Spatiotemporal Crime Analysis in U.S. Law Enforcement Agencies: Current Practices and Unmet Needs

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ABSTRACT: This article compares the current states of science and practice regarding spatiotemporal (space+time) crime analysis within intermediate- to large-size law enforcement agencies in the Northeastern United States. The contributions of the presented research are two-fold. First, a comprehensive literature review was completed spanning the domains of Criminology/Crime Analysis and GIScience/Cartography to establish the current state of *science* on spatiotemporal crime analysis. This background review then was complemented with a set of interviews with personnel from seven intermediate- to large-size law enforcement agencies in the United States in order to establish the current state of *practice* of spatiotemporal crime analysis. The comparison of science and practice revealed a variety of insights into the current practice of spatiotemporal crime analysis as well as identified four broad, currently unmet needs: (1) improve access to externally maintained government datasets and allow for flexible and dynamic combination of these datasets; (2) place an emphasis on user interface design in order to improve the usability of crime mapping and analysis tools, (3) integrate geographic and temporal representations and analyses methods to better unlock insight into spatiotemporal criminal activity, and (4) improve support for strategic crime analysis and, ultimately, public safety policymaking and administration. The results of the interview study ultimately were used to inform the design and development of a spatiotemporal crime mapping application called *GeoVISTA CrimeViz*.

KEYWORDS: crime information, law enforcement, public safety, crime analysis, crime mapping, geographic information systems (GIS), cartography, interactive mapping, spatiotemporal analysis, needs assessment

1. Introduction: The analysis of information on criminal activity

Crime analysis describes the systematic collection, preparation, interpretation, and dissemination of information about criminal activity to support the mission of law enforcement (Boba, 2005). The goal of crime analysis is the unlocking of valuable insights from the collected crime information in order to assist law enforcement with criminal apprehension and crime prevention, to the end of improving the overall quality of life for community residents (O'Shea & Nicholls, 2003). Ideally, crime analysis draws upon both quantitative and qualitative approaches in order to understand criminal activity fully, integrating descriptive and inferential statistical analyses of crime incidents with text reports, information graphics, and prior experience to determine the appropriate response tactics, strategies, and broader policies (Gottlieb et al., 1994; Osborne & Wernicke, 2003). Influenced by the Digital Revolution and associated Information Age, research and development within crime analysis during the past two decades has emphasized the design of computer software that supports the assembly and interpretation of digitally-native crime information (Wilson, 2007). The research reported here focuses upon a critical subset of computing technologies designed to analyze the spatial and temporal (together *spatiotemporal*) components of crime information.

The field of *Geographic Information Science* (GIScience) and its technological counterpart *Geographic Information Systems* (GIS) describe the gamut of tools and techniques available to analyze geographically-referenced information (Goodchild, 1992). GIScience subsumes a variety of topics relevant to spatiotemporal crime analysis, which include geographic information collection (geocoding, GPS technology, remote sensing, and surveying), geographic information maintenance (geographic database management and multi-resolution databases), geographic information analysis (geocomputation, geographic data modeling, spatial analysis, and spatial statistics), geographic information representation

(cartography and geographic visualization) and the use of geographic information and information products (geocollaboration, geovisual analytics, public participatory GIS, and spatial decision support systems) (for a general overview of these topics, see Longley et al., 2005). The term *crime mapping* is used today to describe the application of all GIScience tools and techniques for crime analysis (Getis et al., 2000), although its original use focused on applications of Cartography only (i.e., the representation of geospatial crime information in map form).

There is a substantial volume of work within GIScience examining the treatment of spatial and temporal components of information in conjunction (e.g., Hägerstrand, 1970; Sinton, 1978; Langran, 1992; Peuquet, 1994; Andrienko et al., 2003). Despite this research, there is little implementation of temporal analytical functionality in popular GIS software. Perhaps as a direct result, the analysis of the temporal component of crime has been identified as an under-supported function of crime analysis, with Ratcliffe (2009: 12) stating in an overview of current challenges to crime analysis that "At present, the most under-researched area of spatial criminology is that of spatio-temporal crime patterns." Existing reports on crime analysis indicate that spatiotemporal analysis and visualization often is limited in practice to the generation of one-off, static maps showing crime over a small period of time, usually the past 7-to-30 days (Lodha & Verma, 1999). Thus, the possible use cases for advanced spatiotemporal crime analysis remain undetermined and therefore the positive impacts of spatiotemporal crime analysis remain unrealized.

