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Random-Rate Processes in Navigation in Bacteria, Archaea, and Desert Ants

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Abstract

Movement in life is usually carried out by effectors, body parts that carry out action such as flagella, archaella, cilia, whole bodies that sinuate, or limbs, moving regularly and periodically in an oscillator system. For navigation and orientation, the oscillations that generate movement are sometimes interrupted by stops, turns, or both. I review evidence in bacteria, archaea, and one animal, the Australian desert ant *Melophorus bagoti*, that such interruptions to forward movement take place as random-rate or Poisson processes. At every moment in time, there is a constant probability of the event taking place. On looking for explanations for such random-rate events, some evidence suggests that the bacterium *Escherichia coli* relies on stochastic or random fluctuations to generate turns. I conjecture that relying on noise makes a cheap mechanism in the sense that no dedicated mechanism for generating occasional interruptions is required. Random processes mostly come ‘for free’. The data are too sparse and uncertain for archaea and ants to attempt any explanation. It is not necessary to rely on noise or stochastic processes to produce what look like random fluctuations; various nonlinear mechanisms might do that. My call to action to those studying behaviour is to examine much more the interval or duration of time between events.

Keywords: Eschericia coli, *Melophorus bagoti*, orientation, scanning, turns

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Introduction

In movement ecology (Nathan et al., 2008), a distinction is made between searching and navigation. In searching, the moving organism does not have a known location or preferred direction as a target, but is in search of something such as food. In navigation, in contrast, an organism has a goal and is attempting to get to the goal. The goal might not be one definite place but some more preferred or better place; examples include climbing a chemical gradient (bacteria: Berg & Brown, 1972; Koshland, 1980) or getting away from a spot (dung beetles: Dacke et al., 2019). Such cases of getting to a better place have been called orientation (Cheng 2022, 2023), in contrast to reaching a particular place, such as an ant or bee attempting to find its home, called navigation proper. Here, I will lump these cases and call them all navigation. Searching commonly contains some random component in movement to spread the search beyond one region, forms of which are described next, but I am interested here in what appear to be random components in navigation. Extant data suggest the play of random-rate processes in navigation in various taxa of life, including all domains of Bacteria, Archaea, and Eukaryota. Random-rate processes are unpredictable in time. When the motive is to get to a goal, behaviours that appear to be unpredictable in time seem surprising to me and deserve some scrutiny.

My goals here are twofold: first, to cast a critical look at the data on random-rate processes in navigation, offering some attempt at explaining the data where warranted; and second, to issue a call to action to readers to examine this topic of the timing of behaviours in their study organisms, including data already collected and sitting in video records or spreadsheets. Leaning on the literature on searching, I will first describe some mathematical functions that have been used to characterise behaviour: exponential functions, which incorporate random-rate processes, the power law, and the stretched exponential. I then review data on random-rate processes in navigation across the three domains of life: in one species of bacteria, *Escherichia coli*, two species of archaea, and one species of animals, a desert ant. Finally, I discuss these findings with two main themes: 1) Mechanisms in the case of *E. coli* are considered, and 2) behaviours that appear random in time need not necessarily be produced by stochastic or noisy processes in the organisms exhibiting them.

Distributions in Searching

In characterising search paths, the travel paths are divided into straight segments with turns between them (Schultheiss et al., 2015), although some have argued that search paths are better considered as curved loops (Waldner & Merkle, 2018). Assuming approximately constant speed of travel, the path lengths also become proxies for durations of straight travel. The distribution of the lengths of straight segments is compared against likely functions, plotting path lengths on the x axis and frequency on the y axis, often in cumulative form. Best-fitting functions that have been reported include the exponential, sometimes multiple exponential functions in combination, the power law, and the stretched exponential. In formulae, they are:

Exponential: $y = a * e^{bx}$ (1)

Power law: $y = a * x^{b}$ (2)

Stretched exponential: $y = a * e\text{^}(-x^{b})$, with ^ meaning “to the exponent of” (3)

In these equations, “a” serves as a scaling parameter. The power law is taken to indicate a Lévy walk or flight (Reynolds, 2018) if the parameter b falls between –1 and –3. The Lévy walk is ideal for certain search conditions in which the sought-for resource is sparsely distributed. It is said to be heavy-tailed because it contains more long intervals than the exponential distribution. The longer intervals serve to spread the search out faster from the starting point. The stretched exponential may be a way of approximating a Lévy walk (Ferdous et al., 2018). It too helps to spread the search. The exponential distribution signifies a random walk, and I will explain this case some more before reviewing data on navigation.

