Human Random Search Strategies in a Soccer Field

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Abstract

A lively debate exists on the inherent stochasticity involved in many animal search displacements and its possible adaptive value. When animals have no prior information about the location of targets, such as patches of food resource or potential mates, different random search strategies may provide different degrees of success. It has been suggested that a particular class of random walks, known as Lévy walks, offers optimal stochastic search strategies when faced with environmental uncertainty. The properties of Lévy walks, which include superdiffusion and fractality, have been shown to be particularly useful in non-destructive searching cases; cases in which a site or a resource is not eliminated after it has been located, and therefore can be revisited. In this project we conducted a human behavioral searching experiment on a group blind folded human volunteers whom were asked to search for targets in a soccer field. By recording the walking path of each volunteer, our goal was to categorize the properties of human random searches. Our results show that the general search strategy of blind folded humans resembles pure Brownian motion. However, when categorizing the volunteers according to their degree of success, we found that the searching strategy of the most successful group clearly deviated from a Brownian type of motion towards a Lévy-like type motion. We discuss the relevance of these results in animal search context, and the potential of Lévy walks in terms of adaptive behavior.

Introduction

Random searching should not be considered a totally unstructured type of motion. Indeed, an easy way to organize a random search in space and time would be by discretising it as a set of several foraging trips or moves. Intermittence, that is, movement interruptions or active discretization of displacements due to behavioral or physiological mechanisms, is very common in animal motion (Harnos et al. 2000, Kramer et al. 2001). In a random search situation, animals must attempt to move in such a way as to optimize their chances of locating resources or cues, such as food, mates, shelter, breeding habitats, pheromone trails etc., covering certain regions by generating certain probabilistic effects. Recent investigations have reinforced the idea that a certain class of random walks, the so-called Lévy walks, involve beneficial statistical properties that allow to enhance encounter rates when conducting random searching (Viswanathan et al. 1999, Bartumeus et al. 2001, Bartumeus et al. 2005).

Random walk models are formalizations of the intuitive idea of taking successive steps, each in a random direction. Thus, they are simple stochastic processes consisting of a discrete sequence of displacement events (i.e., move lengths) separated by successive reorientation events (i.e., turning angles). The statistical distribution of displacement lengths on the one hand, and the statistical distribution of changes of direction (i.e., turning angles) on the other, describe the stochastic process. In particular, Lévy walk models involve a uniform distribution for the turning angles and a power-law distribution of their lengths (Lévy 1965). The broad class of distributions arising from the Lévy-stable distribution has relevant statistical properties related to the Generalized Central Limit Theorem (Lévy 1937). Lévy walks are a class of stochastic processes based on the Lévy-stable distribution (Lévy 1937). The stochastic processes arising from such distributions are tightly related to fractal geometry and anomalous diffusion phenomena (Mandelbrot 1977, Shlesinger et al. 1995).

The fundamental statistical properties of Lévy walks emerge from the existence of scale-free displacements: fractality and superdifusion. These two properties are at the root of optimization process of a random search (Bartumeus et al. 2005). The benefits of these two properties are held in a wide range of search scenarios covering different space dimensions (Bartumeus 2007), search dynamics (Raposo et al. 2003, Santos et al. 2004), target sizes, velocities and behavior (Bartumeus et al. 2002, Santos et al. 2004). Lévy walks have been observed in a wide range of animal movement data involving large-spatial and long-temporal scales. To date, it has been observed in soil amoebas (Levandowsky et al. 1997), planktonic organisms (Bartumeus et al. 2003), bumble bees (Heinrich 1979), seabirds (Fritz et al. 2003), large terrestrial herbivores (Marell et al. 2002), social cannids (Atkinson et al. 2002), arboreal primates (Ramos-Fernandez et al. 2004), Arctic seals (Austin et al. 2004) and even in human activities (Bertrand et al. 2005, Brockmann et al. 2006).

