

Efficacy of Standard Deviation Ellipses in the Application of Criminal Geographic Profiling

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Abstract

The premise for this study is that the physical and cultural landscape has a deterministic effect on the location and distribution of serial crime. As a consequence, the distribution of linked crime scenes should exhibit a shape and orientation that is consistent with the underlying landscape. Geographic Profiling models that are able to account for these effects will provide more accurate results than those models that do not. Utilizing basic geographic principles of central tendency and spatial diffusion, this research first analyzed the output of circular and elliptical profile models generated for 30 serial burglaries ($n = 164$) and 67 serial robberies ($n = 370$) in Baltimore, Maryland between 1994 and 1997. A comparative analysis of the model output reveals that the Standard Deviation Ellipse is significantly ($p = 0.000$) better able to predict the home location of a serial offender than profiles generated from circles. Next, the relationship between the orientation of elliptical profiles and the mean linear orientation of the corresponding landscape was assessed to reveal a moderate but significant correlation ($r = 0.511$, $p < 0.001$). Together, these findings demonstrate that landscape does impact the locations of crime, and is a measurable parameter that can improve the efficacy of geographic profiling. Copyright © 2008 John Wiley & Sons, Ltd.

Key words: serial crime; geographic profiling; central tendency; spatial diffusion; circle models; elliptical models

INTRODUCTION

The primary objective of a criminal geographic profile is to analyse the distribution and pattern of linked crime scenes in order to estimate the likely residence of a serial offender. However, developing a meaningful profile is seldom easily achieved. Crime scenes are typically distributed in seemingly random patterns, making it difficult to identify trends

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and characteristics that implicate a single perpetrator (Brantingham & Brantingham, 1981; Canter & Gregory, 1994; Canter & Larkin, 1993; Rossmo, 2000). Yet, research consistently demonstrates that crime scenes are not located randomly (Brantingham & Brantingham, 1981; Canter & Gregory, 1994; Harries, 2006; Kocsis, *et al.*, 2002; Kocsis & Irwin, 1997; Rengert, Piquero, & Jones, 1999; Rossmo, 2000). Rather, they occur at the confluence of offender, target and opportunity (Brantingham & Brantingham, 1981; Cohen & Felson, 1979). As a result, these locations represent a partial record of the offender's spatial preferences that are, to some extent, determined by the immediate landscape, or *target backcloth* (Brantingham & Brantingham, 1981; Capone & Nichols, 1976; Rossmo, 2000). And whilst many contemporary techniques recognise the importance of the landscape, very few models are able to accommodate its effect (Snook *et al.*, 2005; Snook, Canter, & Bennell, 2002; Snook, Taylor, & Bennell, 2004; Canter, 2005). Therefore, this study proposes that geographic profiling models that are capable of parameterising the effects of the landscape will more accurately predict the location of a serial offender's residence.

PRINCIPLES OF ENVIRONMENTAL CRIMINOLOGY

Much of the theoretical bases for geographic profiling can be traced back to fundamental tenants of environmental criminology, including *least effort principle* (Cornish & Clarke, 1986; Zipf, 1949), *offender activity space* (Brantingham & Brantingham, 1981), *routine activity theory* (Cohen & Felson, 1979), *crime pattern theory* (Brantingham & Brantingham, 1981), *rational choice theory* (Cornish & Clarke, 1986), *distance decay* (Capone & Nichols, 1976), *environmental range* (Canter & Larkin, 1993) and *buffer zone effect* (Brantingham & Brantingham, 1981). In general, these theories can be summarised into three basic concepts. First, most crimes occur relatively close to the offender's residence. Second, the frequency of crime decreases as the distance from the offender's home increases. Finally, different crimes will exhibit different spatial patterns.

As a whole, these concepts establish a qualitative framework for examining the complex relationship between the offender, the crime, and the victim. But as Brantingham and Brantingham (1981) cautioned, it is impractical to examine this relationship outside the context of *place*. Accordingly, nearly all contemporary profiling methodologies apply quantitative models that utilise, at their core, fundamental geographical principles. Two of the most prominent principles are *centrography* and *spatial diffusion* (Canter & Larkin, 1993; Rossmo, 2000; Snook *et al.*, 2004; Snook *et al.*, 2005; LeBeau, 1987; Rich & Shively, 2004; Paulsen, 2006). A summary of these techniques and their application to geographic profiling are provided in Table 1.

Table 1. Predominant spatial measures used in criminal geographic profiling

Measure	Model	Strategy	Model input	Model output
Central tendency	Spatial Mean, Median, and Center of Minimum Distance	Spatial Distribution Strategy	Points	Point
Spatial dispersion	Circular Search Area Elliptical Search Area	Spatial Distribution Strategy	Points	Points and Polygons
Spatial diffusion	Distance Decay Algorithms	Probability Distance Strategy	Points	Probability Surfaces

APPLICATIONS OF CENTROGRAPHY

Centrographic techniques characterise phenomena by providing a single measure of central tendency (i.e. an average location) (LeBeau, 1987). This approach constitutes a *spatial distribution* strategy (Levine, 2007). When applied to geographic profiles, these measures summarise a distribution of crime scenes to a single location where the sum of differences between the mean and all other points within the distribution is zero (Ebdon, 1988). The strategy is premised on the assumption that the serial offender will commit crimes within a finite area that is relatively close to their home. This area defines the offender's *activity space* (Brantingham & Brantingham, 1981). Thus, by defining the centre of a crime's distribution, one effectively reveals some portion of the offender's activity space.