Here, we describe research to address directly this challenge of spatiotemporal crime analysis. The aim of our research was the identification of gaps between the spatiotemporal crime analysis techniques reported in the literature and the actual use of these techniques by law enforcement to combat crime. The primary contributions of the research are two-fold. We first completed a comprehensive background review to understand the current state of *science* in spatiotemporal crime analysis, disambiguating and synthesizing relevant research from the knowledge domains of Criminology/Crime Analysis and

GIScience/Cartography. We then conducted a set of interviews with experts from seven intermediate- to large-size law enforcement agencies in the United States (daytime service populations of 125,000 to many millions) in order to compare the current state of *practice* in spatiotemporal crime analysis to the previously reviewed state of science. Such a critical comparison of science and practice is relevant to detectives, officers, and decision makers working in law enforcement as well as municipal, state, and federal administrators and policymakers working broadly in public safety. The interview study also served as the needs assessment stage for the design of a spatiotemporal crime mapping application called *GeoVISTA CrimeViz* (http://www.geovista.psu.edu/CrimeViz) developed in collaboration between the Penn State GeoVISTA Center and the Harrisburg (PA, USA) Bureau of Police (for details on the application, see Roth & Ross, 2009; Roth et al., 2010; Roth, 2011). Therefore, we were interested in identifying the key crime analysis needs of law enforcement agencies that the *GeoVISTA CrimeViz* application must support, with a particular emphasis on those needs not currently supported by readily available spatiotemporal crime analysis software.

The article proceeds in four sections. In the following section, we synthesize background material from the domains of Criminology/Crime Analysis and GIScience/Cartography to establish the current state of science on spatiotemporal crime analysis. In the third section, our interview protocol and qualitative data analysis approach is described. We present the results and discuss the key findings of the interviews in the fourth section, providing an overview of the current state of practice to contrast with the background review. The fourth section is organized according to six key crime analysis needs identified from the background review: (1) geographic information, (2) cartographic representation, (3) cartographic interaction, (4) spatial analysis, (5) temporal analysis, and (6) map and analysis use. The fifth and final section contains our concluding remarks and lists several broad spatiotemporal crime analysis needs that currently are not fully support.

2. Background review: Current state of science on crime analysis

A comprehensive review of existing literature was completed prior to the interview study in order to characterize the current state of science on crime analysis. The following review is organized into three sections: (1) a summary of the origins and purpose of crime analysis from the discipline of Criminology, with an emphasis on the types of crime analysis; (2) a summary of the different kinds of geographic information that may be collected to support crime analysis and the ways to represent this information cartographically (i.e., in map form); and (3) advanced statistical and computation techniques to analyze the spatial and temporal components of these information.

2.1 Origins and purpose of crime analysis

Crime analysis has its roots in 19th century London, where the first modern police department was established (Boba, 2005). August Vollmer, Police Chief of Berkeley (CA, USA) and founding professor of the UC-Berkeley School of Criminology, often is credited with the first application of crime analysis in the United States in the early 20th century, with other important early U.S. work conducted by the 'Chicago School' of sociologists (e.g., Sutherland, 1934; Shaw & McKay, 1942). Vollmer's student, O.W. Wilson, first defined the term 'crime analysis' in his recommendation of information analysis techniques to police departments in the 1950s and 1960s (Wilson & McLaren, 1977). The crime analysis capabilities of law enforcement agencies expanded through the 1970s and 1980s (Emig et al., 1980), due in part to federal grants provided through the National Institute of Justice, a program of the United States Department of Justice. There also was increased interest at this time in crime analysis in academia; a review of this research is provided in Harries (1999).