The fact that Lévy processes can optimize random encounter success (Viswanathan et al. 1999) set the scene for an evolutionary explanation for the ever-present fractality in animal movement. Basically, that Lévy processes could be the basis of animal adaptations to search in highly unpredictable environments (Bartumeus 2007). Overall, it is suggested that fractal intermittence on the move (i.e., stops, strong re-orientations, behavioral distinctive interruptions during the walk, etc.) could be the basis for a stochastic organization of the search whenever strongly reduced perceptual capacities come into play. A fractal timing of reorientations (i.e., scale-free intermittence on the move) should lead to scale-free displacements (whenever velocity is kept more or less constant) and the background idea is that it could be controlled by biological processes at the physiological (e.g., starvation, accumulation of certain metabolites, etc.) or neurophysiological level (e.g., neuronal temporal-firing patterns, patterns in the integration of temporal information, etc.). Some preliminary empirical results point towards this hypothesis (Martin et al. 2001, Bartumeus et al. 2003, Reynolds and Frye 2006).

The purpose of the present study was to analyze some of the statistical properties generated by human random searchers. We focused on the time interval between reorientations, as a surrogate of a measure of displacement lengths. This is as a key variable that we knew could change the diffusive properties of the walks and therein the success of random encounters. We focused on non-destructive search processes in which targets can be revisited successive times. In this type of search, fractality and superdiffusion (i.e., Lévy walk statistical properties) are relevant in solving the spatial trade-off between visiting new targets which are potentially distant, to re-visiting neighboring ones. Overall, we wanted to study the emerging statistical features of human searches when no environmental or cognitive processes are involved. Would these properties be similar to Lévy statistical properties, or alternatively, would they be close to standard Brownian motion (i.e., relating to classical diffusion theory)?

The experiment

The experiment was conducted over the course of two days during June 2007, in the soccer field of St. John's Collage in Santa-Fe, New Mexico (see Figure 1). 19 volunteers, which were noted as *searchers*, were asked to search the field for targets (see Figure 2a). The searchers did not have prior knowledge of the theoretical background of the experiment nor what would be measured during the experiment. The searchers were instructed to attempt locating as many targets as possible, and a prize was rewarded to the searcher locating the highest number of targets. The searchers were given 10 minutes of searching time, and they were allowed to revisit the same targets multiple times. Each searcher was blind folded before entering the field (see Figure 2b) and was then lead to a random starting position in the field. During the experiment, the searchers remained blind folded while they were searching for targets, and were escorted by what we noted as a *follower* (see Figure 2c). While searching for targets, the searchers were allowed to walk in any direction they chose, for as long as they liked. The size of each target was defined as a circle with a radius of 0.5*m* (the center being either a person or a bag), and the total number of targets placed in the field was 5. A searcher was stopped and informed by the follower if a target was hit. At this point the follower moved the located target to a new location which was set at a distanced of 1.5*m* from the searcher, in a random direction. Only then was the searcher allowed to start searching again. Searchers who reached one of the four borders of the field were stopped and relocated to a new random starting point in the field. While running the experiments, up to three searchers were allowed to search the field simultaneously. During the search, the walking path of each searcher was observed by a *watcher* (see Figure 2d). Under the assumption that the movement of searching is intermittent (Harnos et al. 2000, Kramer et al. 2001), the walking time between each turning angle was recorded by the watcher, generating a sample of time intervals between reorientations, which were noted as *flights*. Three types of reorientations were considerer and noted; a reorientation in the searching direction, a reorientation after locating a target and a reorientation after reaching a border. Time intervals which were not part of the actual searching process (e.g., the time spent while a searcher was relocated to a new starting position and the time spent while a hit target was repositioned), were not included in the sample set. Figure 3 shows a schematic demonstration of two such paths measured in the experiment.

