
Measuring Forager Mobility

by P. Jeffrey Brantingham

Mobility plays a large role in generating the patterns of stone raw-material usage seen in forager archaeological sites, but how best to translate these patterns into a complete quantitative characterization of the organization of forager mobility remains a difficult problem. The number of potential variables involved, including raw-material quality and abundance as well as individual movement and technological decisions, makes it extremely difficult to analyze mobility independent of all other influences. This paper develops a formal model of forager mobility based on a well-known stochastic process termed a Lévy random walk. When combined with neutral assumptions about how stone is procured and used, the model may be used to recover detailed quantitative information about the organization of forager mobility from raw-material transport distances. The model has clear behavioral interpretations in terms of levels of planning, risk sensitivity, and time-energy optimization and thus provides several potential currencies for comparative studies of prehistoric mobility strategies. How other behavioral decisions such as raw-material selectivity and even social exchange of raw material might influence patterns of stone raw-material transport is also explored.

Archaeologists often rest inferences about the ecological and social organization of foragers on low-level behavioral models describing how they procure and transport stone raw materials (e.g., Andrefsky 1994; Binford 1979; Goodyear 1989; Kuhn 1995, 2004; Stout et al. 2005; Surovell 2003). The distance over which stone is transferred is often used to infer, for example, territory size, the frequency and magnitude of residential or logistical moves by foraging bands, overall levels of planning, and, for exceptionally long-distance transfers, the presence of social exchange within a regional network of bands (Beck et al. 2002; Féblot-Augustins 1993, 1997a, 1997b, 1997c; Gamble 1999; Kelly 1983, 1992; Kuhn 1995, 2004). Similarly, the direction of stone raw-material transfer and the staging of lithic reduction on the landscape are sometimes used to infer the regular paths followed by foraging bands on their annual rounds (Féblot-Augustins 1997a, 1997b, 1997c; Gamble 1999; Geneste 1988; Jones et al. 2003; Surovell 2003). Raw-material transport patterns in western France offer a case in point. Bergerac chert from spatially localized deposits in the eastern Perigord was exploited extensively by early Upper Paleolithic groups in the region. The direction of transfers shows a strong bias in movement to the east (fig. 1), suggesting organized seasonal movements to exploit reindeer during their fall and winter migrations (see, e.g., White 1989). Bergerac chert is found as far away as 100 km from the source,

but the proportion of material transferred peaks between 25 and 50 km from the source (fig. 2). The middle-distance peak in transfers may reflect the fact that the source of a stone raw material is rarely near the foraging patches that need to be exploited. The decline in transfers at greater distances may reflect maximum distances that foragers are willing to travel to exploit different resources. Indeed, it is common to interpret maximum stone transport distances as the radius of the territory exploited by the foraging groups in question, which in the early Upper Paleolithic in western France appears to have been ca. 100 km (Féblot-Augustins 1997a, 1997b, 1997c).

If we examine the topology of mobility patterns potentially underlying stone raw-material transport patterns, however, it is clear that many of the empirical measures used by archaeologists are at best proxies for the properties of individual mobility strategies (fig. 3). In particular, the distance between the source of a raw material and occurrences of it at one or more archaeological sites measures only the displacement of that stone in space. A number of different logistical or residential movement patterns may be seen as consistent with any given pattern of stone transfers (e.g., Goebel 2004). Yet quantities such as the number and frequency of moves and the mean and variance in individual move lengths are what our low-level behavioral models hope to describe. These behaviors, not simply the displacement of stone in space, were presumably critical in regulating the adaptive costs and benefits of patch choice, risk sensitivity, and planning depth (Cashdan 1992; Nelson 1991; Surovell 2003) or maintaining social ties among a network of mobile foraging bands (Gamble 1999; Hewlett, van de Koppel, and Cavalli-Sforza 1982; Shack-

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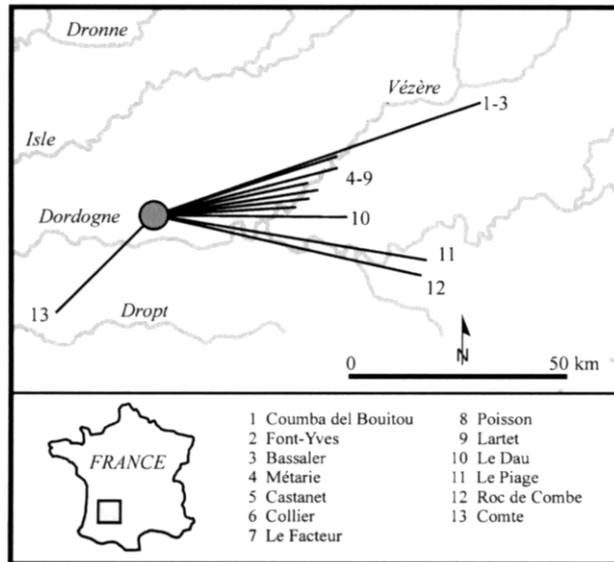


Figure 1. The Aquitaine Basin, France, showing transfers of Bergerac chert between its primary source area along the Dordogne River and early Upper Paleolithic (Aurignacian) sites in the Périgord (redrawn after Féblot-Augustins 1997b, fig. 86).

ley 1996). While this measurement problem has long been acknowledged by archaeologists (Kelly 1992), it has proven very difficult to resolve.

I argue that, except under extraordinary circumstances (e.g., Close 2000), it is only through the application of probabilistic models that we can make specific behavioral inferences about the nature of prehistoric mobility on the basis of stone transport distances. This argument hinges on the supposition that observed patterns of stone raw-material transport are best considered realizations of a stochastic process. In organizing mobility and the use of stone, foragers are faced with a series of potential decisions, for example, decisions about how far to move and in what direction and whether stone should be used continuously as foraging opportunities arise or far more selectively. Whatever the mechanics of this decision making on the ground, a model of the decision process may choose to assign probabilities to the outcome of each unique collection of decisions. One observed instance of stone raw-material transport is a random variable drawn on the set of all possible outcomes. A sequence of transport events, each implemented via the myriad decisions the forager must make, is a series of random variables drawn on the probability space of potential outcomes. The sequence of stone transport events is therefore a stochastic process as classically defined (see Stirzaker 2003). For example, we might say that there is a probability $p = .1$ that a unit of stone raw material will be transported more than 5 km from its source and thus a probability $q = 1 - p = .9$ that it will be transported no more than 5 km from its source. Analysis of an archaeological assemblage might reveal one core and three

flake blanks made on a material whose source is located < 5 km from the site and one tool made on a material whose source is > 5 km from the site. Assuming that each item was discarded independent of the others, each observed transport distance is a realization of the probabilities p and q and technically qualifies as a random variable. The collection of discard events represents repeated, independent realizations of p and q and thus is the product of a stochastic process.

A number of different probabilistic models may adequately describe the stochastic process underlying the procurement and transport of stone, though all should take a fundamental form giving the probability that a forager has moved (and transported stone) a total distance after a certain number of moves. It is the aim of this paper to develop fully one such model and to show how specific properties of forager mobility strategies may be recovered from observed stone raw-material transport distances. Borrowing methods from physics and biology, I begin by presenting a model of forager mobility that has clear behavioral and ecological implications and well-understood analytical connections to neutral mobility models (Brantingham 2003). I then develop an agent-based simulation of stone raw-material procurement and transport in which mobility strategies are compared in terms of differences in planning depth and risk sensitivity. Simulations are used to test the performance of several formal equations that may be used to estimate key behavioral features of mobility from observed patterns of stone transport. Testing of these equations against simulated data is important because the model parameters generating simulated patterns of raw-material transport are completely known. Immediate application to real archaeological data like those for the early Upper Paleolithic of western France would likely generate reasonable results, but the reliability of any conclusions based on these analyses would remain in doubt because of the untested na-

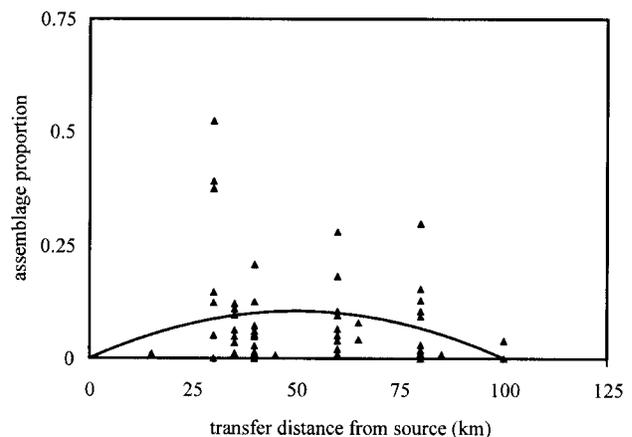


Figure 2. Proportion of artifacts in Chatelperronian, Aurignacian, and Gravettian (Perigordian) archaeological assemblages made on Bergerac chert as a function of distance from the raw-material source (data from Féblot-Augustins 1997c, tables 31–38).

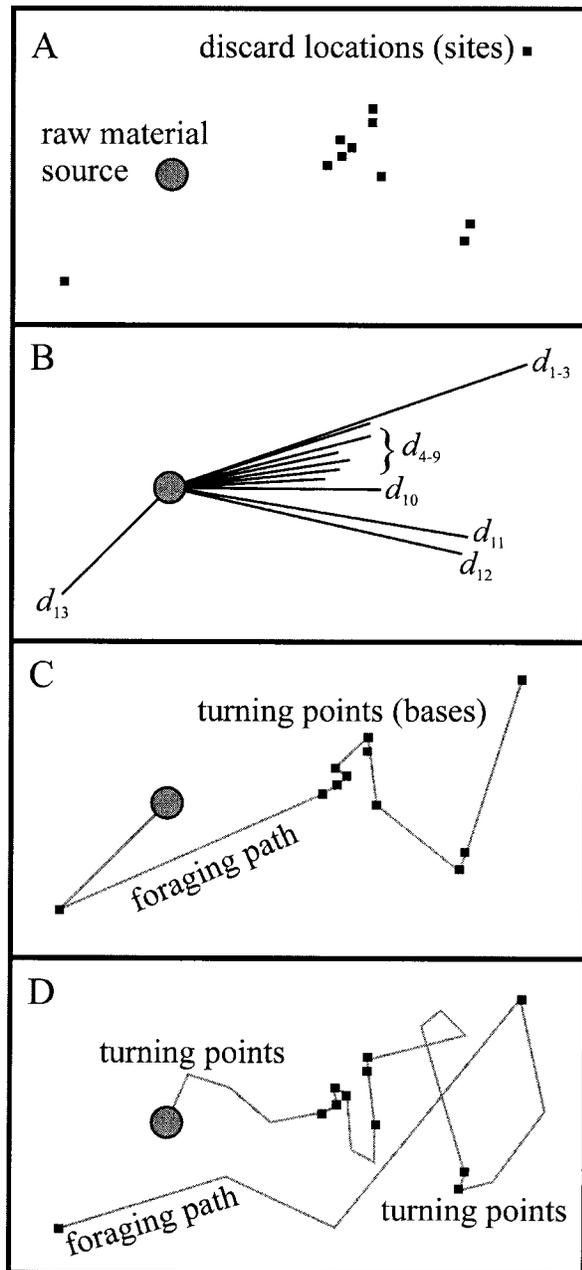


Figure 3. Abstract graphical model for the transport of Bergerac chert. *A*, chert source location and spatial distribution of discard locations (sites). *B*, linear distance measures d_i between the source and each of 13 archaeological sites. *C*, one hypothetical foraging path, in which turning points along the path (i.e., bases) coincide with known sites. *D*, a second hypothetical mobility path with the same distribution of raw-material transport distances as in *A* but twice as many turning points and approximately twice as much distance covered along the total foraging route. The absence of archaeological sites at half of the turning points in *D* may reflect a lack of site formation, poor site preservation, or lack of archaeological sampling at these locations. The strong directional bias seen in *B* is less apparent at the scale of the individual foraging routes in *C* and *D*.

ture of the underlying model. A first essential step is to conduct a controlled test of the model against simulated data that mimic what we might expect to see in the archaeological record.

Formal modeling necessarily involves a series of simplifying assumptions. In the present case I make several extreme assumptions regarding the nature of stone raw-material procurement. Specifically, I assume that (1) raw-material utilization is indifferent to variations in raw-material quality and abundance (Brantingham 2003) and (2) procurement of stone is completely embedded within the mobility strategy (i.e., stone is procured only when encountered in the course of regular movements and never as a result of specialized procurement forays) (Binford 1979). While such assumptions may be perceived as unwarranted oversimplifications of a complex process, they offer the most direct route to executing a controlled, quantitative examination of the impact of mobility strategies on raw-material usage independent of other potentially confounding processes. I eventually relax some of these assumptions to examine how mixed planning-depth foraging strategies, raw-material selectivity, and social exchange of stone between foraging groups might impact our understanding of stone procurement and transport. Ultimately, the mobility model developed herein is a foundation for a rigorous consideration of how behavioral strategies such as the management of stone consumption combine with mobility to generate lithic technological adaptations.

A Formal Model of Forager Mobility

Forager mobility may be described formally in a number of different ways (e.g., Brantingham 2003; Surovell 2003). Here I choose to model forager movement as a Lévy random walk, a discrete approximation of anomalous diffusion named after the physicist Paul Lévy (Shlesinger, Zaslavsky, and Klafter 1993; Viswanathan et al. 2002, 1999). Lévy walks are based on a simple equation stating that the probability of a move of length l is distributed as

$$P(l) = l^{-\mu} \tag{1}$$

Here individual moves of length l are taken as the straight-line paths connecting two stops along a single route on a two-dimensional plane. Forager move lengths thus obey a negative-power law with properties defined by exponent μ (fig. 4). Depending upon the spatial and temporal scale under consideration, foraging stops may be interpreted as turning points along a continuous path representing a single foraging bout, temporary camps or resting spots used by special-purpose activity groups in a logistical foray, or residential camps used by a residentially mobile foraging band. Equation 1 is said to generate a Lévy walk if the forager moves between two points in incremental steps corresponding to a minimum possible step size l_0 , sometimes also referred to as the characteristic step length (Viswanathan et al. 1999). The same

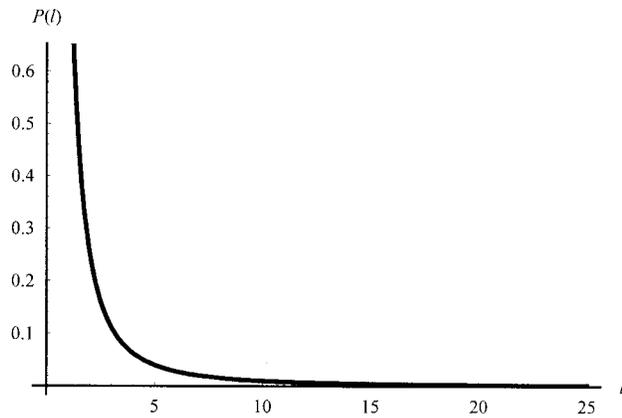


Figure 4. The Lévy probability distribution of move lengths, a negative-power distribution controlled by parameter μ , shown for $\mu = 2.0$. Moves of length l are given in arbitrary distance units.

equation is said to generate a Lévy flight if the forager jumps instantaneously between two points separated by distance l . For example, if two stopping points or bases are separated by five units of distance and the characteristic step size is $l_0 = 1$, then a Lévy walk would take five discrete steps to traverse this distance. A Lévy flight, by contrast, excludes these five intermediate steps, and the forager jumps across the five units of distance in a single step. From the forager's perspective, a Lévy walk allows detection of foraging targets both at the end points of Lévy paths and at intermediate steps between them. In contrast, a Lévy flight allows detection of targets only at the end points of individual flights. For simplicity, I will refer to this general mobility model as "Lévy mobility."