The most common measures of central tendency include the *geographic mean*, *median* and *center of minimum distance*. But analysing distributions using this approach can be limited, as they are only capable of characterising complex processes with a single descriptive measure (Rossmo, 2000; Levine, 2007). As such, centrographic analysis is often augmented by measures of dispersion, including *circles*, *ellipses* and *convex hulls*. One such example has been documented in the application of the *circle hypothesis*, which demonstrates that a circle large enough to encompass the two furthest crimes of a distribution will most likely encompass the serial offender's residence (Canter & Larkin, 1993). Another example includes Newton's geoforensic analysis, which iteratively analyses the sequence of crime scenes in order to define the likely activity space of a serial offender based on the dispersion of the crimes around a central point (Newton, 1988). The combination of central tendency and spatial dispersion has proven to be simple but effective profiling strategies (Leitner *et al.*, 2007; Levine, 2007; Paulsen, 2006; Snook *et al.*, 2002; Snook *et al.*, 2005). However, centrographic techniques are often susceptible to outliers that potentially distort their effectiveness. And on their own, these simple measures are seldom able to reflect the inherent complexities of either the landscape or an offender's perception of place (Canter & Hodge, 2000).

APPLICATIONS OF SPATIAL DIFFUSION

Geographical profiling will also utilise models that apply concepts typically utilised in spatial interaction models. The most common approach is to profile a distribution of crime scenes using empirically calibrated *distance decay* algorithms. These centre-of-gravity techniques constitute *probability distance* strategies which measure the likelihood of finding an offender's residence in the areas immediately surrounding linked crime scenes (Levine, 2007). The strength of this approach lies in its ability to model the condition in which the frequency of crime decreases as the distance from the offender's residence increases (Capone & Nichols, 1976). Not surprisingly, distance decay models have found popular support in nearly all geographic profiling applications (Rich & Shively, 2004). The most well known of these applications include Dragnet® (Canter *et al.*, 2000), Rigel® Criminal Geographic Targeting (CGT) (Rossmo, 2000) and the journey-to-crime routine provided in CrimeStat® III (Levine, 2007). But in spite of their popularity, distance decay methodologies have been criticised for their reliance on homogeneous spatial structures that can distort nuanced, but significant, characteristics associated with the criminal commute (Rengert *et al.*, 1999; Van Koppen & De Keijser, 1997). And like

centrographic techniques, these techniques presume an ideal framework in which the patterns of crime scenes are normally distributed.

LANDSCAPE'S IMPACT ON THE OCCURRENCE OF CRIME

With few exceptions (Capone & Nichols, 1976; Kent, Leitner, & Curtis, 2006; LeBeau, 1987; Rengert *et al.*, 1999), the majority of contemporary geographic profiling techniques have failed to account for the landscape's impact on the occurrence of crime. Instead, contemporary methods consistently adopt an *a priori* assumption that both the crime scenes and the offender residence are located on an isotropic surface where the opportunity to offend is uniformly distributed around the offender's residence. But, as established by Brantingham and Brantingham (1981), and later by Rengert *et al.* (1999), the location of a crime involves complex factors that make it unlikely to occur randomly. In a study on the environmental range of serial rapists, Canter and Larkin (1993), and later Kocsis *et al.* (2002) empirically demonstrated that the location of a serial offender's residence is not generally positioned within the centre of a distribution. Rather, the relationship between the crime scenes and the offender's residence suggests an irregularly distributed activity space that is, in some measure, influenced by the landscape and offender perceptions (Brantingham & Brantingham, 1981; Canter & Hodge, 2000). In effect, these findings validate the premise that crime scenes and offender residences are actually located on anisotropic surfaces. And just as a crime's location is a partial record of the offender's spatial preferences, so too is it a reflection of the irregularities consistent within the underlying physical and cultural landscapes. Such irregularities are typically characterised according to three geographic analysis measures: *location*, *dispersion* and *orientation* (Yuill, 1971).

Newton's (1988) circle-based geoforensic analysis technique is a practical method for measuring these characteristics. First, the model output predicts a location of an offender's residence (what Newton called the '*haven*') according to the geographic centre of the crime distribution. Second, a circle with a diameter defined according to the number and spatial extent of known crime scenes is generated. This output represents a search area in which the offender's residence is expected. Finally, the technique iteratively refines the output as each new crime scene is added to the model, thus accounting for changes to the distribution's location and size over time. However, there are limits to the technique's ability to model a serial distribution. Because the technique utilises a circle-based strategy by default, the circular output presumes an isotropic surface. As such, it is ill-suited to measure variations in the shape and orientation of the distribution in relation to the anisotropic landscape.

As an alternative to the circle, the standard deviational ellipse model is better able to account for irregularities in the landscape. Like the circle, the ellipse is capable of identifying the centre of a distribution, as well as its spatial extents (i.e. dispersion). But unlike the circle, an ellipse measures the shape and orientation of the distribution by summarising the maximum and minimum variance along the x- and y-axes (Ebdon, 1988). As a result, the ellipse is able to account for a non-uniform arrangement of events (Lefever, 1926; Levine, 2007). These differences are illustrated in Figure 1, which depicts circular and elliptical profiles generated for a theoretical distribution of crime events. With both profiles positioned over the geographic centre of a distribution, the elliptical model is better able to match both the orientation and variation in the dispersion. Whilst overly simplistic,

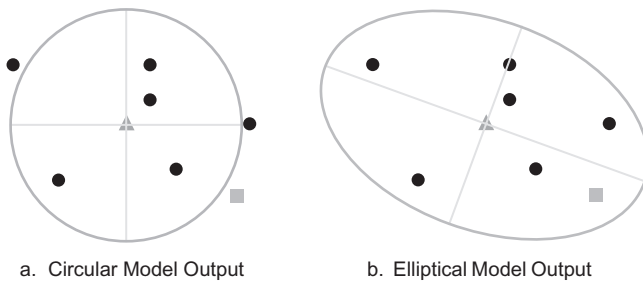


Figure 1. Example of circular (a) and elliptical (b) model output generated by Newton's geoforensic analysis. Each model is positioned over the geographic centre (triangle) of a theoretical distribution of crimes. The offender's residence (square) is captured by the elliptical model, but not the circle.

the graphic in Figure 1 effectively demonstrates that an ellipse is better able to account for the irregular distribution of events than the circular model.