Previous studies show that the statistical features of a walk only become relevant at low densities of targets (Viswanathan et al. 1999, Bartumeus et al. 2005). The average distance between targets, also known as the mean free path, λ, is a key parameter when studying random search strategies, and is scaled as follows:

$$(1) \qquad \lambda = \frac{L_1 L_2}{2RN_T},$$

where L_1 and L_2 are the dimensions of the soccer field (e.g., $L_1 = 100m$ and $L_2 = 50m$), R is the radius of the target (e.g., $R = 0.5m$) and N_T is the number of targets (e.g., $N_T = 5$). The number of targets was set under the assumption that $\lambda = 1000$, which is a value chosen on the basis of previous theoretical work (Viswanathan et al. 1999, Bartumeus et al. 2005).

Analysis

We computed the cumulative distribution of the observed flight lengths, l, as the proportion of observations which were equal to or larger than that flight length, i.e., $P(L > l)$, and plotted the results on logarithmic scale. To assess whether this distribution follows a power-law behavior, we placed the data into 2^k bin widths, dividing the frequency of observations in each bin by the bin width and the total number of flights. This method gives a good estimate of the probability density function for flight lengths:

(1) $f(n_k) = (1/2^k)(s_k/S), \qquad k \in N$

where s_k is the frequency of flights in bin k, S is total number of flights and 2^k is the width of each bin (Pueyo 2006, Sims et al. 2006). We then used a logarithmic transformation on these values to assess the central value for each bin (i.e., the geometric mean of the interval). In this scheme a linear fit would indicate the existence of a power law distribution.

We could also quantify the scaling exponents of the observed distributions by means of maximum likelihood methods (Hilborn and Mangel 1997, Burnham and Anderson 1998). However, these methods are weak when evaluating the behavior of the tails of the distributions (i.e., values in the asymptotic regime of the distribution). Determining the behavior of the tails of flight length distributions reveals the diffusive properties of the walks. It is known from extreme statistics theory that in the limit, there are generally two possible behaviors; power-law like and exponential (Pickland III, 1975). Therefore, to estimate the behavior of the tail of our flight length probability distributions we performed what we named a moving tail test, as described below.

The moving tail test consists of conducting sequential maximum likelihood tests on subsets of the sampled data. At each iteration, two probabilistic models are confronted; the exponential distribution model and the power law distribution model. Model selection is based on AIC weights which determine the likelihood of a subset being better fitted by one model versus the other. Subsets undergoing the moving tail test are defined as $L_j = \{l_i\}_{i=j}^{|L|}$, where L is the total sample set of flight lengths in increasing order (i.e., $\forall i_1 < i_2 : \ l_{i_1} \le l_{i_2}$) and $|\cdot|$ defines the number of components in a set, such that $L_1 = L$. The AIC weights are then plotted as a function of $|L| - |L_j|$.

Results

The number of searchers conducting the experiment was 19, each generating a sample of time intervals between reorientations, which we note as *flights*. The maximum number of flights per searcher was 91, and the minimum was 19, with an average of 36.26 flights. The overall number of flights after pooling all the results was 688. The maximum number of targets found was 8, and the minimum was 0 with an average of 2.79 targets.

The distribution of flight lengths was found to be exponential with α=0.079±0.006 (see Figure 4), with a characteristic time scale of 12.5 sec, suggesting that the overall pattern of the flight lengths represents Brownian motion (i.e., the searchers dispersed through the field by a normal diffusion processes). To test whether the finite boundaries of the soccer field had an impact on the distribution of flight lengths, we united the flights prior to a border collision with those subsequent to relocation of the searchers. The new distribution of flights was found to have a longer characteristic time scale of 17.86 sec, but the distribution was still found to be exponential with α=0.056±0.005 (see Figure 5).

We then pooled our data into 3 sets according to the number of targets a searcher managed to locate; 6 searchers located 0 to 1 targets (noted as group *A*, giving 185 flights), 8 searchers located 2 to 4 targets (noted as group *B*, giving 266 flights), and 5 searchers located 5 to 8 targets (noted as group *C*, giving 238 flights). Groups *A* and *B* showed an exponential distribution with α=0.063±0.01 and α=0.066±0.01, respectively (see Figure 6), which means flight lengths with characteristic scales of 15 sec. Group *C* on the other hand showed strong deviations from an exponential distribution. Indeed the logarithmic binning histogram showed that the distribution of flights of group *C* approached a power law distribution with a scaling exponent of μ~2 (see Figure 7). Results based on moving tail tests confirm the fact that the two first groups followed Brownian search patterns (see Figure 8a, 8b) whilst the most successful group followed search patterns resembling Lévy walks (see Figure 8c).

