New methods used to analyze genomic data, such as PSMC, are a rich resource for probing various questions, including the presumed effects of climatic fluctuations on various taxa. Indeed, while these data can only tell us so much, our ignorance of these remote historical times is ebbing. The study of Nadachowska-Brzyska *et al.* [3] represents thirty-eight small steps towards a more holistic understanding of how organisms have responded to environmental changes in the past. Hopefully the addition of new genomic data from many other species will provide an even more in-depth treatment of these important questions.

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Group Behavior: Social Context Modulates Behavioral Responses to Sensory Stimuli

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A new study reveals an unanticipated role for social context in driving group behavior of a solitary species to a sensory stimulus and is mediated by mechanosensory neurons signaling touch interactions among individuals.

A hallmark of the brain is that a singular input does not always elicit the same output; rather a given input might produce a variety of outputs depending on the current internal behavioral, and external states of the animal. This makes sense, as in order to generate a contextually appropriate behavioral response, an organism must not only objectively discriminate salient sensory stimuli from background noise, but also must assign value or valence to those stimuli, and it is these subjective evaluations that depend on the context or 'state' of the individual. While there exists a strong foundation of experimental and theoretical evidence across species for collective behavioral dynamics aiding in the navigation of sensory cues [1–3], we have a relatively poor understanding of the molecular and circuit machinery that drive such interactions. A recent study by Ramdya *et al.* [4] adds to the growing evidence for external state modulation of behavior by showing how social context modulates reactions to a characteristic sensory signal within the solitary vinegar fly *Drosophila melanogaster*.

Ramdya *et al.* [4] discovered a peculiar 'herd effect' in flies exposed to carbon dioxide (CO_2), which has been shown to drive a robust aversive escape response in walking flies [5,6]. To their surprise, they found that solitary flies only weakly avoid CO_2, and that only a group of flies strongly avoid the CO_2. This finding is broadly reminiscent of a classic study on human group behavior in which subjects were asked to take a written test. Smoke was then pumped through the ventilation system. If there was only one test subject, 75% of the time the subject calmly left the room and reported the smoke. For a test group of three or more, only 10% of the time did somebody get up and report the smoke, even though the room became hazy with smoke that provoked coughing [7]. Ramdya *et al.* [4] use the CO_2 behavioral paradigm alongside computational modeling, genetic mutations, neuronal silencing, and optogenetic activation to begin to dissect apart the molecular and neuronal mechanisms that enable a sensory stimulus to elicit differential behavioral outputs in a population-density dependent manner.

Ramdya *et al.* [4] developed an automated behavioral assay whereby they could observe freely-walking individuals or groups of flies presented with air on one side and CO_2 on the other side of a two-choice olfactory arena. Flies were left to wander around in the arena, and the authors measured the fraction of time an animal spent on the air side of the arena versus the CO_2 side. Interestingly, flies that were tested individually spent very little time avoiding the CO_2. When tested in a group, however, as the population density increased so too did the time spent avoiding the odor. Additionally, the authors revealed that, at the population density that drove peak aversion, flies moved in a more uniform direction away from the odor source.

In order to gain a better understanding of whether individuals could be driving the observed group behavior, Ramdya *et al.* [4] next looked more closely at the locomotion patterns of singular flies and observed that most flies began walking away from CO_2 *only* after they came within contact of another fly, termed an 'Encounter Response'. As would be expected, the number of Encounter Responses increased with population density, and bouts of walking initiated by such an encounter were significantly longer in duration than bouts initiated spontaneously by solitary flies. This finding led Ramdya *et al.* [4] to hypothesize that inter-fly interactions are responsible for generating the 'herd' aversion to CO_2 observed in a group of flies.

Ramdya *et al.* [4] next devised a computational simulation incorporating three observations from the behavioral experiments: that flies initiate more spontaneous bouts of walking in the presence of an aversive odor; that flies are more likely to turn and retreat when entering the odor zone from the air zone; and that an Encounter Response is initiated when a stationary fly comes into close contact with another fly. Their compound model recapitulated the collective behavior observed experimentally, and modulating the probability of an Encounter Response alone could abolish and even invert (aversion to attraction) collective behavior. This computational and experimental evidence led the authors to predict that the inter-fly interaction is the cornerstone of the group avoidance response.