Crime analysis therefore is informed by the discipline of *Criminology*, or the scientific study of the causes and control of crime and delinquent behavior, with the goal of understanding criminal activity, rehabilitating convicted criminals, and improving the quality of life within a community (Sutherland et al., 1992). There are two popular criminological theories that emphasize the importance of spatiotemporal pattern and process (Cahill & Mulligan, 2007). Under *routine activity theory*, an individual criminal

incident requires three conditions to occur concurrently in place: (1) presence of a motivated offender, (2) presence of a suitable target, and (3) absence of a proper guardian, law enforcement or otherwise (Cohen & Felson, 1979). The spatiotemporal dynamics of these three components can be analyzed both to identify locations of elevated crime risk and to prescribe the appropriate policing tactics to attenuate this crime risk (Bruce, 2008). In contrast, *social-disorganization theory* evaluates the ability of a community, or homogenous geographic unit, to combat negative community-level changes and enforce positive ones (Shaw & McKay, 1942). By analyzing the spatial and temporal differences in demographic and environment characteristics between stable and disrupted neighborhoods, long-term policing strategies can be developed and absent public policies can be established to prevent criminal activity in blighted communities (Sampson & Groves, 1989). Together, these two theories reveal the importance of spatial and temporal context during crime analysis (Wilcox et al., 2003).

Boba (2005) describes five types of crime analyses, or the general applications of criminological theory and crime analysis techniques in support of the functions of law enforcement:

(1) *Criminal investigative analysis* describes the process of collecting and analyzing information about a criminal offender. Criminal investigative analysis often involves the construction of offender profiles from known information, which then allows for the inference of offender characteristics (e.g., personality type, social habits, and work habits) based on those profiles (Jackson & Bekerian, 1997); journey-to-crime analysis, described below, is a spatial analysis technique that can be applied to build the geographic component of an offender profile.

(2) *Intelligence analysis* expands investigation of a single individual and single crime series to a larger crime syndicate, focusing upon identification of relationships among offenders, called *link analysis*. Intelligence analysis often is applied in the context of organized crime. By establishing the offender network, law enforcement can identify and target key players in the jurisdiction and diffuse crime from the top down (Innes et al., 2005). White and Roth (2010)

describe the potential of harvesting the geographic information from microblogging and social networking services to build a spatially-anchored offender network for informing and structuring intelligence analysis, although noting potential ethical concerns of harvesting volunteered geographic information.

(3) *Tactical crime analysis* is the reactive investigation of recent crime spikes within a single jurisdiction or across multiple jurisdictions (Bruce, 2008). Tactical crime analysis examines key aspects of recent criminal activity (e.g., crime type, location, time, MO, suspect description) to identify overarching patterns that may explain the recent spike. Such analysis directly informs apprehension, suppression, and target hardening blue force tactics (Bruce & Ouellette, 2008). The application of tactical crime analysis is central to the *CompStat process*, where police captains are required to present statistical analyses and cartographic representations of recent crime in their jurisdiction during regularly scheduled meetings as a way to improve leadership accountability for recent crime spikes (Walsh, 2001); CompStat has the potential for application as a strong strategic tool as well (Weisburd et al., 2002).

(4) *Strategic crime analysis* is the analysis of crime and other police-related issues to identify long-term plans for reducing crime rates and improving the quality of life for a community. Strategic crime analysis embodies the concept of *problem-oriented policing* (Goldstein, 1979), which proactively seeks to understand the underlying causes of persistent criminal activity and to develop intervention strategies to attenuate this activity. There also is an important evaluation component of strategic crime analysis that determines how well previously applied intervention strategies worked to combat crime (Boba, 2001), the results of which may inform broader public policies. Such evaluation is the final step of the strategic crime analysis model recommended by Eck and Spelman (1987) called *SARA*: *S*canning, *A*nalysis, *R*esponses, and *A*ssessment.

(5) *Administrative crime analysis* presents interesting findings of crime research and analysis to audiences within police administration, city government officials, and citizens. Administrative crime analysis directly links the detectives, officers, and decision makers responding to criminal activity and the municipal, state, and federal administrators and policymakers responsible for broader issues in public safety. Such administrative activity includes the allocation of resources within the department, such as assigning cases to detectives, and any other internal collaboration (Zhao et al., 2006). This also includes the preparation of crime reports and graphics for use in court proceedings (Harries, 1999). Finally, administrative crime analysis includes the presentation of criminal activity for public consumption, through town hall meetings or websites, to the end of promoting dialogue about public policy (Rose, 2008).