Discussion

In general we were not able to observe a fractal timing of reorientations in our experiments, that is, scale-free intermittence on the move leading to scale-free displacements. However, we did observe some interesting statistical effects that could explain why some individuals were more successful than others in randomly encountering targets. Basically, the individuals in group *C*, showed a clear deviation from exponentiality for the large values of flight lengths. Indeed, group *C*, showed a flight length distribution with a tail that could be considered power-law like (Figure 7). The moving tail test (Figure 8) shows that, for the case of group *C*, maximum likelihood tests at the tails are not able to assign a clear AIC weight neither to the exponential model nor to the power law model, hence, the behavior at the tails could be considered something between these two. On the other hand, for groups *A* and *B*, moving tail tests always assigned the best fit to the exponential model.

There are two important lessons to be learned from these experiments pointing out the powerfulness of certain statistical properties when conducting a random search. First, even though our results are based on a relatively small set of data, we did observe statistical effects in relation to encounter success in the direction predicted by theory. The most successful individuals were performing displacements close to scale-free behavior with a scaling exponent near 2. Second, the necessary scales to observe these phenomena were large, but not as large as one could expect *a priori*. In the experiments, individuals walked for 10 minutes in an area of 100 by 50 meters, and indeed, many animal searching processes occur at such scales.

Lévy statistics have appeared in many different types of organisms and scenarios, implying that there might be a unique explanation for their existence. Indeed, when the assumption of high unpredictability does not hold, Lévy statistics could be explained as an emergent phenomenon governed by low-level complex interactions or simply reflecting some spatial-extended fractal pattern of resources or environment (e.g., fractal spatial distribution, fractal size structure of patches). Therefore, the evolutionary hypothesis of spontaneous fractal timing of reorientations maybe considered an alternative or complementary explanation of the prevalence of Lévy processes in animal movements. The evolutionary hypothesis assumes the existence of random searchers in nature (i.e., searchers looking for targets of which they have no information about at all), and presupposes the existence of specific biological mechanisms on which natural selection could have impinged in order to develop *inherent fractality* (Bartumeus 2007). There are indications that there is brain internal stochasticity in fruit flies *Drosophila* which is not purely Brownian (i.e., white noise), and that this internal noise could be generated by a specific neural circuitry (called initiator) to generate, for example, certain beneficial motor statistical patterns (Maye et al. 2007). However, in our case, we have no idea what the neurological and the psychological transformations occurring in a human brain would be when suddenly blocking one of the most important sensorial organs, the vision. Perhaps abruptly blinding a human might screen the potential benefits of internal brain noise, if indeed it existed. Also one must consider the existence of rational when conducting experiments on humans. Indeed, some of the searchers reported that they had attempted to implement conscious searching strategies while conducting the experiment. Though all these issues are interesting to discuss or to take into account, they are out of the scope of our study. The real fact is that some of the individuals where indeed closer to performing optimal stochastic searches than others, and that the former where ultimately more successful. Further work is needed to better understand potential biological mechanisms capable of controlling statistical properties of movement in animals (including humans), joined by the understanding that a statistical property can make a difference when looking for targets with no information at all within reasonable spatio-temporal scales.

Acknowledgments

This work was partially supported by the Santa Fe Institute through NSF Grant No. 0200500 entitled "A Broad Research Program in the Sciences of Complexity". Y.A.-R was supported by the Horowitz center for Complexity Science and F.B was supported by a post-doctoral fellowship from the Spanish government (EX-2005-1011) and through NSF Grant No. DEB-0083566. We are grateful to all the volunteers from the Complex Systems Summer School who searched, followed, watched, recruited, photographed, lent their laptops, contributed cold drinks and in general, gave a helping hand on two hot summer days.

