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Predicting Serial Killers' Home Base Using a Decision Support System

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The effectiveness of a geographical decision support tool (Dragnet) for locating the base of serial offenders was compared across 570 models comprised of a range of negative exponential functions, buffer zone components, and normalization parameters. The models were applied to the body disposal locations within each series for 70 U.S. serial killers. Two normalization parameters were compared for all functions. The test of effectiveness was a specifically defined measure of search cost. When applied to the Dragnet predictions it was found that the specially developed normalization parameter (QRange) produced the optimal search costs. The optimal search cost was also found to be for a function that did not include any buffer zone. The optimal, average search cost across the whole sample was 11% of the defined search area. Fifty-one percent of the offenders resided in the first 5% of the search area, with 87% in the first 25%. All resided in the total defined search area. These results support the potential for operational tools using such procedures as well as contributing to our understanding of criminal's geographical behavior. The applicability to other forms of serial crime is considered.

KEY WORDS: serial killers; geographic profiling; environmental criminology; decay functions; search costs.

1. INTRODUCTION

Studies demonstrate that serial offenders tend to live, or have some form of recognizable base, within an area circumscribed by their offenses (reviewed by Brantingham and Brantingham, 1981). One testable formulation of this proposal is the "Circle Hypothesis" described by Canter and Larkin (1993). They showed that 87% of the 45 serial rapists they studied from the South of England each lived within a circle defined by a diameter drawn between that offender's two farthest offenses. Subsequently Kocsis and Irwin (1997) reported that 82% of serial arsonists, 70% of serial rapists, and 49% of burglars in Australia lived within the defined offending circle. In the United States 56% of serial rapists were found in the circle by Warren *et al.* (1995, 1998) and 86% of the 126 U.S. serial killers studied by Hodge *et al.* (1998). Tamura and Suzuki (1997) found support for the Circle Hypothesis in Japan for 72% of the serial arsonists they studied.

Canter and Gregory (1994) developed the implications of the circle hypothesis. They showed that a simple computer-based geometric model, incorporating circular regions around the first offense, indicated with considerable success for serial rapists the general area in which an offender was living. The search areas predicted by this system were on average 19 km^2. This is of some value in assigning priorities to suspects but is not precise enough for general operational utility. It nonetheless supports the utility of developing such approaches further to model serial offenders' geographical behavior and to help identify their base location. The present paper evaluates the effectiveness of one such development.

Whatever the theoretical interest of such geographical models, their practical utility requires that a series of crimes has been linked to a common offender. Such linking can be provided most strongly by forensic evidence such as DNA or fibers. But it can also be indicated by "signature" (Keppel, 1997) or distinguishing *modus operandi* information or multivariate statistics (Green *et al.,* 1976; Canter, 1995). Linking is not addressed in any further detail in the present paper. For practical applications it is assumed that linking will be achieved by an appropriate means.

1.1. Investigative Geography

Warren *et al.* (1998) show that studies of geographical processes for identifying the base location of serial offenders are part of the emerging research that is providing an empirical, scientific basis for "offender profiling" (Ault and Reese, 1990; Canter, 1995). Rossmo (1993) drew particular attention to the assistance that geographical targeting can provide an investigation. This can include the assignment of priorities to suspects who have come to police attention by other means, giving guidance to police patrols, assistance in determining the areas for house to house inquiries or in the focus for appeals for help from the public.

The "base" in question that provides the anchor for the criminal activity may take many forms. For some forms of base, delimiting the area where this base may be will be of more assistance to an investigation than for others. It will be of particular value when the base is in fact the home or some other location with which the offender will be known to have some affinity, such as a workplace or frequently visited recreation facility. It will be of less value when the base is an anonymous stopover point on a lengthy route that the offender is following, or any other location from which it is difficult to identify the offenders.

If the offender is targeting particular types of victims or particular opportunities for victims, for example, street prostitutes who are available in a particular area of a city, then the association between the base location and the target location may be an accident of the local land use. These "commuters," as Canter and Larkin (1993) call such offenders, may not be so open to decision support modeling as those "marauders" who move out from a fixed base to commit their crimes. It is the marauders whose base is located within the hypothesized circle.

The empirical question therefore arises as to how feasible it is to model the base location of a serial offender, when that base is a location that has a clear link to the offender, notably his place of residence. Furthermore, what mathematical functions best represent the possible relationships between the home and the locations of the offenses in a series? For the present study the focus is on the place of residence, which is referred to as the home.

2. MODELS OF OFFENDER TARGET LOCATION SELECTION

Kind (1987) was one of the first forensic scientists to show the direct application of geographical models, such as those studied here, to an ongoing criminal investigation in his pioneering exploration of the location of the offenses of the "Yorkshire Ripper." He showed that a "center of gravity" to the Ripper's crime locations, or as might be termed from geography a "centroid," accurately indicated where the offender was eventually found to live. Being the center of gravity, that point is the only point that simultaneously has the minimum possible distance to each of the offense locations. Kind proposed that the farther a location from this point, the lower the likelihood that that point is the base of the offender.