2.2 Geographic information and cartographic representation in crime analysis

As introduced above, *crime mapping* describes the analysis of the geographic component of criminal activity, both at an individual level of analysis (e.g., investigative analysis of a single crime series) and ecological level of analysis (e.g., comparative analysis across neighborhoods to identify communities with unusually high concentrations of crime) (Eck et al., 2005). Law enforcement agencies are required to collect and maintain several different information sets to document criminal activity and to support crime analysis. Harries (1999) identifies three geographically-referenced information sets commonly maintained internally by municipal law enforcement agencies: (1) crime reports, (2) calls for service, and (3) vehicle recoveries. The *crime report* is the primary information set used by law enforcement agencies and includes both numerical and categorical information for indexing and searching of the record as well as a lengthy, textual narrative of the event compiled by the reporting officer. Many records management systems distinguish between *crime incidents*—which focus on attributes of the crime event such as location, time of day, and characteristics of the victim—and *arrests*—which focus on characteristics of the apprehended offender (Mamalian & La Vigne, 1999). Crime reports are organized according to

uniform crime reporting (UCR) codes for comparison across municipalities and states. Although there is some variation in the exact coding scheme used across municipalities and states, the UCR code commonly includes a two digit *UCR primary* code indicating crime type and a two digit *UCR secondary* code indicating a discriminating condition within the primary crime type. Many municipalities also use the UCR system for indexing the *modus operandi* (MO), or method of committing the crime.

The *calls for service* information set indexes all requests for law enforcement services, typically submitted by phone, and is an order of magnitude larger than the crime incident information set, as most police dispatch does not lead directly to a reported incident or an arrest. Maps of calls for service are interpreted by crime analysts as the general 'demand' for police services within the municipality (Spelman, 1995). The *vehicle recoveries* information set, maintained primarily in larger municipalities, indexes the locations from which vehicles were reported as stolen and subsequently recovered (Chainey et al., 2008). A fourth information set maintained internally by some law enforcement agencies is the *field interview*, or information collected by officers from potential witnesses and offenders while on patrol (Osborne & Wernicke, 2003). Finally, Harries (1999) notes that agencies often utilize external information sources, which may include federal information like Census Bureau information, national crime information like the probation and missing persons lists as well as the sex offender registry, and volunteered information from microblogging and social networking services.

As the name implies, a principle task within crime mapping is the production of *cartographic representations* (i.e., maps) of the aforementioned kinds of geographic information collected on criminal activity. Literature on crime mapping uses alternative terminology from that common in GIScience (specifically within Cartography) to describe the reference and thematic maps produced in support of crime analysis; translations between lexicons are provided below. Boba (2005) describes six types of crime maps generated to support the mission of law enforcement:

(1) *Single-symbol maps* use point symbols to represent the locations of features. In crime mapping, these are commonly referred to as *push pin maps*, drawing on the analog wall map solution used prior to the move to electronic information and GIS (for more on the etiology and evolution of push pin maps, see Wallace, 2011). In GIScience, this kind of map is referred to as a *one-to-one dot map*; when the symbology varies by color, shape, or central icon to represent a nominal difference in kind, the map sometimes is described as containing qualitative point symbols (Roth, 2010). One-to-many dot maps (i.e., *dot density maps*), where one dot represents multiple crimes, are not common in crime mapping, perhaps because of the potential misinterpretation of the meaning of a dot and the associated underestimation of total crime.

(2) *Graduated maps* are described by Boba (2005) as the use of either color or size to represent aggregated information. In GIScience, the use of a color gradient to represent aggregated information is called a *choropleth map*, while the use of size to represent aggregated information is called a *proportional symbol map* (MacEachren & DiBiase, 1991). For all choropleth maps and some proportional symbol maps, the information typically is aggregated to a set of relevant boundaries (i.e., enumeration units), such as police districts or beats. In the case of proportional symbol maps, the information also might be aggregated according to a set of point locations (e.g., apartment complexes, arenas, bars, stores) or linear features (e.g., street blocks).