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Figures

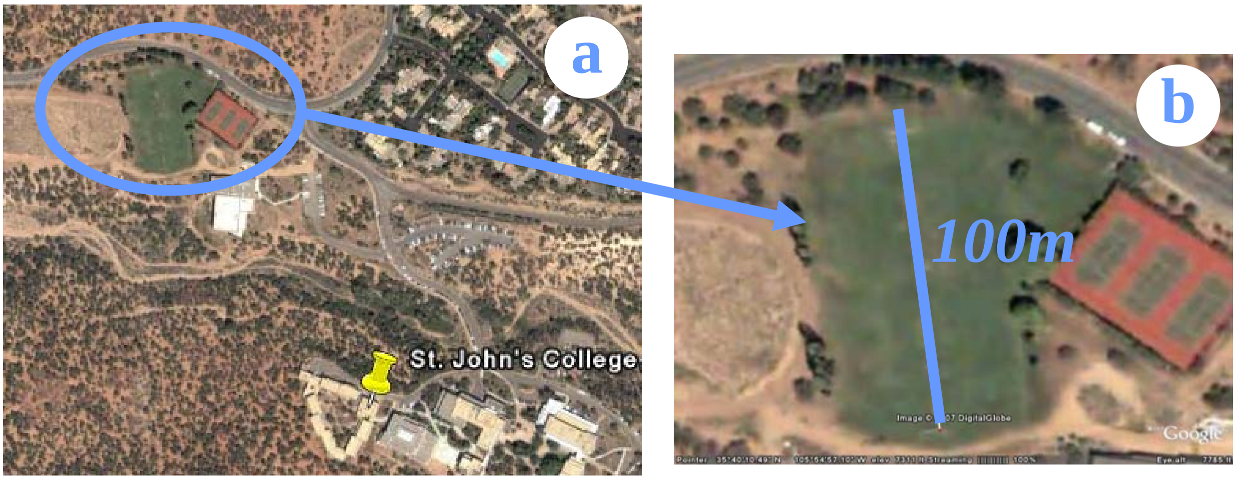

Figure 1: The experiment was held in a 100*m* by 50*m* soccer field of St. John's Collage, Santa-Fe, New Mexico. Photos were downloaded from Google Earth.

Figure 2: 19 blind folded volunteers searched the field for 5 targets. a) Searchers were instructed to search for as many targets as possible with no prior knowledge of the theoretical background of the experiment nor what would be measured during the experiment. b) Each searcher was blind folded before entering the field, and was then lead to a random starting position in the field. c) During the experiment, the searchers remained blind folded while searching for targets, and were each escorted by a follower. d) During the search, the walking path of each searcher was observed by a watcher. The length of time between reorientations, known as a flight, was recorded with software written in visual basic. Photographs were taken by Amelie Veron.

