as characteristic skin color changes. (2) We have observed distinct motions, pushing with its arm, skin color and texture changes that appear to be associated with different emotional states. This includes, e.g., a "frowning" appearance with vertical wrinkles between its eyes when the octopus seems aggravated. (3) The octopus uses gestures that seem to indicate specific needs: a) A distinct 'food gesture' involving pulling the human's hand towards its beak. b) Gesturing towards the TV screen, potentially to request video content. c) Alerting humans to waste in the tank by squirting water or pointing with an arm. (4) The octopus initiates and participates in games with humans, showing a capacity for shared attention and social interaction. (5) The octopus uses gestures that appear to request changes in its environment, such as adjusting lighting or removing obstacles blocking its view of the TV.

While these observations are promising, we face several challenges in their interpretation:

1. Distinguishing between intentional communication and hard-coded behaviors.

2. Understanding the flexibility and context-dependency of certain gestures. E.g., the ‘food gesture’ is sometimes used after feeding while rejecting additional food, likely indicating satisfaction with food rather than hunger, or possibly that that was something the octopus would like to be offered again soon.
3. Interpreting complex sequences of behaviors, such as when the octopus gesticulates towards the TV while holding a human's hand, or pulling with one arm while pushing with another one.
4. Avoiding anthropomorphic bias in our interpretations of octopus behavior.

Figure 1. Human-octopus interaction demonstrating potential communication behaviors.

The octopus extends an arm towards the human's hand and touches it in a possible ‘greeting’ or ‘thank you’ gesture. It is likely the ‘thank you’ variant, since the octopus had just been fed and been awake for some time. The octopus's skin shows the characteristic pattern of pulsating black dots and lines on a pale background, potentially indicating either ‘happiness’ or ‘gratefulness’. Only the body half facing the human is pulsating, thus more likely signaling ‘gratefulness’ towards the human, though it might be an expression of ‘happiness’ too.

To illustrate the complexity of the observed interactions, we present a detailed example of a food-related communication sequence: (1) The octopus initiates the interaction by making eye contact with the human caretaker and extending an arm towards them. (2) The octopus then performs a distinctive ‘food gesture’ by gently pulling the human's hand towards its beak. (3) The human responds by making an OK and thumbs-up gesture, then showing the octopus a set of photo cards representing two or three food options for the day. (4) The octopus gestures towards its preferred food choice with one of its arms. (5) The human acknowledges the choice by taking down the other photos and shows the octopus the selected food item before placing it in a separate container to thaw. (6) While waiting, the octopus often turns its attention to watching videos from its den, seemingly to pass the time. (7) Once the food is ready, the human presents it to the octopus, sometimes incorporating it into a puzzle or enrichment device. (8) After feeding, the octopus typically performs the interaction depicted in Figure 1. In case the food was particularly well liked, the octopus can perform more energetic ‘thank you’ gestures. (9) In special cases, it will perform the ‘food gesture’ in a symbolic way, even though it just ate a large portion, presumably to indicate its satisfaction with the offered food. This has happened with fresh oysters five times so far, since they are a rare treat and very filling, so in this case the food gesture most likely does not mean hunger. (10) The octopus then sometimes assists in cleaning by pushing food remnants towards the human or a designated waste container.

Together, this sequence demonstrates the octopus's ability to engage in a prolonged, multi-step interaction, showing evidence of intention, choice-making, patience, and even cooperation in maintenance tasks. Such complex behaviors challenge our understanding of cephalopod cognitive capabilities and suggest a sophisticated level of interspecies communication.