(3) *Density maps* aggregate crime incidents to an arbitrary grid either directly or using a moving window smoothing function, with the frequency of each grid cell represented by color; these maps are referred to as *hot spot maps* in practice, although there is conflicting use of this term in the crime mapping literature (Chainey et al., 2008). In GIScience, this technique typically is called *isoline mapping* or *surface mapping* (Slocum et al., 2005), although the actual

isolines (i.e., lines of equal crime frequency) are rarely depicted on crime maps, with the underlying interpolation grid instead color tinted. Hot spot maps have the advantage over choropleth or proportional symbol maps in that they are not restricted by political units that have little impact on criminal activity, but they suffer more heavily from the *denominator dilemma*, as the underlying population typically is not known for arbitrary grid cells (i.e., the hot spots only may be indicating where the people are and not where criminal activity is elevated above average) (Ratcliffe, 2009).

(4) *Chart maps* show relative values within a single variable at the same time, such as the percentage of crime types by district. Examples include pie charts and stacked histograms that are placed directly on the map (Andrienko & Andrienko, 1999). The concept of a chart map can be extended to any form of *multivariate symbolization* (i.e., the representation of two or more variables in one map), rather than relative values within a single attribute only. Examples from Cartography include ray glyphs (Buja et al., 1996), star plot glyphs (Klippel et al., 2009), and Chernoff faces (Krygier & Wood, 2005).

(5) *Buffer maps* represent a distance zone around a feature or features of interest, such as a school or bar (e.g., Grubesice et al., 2007). It is possible then to aggregate crime incidents within the buffer zone, representing the frequency using a color gradient (i.e., a buffer map/graduated map combination).

(6) *Interactive maps* leverage a digital environment to allow the map user to manipulate the mapped display according to his or her needs in real time. An interactive map is not a form of cartographic representation, as with the above map types listed by Boba (2005), but rather an additional aspect of a digital map that can be added at varying degrees to any static map (MacEachren, 1994). Thus, cartographic representation (i.e., maps) and *cartographic interaction* (i.e., user interfaces to these maps) are best considered as a fundamental duality

within Cartography and GIScience, both of which requiring consideration during map design and development (Roth, 2011, 2012). MacEachren et al. (1999) further parse cartographic interaction into six interaction operators: (1) *focusing/filtering* (increasing or decreasing the detail of a selected subset of map objects; subsequent scholars have interpreted this operator as *filtering* or reducing the number of map objects in the display according to user imposed constraints), (2) *viewpoint manipulation* (panning, zooming, or changing the user's viewing angle of the map), (3) *brushing* (selecting a portion of the map display through direct manipulation of the map in order to perform some operation to the highlighted features), (4) *sequencing* (dividing the crime information into a set of bins according to time intervals or an attribute of the information), (5) *colormap manipulation* (adjusting the map symbolization, including the map type, color scheme, classification scheme, etc.), and (6) *assignment* (associating a variable in the information set with a component of the map display).

An additional form of cartographic representation discussed by other scholars in crime analysis is the representation of time on maps. The cartographic representation of time focuses on visual depiction of entities and patterns, geographically; it can be used to monitor changing situations and to support more complex spatiotemporal analyses of crime information (which are treated in the subsequent subsection). Spatiotemporal phenomena can be represented by either static maps, which represent temporal change using one or several graphic(s), or animated maps, which represent temporal change in the phenomenon with temporal change in the map (Monmonier, 1990). Starting with the former, there are three general approaches to the representation of multiple points or intervals of time (or any other conceptually bivariate or multivariate representation) on static maps: (1) adjacent displays, (2) separable coincident displays, and (3) integral coincident displays (MacEachren et al., 1998). *Adjacent displays*, or *small multiples*, represent each moment in time or interval of time on a separate map, producing a series of maps with the same spatial extent (Bertin, 1967|1983; Tufte, 1983). A set of small multiples for crime incidents would divide the information set into a series of time intervals, with each interval receiving its