All three of these equations have been found to be best fits for distributions of straight-segment lengths in searching. A thorough review of searching is not my goal, but some examples illustrate the breadth across life of these search patterns. Exponential distributions, often two of them together, characterise searching in different circumstances in ants (Lecheval et al., 2024; Reynolds et al., 2014; Schultheiss & Cheng, 2011, 2013; Schultheiss et al., 2013; review: Schultheiss et al., 2015), although in other conditions, a stretched-exponential provides good fits (Campos et al., 2014; Ferdous et al., 2018). A double-exponential fits path-length data in the nematode *Caenorhabdits elegans* in one study (Srivastava et al., 2009), although the data showed much scatter around the fit line. Exponential distributions of straight-segment lengths are also found in the single-celled eukarayotes *Paramecium caudatum* (Deeti et al., 2024; Deforet et al., 2010), at least in older specimens, and *Euplotes vannus* (Laeverenz-Schlogelhofer & Wan, 2024). Random walks at multiple scales (path lengths best fit by a combination of multiple exponentials) also best describe some, but not all foraging paths of hunter–gatherer humans, the Hadzas (Raichlen et al., 2014). Power-law fits indicating Lévy walks have been found in a wide range of life, including bacteria (swarms: Ariel et al., 2015; individual *E. coli*: Huo et al., 2021), honeybees (Reynolds et al., 2007), marine predators (Sims et al., 2008), and some of the journeys of foraging Hadzas (Raichlen et al., 2014). Paths approximating Lévy walks have even been found in fossil tracks of extinct benthic marine organisms (Sims et al., 2014).

Returning to random-rate processes, a random-rate or Poisson process refers to a distribution of events in time. An exponential distribution considered in the time domain (with duration as x axis) identifies a random-rate process, which is as aperiodic as a process can be. The probability of the event (such as a turn in searching) taking place is constant in time, thus making the prediction of ‘when’ as uncertain as possible. Random-rate processes are said to be memoryless (Riposo, 2023). Mathematically, a random variable that is memoryless "forgets its past" (Riposo, 2023, p. 8, emphasis in the original). How long ago the last target event took place is irrelevant to predicting the next event: it is still a constant probability in time. Nevertheless, a random-rate process is not totally unpredictable. Because of the constant probability of the event taking place, governed by the rate parameter b in equation (1), we can predict approximately how many events will take place over a substantial span of time. A higher rate translates proportionally to more events on average. The rate of events, behaviours for our purposes, can be adjusted to take place more or less frequently.

We must be clear on the relation between an exponential distribution and a random-rate process. The exponential distribution of inter-event intervals serves as a signature for identifying a random-rate process. A random-rate process is the only plausible pattern of data that produces an exponential distribution of inter-event intervals. A random-rate process describes a pattern of data, in which the events appear randomly in time. It does not tell us how the events are generated and, in particular, whether some random process in behaving organisms plays a role in generating the events. I consider this point after reviewing the data on random-rate processes in navigation.