How do these inter-fly interactions drive herd aversion to CO_2? Walking flies initiated Encounter Responses in stationary flies through leg touches, which resulted in a stereotyped walking reaction depending upon which leg was contacted. Ramdya *et al.* [4] tried various manipulations to the visual and chemical environment, but the only sensory modality manipulation that caused a disruption of Encounter Response frequency was genetic ablation of the NOMPC [8,9] mechanosensory channel, adding support to the observation that inter-fly touch interactions drive group behavior. To confirm that mechanical stimulation of the leg was by itself sufficient to elicit Encounter Responses, they substituted a magnet-controlled metallic disc in place of a second fly. Walking responses elicited by the disc were indistinguishable from those elicited by normal fly–fly Encounter Responses, suggesting that mechanosensory stimulation is indeed sufficient to generate Encounter Responses, implicating somatotopic neural circuits that relay touch stimuli to the brain centers controlling locomotion.

To study the underlying neural circuit, Ramdya *et al.* [4] found that genetically silencing leg mechanosensory neurons resulted in a significant decrease in Encounter Response frequency, suggesting that these structures are alone driving the 'herd' effect. The authors then used optogenetics to activate the mechanosensory structures in the leg and observed Encounter Response-like locomotion, confirming that these structures are not only necessary for the herd effect to occur, but also sufficient to cause it. How can a mechanosensory stimulus cause the group-mediated aversion to CO_2? The authors reckoned that either touch increases awareness to the olfactory stimulus or touch elicits an odor-independent 'following reaction' to the group. To discriminate these two possibilities, they genetically inactivated the known CO_2 sensing receptors [6,10,11] and found, surprisingly, that when intermingled within genetically wild-type confederates, even the CO_2-anosmic flies avoided CO_2 in a group-size dependent manner.

One wonders whether the flies are more apt to generally follow one another around than to specifically avoid CO_2, or whether reactions to this odorant are strongly context-dependent. Previous work has shown that CO_2 elicits behavioral reactions ranging from aversion [5,6] to attraction [12,13] to responses in between [14]. The spectrum of value assignments mirrors the ecological roles that CO_2 is known to play in the daily life of the fly, ranging from indicating the presence of an attractive food source on the wing [15] to signaling danger as a co-indicator of fly stress pheromone [5,16]. Because CO_2 has the potential to evoke different value assignments, it makes for an ideal candidate stimulus with which to examine the potential effects of social context as a measure of how external contextual state can modulate the value and salience of sensory information.

Ramdya *et al.* [4] used an elegant combination of tools to reveal a novel circuit that drives collective behavior in the solitary fly, but their results leave open the question of how the cascade is initiated in the first place. Indeed, they indicate that some flies are more sensitive to the stimulus than others and therefore begin to walk more readily, which would initiate collective aversion. Also, sensitivity to the odorant is not necessary for the 'herd' response by individuals. Perhaps there is some sort of 'first responder' effect at play, which provokes the herd. It might be interesting to compare CO_2 reactions using physiological approaches to determine whether a range of sensitivity exists across individuals that might therefore become first responders. It is important to keep in mind that different states, such as flight, alter neuromodulator levels in the brain that change the gain of sensory circuits such as motion detecting neurons [17,18] and may even confer CO_2 sensitivity to an as yet unidentified novel CO_2 detector [12]. Future work could investigate how CO_2-anosmic flies know the direction to walk away. It would be exciting to find that flies touch specific legs of sedentary flies to prod their locomotor direction depending upon the location of the odor source. Finally, it is possible and probable that this type of group effect extends to other sensory modalities as motion-elicited walking responses of flies weaken as population density decreases ([19] and unpublished data). This study sets the stage for using the fly to further investigate the molecules, neurons, and circuits that permit social context to modulate sensory behaviors.

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