own map and no crime incident occurring on two maps. In contrast, coincident displays juxtapose two or more time states or intervals in a single graphic; the map is termed *separable coincident* when each time period can be individually analyzed visually (e.g., crime incidents from the past 7 days in one color and incidents from the past 8-30 days in a second color) and *integral coincident* when only the difference between time periods can be analyzed visually (e.g., using color to represent the change in crime rates by district following a newly implemented policing tactic). The second general method for representing temporal change—*cartographic animation*—describes the display of individual maps (called frames) in rapid succession (DiBiase et al., 1992). While several research applications of cartographic animation to crime analysis have been reported in the literature (Lodha & Verma, 1999; Brunsdon et al., 2007; Wolff & Asche, 2009), Ratcliffe (2009) notes that this has translated into little practical application due to a lack of easy-to-use cartographic animation tools and training.

2.3 Spatial and temporal analysis in crime mapping

In practice, the term crime mapping applies to the complete suite of GIScience tools and techniques when used to support crime analysis, including information assembly, spatial statistics, and geocomputation in addition to the aforementioned cartographic themes of representation and interaction (Harries, 1999). Although there is no established taxonomy of spatial analysis techniques for crime analysis, several methods are discussed regularly in the literature on crime analysis and crime mapping. A primary application of spatial statistics and geocomputation to crime analysis is for identification and interpretation of spatial clusters of crime incidents. The most straightforward calculation is *spatial autocorrelation*, which measures the departure from complete spatial randomness (CSR) observed in a distribution of incidents (Griffith, 1987); positive autocorrelation suggests a distribution in which spatially near objects are likely to be similar (i.e., clustered) and negative autocorrelation suggests a distribution in which near objects are likely to be dissimilar (i.e., a checkerboard pattern). Spatial autocorrelation indices such as Geary's C, Moran's I, and Getis's G provide a single value for the entire distribution; however, these calculations have been extended to provide *local indicators of spatial*

autocorrelation (LISA) that identify the location of clusters in the distribution, rather than simply reporting that a distribution is clustered (Anselin, 1995).

A second spatial analysis technique for the identification of clusters is the *spatial scan statistic* (Openshaw et al., 1987; Kulldorff, 1997; Conley et al. 2005). A spatial scan statistic is a geocomputational routine that calculates a clustering metric (called the likelihood ratio) for a large number of distinct circular or elliptical sampling windows placed over a crime incident distribution; the output of these algorithms is a small subset of the sampling windows that have a significant number of incidents contained within them as compared to the area not within the window (Chen et al., 2008). Numerous scholars in criminology and crime analysis have identified the potential of scan statistics for identifying clusters of elevated criminal activity (Jefferis, 1998; LeBeau, 2000; Zeng et al., 2004; Levine, 2006; Chainey et al., 2008; Nakaya & Yano, 2010). Chen (2009) provides a useful discussion of the conceptual differences between spatial autocorrelation and spatial cluster measures, such as the spatial scan statistics.

Aside from geographic clustering methods, a method of specific interest to crime analysts is *journey-to-crime analysis*, which uses the locations of related crime incidents to determine the most likely areas of offender residence and to forecast the locations of future crimes (Brantingham & Brantingham, 1981). This technique also is referred to as geographic profiling (Rossmo & Velarde, 2008), although this term is being phased out of the literature due to the implication of police surveillance. Two additional, commonly applied spatial analyses are kernel density estimation and buffering, which primarily are applied to generate density maps and buffer maps respectively (described above).

Space and time are paramount to both tactical and strategic crime analysis, as indicated by the dominant theories on criminology described above. As with spatial analyses, temporal analyses and related information graphics primarily are employed for detection of temporal clusters in criminal activity. Modifications to the scan statistic are available to identify crime incident clusters in time alone or in space

and time together (Block, 1995; Zeng et al., 2004; Levine, 2006); for these modifications, the scan is completed with a moving time window, rather than or in addition to a moving spatial catchment area. An alternative technique is the *cumulative summation (CUSUM) algorithm*, which also applies a sliding temporal window to detect aberrations in event activity, such as a spike in crime that is considerably higher than past incident rates (Hutwagner et al., 2003; Maciejewski et al., 2010).