Random-Rate Processes in Navigation in Lifeforms

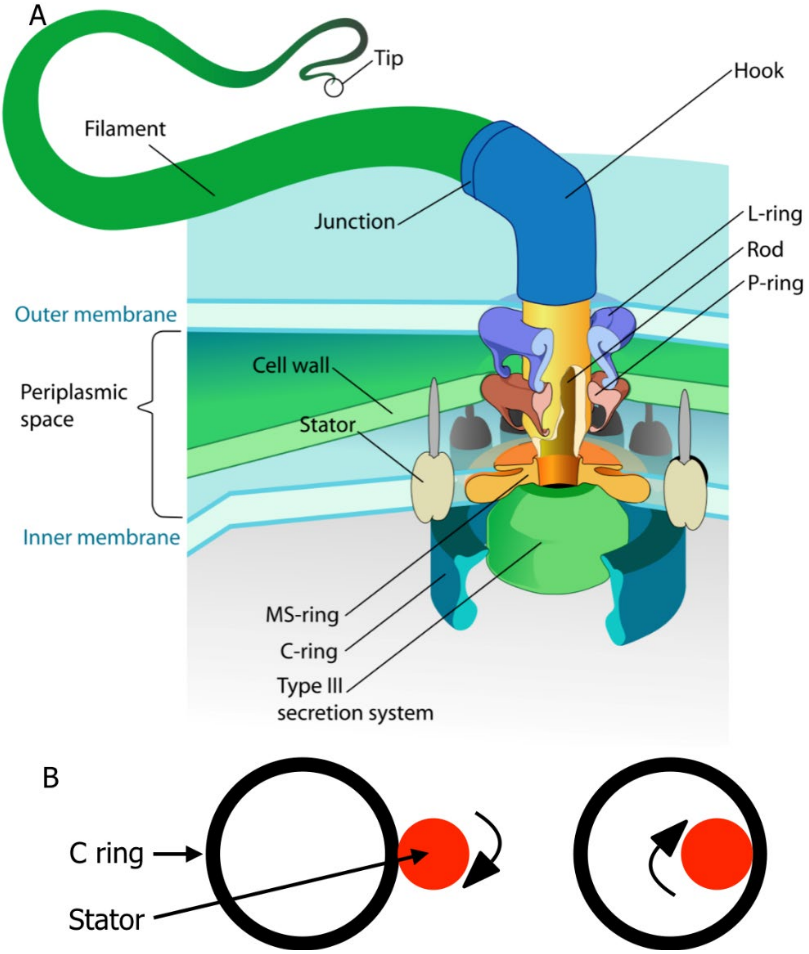
Random-rate or Poisson processes are found in navigation in all domains, although in not many species. I present a critical look at cases in the domains of Bacteria and Archaea as well as one animal, the red honey ant of Central Australia, *Melophorus bagoti*.

Bacteria

The best studied case is the intestinal bacterium *Escherichia coli*, sometimes called a "simple" bacterium, although it possesses some 30 kinds of sense receptors and a complex machinery for motility and directed travel (Koshland, 1980; Sterlling & Laughlin, 2015; Wadhwa & Berg, 2022). A tiny 1 μm by 2 μm in size, the microbe sports about 5 tail-like flagella (singular, flagellum) whose rotation powers movement. The flagellum includes the tail visible in a microscope, the filament, and the machinery that drives the filament. When the motors that drive the filaments turn steadily, the filaments bundle up and rotate much like the tail of a sperm to drive forward motion. Because of the left-handed helical structure of filaments, turning clockwise and counterclockwise are different, and the 'preferred' mode of operation is counterclockwise rotation. The motor that drives the filament turns constantly in one direction, clockwise. Whether the filament turns clockwise or counterclockwise depends on where the motor engages with the 'gear' that turns the filament, called the C-ring (Wadhwa & Berg, 2022; Figure 1). The C-ring is indeed a ring structure, with cogs on the inside and outside for the motor to engage with. When the motor turns outside the C-ring, the opposite rotation is generated in the filament; when the motor ‘clicks’ with the inside cogs on the C-ring, the filament rotates in the same, clockwise direction. Where the motor engages with the C-ring depends on the conformation of the C-ring, which can be and is modified occasionally.

Figure 1

The Motor System Driving Rotations of the Filament in Bacterial Flagellum



Note. A. A series of rings turn to rotate the filament. The rings are driven in gear-like fashion by rotating motors called stators. B. When the stators rotating clockwise, only one of which is shown, ‘gear’ the C-ring on the outside, the ring, and the filament with it, turns in the opposite direction. When the conformation of the C-ring changes so that the stator is ‘gearing’ inside the C-ring, the ring, and the filament with it, turns in the same direction as the stator. Not to scale.
Photo credits. A. From Wikemedia creative commons:
https://commons.wikimedia.org/wiki/File:Flagellum_base_diagram-en.svg
Author: LadyofHats. Public domain. B. Drawn by author.