Equation 1 may be interpreted in terms of the relative frequencies of foraging moves of different sizes within an overall Lévy mobility strategy. Short-distance moves tend to be common (i.e., most of the density of the probability distribution is concentrated around low values of l). However, long-distance moves also occur with finite probability. With $\mu = 2$, for example, a forager faced with a choice to undertake a move of length $l = 1$ km (if measured in these units) will do so with probability $P(l) = 1$. However, the same forager faced with a choice to move $l = 20$ km will do so with probability $P(l) = .0025$. A move of length $l = 50$ km occurs with probability $P(l) = .000044$, a rare event but not improbable over the course of many moves. For certain values of μ , individual realizations of Lévy random walks typically show clusters of many short-distance moves interspersed with occasional long-distance moves (fig. 5).

Equation 1 in fact defines a family of mobility strategies the specific nature of which depends only on μ (Viswanathan et al. 1999). Physical studies have shown that μ typically varies between 1 and 3 (Shlesinger, Zaslavsky, and Klafter 1993), with the most interesting spatial behavior obtaining when

$1 < \mu < 3$. As μ increases toward 3 the probability distribution $P(l)$ becomes increasingly concave and virtually all of the mass of the function is concentrated around low values of l . Short-distance moves dominate, while long-distance moves become very rare or absent (fig. 6). When $\mu \geq 3$, equation 1 approximates a simple random walk (i.e., Brownian motion), provided there is no bias in movement directions. Convergence on a simple random walk occurs because the probability of choosing moves longer than the minimum possible move length l_0 becomes effectively zero (i.e., $P[l > l_0] \approx 0$) (Brantingham 2003; Desbois 1992; Nakao 2000; Shlesinger, Zaslavsky, and Klafter 1993; Viswanathan et al. 1999).

At the other extreme, as μ approaches 1 the distribution $P(l)$ becomes much less concave and develops a fat tail. This means that most moves are still relatively short, but there is a much greater probability of very long ones (fig. 7). Indeed, when $\mu = 1$ there is a finite probability that the forager will undertake an infinitely long move in a single direction (i.e., $P[l = \infty] > 0$) (Viswanathan et al. 1999). This pattern of movement is referred to as a Cauchy flight (Desbois 1992). More richly varied mobility strategies obtain when $1 < \mu < 3$ (Bartumeus et al. 2002). The aggregate movement pattern is neither a simple random walk nor a Cauchy flight. Rather, movements are topologically distinctive and are often cited for their fractal properties (fig. 8) (Shlesinger, Zaslavsky, and Klafter 1993).

The combined simplicity and flexibility of the Lévy mobility model has proven useful in describing the foraging behaviors of a wide range of organisms. It has been shown analytically that Lévy flights with $\mu = 2$ produce an optimal encounter

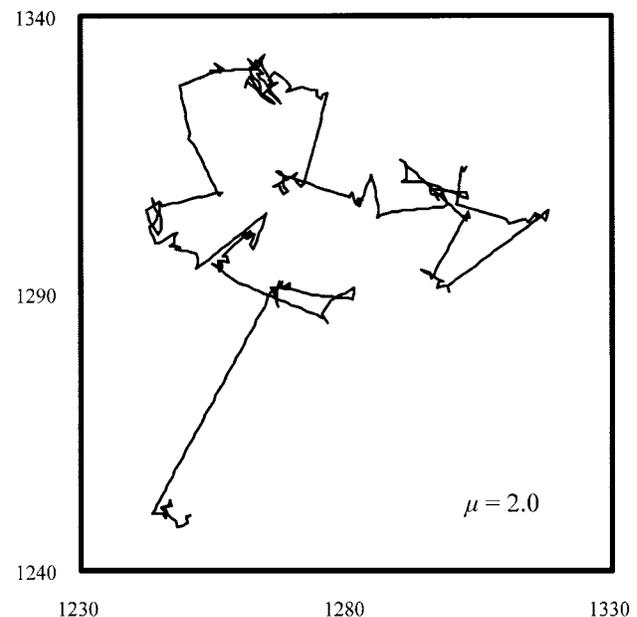


Figure 5. Simulated Lévy mobility path of a forager in a continuous spatial field where $\mu = 2.0$.

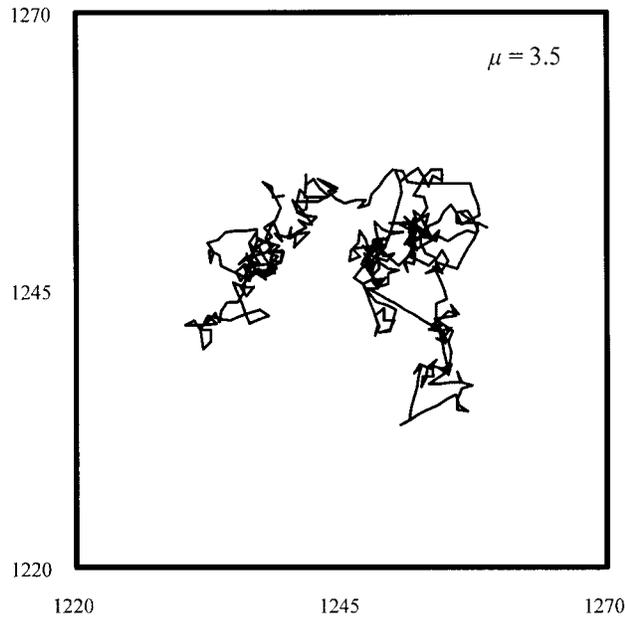


Figure 6. Simulated Lévy mobility path for $\mu = 3.5$.

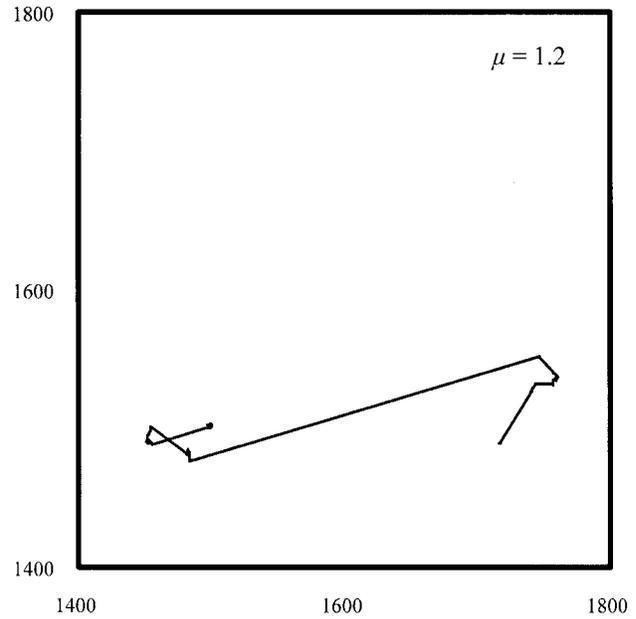


Figure 7. Simulated Lévy mobility path for $\mu = 1.2$.

rate with diffuse foraging targets randomly dispersed in an environment (Viswanathan et al. 1999). They also appear to describe the empirical frequency distributions of move lengths observed for organisms as different as dinoflagellates (Bartumeus et al. 2003), honey bees (Viswanathan et al. 1999), albatross (Viswanathan et al. 1996, deer (Viswanathan et al. 1996, 1999), and howler monkeys (Boyer et al. 2004; Ramos-Fernandez et al. 2004). On both theoretical and empirical grounds, therefore, it is reasonable to expect that mobility strategies for human foragers might also be structured according to equation 1.

The Behavioral Ecology of Lévy Mobility

The behavioral and ecological implications of forager mobility modeled via equation 1 are important to highlight. In particular, the convergence of a Lévy walk on a simple random walk when $\mu \geq 3$ indicates that extreme neutral mobility strategies such as that described in Brantingham (2003) are merely a special case of a broader family of mobility strategies. Lévy mobility can be transformed continuously into neutral mobility simply by varying the value of μ . Both the mechanics and the behavioral implications of neutral mobility are worth repeating, since they provide a point of departure for understanding how planning and risk sensitivity might factor into the broader organization of Lévy mobility strategies.

Neutral mobility can be specified by a simple, compact movement rule. Starting at any given location, neutral mobility obtains if all moves are of a small, fixed size, decisions about where next to move are made anew after the completion of each move, and all movement directions are equally likely

(fig. 9) (Brantingham 2003; Turchin 1998). Played out over many moves, this movement rule produces a simple random walk and an aggregate pattern of regular spatial diffusion. Neutral mobility has four primary behavioral implications (Brantingham 2003). First, a simple random walk is not constrained to stay in a home range but free to follow an infinitely long path away from any given starting location. Second, a

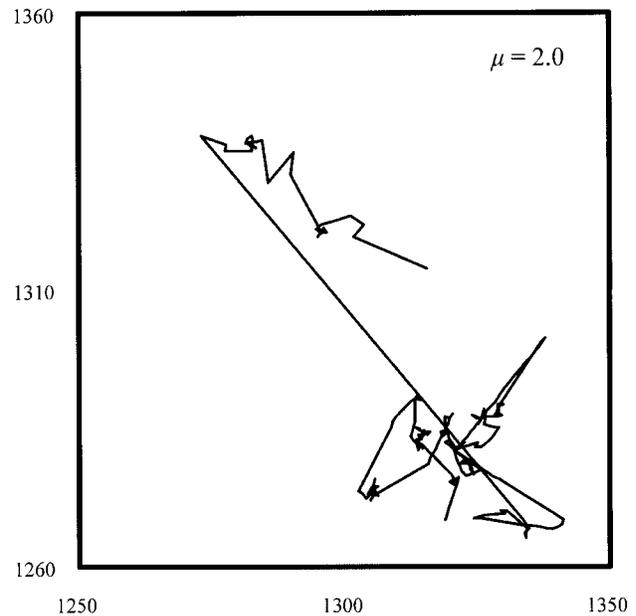


Figure 8. Simulated Lévy mobility path for $\mu = 2.0$.

simple random walk does not optimize any currency associated with movement; it does not provide a mechanism for choosing the time and/or energetically optimal path between any two points out of the large number of unique paths that might connect those two points. Third, and most important in the current context, a simple random walk does not involve any planning depth. Since each move is chosen only one time step in the future, there is no aggregate plan for constructing and following a specific foraging path over longer periods of time. Finally, a simple random walk is risk-insensitive. Because the history of movement is not remembered, the forager is equally likely to return to a location just visited (to find that it had consumed all of the resources there) as to move off in the opposite direction, where resources are more likely to be intact.

All but the first behavioral property are substantially different in Lévy mobility when $\mu < 3$. Lévy walks under these conditions show clusters of short-distance moves interspersed with occasional long-distance moves (see figs. 7 and 8). I reason that this movement topology implies not only increased planning depth but also increased currency optimization and risk sensitivity. Increased planning depth is implied in that incremental moves along paths longer than the minimum characteristic step size require the scheduling of larger blocks of time to accomplish the movement. For example, if two foraging bases are separated by ten units of distance and $l_0 = 1$, then the forager must plan movement *at least* ten time steps in advance to ensure transit between bases. If the forager is following a Lévy walk, in which incremental steps occur at each unit of time, then the path length l provides a direct measure of planning depth.

Linear Lévy walks connecting distant points in space also imply a minimization of travel time and/or energy and strict adherence to a travel plan to stay on the optimal path. Movement between two foraging bases ten units of distance apart, for example, might be accomplished following paths much longer than ten units. Strict following of the shortest linear distance between the two bases ensures minimum time and energy expenditure. Thus, optimization of energetic currencies is suggested for Lévy mobility strategies defined by $\mu < 3$.

Finally, risk sensitivity is also inherent in Lévy walks with $\mu < 3$. Under these conditions, most moves still occur over relatively short distances. Most foraging activities therefore take place in relatively constrained local areas, where resource patches are likely to be similar through spatial autocorrelation (Moloney and Levin 1996). As a consequence, a single foraging adaptation (e.g., toolkit), local knowledge (e.g., prey recognition patterns), and an existing social network are all likely to remain relevant within these local clusters of short moves (see figs. 7 and 8) (Boyd and Richerson 1985; Rockman and Steele 2003). However, any risk of extinction that might come with being trapped in a single declining patch is also circumvented when $\mu \leq 3$ by the finite probability of engaging in a long-distance move to more distant patches, though this

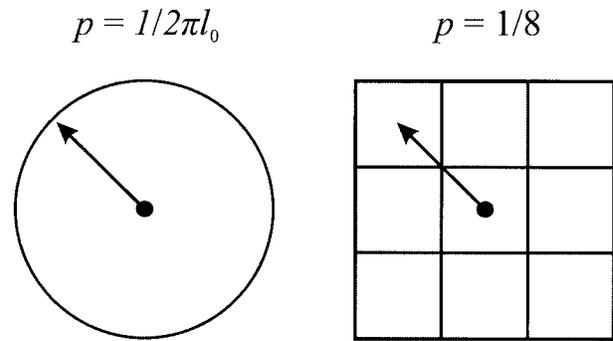


Figure 9. Neutral forager mobility. In continuous space, the forager moves a short distance l_0 and arrives at any location along the circumference of the circle inscribing the current location with probability $p = 1/2\pi l_0$. In discrete space, the forager moves to any of the adjacent eight grid cells with probability $p = 1/8$.

does entail the risk of encountering patches that are substantially unlike the one currently occupied.

In sum, I propose that μ provides a convenient summary measure of planning, energetic optimization, and risk sensitivity in mobility. Values of $\mu \geq 3$ correspond to neutral mobility and no planning, optimizing, or risk sensitivity. In contrast, values of $\mu \rightarrow 1$ imply increases in these behavioral properties. Estimating μ from archaeological data could therefore provide an important basis for behavioral inference and comparative studies of prehistoric adaptations.