Aside from cluster analysis, there is a small amount of research within crime analysis on the use of temporal information graphics and statistical summaries to complete visually-based *trend analysis* (Ratcliffe, 2004; Chung et al., 2005; Townsley, 2008). There also is work on predictive algorithms that attempt to forecast when future crime incidents will occur (Bowers et al., 2004); such research may be considered the temporal equivalent of journey-to-crime analysis. A final potentially useful temporal analysis specific to crime information is *aoristic analysis*, a technique for estimating an exact time stamp for a crime that occurred when the victim is not present (e.g., a burglary) based on the time windows of past crimes of the same crime type (Ratcliffe & McCullagh, 1998).

There are many software applications marketed for crime analysis that provide spatiotemporal analysis; most of these applications also support basic cartographic representations and cartographic interactions. Available software packages include: ATAC (Automated Tactical Analysis of Crime; Bair, 2000), Azavea HunchLab/Crime Spike Detector (Cheetham, 2010), CrimeStat (Levine, 2006), ESRI ArcGIS (http://www.Esri.com/software/arcgis/), GeoDa (Anselin et al., 2006), MapInfo (http://www.mapinfo.com), ReCAP (Brown, 1998), SaTScan (Kulldorff, 2010), STAC (Block, 1995), and STV (Buetow et al., 2003).

3. Method: Needs assessment interviews

3.1 Participants

Seven law enforcement agencies in the United States participated in an interview study designed to assess the current practices and key unmet needs of spatiotemporal crime analysis. Law enforcement agencies were purposefully sampled based on two criteria: (1) the municipal law enforcement agency (six in total) had a daytime service population of 100,000 or greater (all participating law enforcement agencies ultimately had a daytime population of 125,000 or greater) and (2) the police headquarters was within a one day drive (~250 miles) of University Park, PA (the site of the research). One federal law enforcement agency was included in the study to provide a non-municipal perspective. Recruitment was completed via email, with contact information obtained through existing GeoVISTA Center contacts in law enforcement or through agency websites. The sample therefore is representative of intermediate- to large-size law enforcement agencies in the Northeastern United States. The generalizability of results may be limited beyond this context and caution must be applied in interpretation of results due to the relatively small sample of agencies at which interviews were conducted. Each responding law enforcement agency self-identified an individual most appropriate to discuss the spatiotemporal crime analysis practices across their agency. For two of the law enforcement agencies, it was necessary to interview a pair of individuals, as their responsibilities were split according to different internal units; thus, nine interview sessions were completed in total.

A background survey was administered at the start of each interview session to establish several characteristics of the interview participants. Two participants had no post-secondary education, three participants held a Bachelors degree, two participants held a Masters degree, one participant held a PhD, and one participant held a law degree (in addition to a BS in Criminal Justice); outside of the law degree, the degrees were in either Criminal Justice (5) or Geography (2). The participant sample was composed of a near even mixture of primarily producers of spatiotemporal information and associated information products (i.e., crime analysts and crime mappers) and primarily users of this spatiotemporal information and information products (i.e., administrators, detectives, officers, and decision-makers) (Table 1). The majority (7 of 9) of participants reported producing spatiotemporal information and associated

information products at least monthly, with a large minority (4 of 9) completing this activity daily. The

majority (7 of 9) reported using spatiotemporal information and associated information products at least

weekly. Two high ranking officers stated that while they use spatiotemporal information and information

products weekly, they never produce them, while two crime analysts stated that while they produce

spatiotemporal information and information products weekly, they never use them for policing or decision

making purposes. Four participants were sworn officers while the other five held civilian status.