By using what has become known as "distance decay" functions, Rossmo (1995) indicated that the centroid could be generalized to a probability surface to produce a more detailed model of the likely home of the serial offender, although this would usually be effective only for "marauding" offenders, whose residential base is broadly within an area circumscribed by their offenses. These decay functions are the relationship between the probability of offending and the distance from home. Researchers have demonstrated that as the distance from an offender's home increases, the probability of his committing an offense decreases, i.e., the probability "decays" (Rhodes and Conly, 1981; Rengert, 1999). Turner (1969) pointed out that there is potentially a large family of functions which could characterize distance decay. Eldridge and Jones (1991) considered this in detail, pointing out the behavioral implications of different functions. For example, the home could have a very strong influence on the activity of the offender, in which case the function would be expected to be very steep, decaying quickly. Or there could be a much wider area in which the offender based himself, leading to much shallower functions in which the distances decay very slowly. Turner (1969) also argued that, within this decay, there is likely to be a "buffer zone" directly around the offender's home in which there is a reduced likelihood of offending, possibly due to the higher risk of recognition (Turner, 1969).

By using the appropriate decay function, each location around a crime site can be assigned a weighting indicating the likelihood of residence by the offender. For a serial offender the information derived from the weightings around the locations of each of his crimes can then be combined, using, for example, gravitational summation models (Rossmo, 1993), to indicate his likely location of residence. Such models will have practical application if the cases in a series have been linked and relevant information is available on the actual crime locations.

Subsequent work by Rossmo (1995) demonstrated that a computer mapping system based on these principles could indicate the area in which a serial offender is likely to be living. Rossmo states that the crucial constants and exponents in the decay functions on which his software is built are "empirically determined" (p. 233). He does not provide full information on what the empirical basis of this determination is, nor does he make it clear if the same exponent is used in all calculations. The question therefore remains as to what the most effective mathematical function would be across a wide range of crimes. Additionally, without an empirical examination of a sample of solved offense series, it is not possible to identify what the actual success rate of any system is. Furthermore, it is not possible to recognize the situations in which the system would and would not be successful or the degree of success for a particular case. To develop these systems further it is thus necessary to explore the various feasible mathematical functions that describe the distance decay to determine which functions are most effective for which offenders under which conditions.

2.1. A Measure of Effectiveness

If a variety of functions is to be compared it is necessary to determine some measure of their effectiveness. One objective is to reduce the demands on police resources. It is therefore proposed that some index of the "costs" of carrying out any search is determined. Different decay functions can then be examined to determine which is the most cost-effective. Such a measure will reflect the ability of a system to prioritize a search area and identify the location of an offender's home.

The proposed measure is based on the definition of a potential search area for each map of offense locations. Within the present study, a slightly broader definition of search area than the Circle Hypothesis is used. Earlier studies have shown that not every offense will be encompassed by a circle defined by a diameter drawn between the two offenses farthest from each other and therefore locations relevant to the analysis may be excluded. Therefore, in the present study a rectangle was used to define the potential search area, drawn to include all the offense locations. Drawing on the hypothesis that the great majority of offenders will have a base somewhere in the region of their offenses, but allowing for those cases in which the offender may not be living inside the rectangle defined by his offenses, in the present study the potential search area is magnified by 20%.

In the current study the system being used is based around visualization on a computer screen. Therefore the search area rectangle is made up of a finite matrix containing 13,300 square regions, selected to be the minimum size that was just visible on the standard computer monitor screen. This means that any circular structure that emerges from the calculations is an approximation made up of square, "jagged" edges.

The size of the regions as viewed on the screen does not vary, whereas the area represented by the region varies between cases. The software facilitates this by allowing the user to set the scale that the screen size is to represent. This therefore provides a relative search area in which the search for an offender's location can be prioritized. This approach was taken to enable the decision support software to be of value in a range of field conditions.

The effectiveness of any search of this rectangle is then calculated by assigning to each point on the map a weighting indicating the *likelihood* of residence. The weightings are used as an index by which to rank-order locations, referred to as the Base index, which has associated B values. These B-values are derived from the calibrated decay functions as described below. An array of locations ordered by decreasing B-value is then generated. Each point within the array is then searched for the offender's home base, starting at the location with the highest B-value. If B-values are tied, then they count with equal weight to the overall calculations. When the offender's home is reached, the search is terminated and a cost value generated. This value reflects the proportion of all possible locations searched before the location of the offender's home base is identified. A cost value of 0 would indicate that the first location searched (i.e., the location with the highest B-value) contained the offender's home; a cost value of 1 would indicate that the home was in the last location within the array. If the home were not within the search area, the system would give a null value, which would be treated as a failure. The search cost can therefore be seen to reflect the percentage of the rectangle searched. For example, a search cost of 0.5 would mean that 50% of the defined search area rectangle had to be searched before the offender's home was identified.

2.2. Analytical Models

There are a large number of possible mathematical models to describe the decay functions that can be used to determine the likelihood of a location being where an offender is based. Furthermore, no research has been published comparing different functions on any measure of effectiveness, or any set of crime data.

