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Odors from marine plastic debris elicit foraging behavior in sea turtles

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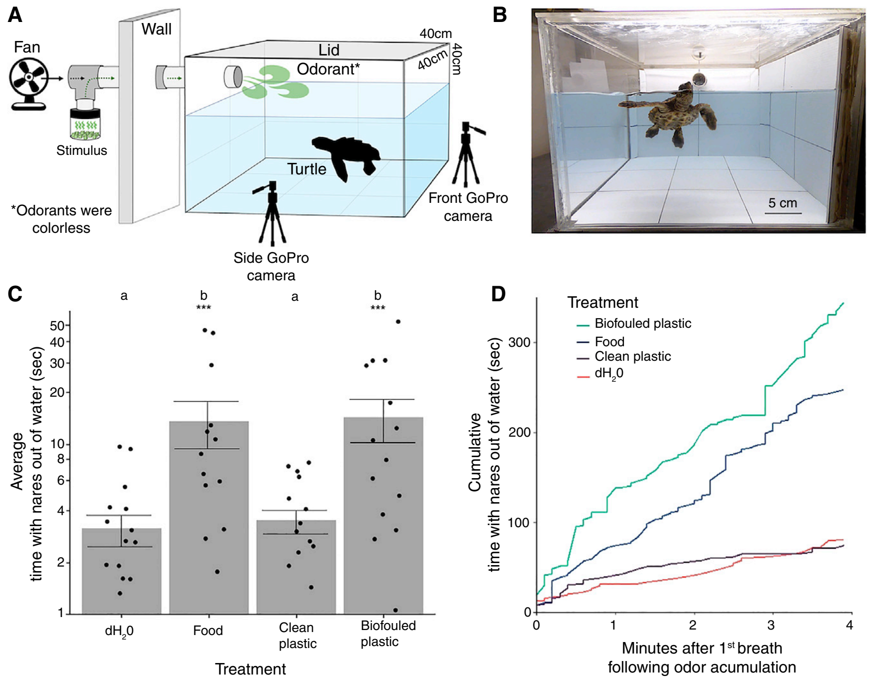

Figure 1. Experimental set-up and the response of sea turtles to odors emanating from biofouled plastic relative to other treatments.
(A) Diagram of experimental setup used to present olfactory stimuli to turtles and record turtle behavior. (B) Turtles respond to olfactory stimuli by extending their nares out of water and sampling the air. (C) Average time with nares out of water (seconds) in response to the four different olfactory treatments: dH_2O (N = 14), food (N = 13), clean plastic (N = 13), and biofouled plastic (N = 14). Y-bars show standard errors, which are more useful when comparing means and when sample sizes are small. Asterisks indicate significant differences in a linear mixed-effects model (p values < 0.005; see Supplemental Information) and different letters (a versus b) indicate significant differences from Tukey's pairwise comparisons ($p < 0.05$). Pairwise comparisons with the same letter (a or b) indicated no significant differences ($p > 0.05$). (D) Cumulative time with nares out of water of all turtles (seconds) in response to the four different olfactory treatments. Each time point represents the total number of seconds for all turtles combined. See also Figure S1 and Table S1.

Plastic debris is rapidly accumulating in the oceans [1]. Nearly 700 species of marine animals, including endangered megafauna like sea turtles and whales, are threatened by plastic debris through ingestion and entanglement [2]. Despite the ubiquity of this threat, little is known about the sensory mechanisms that drive wildlife to interact with plastic debris. Recent findings suggest that marine animals may be attracted to plastic debris not only by the way it looks, but also by the way it smells. The same airborne odorants used by marine predators to identify prey and locate areas of elevated ocean productivity also emanate from marine-conditioned or 'biofouled' plastic debris [3,4]. Whether these sensory cues drive interactions with plastic in marine megafauna has not been tested. Here we report that oceanic-stage loggerhead sea turtles (*Caretta caretta*) respond to airborne odorants emanating from biofouled plastic in the same way that they respond to food odorants. These findings demonstrate that sea turtles detect odorants associated with marine plastic and raise the possibility that such odorants are sensory cues that facilitate fatal interactions.

Experiments were conducted on 15 captive-reared loggerhead turtles collected from Bald Head Island, North Carolina, each approximately 5 months of age. Following a 20-minute air-out period to remove all residual odors, each turtle was placed gently in an experimental arena and allowed to acclimate for approximately one minute prior to adding a stimulus (Figure 1A). Airborne odorants were delivered through a pipe into the experimental arena where the behavior of the turtle was video recorded (Figure 1A). Odors were allowed to accumulate for two minutes in the arena; then, after the turtle surfaced to breathe and could thus sample airborne odorants, we collected behavioral data for four minutes. Each turtle was exposed to four different treatments in random order: deionized water (100 ml); turtle food (a minced 20 g pellet containing fish and shrimp meal); clean plastic (one empty 500 ml water bottle cut into 10 equal pieces); and biofouled plastic (one empty 500 ml water bottle exposed to biofouling by micro- and macro-biota for five weeks in the marine environment and cut into 10 equal pieces). For biofouled plastic, we took care not to remove biofilms or dislodge fouling organisms following the biofouling period, and we used a different biofouled plastic bottle for each trial. Full methodological details are described in the Supplemental Information.