To advance our understanding of octopus communication and address the challenges we have encountered, we propose the following research directions:

1. Enhance our YOLOv8-based system to better handle the octopus's dynamic camouflage and shape-changing abilities.
2. Develop arm tracking algorithms to identify and follow individual arm movements, crucial for gesture recognition and pose understanding, and particularly challenging in octopuses.
3. Develop an algorithm to detect dynamic skin color and pattern changes, with direction of the body half facing the human interlocutor, in particular skin pattern changes around eyes and pupil dilation.
4. Implement eye-tracking to understand the octopus's focus of attention during interactions.
5. Recognize particular behaviors such as the 'telescoping' (hide and seek from behind a barrier).
6. Recognize the 'papillae', small horns that can be extruded above the eyes of octopuses. These structures are thought to be used as a camouflage technique in nature. Octopuses can control the size and shape of their papillae to mimic various textures in their environment, such as algae, rocks, or coral, enhancing their ability to blend in and avoid predators. It is unclear what their meaning could be when visible in interactions with the human while not hiding. Maybe a sign of caution?
7. Develop machine learning models to recognize and classify different interaction contexts (e.g., feeding, play, rest, requesting a video change).
8. Use sequence and multi-modal analysis, integrating visual data (e.g., detection of the easily recognizable feces ejection) with other sensor inputs (e.g., presence of human, water quality, time of day) to provide a more comprehensive understanding of the octopus's state.
9. Design and implement a system of picture cards or symbols that the octopus can use to make choices or express needs more precisely, e.g., to complement its gestures towards the TV.
11. Explore the potential of electro-mechanical interfaces (e.g., levers or buttons) that the octopus could manipulate to communicate specific desires or control devices, e.g., the TV or light.
12. Develop adaptive digital interfaces on the tank's LCD screen, allowing for more complex interaction scenarios, possibly even species-adapted video games such as 'catch the crabs'.

13. Use large language models (LLMs) to analyze patterns in the octopus's behavior and generate hypotheses about potential meanings. E.g., this is how Claude 3.5[9] describes the photo in Figure 1: "The image shows an octopus in what appears to be an aquarium or tank. The octopus is large and has a mottled, textured skin with various shades of gray and brown. Its body is visible, along with several of its tentacles*[sic]*. One tentacle is prominently extended upward, possibly interacting with something out of frame." While octopus arms scientifically are not called tentacles, this nevertheless shows the developing capabilities of already current frontier LLMs to help with the analysis.
14. Implement a system that can suggest new experiments or interaction scenarios based on observed patterns and gaps in our understanding.

For the future, we plan to increase our sample size by replicating the study with multiple octopuses, allowing us to identify individual differences and common patterns, and to extend the study to octopuses in the open sea, with several dens near each other and an entertainment center in the middle of the 'octopus village', together with remote interactions and observation.

From a technological perspective, the challenges posed by octopus communication could drive innovations in AI and machine learning, particularly in the areas of context-dependent pattern recognition and multi-modal signal processing.

We face several significant challenges in this research:

1. Avoiding anthropomorphic bias in our interpretations of octopus behavior.
2. Ensuring that our interactions and experiments do not cause stress or harm to the octopus.
3. Balancing the need for a controlled environment with the desire to observe natural behaviors.
4. Addressing the 'Wittgenstein obstacle' described by Yovel and Rechavi (2023)[6] highlighting the challenge of communicating about contexts outside the octopus's natural repertoire. However, as our observations with light and TV show, this seems less a problem for octopuses.

Ethically, we must consider the implications of developing more advanced communication systems with a non-human species. This includes questions about the potential for exploitation, e.g., for military applications, and the responsibility that comes with increased understanding.

Concluding, our research represents a pioneering effort to understand and facilitate communication between humans and octopuses. While we are still in the early stages, our preliminary observations suggest a rich potential for complex, context-dependent interactions that challenge our preconceptions about invertebrate intelligence and communication. This work not only contributes to the field of animal cognition and communication but also opens up new avenues for exploring intelligence and consciousness. The ability to communicate across species boundaries may prove to be not just a scientific curiosity, but a crucial skill for the future of our planet.

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Ethical Statement and Data Availability: This long-term behavioral study was conducted in a private aquarium, with only sub-threshold interactions w.r.t. EC directive 2010/63/EU of several caretakers with a single Octopus vulgaris (supplier: Flying Sharks, Portugal). Husbandry and enrichment practices followed best practices for octopus aquariums in compliance with FELASA guidelines. The data used in the study are available in a public repository via https://bit.ly/m/octopus-intelligence

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