HYPOTHESIS

This research proposes that the spatial relationship between the locations of an offender's residence and linked crime sites will exhibit spatial patterns and characteristics that are consistent with the underlying landscape. Accordingly, a geographic profiling model that is capable of measuring the *location*, *dispersion* and *orientation* of crime scenes should more accurately predict the residential location of a serial offender. Furthermore, because the landscape has a deterministic effect on the distribution of serial crime, the orientation of elliptical profiles should correlate with the orientation of landscape features that are coincident with the spatial extents of the crime scenes. These measures can be achieved using a standard deviational ellipse model similar to that proposed by Lefever (1926), and later modified by Levine (2007), Ebdon (1988) and Yuill (1971). As such, the hypotheses for this research can be summarised accordingly:

- 1) Geoforensic profiling models using the standard deviational ellipse will produce more accurate profiles than those created using circles.
- 2) The orientation of an elliptical profile will correlate with the orientation of the corresponding physical landscape.

In order to test these hypotheses, Newton's geoforensic analysis was used to calculate both circular and elliptical profiles for 30 burglary and 67 robbery serial offences occurring in Baltimore, Maryland between 1994 and 1997. The output from both profile models were assessed according to their profile accuracy, proximity to the offender's residence, and size of the search area. Next, the angular direction of each ellipse was calculated and compared to the linear directional mean of the underlying road network in order to determine if the orientation of the ellipses matched the orientation of the coincident physical landscape.

These hypotheses are established on a number of assumptions. First, each crime series consists of offences that have been perpetrated by a single individual. Second, a profile's effectiveness assumes that the offenders initiate and conclude all criminal activities from a fixed location (i.e. their residence). The third assumption posits that an offender's spatial behaviour can be organised according to one of two offence characteristics: offend inside

a defined activity space (i.e. *marauder model*), or outside a defined activity space (i.e. *commuter model*) (Canter & Larkin, 1993). The fourth assumption posits that pattern and distribution of the crime types (i.e. burglary and robbery) do not differ significantly, and thus their profile results can be compared equally. Finally, in order to support the hypothesis that the orientation of the crime scenes correlate with the underlying landscape, it is assumed that both crime sites and offender's residence are positioned in locations accessible by existing transportation networks.

METHODOLOGY AND DATA

Evaluation criteria

Contemporary literature details a number of different evaluation methodologies that can gauge profile accuracy (Canter, *et al.*, 2000; Canter & Gregory, 1994; Canter & Larkin, 1993; Paulsen, 2006; Rossmo, 2000; Snook *et al.*, 2005). However, there is currently no one standard for measuring performance (Rich & Shively, 2004). As a consequence, many of these measures have been at the centre of contention within existing literature (Canter, 2005; Rossmo, 2005; Snook *et al.*, 2005). In a report issued to the National Institute of Justice (NIJ), authors Rich and Shively (2004) detailed a collection of geographic profiling evaluation criteria recommended by an expert panel of criminologists and researchers. Based on their applicability to this study, three of the performance measures listed in the NIJ report were chosen to compare the efficacy of circular and elliptical model output:

- *Profile accuracy*—binary value (true/false) that indicates whether or not the offender's residence was located within the predicted search area.
- *Profile error distance*—the Euclidean distance measured from the actual residence to the nearest point on the profile's final predicted search area (i.e. top profile).
- *Profile search area score*—the ratio of the predicted profile search area to the required profile search area (i.e. search cost).

Data

The data used in this analysis were selected from a database of 267 solved serial crimes that occurred in Baltimore County, MD, between 1994 and 1997. The sample chosen for this research consisted of 30 burglary ($n = 164$) and 67 robbery ($n = 370$) crime series. An average of 5.51 (min = 4, max = 12, standard deviation [SD] = 2.07) crimes per series was measured for all 97 offenders. Table 2 provides additional statistics regarding the sample data. In order to accommodate a fair comparative evaluation, the data selected for this analysis followed the recommendations provided in the 2004 NIJ geographic profiling report (Rich & Shively, 2004):

- Crime series should be comprised of at least three offences.
- Data should include both *marauder* and *commuter* offender types.
- Crime series should include a variety of offender traits (i.e. sex, age, race, etc.).
- Data should resemble information actually available to law enforcement agencies.

Additionally, those crime series exhibiting a residential location that was spatially coincident with 50% or more of the crime scenes were removed from the sample. The occurrence of multiple, coincident events resulted in mathematical singularities that made it difficult to analyse a model's output.