Rhodes and Conly (1981), in their examination of serial burglars, robbers, and rapists, observed that the distance decay displayed by their samples of offenders was negatively exponential in nature. This observation differed from the relatively normal distribution (with the exception of the buffer zone) around the offender's home suggested by Brantingham and Brantingham (1981). This is also true for other forms of serial spatial and behavioral phenomena (Golledge, 1987). The present study therefore explored a family of negatively exponential decay functions and function types generated from the equation

$$Y = e^{-px}, \qquad r3 = 1/10, 1/9, \ldots, 1, 2, \ldots, 10 \qquad (N = 19) \qquad (1)$$

where Y is the Base index value, x is the distance of that location from the offense site, 0 is the exponential coefficient, and N is the number of P values tested.

Each of the range of functions that is produced is applied to each offense location within a series. The functions are calibrated so that the maximum B-value is equal to 1 and the minimum is 0.[3] Figure 1 shows the range of functions that are tested in the current study. As the function number increases from 1 (/3 = 10) to 19 (/3 = 1/10) the characteristics of the function change from having a short existence and steep gradient, to having a long existence and shallow gradient. The number of functions tested was limited to 19, as such a range represented a broad selection of the forms of distance decay that may be observed within the sample.

Each function is applied over a distance moderated by a normalization parameter linked to the range of each offender's offense distribution as

'When used operationally in investigations this scale is recalibrated to a range of 0 to 0.5, to reduce the likelihood of unskilled users mistaking the values expressed by the system as direct probabilities.

Function Representation Points

Fig. 1. Family of analytical functions. (1) Function 1; (2) function 19.

described in the following section. Twenty equally spaced model representation points define all models. These points encompass the 19 model representation units, each point being a value by which to define the function.

To model the presence of a buffer zone, steps, areas with a 13-value of 0, and plateaus, areas of a constant 13-value (1 in the present study), of varying sizes are inserted in front of the exponential function. This combination of a step and a plateau was a simplified representation of a buffer zone for the present study. Future research may test more stochastic models such as that proposed by Rossmo (1995).

The step is representative of an area in which the offender will not offend, the plateau being a constant region close to the home in which there is the highest likelihood that the offender will offend. For the present study

a maximum number of 4 units from the original 19 model representation units was used to define the buffer zone. The analysis was then carried out using each permutation of steps and plateaus up to the maximum of 4 units. Each permutation thereby examines a different form of buffer zone.

Figure 2 shows an example function with a step size of 2 units and a plateau of 1 unit. Each permutation within the analysis is referred to as a function "type." A function without a step or plateau is referred to as a "bare" function type. A total of 285 function types was analyzed.

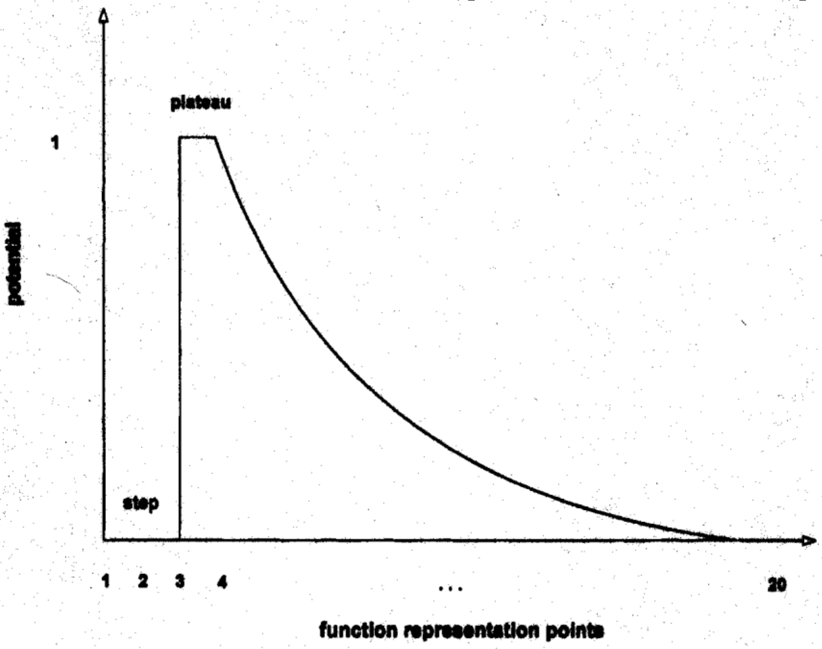

Fig. 2. Example function type.

2.3. Normalization Procedure

Offenders differ in the size of the area over which they carry out their crimes. Therefore any analysis that is to allow comparison between offenders must compensate for this by incorporating a normalization procedure. To do this a method based on the average distance between offenses was implemented. However, theoretical considerations and empirical analysis of the actual distribution of offenses indicate that a normalization procedure that takes no account of any possible axis along which the offenses may be distributed may be less effective than one that does. Therefore two normalization parameters were compared. One was the mean interpoint distance between all offenses (MID). The second was a specifically developed index, the QRange.

The QRange is based on the propositions of Brantingham and Brantingham (1981), Fink (1969), and Rengert and Wasilchick (1985) that the arterial pathways of the offender's movements may be of significance to the locations of his offenses. It is therefore feasible that there is some dominant linear structure to the distribution of offenses. The MID gives equal weight to all distances. Therefore an index was developed that provides a numerical indication of the average distribution of offenses around a notional axis. This axis was determined by calculating the linear regression of the crime scene coordinates within an offense distribution. The QRange was then defined as the mean perpendicular distance of all offenses points to the regressional axis inherent within a distribution of offenses. The closer the offenses lie to the regressional axis, the smaller the QRange value. In the present study the MID and the QRange for each offender were used to normalize each offense map.