As emphasized in figure 3, however, the distribution of move lengths, from which we might be able to infer μ , is not necessarily directly observable from stone transport distances. The analytical solution to this problem is well known (Koponen 1995; Nakao 2000), though it is mathematically very involved. In brief, a stable Lévy density function describing the spatial displacement d of a particle engaged in a Lévy walk is obtained in closed analytical form only for $\mu = 1$ (Cauchy distribution) and $\mu = 3$ (Gaussian distribution) (Denny and Gaines 2002; Desbois 1992; Nakao 2000; Shlesinger, Zaslavsky, and Klafter 1993). For all other values of μ , numerical approximations of the stable distribution may be obtained only via inverse Fourier transforms of a corresponding characteristic function (fig. 10) (Koponen 1995; Nakao 2000; Stirzaker 2003). Because of the mathematical complexities involved, I use simulation to generate data approximating stone raw-material transport under conditions of Lévy mobility. Where reasonably tractable, formal mathematical approaches are used both to ensure that the simulations are generating expected results and to illustrate how key organizational features of mobility may be estimated under realistic archaeological conditions.

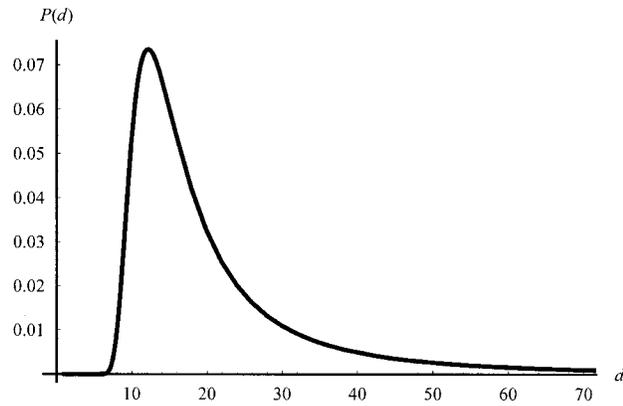


Figure 10. The density function describing the probability that a mobile forager has moved a distance d in a two-dimensional field from its starting location, computed analytically with $\mu = 1.8$.

Lévy Mobility and Stone Raw-Material Procurement

While the Lévy stable probability density function may provide a good model of forager displacement in space (fig. 10), it does not translate directly into a model of stone raw-material usage under such conditions. At a minimum we must build into the model a consideration of stone procurement, transport, and discard. Strategies of stone raw-material usage are complex phenomena in their own right, and there remain many unresolved issues surrounding the effects of raw-material abundance and quality and of strategies for regulating raw-material consumption on the organization of lithic technologies (Andrefsky 1994; Brantingham et al. 2000; Kelly 1992; Kuhn 1995, 2004; Plummer 2004; Surovell 2003). Here I avoid many of these complexities by positing that our mobile forager is indifferent to variations in raw-material quality and abundance (Brantingham 2003). This assumption allows me to concentrate on the effects of mobility alone, while retaining the necessary roles that stone procurement, transport, and discard play in generating the archaeological record. The following general toolkit properties are valid for simulations involving only one raw-material source, as in the present case, or many independent sources (Brantingham 2003):

First, stone raw material is procured from any source encountered without regard for raw-material type and provided that there is space available in the mobile toolkit:

$$a_i = \max(v) - \sum_i v_i, \quad (2)$$

Equation 2 states that the amount of material procured from source i at a single point in time is simply the difference between the maximum toolkit size, $\max(v)$, and the quantity of material from all sources currently in the toolkit, $\sum v_i$. Thus, if the toolkit is close to full when a source is encountered,

then only a small amount of material will be procured. Equation 2 holds even in the case of foraging around a single stone raw-material source whenever the forager backtracks across the source location.

Second, stone raw material is consumed and discarded uniformly through time. The probability that any one unit of a raw material in the toolkit is consumed (c_i) is dependent only on its relative frequency in the toolkit,

$$c_i = \frac{v_i}{\sum_i v_i}, \quad (3)$$

where v_i is the amount of material in the toolkit from source i . The choice of raw material to consume from the toolkit at any one time is made via simple random sampling without replacement. In a multisource environment, where the toolkit may contain more than one raw-material type, equation 3 indicates that raw-material consumption and discard are independent of both raw-material quality and the abundance of material types in the environment. Any one unit of a raw material of type i is consumed with a probability dependent only upon its relative frequency in the toolkit. Thus a nominally high-quality raw material might be completely consumed before a low-quality material if it happened to be much more common in the mobile toolkit. In an environment containing only one source, raw-material quality is irrelevant, since there are no alternatives from which to choose. In this case, equation 3 states that all units of material are consumed with equal probability.

Equation 3 makes no distinction between cores, tools, and debitage. Rather, it describes all consumption and discard events in terms of undifferentiated units of raw material. It might be interpreted to mean, for example, that stone material is reduced to give cores, tools, and debitage that are uniformly 10 g in weight. Similarly, it is assumed that all discarded material becomes part of the archaeological record at the discard location. Material accumulation at a single spatial location reflects very generally the intensity of occupation at that site. The following models could easily be restated in terms of the relationships between raw-material procurement, transport, and site occupation span (Surovell 2003).

The above assumptions are not meant to imply that foragers never attended to differences in raw-material quality and abundance in their stone procurement and discard decisions. Rather, they allow me to investigate the extent to which archaeological patterning can be explained by mobility *alone* with the certainty that specialized adaptations associated with toolkit organization and maintenance *are not* responsible for observed patterns (Brantingham 2003; Gotelli 1996; Hubbell 2001; Kimura 1983).

Simulation Mechanics

Three cases of Lévy mobility with different levels of planning depth are examined for qualitative differences in their impact on stone raw-material procurement and transport.

Lévy mobility paths are simulated via repeated choices of two parameters, β and l , representing a bearing of movement and a path length, respectively. β is a uniform random variable drawn from 1–360°. Therefore there is no spatial bias in move directions. The parameter l is drawn from the Lévy distribution (equation 1) with critical differences in the probability of individual move lengths being determined by the parameter μ . These two parameters are entirely sufficient to specify the sequence of turning points or bases visited in space (Turchin 1998). Sequential independent draws of β and l define a set of turning points or bases conditioned only upon the location of the previous turning point or base; the set is given as $\mathbf{S} = \{(\beta_1, l_1 | \beta_0, l_0), (\beta_2, l_2 | \beta_1, l_1), \dots, (\beta_n, l_n | \beta_{n-1}, l_{n-1})\}$. For example, starting at location $x_0, y_0 = 500.00, 500.00$ in a continuous spatial field, random draws of $\beta_1 = 106.76^\circ$ and $l_1 = 2$ units of distance specify the next turning point or base located at $x_1, y_1 = 501.92, 499.42$. Because this is a Lévy walk and the new stopping point is two units of distance away ($l_1 = 2$), the forager must take two steps of $l_0 = 1$ to arrive there. As a consequence, there is an intermediate step between the two stopping points at $x, y = 500.96, 499.71$.

Lévy mobility strategies and toolkit dynamics are connected in two ways. First, stone raw material may be procured from a source encountered anywhere along a foraging path, including both the incremental steps between stopping points and the stopping points themselves. Because the current model is spatially continuous, it is necessary to specify how the forager detects the presence of a stone raw-material source. Here I assume that the forager has a small field of vision $\rho = .5$ units of distance and that raw-material sources are detected within the circular area with radius ρ of the current location (see fig. 9). In other models of Lévy-walk foraging, mobility paths are immediately terminated if foraging targets are encountered (e.g., Marthaler, Bertozzi, and Schwartz 2004; Viswanathan et al. 1999). The present model allows travel to the predetermined path end point to continue despite raw-material source encounters. This is equivalent to assuming that raw-material procurement is fully embedded in Lévy mobility patterns (Binford 1979). Since the following simulations concentrate on mobility around a single raw-material source, the above conditions apply whenever the forager backtracks across the raw-material source location.

Second, stone consumption and discard occur continuously along foraging paths, with one unit of material being discarded at each time step of the simulation. This means that material is equally likely to be discarded at any point along Lévy foraging paths, including both locations of encountered sources and path stopping points. Both features of toolkit dynamics ensure that raw-material procurement, consumption, and discard remain neutral with respect to Lévy mobility.

All of the simulations presented below adhere to the following additional constraints: The environment is a spatially continuous field, meaning that any location can be occupied with floating-point precision. There is a single stone raw-material source located at the center of the environment. A single forager engages in Lévy mobility according to the rules outlined above and starts with a full toolkit at the central stone raw-material source. The toolkit has an arbitrary $\max(v) = 100$. Following Brantingham (2003), the amount of time that can be spent foraging before the toolkit is cleared of all material is $N = \max(v)/r$, where $r = 1$ is the raw-material consumption rate per unit of time. In all simulations, therefore, the forager runs out of raw material after every 100 time steps unless it is able to backtrack across the raw-material source location before the toolkit is cleared of all material. Finally, whenever the toolkit is cleared of all stone raw material, the forager is placed again at the raw-material source with a full toolkit. This procedure is implemented simply as a matter of convenience. The results are identical to alternative simulation routines that would have either multiple foragers starting at the same time from the central source location or, given enough computing time, a single forager reencountering the raw-material source randomly.

Planning depth in Lévy mobility is simulated by varying the parameter μ to generate different probability distributions of path lengths l . Simulations with $\mu = 3.5$ are taken to represent an absence of planning, with results comparable to those for the neutral model (Brantingham 2003). Simulations with $\mu = 2.0$ and $\mu = 1.2$ are representative of intermediate and high planning depth, respectively. Table 1 lists all model variables, parameter ranges, and variable interpretations.

Simulation Results

Raw-material transport distances. Figures 11–13 present frequency distributions for the number of units of raw material discarded at each distance d from the single, centrally located raw-material source (cf. Brantingham 2003; Féblot-Augustins 1993, 1997a, 1997c; Gamble 1999). Ten simulations each lasting 965 time steps were run at each value of μ .

In figure 11, because $\mu \geq 3$, the mobility pattern approximates a simple random walk in which most moves are the same minimum size $l \approx l_0 = 1$ unit of distance. Consistent with the neutral model of stone transport and the absence of planning in mobility strategies, the distribution shows an internal mode and a moderate right skew. The maximum stone transport distance is 35.5 units from the source, approximately three to six times the modal transport distance.

Following Brantingham (2003) and Viswanathan et al. (1999), the mean stone transport distance \bar{d} may be described quantitatively using

$$\bar{d} = l_0^{\mu-1} \sqrt{\frac{\max(v)}{r * \langle l \rangle}}, \quad (4)$$

Table 1. Description of Model Variables

Variable	Value Range	Units	Description
l	1–100	Arbitrary distance (e.g., kilometers)	Path length between two turning points
$P(l)$	0–1	Probability measure	Probability of a path of length l
l_0	1	Arbitrary distance	Minimum path length; characteristic step size
μ	>1–3.5	Scale-free	Lévy parameter; summary of planning depth
ρ	0.5	Arbitrary distance	Field of vision for detecting raw material sources
a_i	1–100	Arbitrary quantity (e.g., mass, specimens)	Amount of material collected from source i
$\max(v)$	100	Arbitrary quantity	Maximum toolkit size
$\sum v_i$	1–100	Arbitrary quantity	Amount of material in the toolkit from all sources at one time
c_i	0–1	Probability measure	Probability that a unit of raw material from source i is consumed
v_i	0–100	Arbitrary quantity	Amount of material in the toolkit from source i
r	1	Arbitrary quantity per unit time	Raw-material consumption rate
β	1–360	Degrees	Bearing of movement
$\langle l \rangle$	> 1	Arbitrary distance	Mean path length between residential bases in a mobility strategy
N	–	Arbitrary time (e.g., days, years)	Number of simulation time steps; number of residential bases visited in a simple random walk
d	1–100	Arbitrary distance	Stone raw-material transport distance; forager spatial displacement
F	> 1	Turning points	Mean number of turning points or bases visited to generate a mean raw-material transport distance \bar{d}

where $\max(v)$ is maximum size of the toolkit, r is the raw-material consumption rate, and $\langle l \rangle$ is the mean path length:

$$\langle l \rangle = \int_{l_0}^{\max(v)} l^{1-\mu} dl. \tag{5}$$

In both equations, $\max(v)$ may be replaced with $\sum v_i$ if one is considering transport of a quantity of a material of type i less than the maximum toolkit size (see Brantingham 2003). The integral in equation 5 is taken over the interval (l_0 , $\max[v]$) and therefore represents the mean of only those path

lengths that can be detected archaeologically; a path longer than $\max(v)$ cannot be observed because all materials in the toolkit would have been discarded after $N = \max(v)/r$ time steps. Equations 4 and 5 are important on a number of levels. First, they provide a precise statement of how key variables linking mobility to stone transport are related to one another. Second, they provide, in principle, a means for estimating mobility properties not directly observable in the archaeological record. For example, rearranging equation 4 should allow the estimation of the critical parameter μ . At present, equations 4 and 5 may be used to evaluate the performance of the simulation with respect to analytical expectations. When $\mu = 3.5$, for example, equation 4 estimates the mean

Table 2. Simulated and Analytical Estimates of Key Variables in Residential Mobility

μ	Simulation	Analysis	Corresponding Equation
Maximum transport distance $\max(d)$			–
3.5	35.50	–	
2.0	100.26	–	
1.2	100.05	–	
Mean transport distance \bar{d}			4
3.5	7.59	7.42	
2.0	21.34	21.71	
1.2	40.24	37.21	
Mean residential move length $\langle l \rangle$			5
3.5	1.19 ± .86	0.66	
2.0	4.04 ± 16.63	4.60	
1.2	44.12 ± 87.17	48.51	
Number of turning points F to give \bar{d}			6
3.5	–	151	
2.0	–	21	
1.2	–	2	

raw-material transport distance at 7.42 units of distance from its source compared with 7.59 obtained by simulation (table 2).

Increasing planning depth by setting $\mu = 2.0$ changes some features of the frequency distribution (fig. 12). The distribution retains an internal mode, but the right skew has increased, indicating much longer transport distances. The maximum transport distance is 100 units from the source, approximately ten times the modal distance. This is, however, an arbitrary maximum given the constraints of $\max(v) = 100$; larger toolkit sizes could extend the maximum transport distance considerably. Equation 4 estimates the mean transport distance at 21.71 units of distance from the source, which corresponds closely to the 21.34 units of distance obtained via simulation.

Increasing planning depth further by setting $\mu = 1.2$ changes the frequency distribution dramatically (fig. 13). The discrete internal mode has largely disappeared, and discards are far more evenly distributed across the range of possible transport distances. The constraints of toolkit size also determine a maximum transport distance of 100 units from the source. Mean transport distance is estimated by equation 4 at 37.21 units of distance from the source with the simulation mean at 40.24 units of distance. The correspondence between analytical expectations and simulation results in all three cases suggests that the additional assumptions regarding stone procurement, transport, and discard necessary to simulate archaeological site formation have relatively little effect on the precision of the analytical measures. In sum, mean and maximum stone transport distances increase with planning depth, and these changes are measured by lower values of μ .