Table 2. Crime series descriptions—totals

crime type & offender model	Number of crimes	Number of series	Average crimes per series	Average distance between crimes	average max. distance between crimes	Average max. distance from residence	Average criminal offence area
Burglary	164	30	5.47 (SD = 2.13)	7.056 km (SD = 11.047)	10.246 km (SD = 9.634)	11.365 km (SD = 12.993)	27.723 km ² (SD = 45.285)
Robbery	370	67	5.52 (SD = 2.06)	7.522 km (SD = 6.162)	10.198 km (SD = 7.852)	10.893 km (SD = 7.429)	30.789 km ² (SD = 52.544)
Commuters	229	45	5.09 (SD = 1.53)	9.213 km (SD = 10.442)	7.782 km (SD = 7.547)	12.415 km (SD = 11.767)	19.459 km ² (SD = 34.633)
Marauders	305	52	5.87 (SD = 2.40)	5.791 km (SD = 4.360)	12.317 km (SD = 8.584)	9.847 km (SD = 6.699)	38.825 km ² (SD = 59.418)
Totals	534	97	5.51 (SD = 2.07)	7.378 km (SD = 7.938)	10.213 km (SD = 8.392)	11.039 km (SD = 9.433)	29.841 km ² (SD = 50.196)

Assumptions

In order to meet the assumptions and evaluation criteria adopted by this research, each crime series was categorised according to its corresponding offender model. This process was carried out in two steps. First, the offender model was determined according to parameters defined by Canter and Larkin (1993). Because the sample data consists of more robberies (67) than burglaries (30), the spatial patterns (i.e. measured distances between points) observed for burglary and robbery crime types were statistically assessed to determine if their distributions could be analysed together or separately.

Research indicates that spatial patterns observed within a crime series will exhibit distinct characteristics which can be organised according to offender type (Canter & Larkin, 1993; Kocsis & Irwin, 1997; Kocsis, *et al.*, 2002; Meaney, 2004). These types are traditionally categorised as either commuter or marauder offender models. These categories were coined by Canter and Larkin (1993) to describe competing spatial characteristics observed for serial rapists. By definition, the marauder model describes an offender who typically commits crimes within a defined range from a home base of operations (i.e. offends inside a defined activity space). Conversely, the commuter model is characterised as an offender who travels away from a home base to commit crimes in another area (i.e. offends outside a defined activity space). Traditionally, the method for distinguishing an offender's spatial preference is accomplished according to the 'Circle Hypothesis' procedure detailed by Canter and Larkin (1993). For the purposes of this research, their approach was mathematically automated by calculating the ratio of the maximum distance between crime scenes and offender residence to the maximum distance between the two furthest crime scenes (Canter & Larkin, 1993):

$$\text{Offender Model} = \frac{d_{cr}}{d_{cc}} \quad (1)$$

where d_{cr} is the distance from the furthest crime to the offender's residence, and d_{cc} is the maximum distance between crimes. The offender was categorised as a *marauder* if the ratio was less than 1.0, or a *commuter* if the ratio was equal or greater than 1.0.

Next, the spatial patterns of serial burglary and robbery were analysed in order to assess the relationships between crime type (i.e. burglary and robbery). Because the distributions were right-skewed, the Mann-Whitney U test, a non-parametric allegory to the Student's two independent sample t -test, was used to determine if burglary and robbery serial crimes could be analysed equally. In support for the fourth assumption of this research, the Mann-Whitney U test failed to demonstrate a difference between the burglary and robbery distributions [$U = 863$, $Z = -1.668$, $p = 0.095$ (two-tailed)], concluding that average distance between these crime types were not significantly different. As such, burglary and robbery distributions were combined and analysed according to the offender model.

Profiling models

Geoforensic analysis is arguably one of the first geographical profiling techniques operationalised for use in a serial crime investigation (Leitner, *et al.*, 2007). Developed in the late 1980s by Milton B. Newton, Jr., the model calculates both the location and dispersion of linked crime scenes committed by a localised (i.e. marauding) serial offender (Newton, 1988). The approach was developed on the premise that an area surrounding the geographic centre of a crime distribution (i.e. the offender's activity space) may contain a marauding offender's residence, or *haven*. Furthermore, Newton proposed that

the predicted location of the offender's haven will move closer to the actual haven after each successive crime event (Leitner, *et al.*, 2007; Newton, 1988; Newton & Swoope, 1987). To provide a search parameter for this effect, the algorithm generates a circular search area with a radius defined by the extent of the two furthest crime scenes in the sequence. As each new crime scene is added, the size of the search area is reduced (equation 3).

Accordingly, Newton's Geoforensic Analysis is implemented in three steps (Newton, 1988):

- 1) A quadrilateral study area is defined by the distance between the furthest east–west and north–south extents of the known, linked crime sites.
- 2) Coordinates for the geographic centre of the crime distribution is iteratively calculated in sequential order. Each spatial mean represents the predicted location of the haven for the number of crimes observed in the given sequence:

$$\bar{X} = \sum_{i=1}^n \frac{x_i}{n} \quad \text{and} \quad \bar{Y} = \sum_{i=1}^n \frac{y_i}{n} \quad (2)$$

where n is the number of incidents for the i th crime, and the spatial mean ($\bar{X}$, $\bar{Y}$) is calculated for all x_i and y_i values in the sequence.

- 3) A circular search area of varying size, centred on the predicted haven, is calculated using the radius, R , defined by:

$$R = \frac{\sqrt{\frac{rx \cdot ry}{n-1}}}{\pi} \quad (3)$$

where rx is the range along the x-axis and ry is the range along the y-axis; and n is the number of incidents in the sequence.

After the second offence, a map is created to illustrate an area in which a serial offender's residence is likely located. This search area is centred over the calculated geographic centre of the offender's likely activity space. As each new crime scene is added to the routine, the geographic centre is recalculated, and the search area is adjusted (i.e. repositioned and resized). Accordingly, each crime series will have multiple search areas that are successively refined as each crime scene is processed. The final search area is typically referred to as the *top profile*.