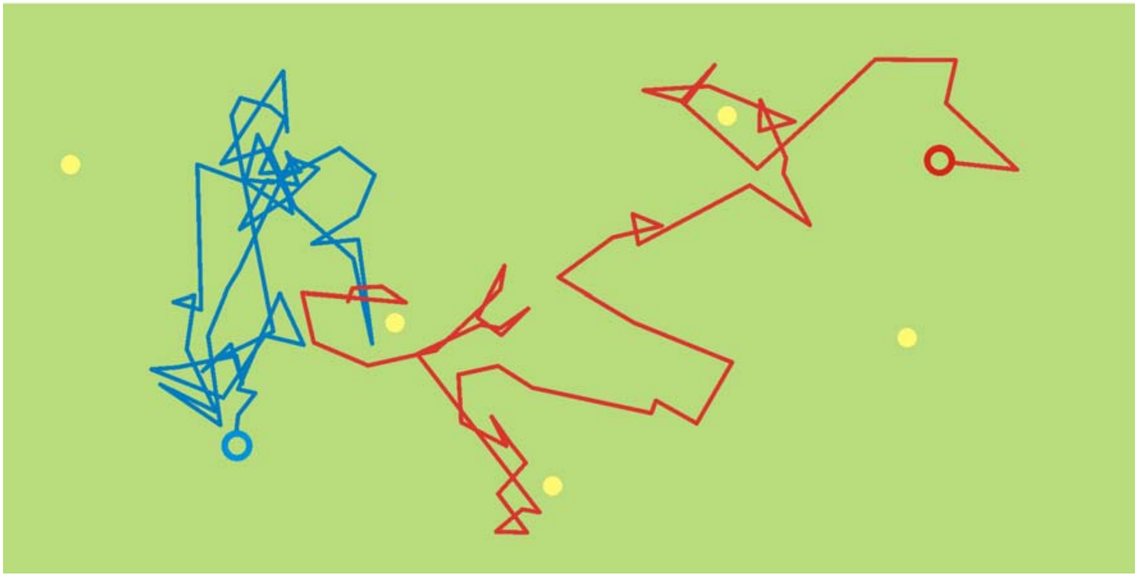

Figure 3: Demonstration of a set of flights observed for 2 searchers. The lengths of the flights sketched here are determined by the duration of time intervals between reorientations (under the assumption that the velocity is constant), and the turning angles for this demonstration were randomly sampled from a uniform distribution. Starting points were chosen randomly, and are marked by hollow circles. Yellow circles represent locations of the targets in the field. The red path is the series of flights for the most successful searcher who hit a target 8 times. The blue path is a series of flights for a less successful searcher who managed to hit only one target. The form of the blue path implies that the less successful searcher showed a distribution of flight length which resembles Brownian motion, dispersing through the field by a normal diffusion processes. The form of the red path on the other hand resembles a power law like distribution of flights.

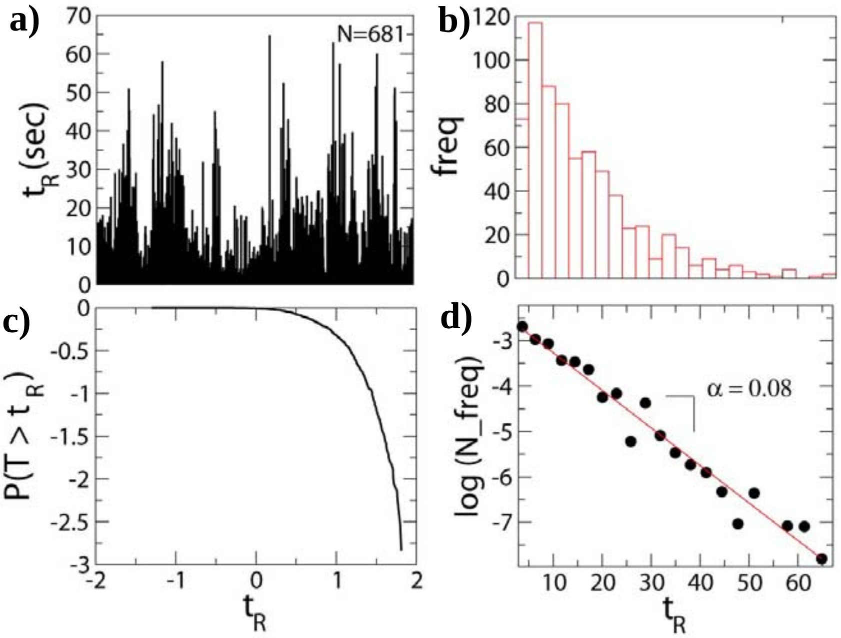

Figure 4: a) Raw data of the variable time between reorientations (t_R). b) Histogram of t_R with 25 bins. c) Cumulative distribution of the observed flight lengths $P\left(\mathrm{T} > \mathrm{tR}\right)$ as a function of t_R. d) A log-linear plot with a linear regression fit, showed to be exponential with α=0.079±0.006, and a characteristic time scale of 12.5 sec, suggesting that the overall pattern of the time between reorientations represents Brownian motion.