To change the C-ring conformation from counterclockwise mode to clockwise mode requires phosphorylation (adding a phosphate group, PO_4^{3-}) of a key chemical called Che-Y (Che for chemotaxis) (Wadhwa & Berg, 2022). Phosphorylated Che-Y increases the chances of a conformational shift of the C-ring from counterclockwise mode to clockwise mode. The end result is that in travelling, *E. coli* occasionally tumbles to face a different direction and then heads off in a straight line again in that direction. The distribution of turn angles peaks at around 45°, tapering off at bigger and smaller values (Thornton et al., 2020; Figure 2D). The tumbles take place when the filaments disengage temporarily from counterclockwise rotation and turn clockwise, if for a short time. When the filaments turn counterclockwise again, straight-line travel resumes.

The tumbles of *E. coli* take place as a random-rate or Poisson process. The distribution of their inter-event intervals is exponential (Berg & Brown, 1972; Block et al., 1983; Thornton et al., 2020). Having at least three different cases from two different labs adds some confidence about the replicability of the data pattern. A note of caution to point out is that all these studies did not report fitting data with other plausible functions and finding the best fit by model comparison. The search literature reviewed in the previous section typically conducts some model comparison.

All this talk of changes in direction at random times should not lead readers to think that *E. coli* uses a random-search strategy for orienting up or down a gradient. Instead, it adjusts the rate at which tumbles take place on average, in effect changing the exponent b in the exponential function describing inter-event intervals. In short, when the going gets better, such as climbing up a food gradient, the rate of tumbling is lowered (Cheng, 2022, 2023; Koshland, 1980; Sterling & Laughlin, 2015), and the random turns are also biased to be smaller (Wadhwa & Berg, 2022). When the going does not get better or gets worse, the rate is increased. At the peak of a ‘desired’ chemical gradient, things do not get better, and the organism turns a lot and ends up milling about there.

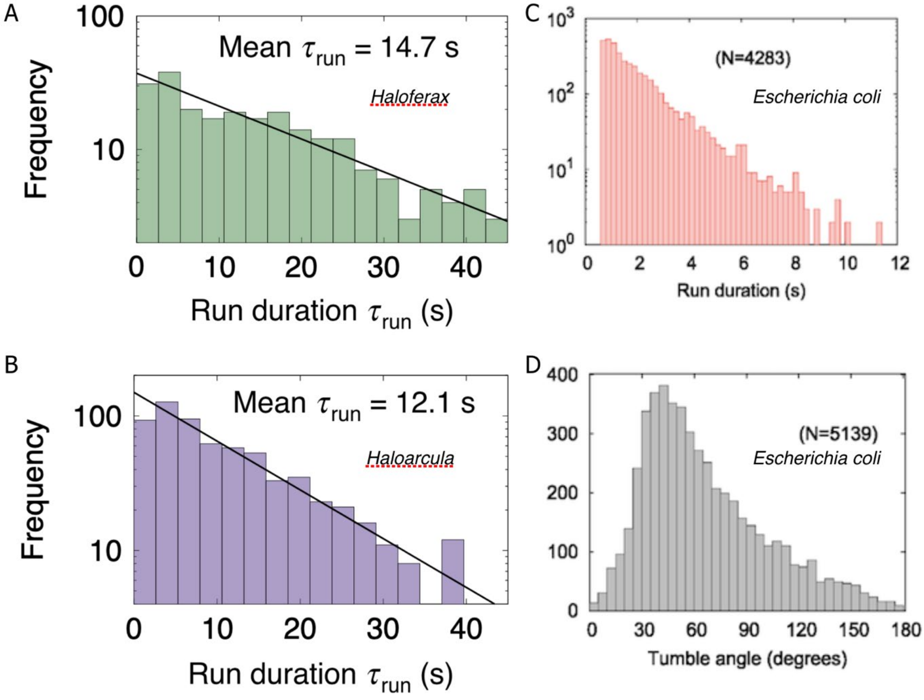
Archaea

As an entire domain, Archaea are thought to have arisen later than did Bacteria. Archaea move by a similar mechanism to *E. coli*, with long filaments in structures called archaella (singular: archaellum) rotating to power forward movement (Quax et al., 2018). Their effectors are not called “flagella” because the archaellum is thought to have a different evolutionary origin from the bacterial flagellum. Archaea show occasional switches in direction of travel much like *E. coli*. Some of the Che system for controlling tumbles is thought to have been ‘borrowed’ from bacteria. Also paralleling bacteria, archaea orient or climb gradients by adjusting the rate at which turns take place, lowering this rate when the going is getting better.