Geoforensic profiles based on the standard deviational ellipse can be generated in a similar fashion. An elliptical search area of varying size centred over a distribution's geographic centre is sequentially determined according to the variance calculated along major and minor axes. The ellipse's major and minor axes are determined by measuring the distribution's SDs along the x- and y-axis such that they are orthogonal to each other (Ebdon, 1988; Levine, 2007; Yuill, 1971).

The standard deviational ellipse model for Newton's geoforensic analysis is generated in four steps (Ebdon, 1988; Levine, 2007):

- 1) Transpose the coordinate system by moving the origin of the ellipse to the geographic centre of the distribution:

$$\acute{x} = (x - \bar{x}) \quad \text{and} \quad \acute{y} = (y - \bar{y}) \quad (4)$$

where the mean, $\bar{x}$ and $\bar{y}$, is subtracted from each of the original x and y coordinates to give the transposed coordinates denoted by $\acute{x}$ and $\acute{y}$.

- 2) Determine the angle of rotation along the x - and y -axis so that the sum of squared differences are minimised:

$$\theta = \text{ARCTAN} \left\{ \frac{\left(\sum \acute{x}^2 - \sum \acute{y}^2 \right) + \sqrt{\left(\sum \acute{x}^2 - \sum \acute{y}^2 \right)^2 + 4 \left(\sum \acute{x} \acute{y} \right)^2}}{2 \left(\sum \acute{x} \acute{y} \right)} \right\} \quad (5)$$

Where θ is the angle of rotation observed in the distribution, and $\acute{x}$ and $\acute{y}$ are the transposed x and y coordinates.

- 3) Calculate the SDs along the transposed axes (Ebdon, 1988; Levine, 2007):

$$S_x = \sqrt{2 \cdot \frac{\text{Cos}^2 \theta \sum \acute{x}^2 - 2 \left(\text{Sin} \theta \text{Cos} \theta \sum \acute{x} \acute{y} \right) + \text{Sin}^2 \theta \sum \acute{y}^2}{n - 2}} \quad (6)$$

$$S_y = \sqrt{2 \cdot \frac{\text{Sin}^2 \theta \sum \acute{x}^2 + 2 \left(\text{Sin} \theta \text{Cos} \theta \sum \acute{x} \acute{y} \right) + \text{Cos}^2 \theta \sum \acute{y}^2}{n - 2}} \quad (7)$$

where S_x and S_y are the standard deviations parallel to the x - and y -axis of the ellipse, θ is the angle of rotation, $\acute{x}$ and $\acute{y}$ are the transposed x and y coordinates, and n is the number of points in the given sequence.

Levine (2007) notes that the SDs on both axes should be estimated using two (2) degrees of freedom in order to produce an unbiased estimator of the two parameters ($\bar{x}$ and $\bar{y}$). Additionally, Levine (2007) proposes that the variance should be multiplied by 2 in order to compensate for the underestimations in x and y (see equations 6 and 7). These notes are more fully explained in the CrimeStat® III documentation (Levine, 2007).

- 4) Finally, the elliptical search area is reduced in accordance with Newton's hypothesis:

$$\acute{S}_x = \frac{S_x}{n - 1} \quad \text{and} \quad \acute{S}_y = \frac{S_y}{n - 1} \quad (8)$$

Where $\acute{S}_x$ and $\acute{S}_y$ represent the final standard deviations on the major and minor axes, respectively, and where n is the number of incidents in the sequence. Finally, the area of an ellipse is measured as $\acute{S}_x \acute{S}_y \pi$.

Similar to the output generated using circular models, elliptical profiles will contain multiple $(n - 2)$ search areas defining the space in which the serial offender's residence is predicted.

Both the circular and elliptical models were separately developed as Python geoprocessing scripts used in ESRI™ ArcGIS® 9.2 environment, and imported as custom tools within

the ArcGIS® Desktop toolbox. The dialog box for the circle-based Geoforensic algorithm prompts the user for three values: (1) input feature class (points), (2) output search area (polygon), and (3) optional output for the profile's geographic centres (points). The elliptical Geoforensic algorithm provides a dialog box that prompts the user for the following three fields: (1) input feature class (points), (2) output search area (polygon), and (3) drop-down menu for selecting the optional SDs.

Evaluation procedure

The comparative evaluation of the circular and elliptical profiles was executed in three stages. First, crime scenes and offender residences were organised according to offender model (i.e. commuter and marauder) and mapped using ESRI's ArcGIS® geographic information systems (GIS) software. All measurements were calculated in metres according to the Universal Transverse Mercator (UTM) coordinate system, Zone 18 North, 1983 North American Datum (NAD83). Next, Newton's Geoforensic Analysis Tool was applied to each crime series in order to generate profiles using circular and elliptical models. Finally, profile effectiveness was calculated according to the measured differences between the profile output and the offender's actual residence. Because these differences were not normally distributed, results were tested for significance using the Wilcoxon signed-rank Z-test; a non-parametric alternative to the Student's paired *t*-test.

The relationship between the orientations of the elliptical profile and the corresponding landscape was calculated using the *Linear Directional Mean* tool found in the ArcGIS® software package. The tool calculated the mean direction of all road features that were coincident with the area defined by the spatial extents of a crime series. The directional angle was measured clockwise from 0° north. Angles greater than 180° were normalised by subtracting 180 from the observed value, resulting in a simple orientation. Finally, the correlation between the orientation of elliptical profiles and orientation of the corresponding road network was calculated using Pearson's product-moment correlation routine.