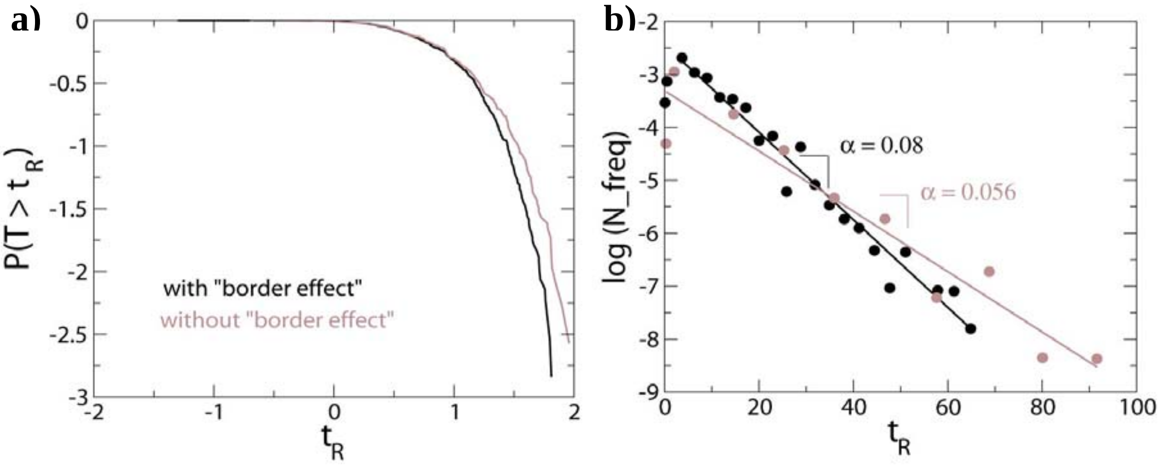

Figure 5: a) Cumulative distribution showing the probability of excedence $P(\mathrm{T} > \mathrm{tR})$ of $\mathrm{t_R}$ with and without border effects. b) Log-linear plots with linear regression fits, show a fit to exponential distributions. The new distribution of flights was found to have a longer characteristic time scale of 17.86 sec, but the distribution was still found to be exponential with α=0.056±0.005.

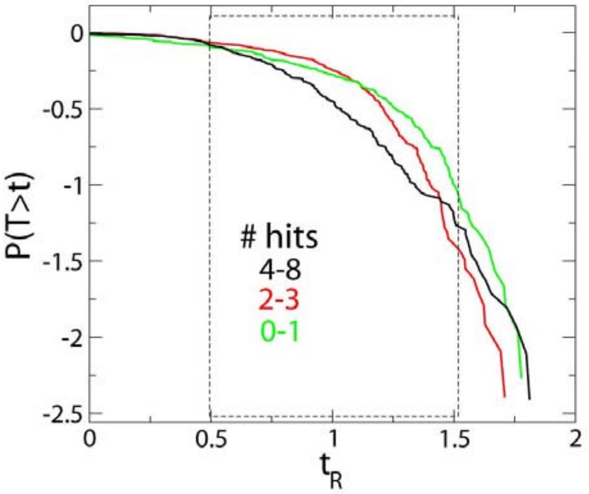

Figure 6: Cumulative distributions showing the probability of excedence $P(\mathrm{T} > \mathrm{tR})$ of $\mathrm{t_R}$. Data pooled into 3 sets according to the number of targets a searcher managed to locate; group *A* located 0 to 1 targets, group *B* located 2 to 4 targets and group *C* located 5 to 6 targets. Groups *A* and *B* showed an exponential distribution with α=0.063±0.01 and α=0.066±0.01, respectively. Group *C* on the other hand showed strong deviations from an exponential distribution.