I found one study examining the inter-event distributions of turns in haloarchaea (salt-loving archaea) orienting up a gradient, genera *Haloarcula* and *Haloferax* from Great Salt Lake, Utah, and an underground salt lake in the UK, respectively (Thornton et al., 2020; the same study that replicated the *E. coli* inter-tumble intervals; Figure 2). The inter-tumble intervals of both groups were well fitted by exponential functions. Again, however, no model comparisons were made.

Figure 2

Random-Rate Run Durations and Chemokinesis in Archaea and in E. Coli



Note. Frequency distributions of run durations in *Haloferax* sp. (A) and *Haloarcula* sp. (B), plotted on a log scale in the *y*-axis. An exponential distribution is evidenced by a straight-line fit when *y* is on a log scale and *x* is on a linear scale. (In contrast, a power-law fit should be a straight line on a log–log plot.) C. Distributions of run durations in *E. coli*, again with the *y*-axis on a log scale. D. Distributions of turn angles in *E. coli*, with the *y*-axis on a linear scale. From Thornton et al. (2020). Open access. Licence: https://creativecommons.org/licenses/by/4.0/

Desert ants, *Melophorus bagoti*

The red honey ant, *Melophorus bagoti*, is found in a wide tract of semi-arid Central Australia and has featured in many studies of navigation (Freas & Cheng, 2022; Wehner, 2020; Figure 3). The red honey ant's habitat is full of trees, shrubs, and grasses, and even a mountain in the MacDonnell Ranges, thus a landmark-filled habitat. The ant navigates to specific locations, to targets such as a feeder site or, importantly, its home. Its mainstay strategies are path integration and view-based navigation. In path integration, it keeps track of the straight-line distance and direction of travel during its trip to compute a vector home (Heinze et al., 2018; Stone et al., 2017; Wehner & Srinivasan, 2003). In view-based navigation, the ant uses views surrounding its nest or feeder to navigate (Cheng et al., 2009; Freas & Cheng, 2022; Wehner, 2020). Views for navigation need to be learned. Stopping to look helps ants to learn views and, later, to find the best view to head towards.

Before heading out to forage, desert ants engage in a number of walks near their nest called learning walks (*Cataglyphis* ants: Fleischmann et al., 2016, 2017, 2018; *M. bagoti*: Deeti & Cheng, 2021). During the learning walks, desert ants stop occasionally in their meandering paths and look in different directions, turning on the spot, called pirouettes or scanning bouts. During a scanning bout, the ants stop occasionally, facing different directions across stops, called fixations. The scanning bout may turn a full circle around 360° or stop short of such a full turn, with the ant sometimes turning back the other way. Each fixation is for a typically short duration much less than 1 s. It is thought that during such fixations, the ant learns what views look like in different directions, including, importantly, the nest direction. Later, when returning home, ants can look for the best views, the views that most resemble the views in the nest direction (Zeil, 2012). The ant does not need to find an exact match or even a near match. As long as it can discern a direction that *best* matches the learned homeward view, chances are high that it is moving in generally the right direction.