Number of stops along a foraging route. Viswanathan et al. (1999) provide a direct method for estimating the mean number of turning points or bases visited over the course of Lévy random walk (see fig. 3, C and D). Where l_0 is the minimum

move length, the average number of bases F visited is given by

$$F = \left[\frac{\bar{d}}{l_0} \right]^{\mu-1}. \quad (6)$$

F measures only the number of turning points or bases visited, exclusive of the number of incremental steps necessary to get between those bases. If $l_0 = 1$, then F is equivalent to the number of Lévy flights needed to move between bases the mean transport distance apart. When $\mu = 3$, equation 6 becomes the standard solution for the mean squared displacement of an agent engaged in a simple random walk (Denny and Gaines 2002; Viswanathan et al. 1999). F is here equivalent to the number of time steps in the random walk and may be estimated as the square of the mean displacement of stone in space (Brantingham 2003). For example, if the mean stone transport distance is 10 units from the source, then it takes on average about 100 flights between bases to accomplish this displacement. When $\mu = 2$, the power disappears, and the number of turning points or bases visited is a linear function of the mean displacement of raw material in space; on average it takes 10 flights to displace stone a mean distance of 10 units from its source. Values of $\mu < 2$ lead to sublinear relationships. For example, with $\mu = 1.5$ it takes only an average of 3.16 flights to displace stone 10 units of distance from its source.

Using mean transport distances determined by simulation to mimic a realistic archaeological setting (table 2), equation 6 suggests that an average of 151 flights between bases is required to displace material an average of 7.59 units of dis-

Table 3. Estimated Lévy Parameter Values Based on Simulated Mean and Maximum Stone Transport Distances

μ	Simulated \bar{d}	Simulated max (d)	Equation Parameters for Mean Path Length $\langle l \rangle$				Estimated μ	Estimated Difference
			Estimate					
			b_0	b_1	b_2	b_3		
3.5	7.59	35.50	17.16	-5.58	0.54	-0.011	2.76	-0.74
3	9.27	59.73	3.70	-0.46	-0.01	0.003	2.88	-0.12
2.8	11.14	94.62	-8.36	2.07	-0.15	0.004	2.72	-0.08
2.2	18.51	100.26	-9.67	2.25	-0.15	0.003	2.26	0.06
2	21.35	99.99	-9.61	2.24	-0.15	0.004	2.07	0.07
1.8	25.79	100.00	-9.61	2.24	-0.15	0.004	1.77	-0.03
1.2	40.24	100.05	-9.62	2.24	-0.15	0.004	1.12	-0.08

tance from its source when $\mu = 3.5$.¹ The numbers shift to 21 for an average displacement of 21.34 units of distance when $\mu = 2.0$ and only 2 for an average displacement of 37.21 units of distance from the source when $\mu = 1.2$. The general pattern implies that increasing planning depth not only increases mean and maximum stone transport distances but also reduces the total number of turning points or bases visited sufficient to generate longer mean transport distances.

Estimating Planning Depth

The analytical tools developed here assume that we know μ . In real archaeological cases, of course, it is necessary to estimate μ before we can quantitatively characterize these properties of a mobility strategy. Assuming that stone raw-material procurement, transport, and discard are neutral, μ may be estimated by rearranging equation 4:

$$\mu = 1 + \frac{\ln(\max(\bar{v})/\langle l \rangle)}{\ln(\bar{d}/l_0)} \tag{7}$$

Only one of the four terms in equation 7 is directly observable without further calculation. For simplicity, I assume that $l_0 = 1$, but assuming that it is some small constant other than unity would not substantially alter results. Two analytical steps are necessary to replace maximum toolkit size and mean path length with terms that may be directly observed. First, given

1. The analytical estimate of number of bases visited following a simple random walk should be 100 given $\mu = 3$. The higher estimate in this case stems from the use of $\mu = 3.5$ and a corresponding expected mean $\langle l \rangle = 0.66$ units of distance. Equation 5 predicts a mean path length $\langle l \rangle \approx 1$ when $\mu = 3$. In discrete simulations, the variance in path lengths leads to results different from analytical expectations. For example, when $\mu = 3$, paths of length $l = 2, 4, 8$, and 16 units of distance occur with probabilities $p(l) = 0.125, 0.0156, 0.0019$, and 0.0002, respectively. Over finite simulation times, observed proportions of paths of each of these lengths are sometimes quite different. Over an infinite period of time the variance in l would become insignificant and the continuous pattern of displacement would correspond to simple diffusion. In finite-time simulations, setting $\mu = 3.5$ ensures closer adherence to a simple random walk. For example, with $\mu = 3.5$, paths $l = 1$ are about 11 times more likely to occur than a path $l = 2$ and 128 times more likely than a path $l = 4$.

a neutral toolkit, the observed maximum stone transport distance ($\max[d]$) serves as a reasonable estimate of maximum toolkit size (see Brantingham 2003). Second, analysis shows that the mean path length varies systematically with mean stone transport distance. This relationship is reasonably well approximated by a generic polynomial equation of the form $\langle l \rangle = b_0 + b_1\bar{d} + b_2\bar{d}^2 + b_3\bar{d}^3$ over all values of μ . Substituting these terms in equation 7 gives

$$\mu = 1 + \frac{\ln\left(\frac{\max(d)}{b_0 + b_1\bar{d} + b_2\bar{d}^2 + b_3\bar{d}^3}\right)}{\ln(\bar{d})} \tag{8}$$

Tests of equation 8 using simulated values of \bar{d} and $\max(d)$ produces results that are close to the known values of μ (table 3). The maximum difference between the estimated and the known value of μ is .74 when $\mu = 3.5$. The minimum difference is .03 when $\mu = 1.8$. The mean difference over all simulation tests is .17. The mean error for estimated μ values translates into discrepancies in estimates of Lévy mobility properties that *increase* as $\mu \rightarrow 1$. Using equation 5, for example, estimated mean path lengths are .60–.75, 3.19–6.98, and 27.3–88.8 units of distance for $\mu = 3.5, 2.0$, and 1.2, respectively, given an error range in each case of $\mu \pm .17$. These results suggest that equation 8 provides an archaeologically tractable way to estimate μ . With μ in hand, calculation of the mean path length and number of stops along a foraging route may be made directly using equations 5 and 6.

Model Application to the Western European Early Upper Paleolithic

A preliminary use of equation 8 with data from the early Upper Paleolithic of western France suggests that high levels of planning depth and risk sensitivity may have characterized mobility strategies at this time. However, concerns about sample size and quality limit the extent to which these results should be used for specific quantitative conclusions. Included in this analysis are data from 53 Chatelperronian, Aurignacian, and Gravettian assemblages in the Aquitaine Basin for

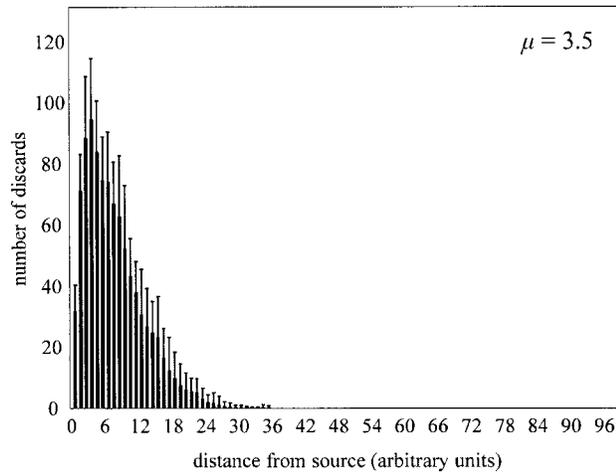


Figure 11. Simulated stone discard frequencies (mean + 1 SD) as a function of distance from the stone raw-material source for $\mu = 3.5$.

which the proportion of the assemblage represented by Bergerac chert is known or can be estimated (Féblot-Augustins 1997c, tables 31–38).

Equation 8 requires that we determine the mean transport distance and estimate the mean path length using an equation such as the polynomial $\langle l \rangle = b_0 + b_1 \bar{d} + b_2 \bar{d}^2 + b_3 \bar{d}^3$. Maximum stone transport distance can be observed without calculation. The mean transport distance for Bergerac chert may be calculated empirically as

$$\bar{d} = \sum_d p_d d, \quad (9)$$

where p_d is the standardized proportion of a raw-material type in all assemblages found at linear distance d from the raw material. For example, Bergerac chert makes up 4.12% and 8%, respectively, of the Aurignacian assemblages from Hui and Toulousette, each located 65 km from the raw-material source (Féblot-Augustins 1997c). The mean proportion of Bergerac chert in these two assemblages is $q_d = .0606$, q being used to indicate the unstandardized quantity. The assemblage-level proportion q_d is standardized across all assemblages in the sample by taking $p_d = q_d / \sum q_d$, which for Hui and Toulousette yields $p_d = .09411$. In other words, the empirical pattern for the early Upper Paleolithic suggests that approximately 9% of all discards in the Aquitaine region should occur 65 km from the source. Using the data provided in Féblot-Augustins (1997c, tables 31–38), equation 9 gives an empirical estimate of the mean transport distance of 50.72 km. The maximum observed transport distance for Bergerac chert is 100 km from the source, recorded at the Gravettian site of Trémoulayre (1997c, table 38). Parameterization of equation 8 also requires that we determine values for the constants $b_0 - b_3$ in the equation $\langle l \rangle = b_0 + b_1 \bar{d} + b_2 \bar{d}^2 + b_3 \bar{d}^3$. Solving

equations 4 and 5 iteratively for multiple values of μ and fitting the polynomial equation to the resulting distribution of points gives $b_0 = -9.61178$, $b_1 = 2.24335$, $b_2 = -0.150598$, and $b_3 = 0.00350464$.

Substituting the appropriate terms, equation 8 yields $\mu = .858807$. This estimate is below the acceptable minimum for μ , which theory indicates should fall in the range $1 \leq \mu \leq 3$. The proximate reason for the low estimate is that the distribution is abruptly truncated relative to the observed mean transport distance. For a mean transport distance of 50.72 km we would expect a longer, gradually decreasing tail extending well beyond the observed maximum transport distance of 100 km. Retaining this mean distance but adding, for example, hypothetical instances of Bergerac chert transport out as far as 200 km from the source (i.e., doubling the maximum observed transport distance) would be sufficient to shift the estimate to $\mu = 1.71$.

Why the Bergerac chert transport pattern is truncated is a much more difficult question to answer. One possibility is that the truncation point represents a hard boundary connected to maximum toolkit size. In other words, Bergerac chert was used at a rate ensuring that all items of this material were cleared from the toolkit before it had been transported more than 100 km from the source (see fig. 13) (Brantingham 2003). Even though mobility strategies may often have carried early Upper Paleolithic foragers beyond this distance, Bergerac chert was regularly used up at shorter distances from the source. That this explanation may hold generally for the early Upper Paleolithic in western France is suggested by the fact that maximum transport distances for all stone raw materials, including Bergerac chert, never exceed 100 km from the source (see Féblot-Augustins 1997b, figs. 91–94). By contrast, maximum transport distances for stone in eastern and central

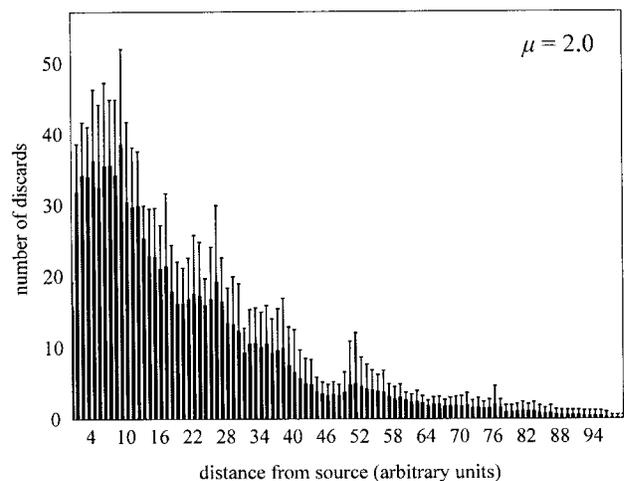


Figure 12. Simulated stone discard frequencies (mean + 1 SD) as function of distance from the stone raw-material source for $\mu = 2.0$.

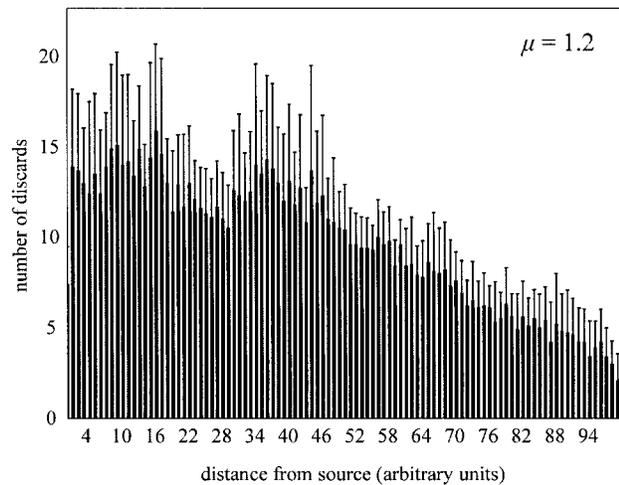


Figure 13. Simulated stone discard frequencies (mean + 1 SD) as a function of distance from the stone raw-material source for $\mu = 1.2$.

Europe are three to seven times greater than those seen in western Europe over the same time period (see Féblot-Augustins 1997*b*, fig. 64). Only during the Magdalenian do maximum transport distances in western Europe reach ca. 125 km from the source. A second possible explanation is that there is a strong sampling bias against sites that are farther than 100 km from the source. While it may be reasonable to assume that sites farther from a raw-material source tend to be smaller (Surovell 2003) and therefore are less likely to be detected, there is no necessary reason that this should apply across all raw-material types.

Accepting the limitations inherent in these data, we may tentatively infer that early Upper Paleolithic procurement and transport of Bergerac chert were linked to a Lévy mobility strategy with $\mu \sim 1$. Comparison of figure 2 with figures 11–13 confirms this suggestion; the empirical distribution for the representation of Bergerac chert in individual assemblages is most similar to simulated Lévy mobility strategies where $\mu = 1.2$. Using a value of $\mu = 1.01$ as an approximation, the expected mean foraging path length is 95.45 km (equation 5), and the mean number of bases visited necessary to transport stone a mean distance of 50.72 is only 1.04 (equation 6). In other words, the mean foraging path length is similar to the maximum observed transport distance, and the mean transport distance is usually accomplished in a single foraging move. Overall, these analyses suggest that early Upper Paleolithic mobility in western France was both maximally planned and organized to minimize the costs associated with movement and exposure to risk. These observations must be treated with some caution, however, given the small sample size, problems entailed in aggregating patterns across such a long archaeological sequence, and the potential sources of

error involved in comparing assemblages analyzed by multiple researchers.