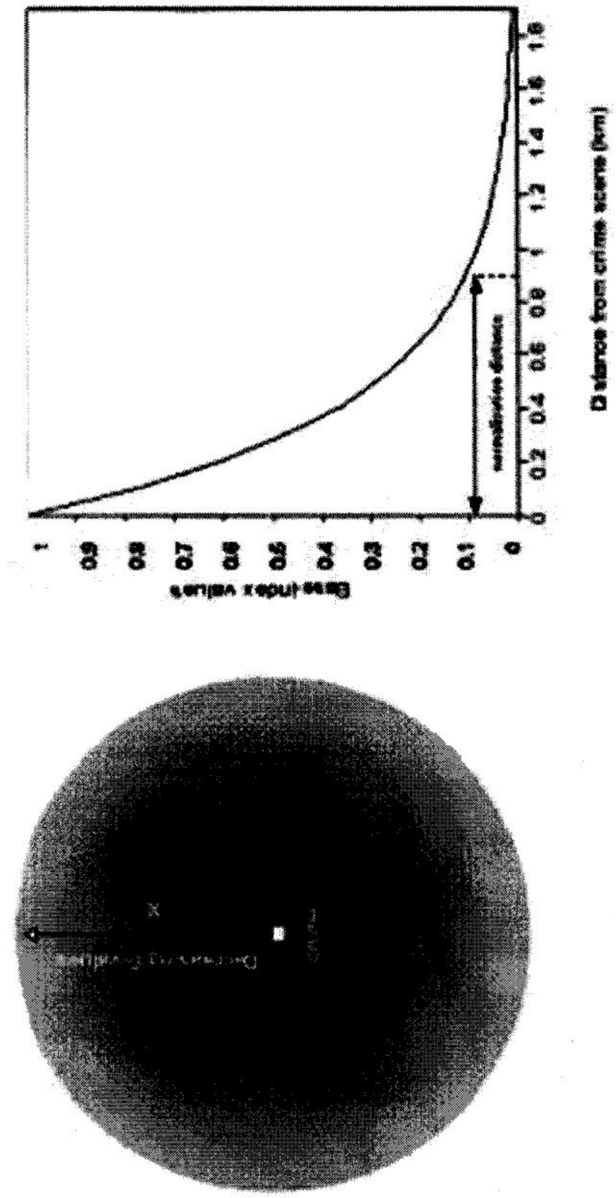

Fig. 3. Application of function to crime scene: (a) aerial view; (b) profile view.

2.4. Application of the Function

For each run of the analysis, i.e., testing one offense series with one function type and one normalization parameter, the normalization value is calculated. The function is then applied in a radial fashion around the crime scene to a distance twice the normalization parameter (distance x in Fig. 3a). The diameter of the resultant circle around the crime scene is therefore four times the normalization parameter. Figure 3b gives an example of how one of the bare functions represented in Fig. 1 is applied to a crime scene and therefore uses physical distances rather than abstract function representation points. This results in the assignment of 13-values to the area directly around one crime scene. For this case a normalization value of 0.95 km is used. The radial assignment of the function is repeated for each crime scene location, producing a range of final 13-values that can be constructed into a final prioritized map. The distribution of values within the prioritized map can be seen as a field in which each of the crime scenes is an influential body. Thus the 13-value for any location is defined as the mean of each of the values assigned to that location by those functions applied to that location. The means are used, as this recognizes the relative reduction in significance of individual crimes by the presence of other crimes as illustrated in Fig. 4.

To understand further the calculation of the 13-values, consider Fig. 4 as an example. Location x is 0.2 km from the crime scene 1 (csl). The function (A) applied to the crime assigns a 13-value of 0.60 to that location. The radial application of the function (13) around crime scene 2 (cs2) produces an overlap with that around crime scene 1. Location x is 0.2 km from crime scene 1 and 1.6 km from crime scene 2, for which it receives 13-values of 0.60 and 0.02, respectively. The relative significance of location x to the location of the offender's home with respect to the first crime is reduced on the introduction of the new crime scene. Therefore the 13-value for that location is calculated as the mean of the two values 0.60 and 0.02, 0.31. The dashed line in Fig. 4 indicates the resultant distribution of 13-values between the two crime scenes after this process is repeated for each individual

Fig. 4. Radial assignment of function to two crime scenes.

location. This process is repeated for each of the functions applied to the crime scene locations, producing a final map that is prioritized by B-values. The 13-values for any location is the mean of the values assigned to that location by the calibrated function radially assigned to each crime location within the series. This process is an extension of Kind's (1987) work in that, rather than producing a single point as an indication of the offender's residence, a more comprehensive prioritized map is produced. It is also more detailed than the system studied by Canter and Gregory .(1994), in which broad regions were indicated.