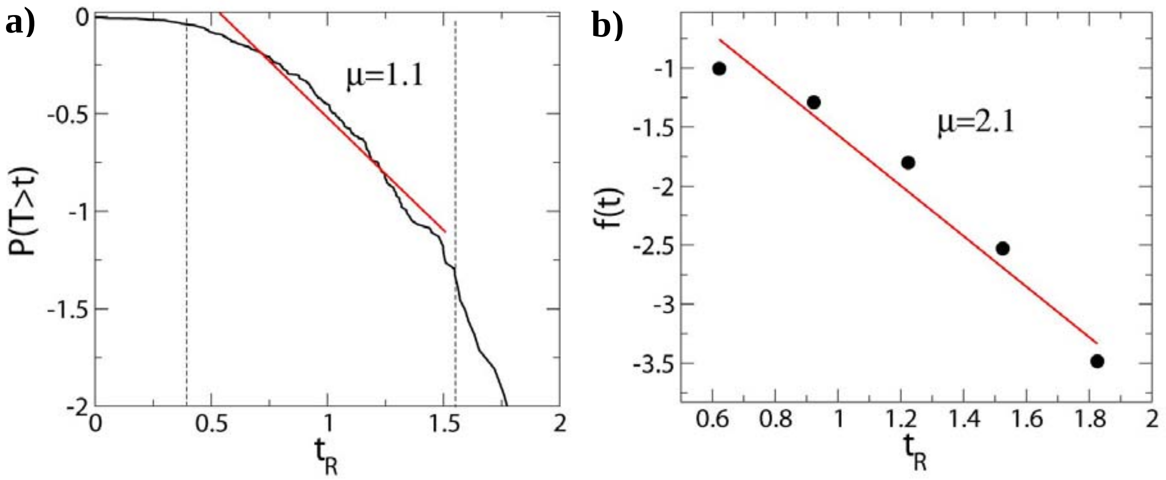

Figure 7: a) Cumulative distribution showing the probability of excedence $P(\mathrm{T} > \mathrm{tR})$ of t_R. A linear regression fit shows a power-law regime. b) Logarithmic binning histogram showing that the distribution of time between reorientation of group *C* approached a power law distribution with a scaling exponent of μ=2.1.

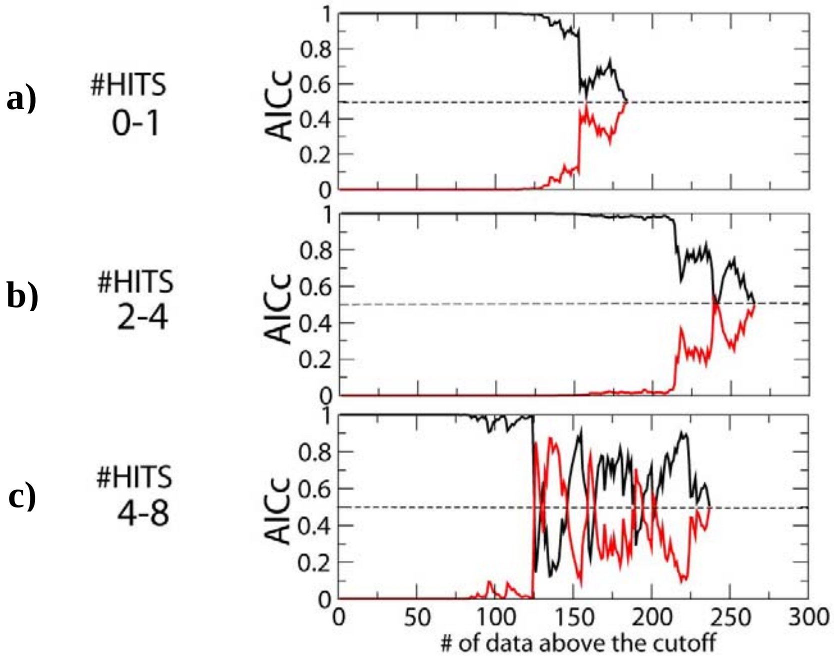

Figure 8: Results based on moving tail tests confirm the fact that the two first groups (*A* and *B*) followed Brownian search patterns whilst the most successful group (*C*) followed search patterns resembling Lévy walks. bution would indicate the existence of Lévy walks.