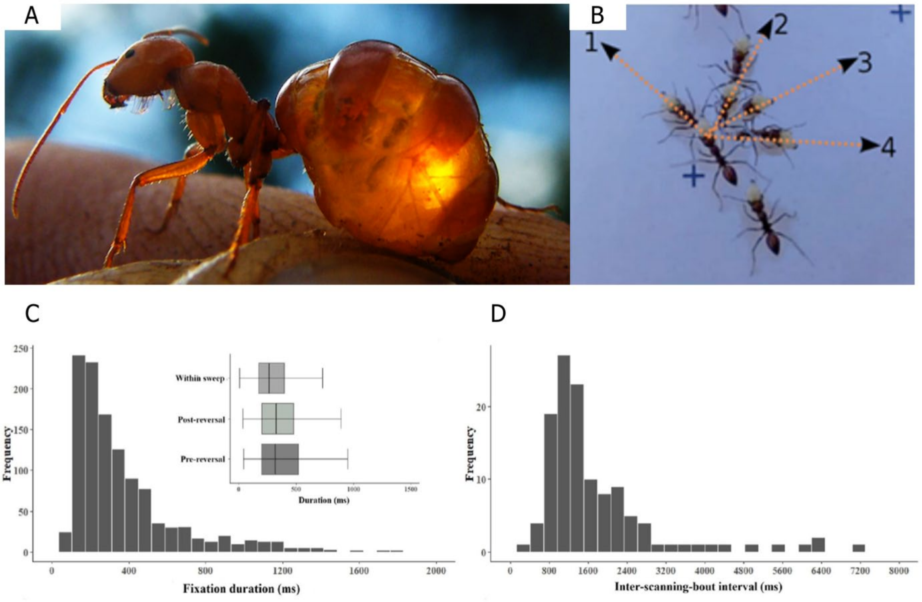
Pirouettes or scanning bouts also take place on trips home from experimental feeders, perhaps especially so because such feeders are sunk into the ground, thus depriving foragers of a panoramic view inside (Wystrach et al., 2014). The function of such scanning bouts is thought to be an attempt to find the best view to head towards. Like bacteria and archaea, this rate of scanning bouts can be and is adjusted according to circumstances. In conditions that experimenters would consider more uncertain, the ants exhibit more scanning. For example, if an experimenter picks an ant up near the end of its journey home from a feeder and places it back on the homeward path again, the ant would still head in the homeward direction, but would scan more (in desert ants: Wystrach et al., 2019; in bull ants: Deeti, Islam, et al., 2023; Lionetti et al., 2024). More scanning means gathering more visual information, coming at the cost of the time taken to get home.

The timing of these initial scanning bouts was examined in one study (Deeti, Cheng, et al., 2023). Both the intervals between the starts of scanning bouts and the durations of individual fixations were examined (Figure 3). The Gaussian function was considered a poor fit and thus did not enter into the model-comparison process. The power-law and stretched exponential functions were compared with the exponential function in fitting the data. For both inter-bout intervals and durations of fixations, the exponential function fits the best by model comparison standards, with

Akaike Information Criterion weights close to 1. In fact, the durations of entire scanning bouts were also best fitted by the exponential function.

Figure 3

Exponential Distribution in Scanning in Desert Ants, Melophorus bagoti



Note. A. Photo of a 'honeypot' red honey ant, *M. bagoti* with its abdomen filled with sugary plant exudate. B. A scanning bout in *M. bagoti*. The travelling ant stops its forward movement and turns to face different directions shown in 1–4, each fixation for a short duration. C, D. Frequency distributions of durations of individual fixations (C) and of intervals between scanning bouts (D). The inset in C shows that average fixation duration differs within scanning bouts. The durations are longer just before and just after the ant changes direction of turning from left to right or from right to left.
Photo Credits. A. Patrick Schultheiss. B–D. From Deeti, Cheng, et al. (2023). Open access. Licence: https://creativecommons.org/licenses/by/4.0/

Despite the good fits and the Akaike Information Criterion weights, we should be wary of accepting the pattern of data as indicating random-rate processes, especially in the case of interbout intervals (Figure 3D). The peak at the left is uncomfortably rounded, characteristic of a distorted Gaussian function rather than an exponential function, and the right tail is uncomfortably long. The power law and the stretched exponential functions provide worse fits, but only slightly worse, both providing good fits. For all these functions, however, the misfits look systematic rather than unsystematic, suggesting that all three functions have missed some characteristics of the data. The study also provides only one case of such distributions. All in all, it is too early to try to explain the pattern of data, although the authors (Deeti, Cheng et al., 2023) of course made an attempt.

Discussion

The reviewed results show in a few cases evidence for random-rate processes in interrupting forward movement in navigation, in *E. coli* (bacterium), two species of archaea, and one species of desert ants. Of the four species, only the bacterium *E. coli* has found support in multiple studies. I consider the other cases as too sparse in supporting data for attempting to find an explanation, but I will consider the case of *E. coli* and make some general remarks about explaining these seemingly random events. To start, I will consider the role that these interruptions play in navigation in these organisms.