The process presented here examines all locations around each of the crime scenes rather than seeking to identify one single point as an indication of the offender's residence. Figure 5 provides an example of an actual prioritized search area derived from a recent police investigation. Included within the diagram are the center of gravity (C) for the crime series and the actual location of the offender's home base (H). The range of B-values is displayed from highest to lowest by, respectively, darker to lighter shades of gray (the operational Dragnet system uses a range of different colors). The location of the offender's home within one of the darkest regions illustrates the success of the methodology for this case. The diagram identifies the contrasting amounts of information that are produced from the two forms of analysis and shows how the centrographic method can be misleading as a result of the geometrical shape of an offense distribution. The center of gravity is

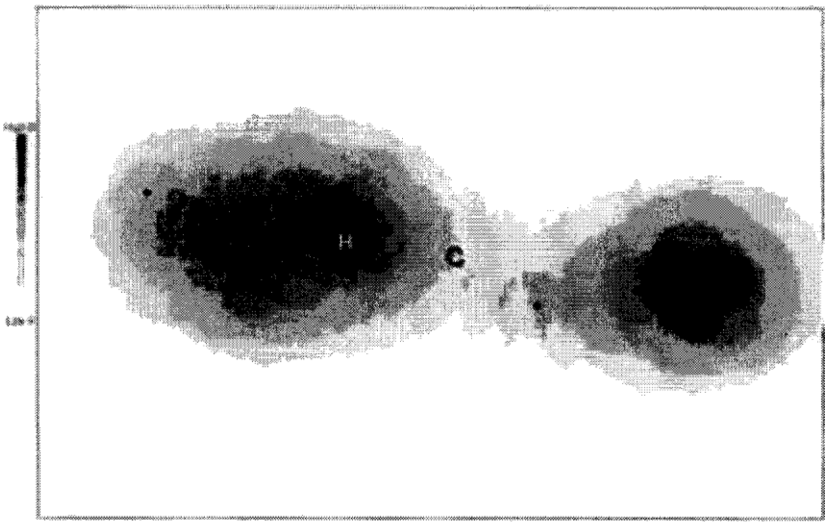

Fig. 5. Prioritized search map.

actually a unilocational summary or mean of the information represented in the prioritized map.

In this example also, two domains of operation are apparent. After the trial it was found that the area to the right circumscribed the residence of the offenders estranged wife, whom he sometimes visited. The distribution of possible bases in this plot therefore does capture some important aspects of the offender's activity spaces.

Figure 5 also serves to illustrate ways in which a mere "eyeballing" of the geographical distribution of offense locations can be unproductive. In this particular case the centroid might be assumed to be the obvious location for a base. The solution provided by the algorithm might be rather unexpected, even though, as it happens, it turns out to be more accurate. Of course, local knowledge about land use, the road network, and sociodemographic and other inofrmation that could help indicate where offenders may live can all contribute to formulating a view about an offender's base location beyond the indications of uninformed software. That is why it seems appropriate to regard such software as a decision support tool rather than an "expert system." If it has any validity, it can provide only general guidance to an inquiry, not the precise identification of a residential location.

3. METHOD

To test the effectiveness of the Dragnet system described, digital offense maps were generated for solved cases in which the home base of the offender was known. The maps contain the location of the offender's home and the location at which a crucial aspect of the crime took place. In the present study, as discussed below, this aspect was the location at which the bodies of the offender's victims were found.

No land use or topographical information is incorporated into the representation. A calibrated decay function of B-values is applied to a normalized map of each of the offense series. As the analysis is working at a level of abstraction that does not take account of land use or topographical characteristics, there are likely to be instances where actual locations such as parks, lakes, or zoos are assigned values indicating the possibility of the offender's living there. In operational use local knowledge would take account of this and limit searches accordingly. The tests applied in this study therefore underestimated the effectiveness of any localization of an offender's residence. The use of the Base index acknowledges this.

Each segment of the map is assigned a specific B-value. The possible B-values decrease from 1 to 0. A rank-ordered search of locations with decreasing B-values is then conducted. A search cost value is then produced, reflecting the proportion of the original rectangular search area that needed to be searched before the offender's home base was identified.

For each offense series this process was repeated using 285 forms of the negative exponential decay function types and 2 normalization parameters. Therefore each of the cases tested in the present study was analyzed 570 times. A mean search cost per function type was produced across all the offense series studied.

3.1. Analysis

3.1.1. Sample

The procedure described is applicable to any series activity that has a geographical location. However, one of the most challenging investigative contexts is in the search for a serial killer. Furthermore, because of the public interest in such offenders, once they are caught, details of their offenses and the locations at which they occurred, as well as where the offender was living at the time, are available from public records for many offense series. The details of these published accounts can also often be checked with investigating officers who, especially in the United States, are prepared to comment on published reports if required.

By consulting published accounts of U.S. serial killers who had been convicted since 1960, a list of offenders was drawn up. The location at which they had been residing at the time of their offenses was then determined from at least two independent sources. If these sources did not corroborate each other, the offender was dropped from the sample. Attempts were then made to contact police officers or local journalists who had worked closely on the cases in question to test further the reliability of the residential location information. At this stage corroboration was also sought for the published information on the locations at which the bodies of the victims were found. By this means information became available on 79 U.S. serial killers. Each of the cases therefore satisfied the aforementioned conditions.