RESULTS AND DISCUSSION

Geoforensic analysis results

Summarised profiled results for each of the test criteria are presented in Table 3. There is an important distinction to be made between geoforensic analysis and other circle-based techniques in that the generated profiles are iteratively refined over the sequence of analysed crime scenes. That is, the size and location of the search area varies according to the spatial extent and number of the crimes analysed. As such, Newton's method generates three distinct output characteristics (Leitner, *et al.*, 2007; Newton, 1988): first, the predicted residence will move closer to the actual residence; second, the search area will vary (e.g. shrink) with the inclusion of each additional crime scene; and finally, the actual residence will fall within the predicted search area (i.e. profile accuracy).

The results obtained for this research closely matched those detailed by Leitner *et al.* (2007). That is, the assumed movements and varying size of the profiled search area were observed for both circular and elliptical models. And consistent with their previous findings (Leitner *et al.*, 2007), the third assumption regarding profile accuracy was marginally successful for circular search areas. However, profile accuracy increased substantially for

Table 3. Geoforensic profiling summary results

Profile model	Commuter profile accuracy	Marauder profile accuracy	Mean commuter profile error distance	Mean marauder profile error distance	Mean commuter search area score	Mean marauder search area score
Circle	0 (0.00%)	3 (3.09%)	7.773 km (SD = 9.401)	2.854 km (SD = 3.180)	0.055	0.222
Ellipse 1 SD	1 (1.03%)	2 (2.06%)	7.341 km (SD = 9.544)	2.399 km (SD = 2.717)	0.131	0.229
Ellipse 2 SD	7 (7.23%)	16 (16.49%)	6.229 km (SD = 8.792)	1.522 km (SD = 2.322)	0.278	0.522
Ellipse 3 SD	10 (10.31%)	27 (23.84%)	5.354 km (SD = 8.011)	1.075 km (SD = 1.929)	0.397	0.681

elliptical models. In fact, elliptical models exhibited a quantifiable improvement over circular outputs for each of the three evaluation criteria: *profile accuracy*, *error distance*, and *search area score* (Table 3).

Profile accuracy

A profile was considered accurate when the location of the offender's actual residence was topologically coincident with a profile's predicted search area.

As detailed in Table 3, circular geoforensic profiles were accurate for 3 of 97 (3.09%) crime series. Not surprisingly, these three successes were captured for marauding offenders, whose patterns of criminal activity occur within a distinct area surrounding a fixed base of operation (Canter & Larkin, 1993). Elliptical models at 1 SD performed equally well, accurately predicting one Commuter and two Marauders. As the number of standard deviations increased, so too did the performance. Overall, elliptical profiles were more accurate than circles when constructed with 2 SD and 3 SD, accurately profiling 23 (23.7%) and 37 (38.1%) residences, respectively.

The performance observed for elliptical models is noteworthy. In their study of serial crimes occurring in London, UK, Leitner *et al.* (2007) were able to predict 19.3% ($n = 57$) of serial offender residences in any of the multiple search areas derived by Newton's method. Of those predictions, only one model (1.75%) predicted the offender's residence in the final search area. With a maximum of 37 residences accurately predicted, the elliptical model shows a clear improvement in the technique's ability to predict an offender's haven. What is more, approximately one-third of the successful elliptical profiles were commuter offenders. A likely explanation for this observation is that both the elongation and orientation of the elliptical models more accurately match the shape and direction of the commuter's crime scene patterns.

Profile error distance

Profile error distances were measured according to the Euclidean distance from the offender's residence to the nearest edge of a profile's final predicted search area (i.e. top profile). Shorter distances indicate better results.

The combined measures for commuter and marauder offender models revealed that error distances were generally shorter for elliptical profiles than for the circular profiles (Table 3). And as expected, marauding offenders demonstrated shortest profile error distances across all profiles. Ellipses constructed using 1 SD exhibited modest improvement over circular profiles. However, the shorter error distances were more significant for profiles constructed using 2 and 3 SD (Table 4). This is primarily attributed to the fact that the

Table 4. Profile error distance—Wilcoxon signed-ranks test statistics

	Circle and ellipse (1 SD)	Circle and ellipse (2 SD)	Circle and ellipse (3 SD)
Combined results: Z	-3.950	-7.559	-8.124
Asymp. Sig. (two-tailed)	0.000	0.000	0.000
Commuter results: Z	-3.414	-5.841	-5.841
Asymp. sig. (2-tailed)	0.001	0.000	0.000
Marauder results: Z	-2.287	-4.859	-5.645
Asymp. sig. (2-tailed)	0.022	0.000	0.000

Table 5. Profile search area score—Wilcoxon signed-ranks test statistics

	Circle and ellipse (1 SD)	Circle and ellipse (2 SD)	Circle and ellipse (3 SD)
Combined results: <i>Z</i>	-1.813	-7.442	-8.117
Asymp. sig. (two-tailed)	0.07	0.000	0.000
Commuter results: <i>Z</i>	-2.69	-5.488	-5.712
Asymp. Sig. (two-tailed)	0.007	0.000	0.000
Marauder results: <i>Z</i>	-0.230	-5.342	-5.874
Asymp. sig. (two-tailed)	0.822	0.000	0.000

increased number of SDs made the ellipses larger than the default (1 SD) elliptical model.

Profile search area score

The profile search area score indicates how much of the required search area was predicted by the model. The score was measured as the ratio of the predicted search area (i.e. modelled output) to the required search area (i.e. theoretical search area needed to encompass the offender's residence). To calculate the required search area, the top profile output was scaled until its outer edge intersected the offender's residence. The resulting ratio provided a relative measure of search cost where higher scores values indicate more accurate profile output.