Discussion

Differences between types of stone raw materials are one of the most visible features in an archeological assemblage and stone transport distances one of the least ambiguous attributes to quantify (Eerkens and Rosenthal 2004; Féblot-Augustins 1997*b*; Jones et al. 2003). It has long been recognized, however, that interpreting stone transport distances is by no means straightforward (Brantingham 2003; Kelly 1992). Jones et al. (2003), Kuhn (1995, 2004), and Surovell (2003) provide insightful discussions of how an examination of the staging of lithic reduction at landscape scales may be used in combination with measured stone raw-material transport distances to refine interpretations of land-use strategies. While the former researchers have concentrated on mobility, Surovell (2003) has developed the theoretical and empirical basis for linking the staging of lithic reduction to the length of site occupation. Their results are comparable, despite the differences in perspective, because occupation length is the inverse of the frequency of movement. In all of these cases, however, it may be argued that the complexities inherent in the organization and maintenance of stone toolkits may confound any direct analysis of the independent impact of mobility on stone raw-material usage. For example, it is generally difficult to determine conclusively whether raw-material quality and abundance, mobility decisions, technological design, or discard decisions are dominant in driving stone transport and reduction staging patterns, let alone what the combined contributions of these behaviors might be in the organization of lithic technology.

This paper has attempted to tease apart some of these complex interactions through a controlled examination of the effects of mobility on stone usage, holding other behaviors constant. To accomplish this it has been necessary to make a number of simplifying assumptions. On the one hand, it has been deemed prudent to drop from consideration some variables that might otherwise be important. For example, the Lévy mobility model excludes any measure of how topography might influence mobility. Its inclusion would present a number of unnecessary complications that might confound the analysis of the core dynamics of mobility. On the other hand, it has also been necessary to make formal assumptions that control for the operation of essential processes while at the same time including them in the model. The simplifying assumptions concerning how exactly foragers procure, use, and discard stone fall into the second category of modeling choices. It is necessary to retain such processes, of course, because they are responsible for generating an observable archaeological record. Assuming that foragers are indifferent to stone raw-material quality and abundance is an extreme position to start from, but it is a necessary formality if we want to be able to assess the unique role that mobility plays in

generating stone transport patterns independent of the processes related directly to stone use. It is not the intention to suggest that foragers were oblivious to differences in raw-material quality and abundance or were incapable of sophisticated toolkit design and maintenance.

Relaxing some of these extreme assumptions points to the potential for future research building on the foundation of a Lévy mobility model. The model at present treats Lévy mobility strictly in terms of a fixed planning depth and risk sensitivity determined by the parameter μ . This approach would be at home in the study of premodern humans, where it is often assumed that behaviors such as planning depth are species-level characteristics; for example, *Homo ergaster* is often assumed to be characterized by a fixed ability to plan foraging activities. While arguments of this nature may be debated, even for the earliest hominids (e.g., Brantingham 1998), in the case of anatomically modern humans we might also want to consider the impact of variable degrees of planning deployed depending upon conditions encountered. For example, some environments may require much greater planning to exploit effectively than others. Mobility strategies involving different degrees of planning might be deployed strategically to ensure survival under different environmental conditions.

The situation could become very complex if, for example, mobility strategies with substantially different planning depths were deployed in alternate seasons. Figure 14 simulates a scenario in which half of the year involves low planning depth ($\mu = 3.5$) and the other half high planning depth ($\mu = 1.8$). The resulting distribution shows a combination of features characteristic of the two discrete Lévy mobility strategies, including a very large peak in discard frequencies close to the source of the material and a long, gradually decreasing tail in discards farther away. Equation 8 gives $\mu = 2.34$ for this mixed mobility strategy. In other words, the long-term pattern of stone raw-material transport distances represents some intermediate level of planning depth and risk sensitivity between the maximum and minimum levels deployed by the foraging group in alternate seasons.²

A separate hypothetical scenario involving differential treatment of stone raw materials based on raw-material quality leads to a very similar result. Imagine that our Lévy forager has access to two different raw-material types, one high-quality and the other low-quality. Assume that the forager has a toolkit divided into two equal-sized partitions such that the quantity of material procured from one source never exceeds some maximum amount, even though there may be space available in that portion of the toolkit dedicated to the other

2. One might expect that the value of μ from summing seasonal transport patterns should be close to the arithmetic average of the values for the two strategies ($\mu = 2.65$). However, the tail of the distribution, which is generated primarily by Lévy mobility with $\mu = 1.8$ has a much greater effect on the combined estimate of μ . The annual mobility strategy thus shows a greater than expected planning depth and risk sensitivity in proportion to the time spent in the high-planning-depth state.

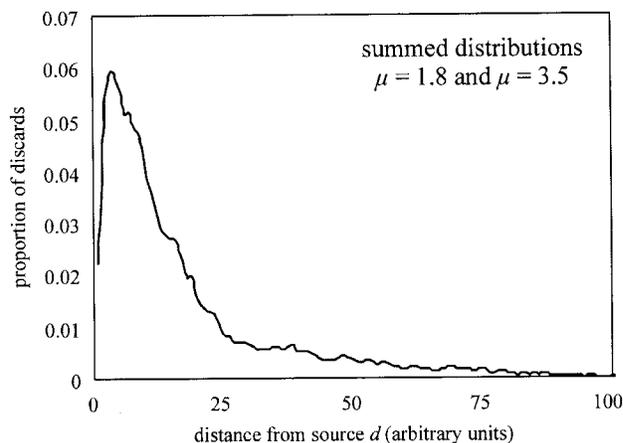


Figure 14. Stone transport patterns in a single region around one raw-material source where half of the year is spent using a high-planning-depth strategy ($\mu = 1.8$) and the other half a low-planning-depth strategy ($\mu = 3.5$). The annual stone transport distribution is represented by the sum of the two curves for the individual strategies.

material type. For example, the forager may procure only 50 units of obsidian even if it is currently carrying only 25 units of quartzite and vice versa. Now suppose that the forager consumes only the high-quality material when using a high-planning-depth mobility strategy (i.e., when $\mu = 1.8$) and only the low-quality material when engaged in a low-planning-depth strategy (i.e., when $\mu = 3.5$). In other words, the high-quality material is curated for use in high-planning-depth activities while the other material is used in expedient, low-planning-depth activities (Nelson 1991). In this scenario, all of the high-quality material procured, transported, and discarded will carry a high-planning-depth signature. The raw-material transport pattern for this material alone should resemble figure 12, and an estimate of μ using equation 8 should be close to the expected value of $\mu = 1.8$. Conversely, all of the low-quality material procured, transported, and discarded should carry a low-planning-depth signature. The raw-material transport pattern should more closely resemble figure 11 and the value of μ recovered using equation 8 should be close to the expected 3.5. If we look at the aggregate transport patterns for the two materials, however, the combined distribution will resemble figure 14 and the estimate of μ will be some intermediate value (here 2.34). Our inferences regarding mobility planning depth will reflect the combined influences of mobility structure around differential treatment of stone raw-material types. While these suggestions are interesting, further work is needed to develop more realistic scenarios where, for example, the size of the partitions dedicated to different raw-material types can be changed depending upon encounters with different raw-material sources.

A final complication that should be evaluated involves the possibility that some proportion of the stone utilized by for-

agers might be obtained via social exchange. Gamble (1999) is a particularly strong proponent of this view of raw-material transfers. One simple scenario might involve two bands that occupied nonoverlapping foraging territories but met regularly at some point where their territories were in contact. If, upon meeting, they exchanged stone raw materials from their respective territories, material from very long-distance sources might enter the archaeological record. Inserting very long-distance stone raw-material transfers into the Lévy mobility model has a counterintuitive effect. Figure 15 shows a case in which most materials are procured via a Lévy mobility strategy with $\mu = 1.8$. A single unit of raw material ($\sim .01\%$ of all discards) obtained via social exchange is discarded at a point 250 distance units from its source. The traded material extends the maximum stone transfer distance by 150 units of distance beyond that obtained via direct procurement. Visually, the impact of introducing a long-distance transfer is to make the primary distribution of discards appear concentrated closer to their source relative to the maximum transport distance (compare fig. 15 with figs. 11 and 12). Mathematically, μ increases toward 3, implying a *decrease* in the planning depth and risk sensitivity attributed to the Lévy mobility strategy. It is interesting to speculate that a Lévy mobility strategy that involves substantial planning depth and risk sensitivity in the absence of social exchange may decrease in relative planning depth and risk sensitivity once social exchange becomes an option. It seems plausible that the downward shift in planning depth and risk sensitivity associated with mobility is taken up by increased planning depth and risk sensitivity mediated through social relationships. In other words, planning depth and risk sensitivity executed solely via mobility become less important as social exchange becomes more important. Substantial analytical and simulation work is needed, however, to explore the implications of this observation and to deal with more realistic exchange models including down-the-line trading (Gamble 1999; Janetski 2002).

The Lévy mobility model is in no way dependent upon assuming that foragers move solely for the purposes of obtaining food resources. It is well known that foragers move for many reasons, visiting relatives being one common proximate explanation for shifting camp (Hewlett, van de Koppel, and Cavalli-Sforza 1982; Shackley 1996). If we were willing to define social resources such as relatives' camps as patches distributed diffusely in a landscape, then we could easily rewrite the ecological model developed here with one that concentrated either completely or partially on the social landscape. In this context, for example, one group would procure some or all of the stone it used while moving to visit relatives.

Conclusions

Despite the many simplifications of the Lévy mobility model, the preliminary results presented here are not inconsistent with expectations derived from less formal models. In particular, the Lévy mobility model suggests that greater mean

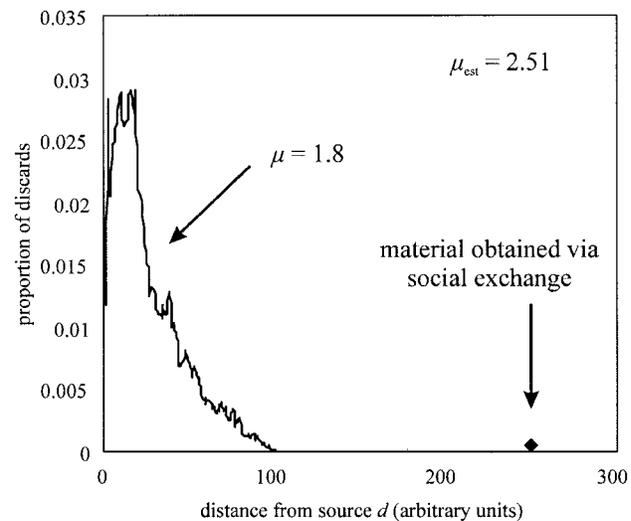


Figure 15. Proportion of discards at different distances from source produced by a Lévy mobility strategy with $\mu = 1.8$ and a single discard ($\sim .01\%$ of all discards) of a different material obtained via social exchange from a source 250 distance units away. The combined estimate is $\mu_{\text{est}} = 2.51$.

and maximum stone transport distances may indeed reflect increases in planning depth, greater optimization of mobility, and greater risk sensitivity. It is also clear that an analytical approach such as that offered here is necessary to extract quantitative behavioral information from stone raw-material transport distances. It was argued at the outset that the most appropriate avenue of analysis is the application of probability models describing the displacement of stone in space via different stochastic mobility processes. It has been shown using both simulation and mathematical analysis that stone transport distances may be modeled using a Lévy walk stochastic process combined with simple assumptions about toolkit dynamics. Surprisingly, perhaps, this simple model can be made to yield a general summary measure of planning depth, mobility optimization, and risk sensitivity μ (equation 8), which in turn may yield specific information both about mean foraging move lengths (equation 5) and the number of turning points or bases visited (equation 6). Additional information about the staging of reduction and provisioning of people and places can be used as an independent test of such conclusions.

While the present model and associated analytical equations may be used unmodified in archaeological analyses—for example, in estimating μ for individual archaeological cases based on observed mean and maximum stone transport distances—such applications necessarily incorporate the assumption that toolkit dynamics are entirely neutral. There is nothing inherently wrong with such an assumption. Whether toolkits were in fact neutral is a topic for continued analytical and empirical work.

Finally, the model presented herein does not imply that

foragers carried around in their heads a probabilistic routine that structured all mobility as a Lévy random walk. The inspiration for modeling forager mobility as a Lévy process is linked to a fundamental ecological problem confronted by all organisms—how to bring individuals and food together at the same time and place (Cashdan, 1992; Potts 1988; Stephens and Kerbs 1986). The models are intentionally ambiguous about what was going on in the heads of the foragers who may have deployed such foraging strategies. Ecologists studying nonhuman animals (Viswanathan et al. 2002, 1999) favor the assumption that foragers have no prior knowledge of the distribution of resources in their environment. They conclude that natural selection has led to the evolution of behaviors approximating a Lévy random search because these offer an optimal solution to finding diffuse, randomly distributed resource packages.

While it is not unreasonable to expect that humans may have deployed similar simple Lévy random search strategies when moving into a new environment about which they had no information (see Brantingham et al. 2003; Rockman and Steele 2003), once information had been gathered random search would likely no longer have been necessary. If the Lévy model still provides an adequate description of forager mobility in these cases, it is probably because we lack information about why moves were made to certain locations at different distances. Given the coarse-grained paleoenvironmental proxy records available to us, we are rarely able to discern which patches were present in an environment and where. Moreover, millennial-scale and higher-frequency climatic and environmental fluctuations may mean that the spatial locations, sizes, and qualities of patches were constantly changing. Although foragers may have been able to track these changes quite easily, all we may be able to assume for analytical purposes is that foraging patches were randomly and diffusely distributed in space. A Lévy mobility model may continue to provide an adequate statistical description of mobility precisely because of our inability to track these processes at a fine enough scale.

Comments

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The application of the Lévy random walk to forager mobility strategies is particularly valuable in prehistoric contexts because it offers an alternative to the problematic common practice of mapping modern foragers directly onto prehistoric ones. The Lévy equation is suited to the task of broadening our understanding of prehistoric mobility patterns for several reasons. First, it has been shown analytically that foragers following a Lévy walk will optimize their encounter rates in

environments that contain diffuse and randomly distributed resources, and this makes the model a solid theoretical foundation from which to derive hypotheses for testing against archaeological data. Second, empirically observed mobility patterns among several species of animals compare favorably with predictions derived from Lévy walks. This suggests that some species have internal mobility algorithms that replicate optimal encounter rates in some environments. (It does not mean, of course, that the algorithms they follow are necessarily Lévy equations.) Finally, the Lévy equation is relatively simple, facilitating the generation of predictions for testing.