- A series of crimes linked by forensic or other means-murders,
- Specific associated locations-body disposal sites.

Of the geographical information available to the police, the disposal site of the victim's body is the most reliable. Other locations, for example, where the victim was first encountered or abducted or where a body might have been kept before disposal, are of interest but are not often known, or if known published, with the same degree of reliability as the disposal site. It does seem likely, though, that these other forms of location may require types of models different from those studied here. For the current study it was decided to use the location that is consistently the most readily available to a serial murder investigation, the body disposal site.

Using the above conditions of a linked series of crimes and associated locations, it is apparent that not all kinds of serial killers can be analyzed using this methodology. John Wayne Gacy, for example, buried the bodies of 29 victims underneath his house and driveway during his 6-year offense series in the 1970s. As a result the identification of the body disposal locations was an integral part of identifying the offender. They were not known until the offender had been identified. Therefore offense series for which the body disposal sites are not known at the time of the investigation are not suitable for this form of analysis and were not included in the present study. In such cases other crime-related sites could be utilized, although as mentioned above, an alternate model to that for the body disposal sites may be more relevant.

The geographical locations of the addresses of the body disposal sites and the offender's residence at the time of the offense were determined through street maps and gazetteers. These were input into a flexible decision support system (Dragnet) as raw coordinates. The decision support system allowed modification of the scale for each "map" so that it would fit a computer screen, and further batch software was applied to this to test the effectiveness of the different functions. Therefore the 79 offenders were an *ad hoc* sample unbiased by any assumptions as to which subsets of offenders may be most open to modeling by the system used.

There are doubtless problems with such data. The information available to the authorities itself may have unreliability within it, they may not have recorded the information correctly, or they may have been misled due to incompetence or malice. Distortions can also arise due to reporting strategies and concern to protect victims' families or avoid sites becoming Meccas for ghoulish tourists. Unreliability is also introduced due to confusion over which victims really were the consequence of the actions of a particular individual and at which location the offender really was residing at the time that any particular victim's body was disposed of. Attempts to counteract all these problems were made during the data collecting process, which took a number of years to complete. However, although the full reliability of the data can probably never be precisely gauged, crosschecks on its internal consistency have been very encouraging. Furthermore, the errors introduced by unreliability are most likely to add noise to the data and thereby reduce the possibility for finding support for the models tested. Any support for the models, through low search costs, may therefore be considered in part as support for the reliability of the source data. But, as in any other area of research, the acid test is through the examination of other data sets by other researchers.

In the sample of 79 serial killers studied, their offense series ranged from 2 to 24 crimes (mean, 8; SD, 4.53) and contained distances from 0 to 845 km (mean, 46.39 km; SD, 85.71 km). The series were drawn from all over the United States across a range of geographical settings. This eliminates the effects of biasing that can be generated from using multiple series from one geographial area of type of land use.

4. RESULTS

4.1. Effectiveness of the Search Area

All of the home bases of the 79 serial killers were located within the search area defined by the decision support system. This 100% result is considerably higher than the results reported for the "marauder circle" in earlier studies. It clearly needs to be tested by replication on other data sets. However, for the present sample at least, this result does support the utility of exploring further the power of different functions in helping to localize the search *within* that overall search area.

4.2. Bare Functions

Figure 6 shows the distribution of mean search costs produced from all bare function types with no steps or plateaus. Two major findings are highlighted from this chart.

1. For both the MID and the QRange there are optimal functions which produce minimal search costs. The optimal functions for the MID and QRange are 10 and 11, respectively, producing mean search costs of 0.19 and 0.11. This shows that the original potential search areas were reduced to mean, actual search areas of 19 and 11% of their original size, respectively.
2. For each bare function the QRange is a more economical normalization parameter than the MID.

The difference between the two normalization parameters was found to be significant using a paired-samples t test ($t = 14.45$, $P < 0.05$). It is evident that the mean search costs produced using the MID are more sensitive to changes in the function than the search costs produced using the QRange due to the steeper well of lower search costs for the MID distribution. Additionally, the search costs are more sensitive to a reduction in the depth and existence of the function than an increase, for both parameters.

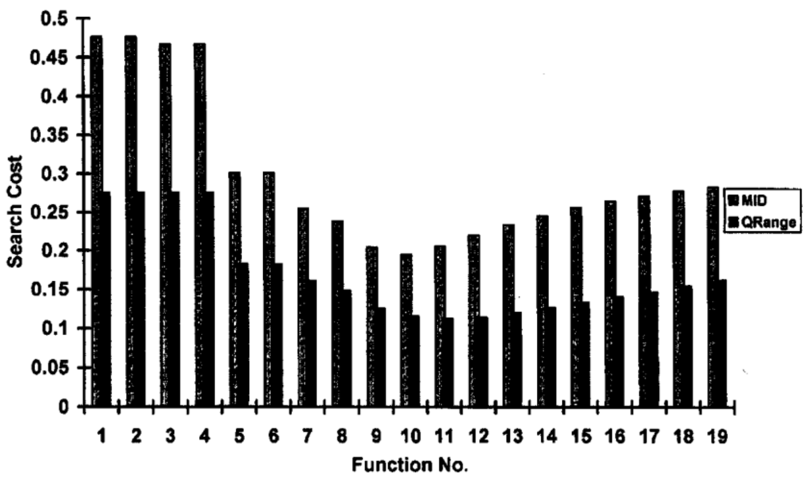

Fig. 6. Distribution of mean search costs for bare functions.