Elliptical models once again outperformed the circle model (see Table 3). However, the difference between the circular and elliptical profile generated at 1 SD was not found to be significantly different according to the Wilcoxon signed rank test [$Z = -1.813$, $p < 0.07$ (two-tailed)] (Table 5). The reason becomes clear when examined according to offender model: At 1 SD, circular and elliptical marauding profiles results are nearly identical [$Z = -0.230$, $p = 0.822$ (two-tailed)]. Conversely, elliptical profiles constructed using 2 SD and 3 SD were significantly different from circles [2SD: $Z = -7.442$, $p < 0.00$ (two-tailed); 3SD: $Z = -8.117$, $p < 0.000$ (two-tailed)]. The success of elliptical models can be attributed to the large search areas defined by the 2 and 3 SD. Whilst these search areas are considerably larger than the circular and 1-SD ellipse, they are successful at locating offender residences for both commuter and marauder offender types.

Directional correlation

According to the criminal *range hypothesis* (Canter & Larkin, 1993), the spatial pattern observed for a marauding serial offender can be expressed as a linear relationship between the maximum distances between crimes, and the distance between the offender's residence and the furthest crime. The researcher's posit that this relationship, represented by the regression coefficient, serves as a comprehensive indicator of the location of the offender's residence within a distribution (Canter & Larkin, 1993). Accordingly, a coefficient value of 0.5 indicates that the residence is located within the centre of the distribution; alternatively, a value greater than 0.5 and less than 1.0 indicates eccentricity within the distribution.

The scatter plot in Figure 2 depicts this relationship for the marauding crime series used in this study. Accordingly, the regression coefficient was calculated as 0.745, which is

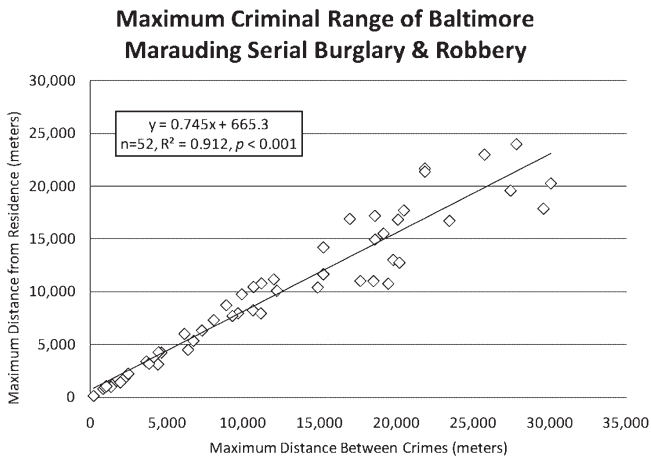


Figure 2. Maximum criminal range: the relationship between the maximum distance between offences and the maximum distance between crimes and the marauding offender's residence.

supported by a strong coefficient of determination (R^2) of 0.912 [$F(1,50) = 520.4, p = 0.000$]. As the coefficient value reveals, there is reason to conclude that, on average, a marauding offender's residence is unlikely to be located near the centre of a distribution (Canter & Larkin, 1993; Kocsis *et al.*, 2002).

Of course, an eccentric finding is not unexpected as it demonstrates that a marauding offender commits crimes within an anisotropic activity space where opportunity to offend is not equally distributed. This effect can be measured by comparing the angle of rotation of each ellipse to the angle of rotation of the directional mean of the underlying road features that are coincident with the spatial extents of the crime scenes. The findings reveal a moderate but significant correlation ($r = 0.511, p < 0.001$) between the two angles, which differed on average by 31.77° (min = 0.00; max = 125.25° ; SD = 29.07). When examined according to offender model, the relationship between ellipse and road network exhibited a slightly weaker correlation ($r = 0.489, p < 0.001$) for the commuter offender type. Conversely, the marauder offender exhibited a slightly stronger relationship ($r = 0.525, p < 0.000$). Whilst not very large, these moderate correlations support the premise that the general orientation of the crime scenes is partially related to the orientation of the underlying landscape. In other words, the existing transportation network governs the offender's journey-to-crime behaviour.

CONCLUSION

The primary objective for this research was to parameterise the effects of an irregular landscape in the application of geographic profiling. Newton's geoforensic analysis demonstrated how a simple and intuitive geographic profiling technique could be utilised for the investigation of a serial crime. The application systematically analysed a distribution of crime scenes in order to predict the geographic centre and estimate the areal extents of a serial offender's activity space. However, the circular search areas defined by this profiling technique, as with other circle-based methodologies, assume an isotropic surface

whereby any location within the profile's extents has an equal opportunity at being the offender's residence. Yet, research demonstrates that serial crime events are distributed as phenomena which are influenced, in part, by the physical and cultural landscape (Brantingham & Brantingham, 1981; Rossmo, 2000; Rengert, Piquero, & Jones, 1999; Kocsis *et al.*, 2002; Harries, 2006; Capone & Nichols, 1976; LeBeau, 1987; Canter *et al.*, 2000). In effect, the spatial patterns observed in the distribution are actually a reflection of the irregularities consistent within the underlying landscape. As such, they exhibit spatial characteristics that can be geographically analysed according to their location, dispersion, and orientation.