We have learned much about prehistoric behavior in the past several decades by comparing the archaeological record against predictions derived from theoretically informed computer simulations. Such research has been fueled, in part, by the ease of use and increasing speed of computing technology. The model presented by Brantingham and others like it are an important direction for archaeological research on mobility. If we can make some assumptions about the distribution of prehistoric resources, such models will allow us to evaluate whether foragers in the past organized their mobility for optimal encounters with various types of resources. The use of such models points to the importance of regionally based research programs and 100% survey coverage and the research value of small sites, elements only too rarely incorporated into archaeological research. I will confine the remaining discussion to three main areas where I think additional research will be fruitful.

First, there is more than one way of achieving a Lévy-like walk. Foragers may actually follow a different algorithm but one that in practice happens to look like Lévy. Without further simulation, it is not clear to me whether such a distinction is merely splitting hairs. An algorithm that produces similar output might have quite different relationships between risk, the degree of planning, and other variables that influence choices foragers make about moving across a landscape. Because we do not know the mechanism/algorithm that produced the results (i.e., an empirically observed settlement pattern) it may be misleading to assume one. More research will be needed to develop independent means for testing such secondary and derived results.

Second, it would be instructive to compare mobility and tool use-and-discard patterns in a group of ethnographically studied foragers with the Lévy walk. While ethnographic reports may not have the perfect type of information for this, they should have enough for a cursory evaluation. It will be instructive, also, to model the mobility and tool-discard behaviors of individuals rather than of a hypothetical and homogeneous “group” of foragers. I suspect that some movements of individuals within a “group” will overlap in time and space but others will not. Additional modeling should indicate the effects of such individual behaviors.

Finally, additional research is needed to generate archaeological data amenable to analysis using Lévy walk models. As Brantingham points out, reconstructing mobility has been

difficult, and Lévy models will require fairly fine-grained data about the movements of individual foragers. Beyond some of the issues he brings up, such as seasonal changes in mobility, I think it will be difficult to tease apart artifacts deposited by a single “group” while on a seasonal round from those deposited across decades, centuries, or even millennia. Furthermore, aside from some exceptional cases (e.g., Close 2000) direction of movement between sets of sites will be impossible to determine, and such a measure is important for reconstructing the distance between sequential movements. Brantingham attempts to circumvent such issues by using proxy measures of mobility, but in his application of the model to the early Upper Paleolithic in France he derives values that are outside the limits deemed legitimate. I am worried that, combined with archaeological biases (due, for example, to incomplete survey coverage and a focus on cave sites), difficulty in delineating the remains of discrete entities of foragers (be they “groups” or individuals), and the complications of trade and exchange, the use of such proxy measures will compound errors and eventually outweigh the value of using a formal and quantitatively based model for understanding behavior.

Fortunately, our methods of data collection are driven by our theoretical models. New models often require novel means for collecting data to test hypotheses generated from them. Brantingham’s paper will undoubtedly do this, and I look forward to future research by him and others that will address these three issues.

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This highly significant and original paper presents an exciting analytical solution to a problem faced by archaeologists intent on inferring mobility strategies from plots of stone raw-material transfer distances and associated quantities. How can these distributions be confidently translated into quantified mobility properties? I find the paper extremely welcome, all the more so because a wider range of behavioural issues can arguably be addressed on the foundation of the Lévy mobility model.

Since I am familiar with European stone raw-material transfers, my comments will focus on Brantingham’s application of equation 8 to data from the early Upper Palaeolithic of western France. He rightly emphasizes that the conclusions drawn from the results should be treated with some caution. For reasons developed below and relating directly to the key variables \bar{d} and $\max(\bar{d})$, it is clear that the Bergerac chert example should be considered not as a formal test but as an illustration of how the Lévy mobility model can be applied to a real archaeological case. As an illustration, however, it is

very useful, fleshing out the simulation test and highlighting the potential of the model for future research.

In the first place, there are difficulties linked not only to sample size but to the heterogeneous nature of the data drawn from Féblot-Augustins (1997c), which explicitly includes assemblages recovered from both old and recent excavations. As a result, the inventoried proportions of Bergerac chert are not comparable. It is only in recently excavated sites that these proportions are based on whole assemblages. In the large Aquitaine sites excavated early in the last century, only tools and at best other significant pieces were set apart and recorded according to individual layers, the debitage from several layers being lumped together. This means that in a large number of cases available proportions of Bergerac chert are based on tools only or on a little-representative sample made up of tools, blade and bladelet blanks, burin spalls, cores, and some flakes or less often on cores only. Using Bergerac chert proportions based on tools only has proved relevant for highlighting selectivity in raw-material choice, as demonstrated by Demars (1989, 1994), who showed a positive correlation between the proportions of this material in the tool component of an assemblage and the laminar tool index. Brantingham may have suggestions about how best to incorporate tool and/or core data into the Lévy mobility model when no information about debitage is available. However, I suspect that using proportions based on different material sets in the current example has introduced a bias. This bias, resulting in high proportions of Bergerac chert (for instance, 28% of tools at 60 km and close to 30% of a little-representative sample at 80 km [see fig. 2]), possibly accounts for the high mean transport distance (50.72 km). My guess is that \bar{d} would be much lower if only proportions based on whole assemblages had been used. In the second place—but Brantingham cannot have been aware of this—there is very recent evidence for long-distance transfers in France during the Aurignacian and the Perigordian (Féblot-Augustins n.d.): 38 occurrences greater than 100 km, 15 of which are greater than 200 km, with maximum distances of 320 and 380 km. Five of these transfers pertain to Bergerac chert, transported once over 160 km (0.6%), three times over 220 km (0.4%, 0.2%, 1.8%), and once over the maximum distance of 270 km (0.6%) (Bon, Simmonet, and Vézian 2005; Bordes, Le Brun-Ricalens, and Bonn 2005; Primault 2003). Incorporating these distances would make the distribution appear less truncated, a transport pattern that the Brantingham finds difficult to account for. In addition, the new data would shift the estimates of away from 1 and closer to 2, as indeed is suggested by Brantingham when he hypothetically doubles the initial maximum transport distance of 100 km. A value of μ closer to 2 for the Early Upper Palaeolithic in western France and the Perigord in particular, representative of intermediate planning depth (or of mixed strategies?), would be more in keeping with inferences based on fine-grained comparisons of lithic and other data such as faunal procurement, paleoenvironment, and topography (Blades 2001). These suggest that long-distance movements in the Aurignacian (i.e., from Bergerac sources to the Vézère sites)

varied significantly in frequency according to both spatial and temporal patterns.

Reservations about its conclusions concerning maximally planned and organized Palaeolithic mobility in western France do not in the least detract from the interest of this novel contribution. They should be considered as an incitement to conduct a formal test based on a clearly defined set of criteria for accepting and rejecting cases to be included in analysis.

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11 I 06

This is an exemplary work, and Brantingham is to be commended for attempting to build a model that can be used to make inferences about forager mobility using stone transport distances. The model represents a thorough application of formal equations used by biologists to describe the optimization of time and energy in nonhuman forager mobility. I would agree that probabilistic models are best for modeling human behavior. I also think that their use in a holistic approach would be a more powerful heuristic device than optimality models. In the end, the archaeological application of the reductionist model fails because of the complexities of human behavior and/or the incompleteness of the archaeological record.

The main problem in applying this in an archaeological case is the need to know μ . Brantingham provides a mathematical solution to this for the simulation. The problem will come when applied to actual foragers or archaeological situations. The number of simplifying assumptions required to achieve the goals of the paper raises significant problems for real-world application. Brantingham acknowledges most of the problems of such a reductive approach as he undertakes the endeavor.

A critically important problem regards the use of different mobility strategies during different seasons. This represents a serious problem in the interpretation of archaeological sites and their distribution across the landscape. How do we recognize overlapping or discrete territories if there are seasonal differences in mobility? Are we not then dealing with palimpsests on a landscape scale? These are the same problems faced by researchers investigating subsistence strategies. If one could tease out a record of penecontemporaneous sites representative of a seasonal mobility strategy, then the model could be applied. One could envision using it to test whether there was a quantitative increase in planning depth during the Paleolithic.

Where, then, does measuring planning depth lead? If we measure it as the ability to optimize time and energy at gradually increasing distances, does that ultimately lead to an evaluation of the ability of a forager group to adapt to an ideal behavior?

In behavioral ecology most researchers focus on energy as a currency for measuring efficiency. Optimization is the evolutionary outcome of behavior. Often there is a dichotomy between behaviors that maximize energy and those that minimize

risk. In the Lévy mobility model, energy optimization and risk sensitivity are seen as indicators of planning depth. Foragers who would move over longer distances between moves are assumed to have an increased need to think ahead if they are optimizing time and energy. Do humans behave this way? Problems of equifinality aside, human beings do things for many reasons other than optimizing time and energy. In our own society, conflicts between different interests result in unequal distribution and consumption of resources. This certainly happens in foraging societies. At some point, do we not have to stop and question whether continuing to use models built for animal behavior is a useful exercise? After all, what is culture? Does it qualitatively separate us from the animal world or not?

We like to believe that modeling exercises make possible a better understanding of how complex systems behave by isolating one or a few variables and attempting to control for the rest. These are intended to be heuristic devices whereby we learn about human behavior by trying to measure the relative importance of quantifiable variables. One of Brantingham's goals is "to show how specific properties of forager mobility can be recovered from observed stone raw-material transport distances." It might seem intuitively obvious (and is confirmed by the simulation) that more dispersed food resources require more and longer moves, thereby requiring a high degree of planning and anticipation.

Isolating one or two variables and discarding everything else is a problematic approach to the understanding of human behavior. Despite the claims made by proponents of human behavioral ecology, human behavior is not best understood through a reductionist approach. Critics of the particularist tradition in anthropology claimed that archaeologists needed to seek out general principles governing human behavior. Which is more interesting—to show that 20%, 50%, or 75% of human behavior accords with that observed in honey bees or squirrels or to show that culture has permitted an infinite number of adaptive expressions contingent upon the multiple actions of individuals in different times and places? The lack of fit between the model and the Upper Paleolithic case study suggests that one or more of the excluded variables (e.g., social exchange) may have been equally or more important in patterns of stone transport.

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At the outset I confess my innocence of Lévy functions and the formidable mathematics that undergird them. My comments pertain to the substantive, not the formal, qualities of Brantingham's model and its application to archaeological data.

Archaeologists routinely—and casually—infer hunter-gatherer land use from the distribution and abundance of tool

stone from known natural sources. “Land use” consists of range or scale and mobility frequency and magnitude (Kelly 1983; Shott 1986). Inferring land use from tool stone distributions assumes that primary (and possible secondary) sources are known. Of course archaeologists should use whatever information resides in the distribution and abundance of stone across the landscape. Unfortunately, our approach is often naïve in its assumptions both about the organization of hunter-gatherer land use and about the way in which the archaeological record registers behavior. Brantingham shows that the distribution and abundance of tool stone across the landscape do not simply reflect ancient hunter-gatherer land use any more than my frequent-flier mileage reflects my commuting distance to work. Instead, the complexities of hunter-gatherer land use and chert acquisition (and the equal complexities of assemblage formation) mean that archaeological tool stone distributions are highly refracted products of land use and other factors as well.

Before Brantingham’s impressive formal model, Ingbar (1994) questioned the common archaeological practice of inferring range from distance-to-source. Like Brantingham’s, Ingbar’s simulation did not replicate prehistoric land use or tool stone exploitation in detail but explored the complex relationships between variables even in simple systems. Holding constant number and location of tool stone sources, direction of movement, mobility magnitude, and rate of tool use at each location, simulations varied only mobility frequency and size of tool inventory. Ingbar found that tool stone proportions varied widely between places and that frequently tools were used in places where they were not discarded. Not surprisingly, he concluded (1994, 46) that “there is not a good correlation between raw material source proportions” and land use. Similarly, Bradbury and Carr (2000) have demonstrated the effects of technology of reduction, tool-class longevity, and replacement mode (e.g., immediate or delayed until return to source) on tool stone distribution and abundance independently of land use. Significantly, their modeling considered not just cores and tools but also flake debris. Industrial debris from tool production and resharpening debris from tool maintenance during use are both abundant in assemblages when curation is high. Debris reflects land-use scale and pattern somewhat differently from retouched tools.

I do not entirely follow Brantingham’s argument that neutral mobility is described by moves of short, fixed distances and that, by extension, occasional moves of greater distance imply “increased planning depth.” This logic underlies his plausible interpretation of the power-law exponent μ as a measure of planning depth. Accepting it at face value, the reasoning may be his most significant accomplishment if it allows for precise measurement of ancient land use from stone distribution and abundance.

Discard rate must vary among tool types and perhaps raw materials. These may be mere complications to Brantingham’s model, but they compound the difficulty of its empirical

grounding. What is more, discard rate itself is probabilistic and governed by separate factors such as attrition and chance that themselves must be accounted for in formal models. Relevant work has begun (e.g., Shott and Sillitoe [2005], which measured tool curation rate as the shape parameter β of the Gompertz-Makeham model), but models for the wide range of tool classes that Brantingham’s mobility model must accommodate will require more research.

Its value accepted, Brantingham’s model threatens to outpace archaeology’s ability to ground it in empirical data. First, estimating planning depth by μ requires knowing or assuming toolkit size ν , tool discard or consumption rate r , and mobility parameters such as frequency and magnitude. In most contexts, if one knows these quantities it may be a small matter to estimate planning depth. Second, most archaeological deposits are time-averaged palimpsests whose contents are the products of many occupations differing in size, composition, duration, and activity of the resident group. Unless all occupations of a place were identical in salient respects (which is extremely unlikely), archaeologists must parse aggregates into their constituent occupations before applying Brantingham’s model. (This is no criticism but pragmatic acknowledgment of the model’s nature and imperfect fidelity to the scales at which archaeological data accumulate.) In effect, like most archaeological modeling in recent years Brantingham’s work is situated in ecological time whereas the archaeological record accumulated in evolutionary time. We must translate between these levels or scales before applying ecological models to evolutionary data. Failing this, formal models of the greatest detail and rigor are castles in the air.

On balance, Brantingham has accomplished a model-building exercise of impressive rigor and considerable detail. My only advice is that he take into account the way the archaeological record forms, not just the way model or actual hunter-gatherers acted. Our ability to understand the past depends on both the behavioral or ecological theory that Brantingham’s model represents and the intrinsically archaeological theory that translates such model expectations for testing against evidence.