4.3. The MID

The search costs using the MID for bare function 10 are displayed in Fig. 7. The graph highlights that search costs are distributed in an approximately negatively exponential fashion, with the higher percentage of the sample having a low search cost. If the home of the offender lay outside the potential search area, a search cost of "null" would be produced. As no searches produced this value, the rectangle defining the potential search area encompassed the offender's home in all cases. Fifty-five percent of the sample required searches of less than 15% of the search area; 74%, less than

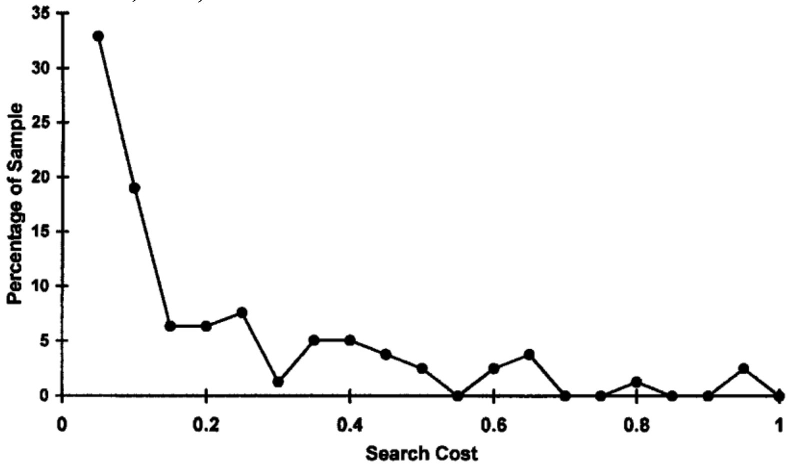

Fig. 7. Range of search costs for optimal MID function.

30%. Figure 8 gives a detailed representation of those search costs below 0.3.

4.4. The QRange

The search costs using the QRange for bare function 11 are displayed in Fig. 9. The graph reveals that there is a high frequency of small search costs accompanied by a small number of larger search costs, generating the

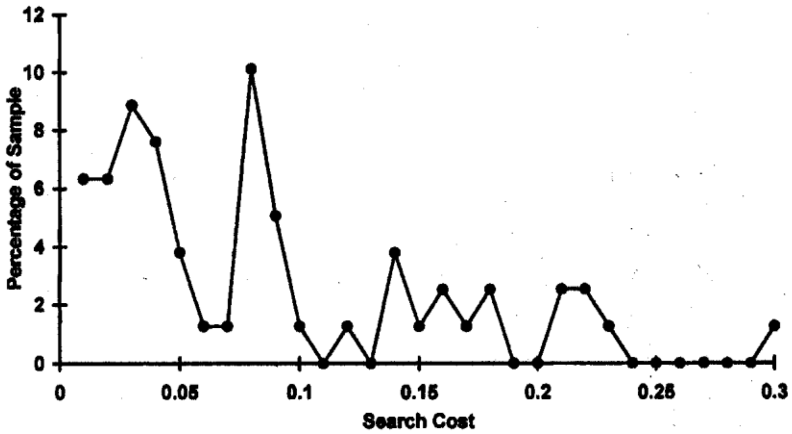

Fig. 8. Range of search costs below 0.3 for optimal MID function.

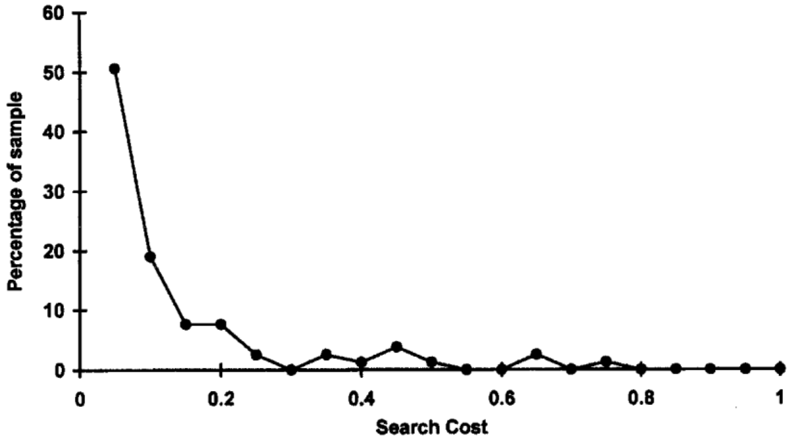

Fig. 9. Range of search costs for optimal QRange function.

average requirement to search 11% of the potential search area. For 51% of the offenders (N=40), less than 5% of the area needs to be searched; or 87% of offenders (N= 69), less than 25%.

A closer examination of the 87% of the sample in which the search cost was less than 0.25, indicated in Fig. 10, reveals that for 15% of the sample, the search cost was below 0.01.