Interruptions to Travel in Navigation

Interruptions to travel are likely necessary for navigation in all reviewed cases. In *E. coli* and in archaea, interruptions by stopping and reversing the direction of turning of the flagella or archaella are their way of generating turns in the direction of travel. Turns are necessary for climbing a gradient. These minute lifeforms do so by adjusting the rate of turning, reducing that rate when the going is getting better (Berg & Brown, 1972; Cheng, 2022, 2023; Koshland, 1980; Quax et al., 2018; Thornton et al., 2020; Wadhwa & Berg, 2022). Homing ants might need to stop and look at the environment occasionally to ensure that they are going in a near-optimal direction. This is especially the case at the beginning of a trip home, which is the period that the study of the timing of scans in ants focused on (Deeti, Cheng et al., 2023). In general, even on a familiar and much-travelled route home, it likely benefits the homing ants to scan the environment occasionally, reflecting a great trade-off between exploitation, in this case, travelling the well-known route home, and exploration for learning and checking progress (Brembs, 2011, 2021). The trade-off is likely reflected in one other navigational behaviour that ants engage in: oscillating left and right as they travel (Clement et al., 2023; Collett et al., 2014; Deeti & Cheng, 2025; Lent et al., 2013; Murray et al., 2020), at least in navigation based on the surrounding visual panorama. The path winds left and right quite regularly. Brembs (2011, 2021) has argued that some variability in behaviour has great fitness benefits, in being unpredictable to predators, in searching a ‘solution space’ for optimal behaving, and in exploration. In navigating home, some exploration is likely necessary for finding a direction to travel in. The ants probably cannot take one look in one direction at the panorama and be able to compute the angle to turn for the best direction home. Looking around and finding the best direction is their way of bypassing the need for that kind of computation (Cheng, 2018).

What is less obvious to me is why these interruption processes should come out as random-rate processes or at least something resembling random-rate processes, with exponential distributions providing reasonable fits to the interevent data in all cases. For example, an oscillatory process that produces turns or scans at regular intervals would do the job, as long as the frequency of oscillations can be adjusted. With this much in mind, I now examine the case of *E. coli* and make some remarks about other random-rate processes in behaviour.

Mechanisms of Random-Rate Turns in *E. Coli*

Turns in *E. coli* take place as random-rate events. Does this mean that the mechanisms that generate these events must rely on some stochastic process? The answer, explained in the next section, is not necessarily, but for *E. coli*, this might be the case. One proposal for generating reversals of the motor driving filaments in *E. coli* is based on threshold crossings (Koshland, 1980). Fluctuations of some purported “response regulator” (p. 51) near a threshold level for switching from counterclockwise rotation of filaments to clockwise rotation generate occasional reversals. This conceptual model was not fitted quantitatively to data. Later and more quantitative analyses suggest that such a model does not match the data (Block et al., 1983; Scharf et al., 1998). Too many long inter-turn intervals are generated from a threshold-crossing model. What is needed to account for the exponential distribution of inter-turn intervals is a stochastic model (Scharf et al., 1998). When it comes to the effects of the number of Che-Y molecules bound to the motor driving filaments, in the words of Scharf et al. (1998), “the number bound only determines the probability of CW or CCW rotation, and the switch is thrown by thermal fluctuations” (p. 201). Even though turns take place frequently on a human timescale, these events are said to be rare when considered in terms of periods of molecular vibrations. Molecular ‘noise’ seems to play a key role. The model can be interpreted to say that a change of state (e.g., from counterclockwise to clockwise rotation of filaments) is probabilistic rather than deterministic.

I note again that the overall rate of tumbles is adjustable, making the rate parameter a dial that can be turned up or down. As reviewed already, the concentration of phosphorylated Che-Y regulates (upwards) the rate of tumbling (Wadhwa & Berg, 2022).

On a far more speculative (hence, brief) note, relying on such noisy processes might come cheaper, in terms of energy consumption and hardware, than any other dedicated process such as an oscillator that generates regular oscillations (switches in the direction of the motor that drives the flagella). A dedicated oscillator would require control hardware and software, while noise might come ‘for free’.

A final comment is that, as already reviewed in the introduction, *E. coli* does not always exhibit a random-rate process in turns characterised by an exponential distribution of the inter-turn intervals. In a medium without a chemical gradient, in which the organism is presumably engaging in search rather than gradient ascent or descent, the inter-turn intervals show a power-law distribution characteristic of a Lévy walk (Huo et al., 2021).