In order to address this premise, this study proposed that geographic profiling models capable of parameterising the effect of the landscape will more accurately predict the location of a serial offender's residence. Circular and elliptical models were used to generate profiles for 97 serial offences that occurred in Baltimore, MD, during the late 1990s. Each profile was assessed according to profile accuracy, error distance, and search cost in order to identify which model more effectively predicted the serial offender's residence. To further demonstrate the validity of this approach, this study proposed that the orientation of the underlying road network would correlate to the elliptical profile's angle of rotation, thus revealing the mechanics behind the anisotropic distribution of incidents. The strength of this relationship was determined by comparing the angle of rotation of each elliptical profile to the linear directional mean of the road features coincidentally located within each of the crime's study area.

Before the analysis could proceed, four assumptions regarding offender characteristics needed to be satisfied. The first two assumptions were validated by filtering the dataset for those offenders that had his/her residence located within the study area, and that all criminal activity initiated and concluded from this fixed location. These two assumptions were used to classify offenders as either a commuter or marauder, the third assumption. Next, the non-parametric Mann-Whitney *U* test was used to confirm the assumption that each serial event could be analysed comprehensively and according to offence style (i.e. commuter or marauder), regardless of type (i.e. burglary or robbery). The final assumption established that both crime sites and the offender's journey to the crime are governed by the existing transportation network, which was confirmed by examining the orientations of crime events along the Baltimore, MD, road network.

As the findings revealed, geoforensic analysis models based on the standard deviational ellipse will generally perform better than circular models. It does so because the standard deviational ellipse is summarising the minimum and maximum variance within the distribution (i.e. variance measured along a rotated x- and y-axes). What is more, because the model is based on the standard deviations measured along the distribution's x- and y-axes, it is possible to modify the size of the ellipse according to the empirical rule of statistics. In effect, this functionality allows the standard deviational ellipse to perform like a two-dimensional confidence interval; as the interval increases, so too does the size of the ellipse and the likelihood of capturing the offender's residence (see Table 3).

In addition to demonstrating the efficacy of elliptical profile models, this study also confirmed the second hypothesis that the orientation of elliptical profiles should correlate with the orientation of the underlying landscape. As the findings revealed, a moderate but significant correlation was observed when comparing the ellipse's angle or rotation with the directional mean of the underlying road network. Whilst a few extreme values were measured, the results further validate the premise that the landscape impacts the location of crime scenes. Further research should be applied to identify the extent to which the

road network, and other factors, demonstrates a deterministic effect on the direction and dispersion of crime scenes.

The standard deviational ellipse model works because crime does not occur randomly in space. Rather, the fundamental tenants of environmental criminology propose that crime represents a remarkably complex framework of social, economic and environmental factors that are characterised by physical and social conditions. In this context, place not only represents that discrete location in which a crime occurs; it has a deterministic impact on the other dimensions of crime (i.e. offender, target, and law) (Brantingham & Brantingham, 1981). That is, place serves as the independent variable in which offender, target, and law are dependent. By parameterising the effects of an anisotropic landscape, the theoretical constructs of environmental criminology are applied more meaningfully to the profiling process. In this way, Canter and Larkin's observation of eccentrically located offender residences represent both psychological and environmental factors (Canter & Larkin, 1993).

However, the techniques presented here are not beyond reproach. An initial challenge for this study was to generate profiles from a sample that consisted disproportionately of more robberies (67) than burglaries (30). In order to eliminate the possibility of differing spatial characteristics, it was necessary to determine if the observed distributions for the two crime types could be analysed comprehensively, as if they originated from the same population. Whilst tests suggested that this was appropriate for the sample, future research would benefit from a larger sample with even number of crime types and offender characteristics. Furthermore, this assessment was limited to one major metropolitan area. Future evaluations should assess these hypotheses in different geographic locations, especially those that consist of urban, rural, and/or a combination of both land use characteristics.

Additional criticisms can be applied to the modelling techniques employed. First, research by Snook *et al.* (2005), Paulsen (2006), and Levine (2007) demonstrate that the centre of minimum distance (CMD) is often a better measure of a distribution's central tendency. CMD calculates the location where the travel distance to each event is the smallest. Further research should examine geoforensic analysis models that calculate the CMD and similar measures, such as median centre. Furthermore, future studies should consider comparing the performance of standard deviational ellipses against circles of similar areas. In doing so, one can more accurately judge the effectiveness of the elliptical model. Finally, larger ellipses result in prohibitive search costs. And whilst these search areas may not be as large as those derived from the circle hypothesis (Canter & Larkin, 1993), such search areas remain quite daunting for those investigations operating with limited budgets and man power.

An unexpected finding from this study suggests that Newton's geoforensic analysis technique may offer a new strategy for apprehending an active serial offender. As one of the assumptions set forth by Newton, the central location of the profile's search areas was successively refined as each new crime was added to the model. Because of its operational nature, the standard deviational ellipse was able to reveal the positional and dispersal trends of the crime events as they were sequentially modelled. For example, if an offender's spatial behaviour caused the number of crimes to cluster in a fixed geographic space, then the elliptical output consistently revealed a stable geographic location characterised by generally symmetrical major and minor axes (i.e. more spherical than elliptical). Conversely, if the offender's spatial preferences caused the crimes to move outward in specific directions, the resulting elliptical profiles began to mimic the outward movement,

characterised by a generally unequal major and minor axes (i.e. more elliptical than spherical). As indicated in Table 2, the size of the Commuter's offence area is notably smaller than the area defined by marauders. Whilst seemingly counter intuitive, this is likely the result of elongated convex hulls defined by offences that occur along the transportation network. And like the results noted by LeBeau (1987) and later by Kocsis *et al.* (2002), commuter-style offenders generally exhibit narrow dispersion patterns with orientations that correlate with the transportation corridors. With further research, this roving profile effect may be exploited for use in predicting future serial crime events.

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