4.5. Steps and Plateaus

Figure 11 shows that the inclusion of steps and plateas for function 11 using the QRange increases the mean search costs. It is evident that

Fig. 10. Range of search costs below 0.25 for optimal QRange function.

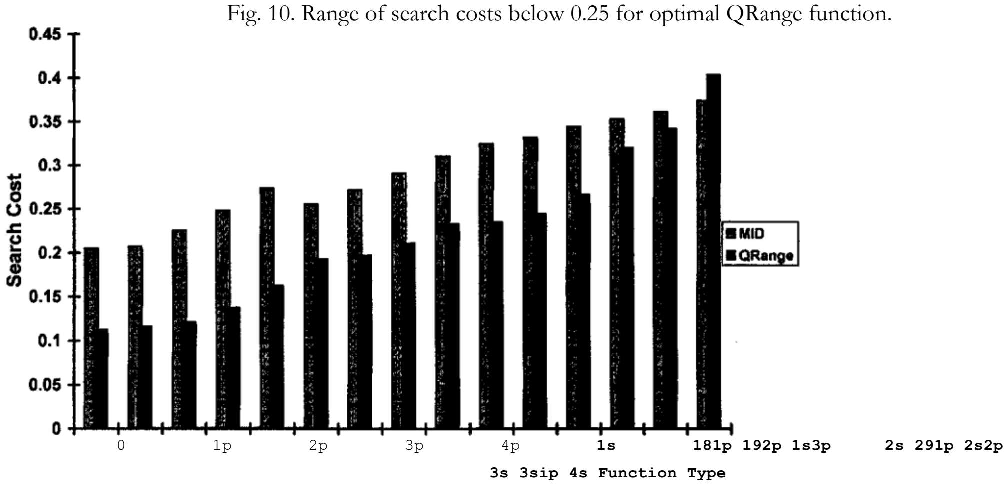

Fig. 11. **The effects of steps and plateaus.**

including a plateau is more economical than including a step, which is more economical than including a combination of a step and plateau. Furthermore, the inclusion of up to four plateaus is more economical than the inclusion of one step or any combination of steps and plateaus. The same trend is also apparent for the MID normalized functions, with the exception that for this parameter the use of four plateaus is less economical than the use of one step. With the inclusion of three steps and all subsequent combinations of function type, the mean search cost using the QRange becomes increasingly sensitive until it becomes more economical to use the MID than the QRange when the function type with four steps is implemented.

The most economical search value produced from all 285 function types was that of bare function using the QRange normalization parameter, requiring on average a search of only 11% of the total designated search to find the home location.

5. CONCLUSIONS

The current methodology has shown that for each of the bare functions, normalization using the QRange provides more cost effective searches than the MID. The identification of an optimal search function has additionally shown that it is possible to generate a mean search cost of 0.11, therefore, on average, reducing the rectangular potential search area to just below 11% of the original size.

Using the optimal function, and QRange normalization parameter, the home base for 15% of the sample was identified within the first 1% of the rank-ordered locations, 51% within the first 5% of locations, and 87% within the first 25%. Such a high proportion of accurate findings indicates that, for the current sample of 79 U.S. serial killers,

(a) the use of function 11 with the QRange parameter is highly effective in identifying the location of a serial killer's home base, and (b) there is a high degree of substantive import within the psychological principles on which the system is built.

Such accurate results are complemented further by the fact that the maps used within the analysis contained no land use or topographical information. Hence within any search the current system will have included areas in which the offender is very unlikely to have lived, such as rivers and lakes. The subsequent inclusion of any such information would therefore improve the results already obtained.

The increased search costs generated with the use of various combinations of steps and plateaus do not support the assumption of a simple buffer zone of the form studied here.

The limitations on the results presented are a function of the data set used. Only offenders who have been caught were included in the sample, so it is an open question whether their parameters of movement are the same as those of offenders who evade detection. Similarly, the models apply to offenders who come to police attention due to the discovery of the locations where the victims' bodies have been disposed of. Those offenders who bury the bodies in their own house or garden would not be drawn into the type of investigation in which the offender's residential location is problematic, and thus the current models would not be relevant.

Perhaps of more general interest at this stage, beyond the practical implications, is the fact that, despite the vagaries of the data used, some strong and consistent patterns have been found. These are consistent with the many claims in the published literature that a criminal's choice of location can be modeled using relatively simple, relatively context-free mathematics. That makes the further test of current and related models a worthwhile enterprise that offers further routes toward the understanding of the geography of criminal behavior.

In principle, any series of offenses in which the offender has direct contact with a geographical location to commit his crime is open to this form of geographical profiling. The models presented here can therefore be used to test the possibility that offenders are operating according to similar mathematical functions. By carrying out analyses similar to the present study with other crimes, such as burglary, it will be possible to determine the most appropriate functions for those types of crime. Thus the next step is to apply the same methodology to other serial crimes such as rape and arson as well as the higher-volume crime of burglary. Functions may also be developed in relation to local topographical constraints, land use, target distributions, and transport networks, as Canter and Snook (1999) have reported. However, to evaluate the effectiveness of such explorations, a measure that takes account of the relationship between the proportion of offenders accurately located and the proportion of the area searched needs to be used. The "search cost" described in the present study seems to be one productive way of doing this.

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