Can brains perform second-order optimization?

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Abstract

In ecological setup, a wide variety of organisms search over space to obtain reward using information obtained via multiple senses. In the simplest scenario of scalar search, a single quantity, e.g. concentration of a chemoattractant, is measured at different locations. Though gradient is considered a crucial component of scalar search, whether organisms rely solely on the gradient is unknown. We hypothesized that scalar search benefits from information other than gradient, including curvature (second-order derivatives) and long-term memory information integration. To test our hypothesis, we devised an information foraging task. In our task, human subjects control a circular avatar to find a peak of the contour by making brief fixations. They were rewarded when they approached the peak within the predefined maximum number of fixations. In our preliminary data, observed search trajectories deviated from what is expected from the gradient-based search, suggesting that the subjects utilized information beyond the gradient. We also manipulated the perception and action components of the task to examine the sensitivity of the adopted strategies to variations of the task design.

Keywords: foraging; Lévy walks; gradient; second-order optimization; directed search;

Introduction and Background

Arguably, one of the main functions of any naturally evolved cognitive system is to locate resources. Humans and other primates benefit from multiple senses, long-term memory, and inductive and deductive reasoning, that allow them to efficiently explore and utilize their environment. This complicated machinery, however, evolved from and still rely on many simple algorithms that had once been used by our ascendants. It is therefore important to identify features of search processes that appear in a wide range of organisms, as they may shed light on the evolutionary preserved strategies adopted by life in general and our brains in particular. Optimality theory can then be incorporated as a guiding principle to point where to look for such strategies or to explain why they might have appeared (Parker & Smith, 1990) (see Gould & Lewontin, 1979) for a discussion of the limitations of such an approach.

In a relatively recent example, non-gaussian, superdiffusive patterns of movement have been observed in a number of organisms, including bacteria (Korobkova, Emonet, Vilar, Shimizu, & Cluzel, 2004; Ariel et al., 2015), wide range of flying (G. M. Viswanathan et al., 1996; A. M. Reynolds et al., 2007; A. M. Reynolds & Frye, 2007) and swimming animals (Sims et al., 2008), human mobility patterns (Brockmann, Hufnagel, & Geisel, 2006; Raichlen et al., 2014), and even in the patterns of human gaze (Brockmann & Geisel, 2000), see (G. M. Viswanathan, Da Luz, Raposo, & Stanley, 2011; A. Reynolds, 2015; A. M. Reynolds, 2018) for more comprehensive lists. Such behavior can be modelled with Lévy flights/walks (LFs) (Shlesinger & Klafter, 1986; Zaburdaev, Denisov, & Klafter, 2015). LFs have been shown to offer an efficient random search strategy in many scenarios (G. M. Viswanathan et al., 1999; Bartumeus, Catalan, Fulco, Lyra, & Viswanathan, 2002; Bartumeus, da Luz, Viswanathan, & Catalan, 2005; Kuśmierz, Majumdar,Sabhapandit, & Schehr, 2014; Kuśmierz & Gudowska-Nowak, 2015) (but see (James, Plank, & Brown, 2008; Palyulin, Chechkin, & Metzler, 2014) for counterexamples), which has led to the hypothesis that such non-diffusive random walks appear as a result of natural selection (G. Viswanathan, Raposo, & Da Luz, 2008). Regardless whether this is true or not, the possible mechanisms behind the appearance of LFs are of great interest and multiple models showing different mechanisms of emergence of LFs have been put forward to date, see (G. M. Viswanathan et al., 2011; A. Reynolds, 2015) for reviews.

Importantly, even the simplest organisms have the ability to act and react to environmental signals, leading to

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Method

The experimental design

The preliminary result includes 3 human subjects. The goal of subjects at each trial is to move a self-representing avatar closer than 100 pixel from the peak of mountain (target). The subjects controlled the yellow circular avatar at screen by joystick. The peak of mountains is not revealed, but only gray screen was shown. Only when the subjects hold the joystick for 300 ms at one location, the gradient information (a small circular view of the landscape) is revealed.

The information about the location of the target is provided by the visible pixels intensity through the scalar function

\[ f(x) = \frac{1}{1 + (x - \mu)^T \Lambda (x - \mu)}, \]

where the location vector \( \mu \) and matrix \( \Lambda \) are generated randomly at each trial. Eigenvalues of \( \Lambda \) are independent and uniform in the interval \((100, 700)\), the position of the target is uniform over the landscape, and a random rotation is applied to \( \Lambda \) so that no particular direction is statistically preferred.

\( ^1 \)Hessian \( \mathbf{H} \) calculated at the location of the maximum \( \mu \) is related to \( \Lambda \) through the relation \( \mathbf{H} = -2\Lambda \).

The session for each subject is consisting of 8 blocks and each block has 30 trials (total 240 trials per each subject). The three major parameters changed at each block are 1) amount of information revealed once fixating (35 pixels vs. 50 pixels), 2) maximum number of fixation (5 vs. 8), and 3) maximum speed of avatar movement (12 pixels/sec vs. 24 pixels/sec). These parameters varied to examined the effect of perception, memory, and action, respectively. The block sequence was randomized.

The score they obtain at each trial is intended to incentivize the subjects. The whole landscape was revealed to subjects regardless of their results. To prevent subject being less motivated, we impose 30 seconds time out limits. The block changes were indicated by written message but the parameter change has not informed.

Result

Human subjects deploy other information than the gradient

Our preliminary results suggest that humans can employ information beyond gradient, see Fig. 2. However, this can be attributed to either integration of information over time or memory of environment. Thus, we selected only the first fixation of each trial and repeated our analysis. our result is also true if only first fixation at each trial are considered, removing the influence of memory. This result suggests that subjects might have used curvature information in their search. More data is needed to dissect the exact strategy and its sensitivity to the task design.
Lack of evidence for Lévy walks

Our results suggest the lack of evidence for Lévy walk pattern, see Fig. 3. To examine the pattern of search, we calculated jump length at each movement. If search pattern mimics Lévy walk, then the jump length distribution should be a power-law that spans a few orders of magnitude. However, we did not find any signatures of such strongly long-tailed distribution. Retrospectively, it is easy to understand why we should not expect such power-law distributions to appear in our task. The circular fixation point sets a minimal jump length that makes sense for the subject, which is of the order of 100 pixels. On the other hand, the movement is constrained by the screen size and thus the maximum possible jump length is of the order of 1000 pixels. There is simply not enough orders of magnitude to span in order to create a power law.

Discussion

Here, we present an empirical paradigm that examines the source of information being used for search. We find that the human subjects do not exclusively rely on the first order information. By separating the initial step only, we show that memory and information integration are not necessary for the appearance of the effect. Although we modified conditions to isolate the factors influencing search patterns (e.g. perception or action), we did not see significant conditional difference. Instead, we observed that the success rate significantly differed between conditions with maximum number of fixation points, which is a proxy for the urgency. Thus, two goals for the future study are: splitting our result by the urgency and creating empirical conditions where perception or action parameters differ saliently so that subjects can take distinctive search strategy. By this device, we expect to examine the attributing factor for search strategy. Furthermore, we expect to add the gaze and pupil data so that we can exhibit effect of attention.

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References