Explaining Random-Rate Events

One might suppose that explaining events that appear random, such as the scanning in desert ants at the beginning of a trip home (Deeti, Cheng, et al., 2023), requires some stochastic process that generates such events at random. This is not the case. Nonlinear mechanisms may produce fluctuations that appear random (Hsieh et al., 2005). These authors were examining fluctuations in ecological variables in the ocean, both biological and abiotic or physical measures. They devised a method to examine the extent to which increasingly nonlinear models provide better accounts of out-of-sample data, that is, of data that were not used to construct the model. In short, if the accounts of out-of-sample data become better and better with increasingly nonlinear models, this suggests a nonlinear system at play rather than stochastic noise. If the models perform similarly no matter how nonlinear they are, this suggests a stochastic system, perhaps one with so many variables contributing to the phenomena that the system essentially reflects noise. These authors found that all the physical variables were best considered stochastic, while all the biological variables were best considered as nonlinear systems.

This method has been applied to decisions in the behaviour of *Drosophila* flies (Maye et al., 2007). Consistent with the ecological study (Hsieh et al., 2005), the flies' decisions are best considered as reflecting an intrinsic nonlinear system rather than as reactions to noise.

A more recent proposal in terms of dynamical systems revolves around mathematical entities known as heteroclinic networks (Morrison & Young, 2022). Such networks have a number of equilibrium points corresponding to behavioural states, such as forward movement in *C. elegans* or in desert ants. The model transitions between equilibrium points, representing transitions between behaviour. These authors used heteroclinic networks to model behavioural transitions in two sets of data on the nematode *C. elegans*, including dwell times on behaviour, without any noise in the system. In their words, "switching in our model is generated by deterministic dynamics … neural activity may randomly roam between various states without the necessity of noise" (Morrison & Young, 2022, p. 1). As a mathematical formulation, these heteroclinic networks may be used to model other kinds of behavioural transitions.

Conclusions and Call to Action

In goal-directed movement, evidence for random-rate processes governing interruptions to forward movement in navigation has been reported for bacteria, archaea, and one species of desert ants. Stochastic processes relying on noise might be generating the random-rate turns in *E. coli*, but the generating mechanisms are unclear for archaea and the desert ants. My call is that more investigations of the timing of behaviours would benefit the field of comparative psychology, and other disciplines in the study of behaviour too, especially of but not restricted to the exploratory behaviours that organisms engage in before launching on solving a task. Without examining the exploratory behaviours that are key to learning and deploying behaviours to make use of resources, including other organisms, and without examining the organisation of behaviours that allow organisms to balance exploration and exploitation, comparative psychology remains sorely incomplete. Some of the timing of behaviours is already sitting in video records of behaviours or in spreadsheets, and in addition to scientific benefits, researchers have the ethical obligation to funders to publish as much from collected data as possible.

The timing of human behaviours provides some intriguing illustrations of two of the functions described in the Introduction, the exponential and power-law functions. In poets across four centuries, from William Shakespeare to Robert Frost and encompassing 19th century poets and writers of both sexes, the appearance of new words, in the sense of a word that has not appeared in the poem before, follows a random-rate process (Badalamenti et al., 1994). The interval in number of words between the appearance of new words follows an exponential distribution, suggesting to the authors a fundamental drive to innovate. In the correspondence of Charles Darwin and Albert Einstein, on the other hand, the distribution of durations between receipt of correspondence and their reply follows a power law (Oliveira & Barabási, 2005), much like the rest of us, as the authors attest. Oliveira and Barabási wrote that the famous authors did not escape universal scaling laws. We can ponder, as Badalamenti et al. (1994) did, whether these lawful distributions reflect "powerful isomorphisms between physical and psychological nature, mind and body, and the material and immaterial worlds" (p. 61). As a call to action, I can do no better than quote Badalamenti et al. (1994) again: "Waiting times between events appear to be as important as the events themselves" (p. 60).

Author Contributions Statement

K. C. was the sole author and was responsible for every aspect of conceiving of ideas and writing the paper.

Ethical considerations are not applicable as no new data are presented.

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