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I could not agree more with the basic premise of this article. Building models from first principles is a critical step in any research program aimed at understanding such complex spatio-temporal processes as foraging movements. Explicit models are also essential in analyzing empirical patterns. Such models necessarily oversimplify the complex and messy reality, inviting criticism from less theoretically minded workers in the field. But simplification is indispensable in modeling. The history of theory development and testing in spatial ecol-

ogy, a field with which I am most familiar, yields two lessons. First, the initial very simple models, based on random walks and diffusion, were subjected to a withering storm of criticism from the empiricists. In the end, however, these models turned out to be surprisingly adept at describing the observed patterns of movement not only in animals with rather simple brains (e.g., insects) but also in large mammals that have impressive cognitive abilities and nontrivial social organization (e.g., elk). Second, in those cases where initial simple models did not work properly, the deviations between their predictions and data patterns suggested how the models could be improved—what sources of complexity and realism had to be incorporated into the mathematical description. I fully expect to see similar developments as models (and empirical tests) of human foraging movements mature.

A cautionary note, however, is that the ability of simple models to describe empirical patterns has an obverse side. As is well known, the mapping of theoretical mechanisms to empirical patterns is many-to-one. In other words, any specific pattern in data can be generated by a potentially infinite number of mechanistic models. This means that when we estimate some parameter from data we usually cannot infer the action of a specific process. This caution applies particularly to the parameter μ of a Lévy random walk. This parameter is an exponent of the frequency distribution of move lengths. A power law is a *phenomenological* description rather than a mechanistic, processual model. The exponent μ simply cannot be interpreted as measuring the degree of planning depth or optimization of mobility or any other specific mechanism.

To illustrate this idea, I can argue that lower μ (resulting in “heavier-tail” move-length distributions) can as easily result from great lack of foresight as from increased degree of planning. Under certain assumptions about the distribution of resources, the move-length distribution in a population of “smart” foragers would be characterized by the absence of a tail, because no one would move far away from a good resource patch. In a population of “dumb” foragers, some would foolishly stumble out of a good patch and then, having insufficient cognitive abilities to find their way back, would be forced to move on and on. The overall distribution of move lengths would therefore have a long tail. This is actually not a purely theoretical scenario but something that we observed in our empirical study of translocated elk. A certain proportion of males (the more venturesome sex in deer as in humans) left the area compactly inhabited by the herd and then kept traveling, sometimes covering hundreds of kilometers (we can trace their movements because all study animals were fitted with radiocollars). It is clear why they kept traveling (in contrast to animals that stayed with the herd)—there were no conspecifics in the areas they passed through, and, at the very least, they had to find conspecific females to mate with. So they kept traveling until they were hit by a car, killed by a hunter or another predator, or simply died from malnutrition in winter. The overall distribution of move

lengths was characterized by a long tail, but it certainly did not result from an increase in planning depth on the part of elk.

In general, an exponent of power laws and related parameters such as the fractal dimension tell us little if anything about the mechanisms generating the observed patterns. I made this argument some years ago in the ecological literature (Turchin 1996). Rather than trying to interpret the estimated value of a single parameter that integrates all kinds of characteristics in the data, a better approach is to construct explicit theoretical alternatives based on differing assumptions about the dynamic process and then use the data to distinguish between them (see Turchin 2003, 18).

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Brantingham considers a topic that surprisingly few researchers have addressed in a formal manner (but see Ingbar 1994): the relationship between the regional distribution of lithic raw material and patterns of mobility, specifically the frequency and length of residential moves by foragers. He emphasizes the fact that models of lithic raw-material transport and discard should consider that a forager has transported stone through a certain number of residential moves, not a single move between source and find. As intuitive as this statement may be, its implications are difficult to assess systematically in the archaeological record. The conclusions should surprise few researchers: constant short moves or moves of equal lengths denote low levels of planning depth and risk avoidance. Longer moves or increased variability in the length of moves suggest that these behaviors are at least periodically activated.

Brantingham rightly points to the necessity of simplifying or omitting many behaviors in assessing the relationships that exist between a limited number of variables. This corresponds to the model's “conceptual utility” as “a rethinking of stale concepts and assumptions” (Aldenderfer 1978, 20). I am less convinced about its “output utility,” as there are shortcomings in the model's application to the archaeological record. In fact, most of the limitations that one can expect become evident in the western French Upper Palaeolithic case. Some of those limitations deserve scrutiny. For instance, it seems that, for the model to be effective, near-total knowledge of the archaeological record of a region—and beyond that region—is required. In Brantingham's demonstration, is not the unexpectedly low value of μ a symptom of that very problem? There are unavoidable gaps in the record that prevent expected results from being obtained. Additionally, field application would be sounder if the archaeological sites were the result of a single depositional event or, at most, of a regular, unchanging, and repeated pattern of deposition. This being

said, much of the usefulness of creating a formal model sometimes lies not in the results or across-the-board applicability but in its conceptualization. For instance, Brantingham identifies important trends based on data that are directly observable. Among these, he shows that the observed maximum transport distance is a reasonable estimate of maximum toolkit size and that the mean path length varies systematically with mean transport distance.

I am altogether uncertain about Brantingham's dismissal of exchange as a major factor in the spread of raw material over the landscape, even if it is for the purpose of the model's elaboration. How is it possible to determine whether the farthest incidence of a raw material reflects maximum transport distance or the presence of social exchange? Usually, much material changes hands (Gamble 1999), and lithic material is seldom deposited by the individual or the band that extracted it, even within the region that is presumed to be a group's foraging range. In this light the extreme example provided by Brantingham is unsatisfactory. Specifically, the introduction of an aberrant case in figure 15, interpreted as an indication of social exchange and thereby increasing the *mathematical* value of μ , does not actually signify increased risk management or planning depth in the presence of trade. The distribution within the 100-unit hypothetical foraging range does not change, regardless of the presence or absence of one outlying case, nor are risk avoidance and planning depth behaviors modified because of the presence of that one outlier. Here Brantingham seems to lose sight momentarily of exactly what is being measured in this case.

A solution would be to determine, case by case, the territory that is likely to have been visited by the same group that extracted the material, given known landscape use, mobility practices, and relationships with neighboring bands. This introduces a serious challenge to the model's general applicability, but such estimates can certainly be generated with reasonable accuracy if local contingency is considered.

It would be interesting to see the model confronted with other known or assumed characteristics of regional lithic distribution, such as reduction type in relation to distance from source (Beck et al. 2002; Parry and Kelly 1987), tool curation practices (Bamforth 1986), and ecological factors such as resource patch distribution. Furthermore, one of the promises of the model will undoubtedly lie in the realm of comparison, an opinion that Brantingham seems to share. In other words, perhaps μ is not so useful as an absolute measure of behavior because of the incompleteness of the archaeological record. Instead, it should be considered an approximation used in measuring differences between group mobility patterns in different regions among a series of measures and indications.

Brantingham is to be commended for undertaking a difficult intellectual feat and presenting the results rigorously, with much transparency of thought. In the end his work may raise many questions; such is the price of ambitious, stimulating work.

Reply

I thank the commentators for their insightful and constructive comments. The goal of this paper was to present a simple but explicit formal model of what must undoubtedly be a complex process. The model is intended both to serve as a gauge of the degree to which complex empirical patterns might have a relatively simple origin and, where they are inconsistent with such, to point to other processes that need to be considered. Eventually I want to pursue a formal test of the model, though, as most of the commentators point out, the data that would be necessary to reject it as a basis for explanation may not yet be available. It is useful to remember, in this regard, that the staple model of forager mobility, Binford's (1980) dichotomy of foragers and collectors (and several variants thereof), has never been formally tested, in part because rigorous expectations about corresponding archaeological signatures have never been developed.

My model makes a series of simplifying assumptions aimed at isolating the unique effects of mobility on the procurement and transport of stone. Care was taken to be explicit about what assumptions were being made and what impact they might have on conclusions drawn from application of the model. Virtually all of the commentators see a need to incorporate a more complete treatment of lithic reduction. Shott points to important evidence that discard rates vary substantially across different tool types, as does Surovell (2003) for core technologies. The absence of these processes from the model does not imply that they were not important to the organization of forager adaptations; it merely is a formal equivalent of the expression "other things being equal." Future models can begin to examine how different stone use and discard processes impact the distribution of technological types seen in the archaeological record. The extent to which such processes also impact the distances over which stone is transported should be investigated, and, in principle, the current model serves as a baseline for comparison. We may find that differential reduction and discard patterns override a core mobility signature, but we may not.

There are other assumptions that, in retrospect, should have been made more explicit. Turchin points out that our ability to assess the optimality of Lévy mobility strategies is dependent upon knowledge about the distribution of resource patches that were targeted by foraging movements. He would be absolutely correct if the focus of the model were on trying to understand the relationship between mobility patterns and foraging return rates. It has been demonstrated via simulation that Lévy mobility strategies with $\mu \rightarrow 3$ (i.e., Brownian motion) maximize resource encounter rates when resource patches are abundant ($\geq 40\%$ of an environment) and their distribution is spatially autocorrelated to form large, continuous clusters (Sole, Bartumeus, and Gamarra 2005). By con-

trast, when resource patches are rare ($\leq 40\%$ of an environment) and their distribution is fragmented, Lévy mobility strategies with $\mu \rightarrow 1$ maximize resource encounter rates. These simulations confirm Turchin's general observation that "heavy-tail" mobility strategies (i.e., $\mu \rightarrow 1$) may be suboptimal when resources are distributed in certain ways. I concur and suggest that this should be an area of further model development, especially since it exposes the fallacy that Brownian motion is inherently "dumb" and non-Brownian movement strategies inherently "smart."

It is important to emphasize, however, that the model makes no explicit claims about the density or distribution of resources in the environment. Behavioral interpretations about planning depth, optimization of time and energy expenditures, and risk sensitivity concern only the topology of movement patterns, not, as discussed above, resource encounter or return rates. Moreover, the procurement, use, and discard of stone, which occur only as a by-product of movement, have no impact on the optimality of mobility. The conclusions that longer individual and average foraging paths require greater advance planning and that time and energy expenditures are minimized by following the straight-line path between two turning points are separate from the issue of whether a mobility strategy is optimal with respect to resource encounter and return rates. It is assumed that selection and/or learning mechanisms are capable of generating Lévy mobility strategies that are optimal for the resource distributions present in an environment. The Lévy model allows one to recover information about planning depth in these realized mobility strategies. It might be tempting to conclude that the evolution of mobility strategies will be toward those that emphasize a "heavy-tail" move-length distribution. However, this is not a prediction of the model. Indeed, I would not be surprised to find archaeological sequences in which the reverse, or long-term stability, is observed. For example, one might expect to see, in temperate environments, a reduction in the magnitude of mobility at the end of the Pleistocene, modeled as a shift from Lévy mobility strategies with $\mu \rightarrow 1$ to those with $\mu \rightarrow 3$, as resource distributions became less fragmented. Similarly, one might expect stability in Lévy mobility strategies over the same time period in arctic and subarctic environments, where resource distributions generally remain fragmented regardless of changing climate. As Van Gijseghem suggests, the greatest utility of the Lévy mobility model may be found in such comparative contexts.

Turchin notes that μ is not a mechanistic measure but only a phenomenological description. This is correct, but only in that μ is alone a scale-free parameter. Its usefulness is realized through the derived quantities $P(l)$, $P(d)$, \bar{d} , $\langle l \rangle$, and F , each of which specifies a unit of measurement and thus the possibility of quantitative evaluation of predictions against empirical data.

Both Turchin and Eerkins wonder how the current model is positioned with respect to alternative descriptions of mobility, the latter raising the issue of what alternative algorithms would generate similar patterns of movement and stone trans-

port. With the exception of Ingbar (1994) and Surovell (2000, 2003), there are few formal archaeological models of mobility from which we can derive explicit, quantitative predictions. If the ecological literature provides any guide, then there is still ample room to develop alternative mobility models and good theoretical reason to explore these alternatives. Turchin (1996), for example, argues that a correlated random walk serves as a better null model for animal movement than directionally unbiased movement routines, and using simulations he shows that a correlated random walk generates patterns of movement similar to Lévy mobility over some spatial scales. In the interim, the current model has the advantage that, by varying μ , it may be used to represent a continuous array of mobility strategies, each of which may serve as the basis for empirical testing.

Several commentators suggest that the current model has unreasonably strict data requirements. Eerkins is more optimistic in seeing the model as a call for regionally based research. It is not true, however, as implied by Haws, Shott, and Van Gijseghem, that it may be impossible to ground the model empirically. Three specific points deserve response. First, Shott is right to emphasize that the model requires us to know or assume values for three parameters—maximum toolkit size, raw-material consumption rate, and minimum step size. Reasonable estimates could be made for each of these based on ethnographic and/or experimental evidence, thereby grounding the model. However, it is by no means a trivial exercise to translate such empirical estimates into a quantitative characterization of mobility. The current model shows one way in which these parameters fit together as part of overall mobility.

Second, Van Gijseghem suggests that the model requires near total knowledge of the archaeological record. This is certainly not true from a statistical standpoint. As with any statistical analysis, the power of a test tends to increase *asymptotically* with sample size. In other words, an increase in sample size yields a marginal gain in the ability to reject a null hypothesis, and no model can be tested with absolute certainty, no matter how large a sample may be. While current sample sizes are clearly insufficient, a 100% sample is both unrealistic and unnecessary.

Third, most of the commentators find cause for concern in the final cases in which I relax assumptions to consider the effects of raw-material selectivity, seasonally variable mobility strategies, and the social exchange of stone. None of the cases was meant to provide a full explication of these important behavioral processes. In particular, social exchange of raw material was not dismissed as insignificant, as suggested by Van Gijseghem, but left for future detailed consideration. The limited goal was to show that changes in assumptions could be accommodated by the model and that such changes might have important counterintuitive consequences. On a related front, because the archaeological record suffers generally from the effects of time averaging, disturbance, and biased recovery methods, as discussed by Féblot-Augustins,

it may be impossible to tease out the fine-grained behavioral information necessary to examine something like seasonal variability in mobility strategies. However, the Lévy mobility model is no more constrained by these problems than any other archaeological model. Estimates of mobility planning depth, optimization, and risk sensitivity are time-averaged and aseasonal, just as estimates of subsistence organization are time-averaged and aseasonal, unless discrete occupational events and seasonality can be confidently parsed from the record.

Féblot-Augustins is right to urge caution in examination of the western European Upper Paleolithic stone transport data. Nevertheless, I greet with great excitement the new data she mentions on the long-distance transport of Bergerac chert. When added to her already impressive compendium, published in 1997, these data have the exact effects she anticipates. Dropping the two questionable cases from 60 and 80 km reduces \bar{d} to 46 km. Adding the evidence for long-distance transport to 160, 220, and 270 km from source increases \bar{d} again to 53.78 km. The tail of the distribution is no longer truncated, and, assuming $l_0 = 1$, equation 8 estimates μ to be 3.22. The corresponding mean foraging path length is 3.19 km (equation 5), and the number of stopping points needed to transport stone the mean 53.78 km is 131 (equation 6). These estimates are more reasonable, though they should still be treated with caution for all of the reasons suggested by Féblot-Augustins. Technological representation and resharpening intensity, among other attributes, could be used as independent tests of these conclusions.