Previous studies have shown that sea turtles can detect airborne odorants, including odors from food and dimethyl sulfide, a volatile organic compound found in productive oceanic foraging areas [5,6]. In response to these sensory cues, turtles become more active and spend more time with their nares protruding out of the water (Figure 1B), behavior that presumably reflects increased sampling of the air and represents the start of foraging behavior. We used the time that each turtle spent with its nares out of the water and the number of breaths taken as objective behavioral responses to different experimental treatments.

Our results indicate that odors from food and biofouled plastic elicited indistinguishable behavioral responses ($p = 1.0$), which were significantly stronger than responses to other treatments (deionized water and clean plastic; p values < 0.01) (Figure 1C; Table S1). Specifically, we found that turtles kept their nares out of the water more than three times longer in response to odors from their food and biofouled plastic relative to control odors (Figure 1C,D). We found the same qualitative pattern for the number of breaths taken by turtles (Figure S1, Table S1). These results indicate that sea turtles can detect airborne odorants emanating from biofouled plastic and respond to them in the same way that they respond to food odors. Moreover, these findings are consistent with the hypothesis that odors emanating from biofouled plastic stimulate foraging behavior in sea turtles and contribute to turtles' attraction to marine plastic debris.

Sea turtles encounter marine plastic debris throughout the marine environment, but why turtles are attracted to floating and submerged plastic has remained enigmatic. One hypothesis is that sea turtles *visually* mistake plastic debris such as plastic bags for jellyfish prey [7]. However, sea turtles also ingest other plastics that bear no clear resemblance to jellyfish [8] and occasionally become entangled in large mats of plastic debris that presumably are not being confused with food [9]. The 'plastic-jellyfish' hypothesis therefore fails to capture the true scope of interactions between turtles and plastic debris or the sensory mechanisms involved. Instead, our findings provide a possible unifying explanation for why such incidents frequently occur.

The exact nature of the plastic-associated odorant(s) detected by the turtles cannot be determined from this study. One possibility is that the observed response was attributable to dimethyl sulfide, a volatile odorant perceived by turtles [6] and that emanates from the algal and microbial biofouling community associated with marine plastic [3]. In addition, plastic debris provides a substrate for other fouling organisms such as encrusting bryozoans, hydrozoans, and crustaceans, some of which might produce volatile organic compounds [10]. Although the present study focused on airborne odorants, it is also possible that waterborne chemical cues associated with plastic, or a combination of airborne and waterborne odorants together, elicit responses from turtles. Indeed, the possibility that airborne odorants dissolved into the sea water during trials cannot be excluded, although previous results suggest it is unlikely [5]. Further research will be needed to identify the precise odorants to which turtles respond and the effects that they have on turtle behavior.

Airborne odorants provide sensory cues that attract marine predators, like sea turtles, to areas with enhanced foraging opportunities [3,6]. If biofouled plastic debris provides similar cues, then areas of concentrated plastic debris could become 'olfactory traps' that attract turtles from considerable distances away and cause normally adaptive foraging strategies to become detrimental or even lethal [4]. Whether through ingestion or entanglement, foraging strategies that increase the frequency of interactions with marine plastic debris threaten both wildlife and their role in the ecosystem. Understanding the mechanisms that underlie the attractiveness of marine plastics is therefore critical for optimizing mitigation efforts to protect wildlife and ecosystems threatened by the ever-rising levels of marine plastic debris.

DATA AND CODE AVAILABILITY

The dataset generated during this study is available at GitHub [https://github.com/kaylago/Pfaller_etal_Turtle_Odor_Data/invitations].

SUPPLEMENTAL INFORMATION

Supplemental Information includes one figure, one table, experimental procedures, and supplemental references and can be found with this article online at https://doi.org/10.1016/j.cub.2020.01.071.

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AUTHOR CONTRIBUTIONS

Conceptualization: J.B.P., M.A.G., M.S.S. Data curation, investigation, visualization, and writing of the original draft: J.B.P., K.M.G. Formal analyses: K.M.G., M.A.G. Methodology: J.B.P., K.M.G., M.A.G., M.S.S. Resources: J.B.P., K.J.L. Supervision: M.A.G., M.S.S., K.J.L. Writing at the review stage and editing: M.A.G., M.S.S., K.J.L.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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