Finally, I take up some of Haws's comments regarding the failure of reductionism in archaeology. Some anthropologists tend to view with great skepticism models of human behavior that either (1) are derived from studies of nonhuman animals, (2) make dramatic simplifying assumptions, or (3) suggest that human behavior might incorporate large amounts of stochasticity. Somehow these modeling approaches are seen as incompatible with the complexity of human behavior. On the first point, I would argue that finding evidence for a behavioral strategy across a range of taxa is itself reasonable justification to expect that natural selection and/or social learning processes might have produced similar strategies in human groups (Brantingham, Kuhn, and Kerry 2004). Models developed to study these behavioral strategies among simpler, nonhuman animals should thus find application in the study of humans. On the second point, not only is there ample evidence to suggest that the apparent complexity of a system in no way obviates the use of simple models but this complexity is often better handled by formal reductive models than by holistic approaches because of the quantitative rigor engendered by the former. Finally, far from representing simply noise that is to be ignored or stripped away in analysis, stochasticity is a fundamental raw material of evolution in biological systems. Humans would be truly unique if they did

not also harness stochasticity in the organization of behavior and in cultural evolution.

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References Cited

- Aldenderfer, Mark S. 1978. Computer simulation of archaeology: An introductory essay. In *Simulations in archaeology*, ed. Jeremy A. Sabloff, 11–49. Albuquerque: School of American Research University of New Mexico Press. [HV]
- Andrefsky, W. J., Jr. 1994. Raw-material availability and the organization of technology. *American Antiquity* 59:21–34.
- Bamforth, Douglas B. 1986. Technology efficiency and tool curation. *American Antiquity* 51:38–50. [HV]
- Bartumeus, F., J. Catalan, U. L. Fulco, M. L. Lyra, and G. M. Viswanathan. 2002. Optimizing the encounter rate in biological interactions: Levy versus Brownian strategies. *Physical Review Letters* 89:097901–1–4.
- Bartumeus, F., F. Peters, S. Pueyo, C. Marrase, and J. Catalan. 2003. Helical Levy walks: Adjusting searching statistics to resource availability in microzooplankton. *Proceedings of the National Academy of Sciences, U.S.A.* 100:12771–75.
- Beck, Charlotte, Amanda K. Taylor, George T. Jones, Cynthia M. Fadem, Caitlyn R. Cook, and Sarah A. Millward. 2002. Rocks are heavy: Transport costs and paleoarchaic quarry behavior in the Great Basin. *Journal of Anthropological Archaeology* 21:481–507. [HV]
- Binford, L. R. 1979. Organization and formation processes: Looking at curated technologies. *Journal of Anthropological Research* 35:255–73.
- . 1980. Willow smoke and dogs' tails: Hunter-gatherer settlement systems and archaeological site formation. *American Antiquity* 45:4–20.
- Blades, Brooke S. 2001. *Aurignacian lithic economy: Ecological perspectives from southwestern France*. New York: Kluwer Academic/Plenum Publishers. [JF]
- Bon, François, Robert Simonnet, and Jean Vézian. 2005. L'équipement lithique des Aurignaciens à la Tuto de Camalhot (Saint-Jean-de-Verges, Ariège), sa relation avec la mobilité des groupes et la répartition de leurs activités dans un territoire. In *Territoires, déplacements, mobilité, échanges durant la préhistoire: Actes du 126^e Congrès national des Sociétés Historiques et Scientifiques, Toulouse, 2001*, ed. Jacques Jaubert and Michel Barbaza, 173–84. Paris: CTHS. [JF]
- Bordes, Jean-Guillaume, Foni Le Brun-Ricalens, and François Bon. 2005. Le transport des matières premières lithiques à l'Aurignacien entre le Nord et le Sud de l'Aquitaine: Faits attendus, faits nouveaux. In *Territoires, déplacements, mobilité, échanges durant la préhistoire: Actes du 126^e Congrès national des Sociétés Historiques et Scientifiques, Toulouse, 2001*, ed. Jacques Jaubert and Michel Barbaza, 185–98. Paris: CTHS. [JF]

- Boyd, R., and P. J. Richerson. 1985. *Culture and the evolutionary process*. Chicago: University of Chicago Press.
- Boyer, D., O. Miramontes, G. Ramos-Fernandez, J. L. Mateos, and G. Cocho. 2004. Modeling the searching behavior of social monkeys. *Physica A: Statistical Mechanics and Its Applications* 342:329–35.
- Bradbury, Andrew P., and Philip J. Carr. 2000. Understanding raw material use patterns: A simulation approach. Paper presented at the 65th annual meeting of the Society for American Archaeology, Philadelphia. [MS]
- Brantingham, P. J. 1998. Mobility, competition, and Plio-Pleistocene hominid foraging groups. *Journal of Archaeological Method and Theory* 5:57–98.
- . 2003. A neutral model of stone raw material procurement. *American Antiquity* 68:487–509.
- Brantingham, P. J., M. A. Haizhou, J. W. Olsen, X. Gao, D. B. Madsen, and D. E. Rhode. 2003. Speculation on the timing and nature of Late Pleistocene hunter-gatherer colonization of the Tibetan Plateau. *Chinese Science Bulletin* 48:1510–16.
- Brantingham, P. J., S. L. Kuhn, and K. W. Kerry. 2004. On the difficulty of the Middle-Upper Paleolithic transitions. In *The Early Upper Paleolithic beyond Western Europe*, ed. P. J. Brantingham, S. L. Kuhn, and K. W. Kerry, 1–13. Berkeley: University of California Press.
- Brantingham, P. J., J. W. Olsen, J. A. Rech, and A. I. Krivoshapkin. 2000. Raw material quality and prepared core technologies in Northeast Asia. *Journal of Archaeological Science* 27:255–71.
- Cashdan, E. 1992. The spatial organization of habitat use. In *Evolutionary ecology and human behavior*, ed. B. Winterhalder and E. A. Smith, 237–66. New York: Aldine de Gruyter.
- Close, A. E. 2000. Reconstructing movement in prehistory. *Journal of Archaeological Method and Theory* 7:49–77.
- Demars, Pierre-Yves. 1989. L'indice laminaire de l'outillage dans le Paléolithique supérieur en Périgord. *Paléo* 1:17–30. [JF]
- . 1994. *L'économie du silex au Paléolithique supérieur dans le Nord de l'Aquitaine*. Ph.D. diss., Université de Bordeaux I. [JF]
- Denny, M., and S. Gaines. 2002. *Chance in biology: Using probability to explore nature*. Princeton: Princeton University Press.
- Desbois, J. 1992. Algebraic area distributions for 2-dimensional Levy flights. *Journal of Physics A: Mathematical and General* 25:L755–L762.
- Eerkens, J. W., and J. S. Rosenthal. 2004. Are obsidian subsources meaningful units of analysis? Temporal and spatial patterning of subsources in the Caso Volcanic Field, southeastern California. *Journal of Archaeological Science* 31: 21–29.
- Féblot-Augustins, J. 1993. Mobility strategies in the Late Middle Palaeolithic of Central Europe and Western Europe: Elements of stability and variability. *Journal of Anthropological Archaeology* 12:211–65.
- . 1997a. Middle and Upper Paleolithic raw material transfers in Western and Central Europe: Assessing the pace of change. *Journal of Middle Atlantic Archaeology* 13:57–90.
- . 1997b. *La circulation des matières premières au Paléolithique: Synthèse des données, perspectives comportementales*. Vol. 1. Liège: Université de Liège.
- . 1997c. *La circulation des matières premières au Paléolithique: Synthèse des données, perspectives comportementales*. Vol. 2. Liège: Université de Liège.
- . n.d. Revisiting European Upper Palaeolithic raw material transfers: The demise of the cultural ecological paradigm? MS. [JF]
- Gamble, C. 1999. *The Palaeolithic societies of Europe*. Cambridge: Cambridge University Press.
- Geneste, J.-M. 1988. Les industries de la Grotte Vaufray: Technologies du débitage, économie et circulation de la matière première. In *La Grotte Vaufray: Paléoenvironnement, chronologie, activités humaines*, ed. J.-P. Rigaud, 441–517. Mémoires de la Société Préhistorique Française 19.
- Goebel, T. 2004. The Early Upper Paleolithic of Siberia. In *The Early Upper Paleolithic beyond Western Europe*, ed. P. J. Brantingham, S. L. Kuhn, and K. W. Kerry, 162–95. Berkeley: University of California Press.
- Goodyear, A. C. 1989. A hypothesis for the use of cryptocrystalline raw materials among Paleoindian groups of North America. In *Eastern Paleoindian lithic resource use*, ed. C. J. Ellis and J. C. Lothrop, 1–9. Boulder: Westview Press.
- Gotelli, N. J. G. G. R. 1996. *Null models in ecology*. Washington, D.C.: Smithsonian Institution Press.
- Hewlett, B., J. M. H. van de Koppel, and L. Cavalli-Sforza. 1982. Exploration ranges of the Aka Pygmies of the Central African Republic. *Man* 17:418–30.
- Hubbell, S. P. 2001. *The unified neutral theory of biodiversity and biogeography*. Princeton: Princeton University Press.
- Ingbar, Eric E. 1994. Lithic material selection and technological organization. In *The organization of North American chipped stone tool technologies*, ed. P. Carr, 45–56. International Monographs in Prehistory 7. [MS, HV]
- Janetski, J. C. 2002. Trade in Fremont society: Contexts and contrasts. *Journal of Anthropological Archaeology* 21:344–70.
- Jones, G. T., C. Beck, E. E. Jones, and R. E. Hughes. 2003. Lithic source use and paleoarchaic foraging territories in the Great Basin. *American Antiquity* 68:5–38.
- Kelly, R. L. 1983. Hunter-gatherer mobility strategies. *Journal of Anthropological Research* 39:277–306.
- . 1992. Mobility sedentism: Concepts, archaeological measures, and effects. *Annual Review of Anthropology* 21: 43–66.
- Kimura, M. 1983. *The neutral theory of molecular evolution*. Cambridge: Cambridge University Press.
- Koponen, I. 1995. Analytic approach to the problem of con-

- vergence of truncated Levy flights towards the Gaussian stochastic process. *Physical Review E* 52:1197–99.
- Kuhn, S. L. 1995. *Mousterian lithic technology: An ecological perspective*. Princeton: Princeton University Press.
- . 2004. Upper Paleolithic raw material economies at Ucagizli Cave, Turkey. *Journal of Anthropological Archaeology* 23:43–48.
- Marthaler, D., A. L. Bertozzi, and I. B. Schwartz. 2004. *Searches based on a priori information: The biased Levy walk*. UCLA Center for Applied Mathematics Report 04–50.
- Moloney, K. A., and S. A. Levin. 1996. The effects of disturbance architecture on landscape-level population dynamics. *Ecology* 77:375–94.
- Nakao, H. 2000. Multi-scaling properties of truncated Levy flights. *Physics Letters A* 266:282–89.
- Nelson, M. C. 1991. The study of technological organization. *Archaeological Method and Theory* 3:57–100.
- Parry, William J. and Robert L. Kelly. 1987. Expedient core technology and sedentism. In *The organization of core technology*, ed. Jay K. Johnson and Carol A. Morrow. London: Westview Press. [HV]
- Plummer, T. 2004. Flaked stones and old bones: Biological and cultural evolution at the dawn of technology. *American Journal of Physical Anthropology* 125:118–64.
- Potts, R. 1988. *Early hominid activities at Olduvai Gorge*. New York: Aldine de Gruyter.
- Primault, Jérôme. 2003. *Exploitation et diffusion des silex de la région du Grand-Pressigny au Paléolithique*. Ph.D. diss., Université de Paris X. [JF]
- Ramos-Fernandez, G., J. L. Mateos, O. Miramontes, G. Cocho, H. Larralde, and B. Ayala-Orozco. 2004. Levy walk patterns in the foraging movements of spider monkeys (*Ateles geoffroyi*). *Behavioral Ecology and Sociobiology* 55: 223–30.
- Rockman, M., and J. Steele, eds. 2003. *Colonization of unfamiliar landscapes: The archaeology of adaptation*. London: Routledge.
- Shackley, M. S. 1996. Range and mobility in the early hunter-gatherer Southwest. In *Early Formative adaptations in the southern Southwest*, ed. B. J. Roth, 5–16. Madison: Prehistory Press.
- Shlesinger, M. F., G. M. Zaslavsky, and J. Klafter. 1993. Strange kinetics. *Nature* 363:31–37.
- Shott, Michael J. 1986. Forager mobility and technological organization: An ethnographic examination. *Journal of Anthropological Research* 42:15–51. [MS]
- Shott, Michael J., and Paul Sillitoe. 2005. Use life and curation in New Guinea experimental used flakes. *Journal of Archaeological Science* 32:653–63. [MS]
- Sole, R. V., F. Bartumeus, and J. G. P. Gamarra. 2005. Gap percolation in rainforests. *Oikos* 110:177–85.
- Stephens, D. W., and J. R. Kerbs. 1986. *Foraging theory*. Princeton: Princeton University Press.
- Stirzaker, D. 2003. *Elementary probability*. 2d ed. Cambridge: Cambridge University Press.
- Stout, D., J. Quade, S. Semaw, M. J. Rogers, and N. E. Levin. 2005. Raw material selectivity of the earliest stone tool-makers at Gona, Afar, Ethiopia. *Journal of Human Evolution* 48:365–80.
- Surovell, T. A. 2000. Early Paleoindian women, children, mobility and fertility. *American Antiquity* 65(3):493–508.
- . 2003. The behavioral ecology of Folsom lithic technology. Ph. D. diss., University of Arizona.
- Turchin, P. 1996. Fractal analyses of animal movement: A critique. *Ecology* 77:2086–90. [PT]
- . 1998. *Quantitative analysis of movement: Measuring and modeling population redistribution in animals and plants*. Sunderland: Sinauer Associates.
- . 2003. *Historical dynamics: Why states rise and fall*. Princeton: Princeton University Press. [PT]
- Viswanathan, G. M., V. Afanasyev, S. V. Buldyrev, E. J. Murphy, P. A. Prince, and H. E. Stanley. 1996. Levy flight search patterns of wandering albatrosses. *Nature* 381:413–15.
- Viswanathan, G. M., F. Bartumeus, S. V. Buldyrev, J. Catalan, U. L. Fulco, S. Havlin, M. G. E. da Luz, M. L. Lyra, E. P. Raposo and H. E. Stanley. 2002. Levy flight random searches in biological phenomena. *Physica A: Statistical Mechanics and Its Applications* 314:208–13.
- Viswanathan, G. M., S. V. Buldyrev, S. Havlin, M. G. E. da Luz, E. P. Raposo, and H. E. Stanley. 1999. Optimizing the success of random searches. *Nature* 401:911–14.
- White, R. 1989. Husbandry and herd control in the Upper Paleolithic: A critical review of the evidence. *Current Anthropology* 30:609–32.