Regularity of Activity	Produce S-T Info	Use S-T Info.
Daily	4	2
Weekly	1	5
Monthly	2	
Yearly		
Rarely	2	2
Total	**9**	**9**

Table 1: Interview Participant Regularity of Producing and Using
Spatiotemporal Information and Associated Information Products

3.2 Materials and procedure

Interviews vary on the degree of structure in their questioning (Robinson, 2009). Structured interviews

include a series of focused questions that typically prompt short and equally focused responses; all

participants are asked the exact same set of questions in the same order. On the other end of the

continuum, unstructured interviews include a set of broad discussion topics or general themes, with no

preset order; these types of questions are exploratory in nature and typically prompt longer, open-ended

responses that vary greatly from person to person. Many interview protocols follow a semi-structured

approach, which starts with a set of focused questions but allows the interviewer to ask follow-up or

probe questions as he or she sees fit and change the order of questioning if appropriate (for an example in

crime mapping, see Ratcliffe, 2000)

Introduction	
Background	
1	What is your agency, department, or organization, job title, and responsibilities at this position?
2	Are you a sworn officer or a civilian?
3	Please describe your prior education and formal training?
4	Please describe any previous employment relevant to crime mapping and analysis?
5	How frequently do you produce spatiotemporal information and associated information products (maps, analyses, etc.) in your daily work?
6	How frequently do you use spatiotemporal information and associated information products (maps, analyses, etc.) in your daily work?
Information	
7	Please list the types of spatial or temporal phenomena for which your agency collects information.
8	For each collected information set, describe its: format, number of entities/records, geographic and temporal resolution, scale of analysis and mapping.
9	Does your agency use any external information sources?
10	Is the information your agency collects text/report-based or entered into a table or database?
11	Are there any information sets not collected by your agency that would be useful in crime mapping and analysis?
Mapping and Analysis	
12	Please describe the kinds of maps produced by your agency.
13	Please list the reference or basemap information your agency uses on these maps.
14	What spatial analyses or data transformations does your agency apply to the collected raw information?
15	What temporal analyses or models does your agency apply to the collected raw information?
16	Does your agency aggregate your point incident information in space or time?
17	Does your agency filter your point incident information prior to mapping?
18	Does your agency represent the temporal component of your information directly on maps?
Use	
19	How are maps and analyses used in a tactical way at your agency?
20	How are maps and analyses used in a strategic way at your agency?
21	What is the workflow from generation of maps and analyses to usage of these information products at your agency?
22	Please describe a successful use of mapping and analysis at your agency?
23	Please describe an unsuccessful use of mapping and analysis at your agency?
Do you have any last questions or comments before we conclude the session?	

Table 2: A Summary of the Interview Questions

ID	Name	Source
Geographic Information: *Statements about the information sets used and their characteristics*		
G1	crime reports (incidents and arrests)	Harries (1999)
G2	calls for service	Harries (1999)
G3	vehicle recoveries	Harries (1999)
G4	field interviews	Osborne & Wernicki (2003)
G5	external information sources	Harries (1999)
Cartographic Representation: *Statements about the way information sets are mapped*		
R1	push pin maps (i.e., one-to-one dot or single-symbol maps)	Boba (2005)
R2	choropleth maps (i.e., graduated maps using color)	Boba (2005)
R3	proportional symbol maps (i.e., graduated maps using size)	Boba (2005)
R4	hot spot maps (i.e., density maps)	Boba (2005)
R5	multivariate symbolization (i.e., chart maps)	Boba (2005)
R6	buffer maps	Boba (2005)
R7	maps representing time	Monmonier (1990)
R8	reference or basemap symbolization	Dent (1999)
Cartographic Interaction: *Statements about the way in which maps are manipulated*		
I1	focusing/filtering	MacEachren et al. (1999)
I2	viewpoint manipulation	MacEachren et al. (1999)
I3	brushing	MacEachren et al. (1999)
I4	sequencing	MacEachren et al. (1999)
I5	colormap manipulation	MacEachren et al. (1999)
I6	assignment	MacEachren et al. (1999)
Spatial Analysis: *Statements about applied spatial statistics and geocomputation*		
S1	spatial autocorrelation measures	Griffith (1987); Anselin (1995)
S2	spatial scan statistics	Openshaw et al. (1987)
S3	journey-to-crime analysis (i.e., geographic profiling)	Brantingham & Brantingham (1981)
Temporal Analysis: *Statements about applied temporal transformations and models*		
T1	temporal and spatiotemporal cluster analysis	Zeng et al. (2004)
T2	trend analysis	Ratcliffe (2004)
T3	predictive analysis	Bowers (2004)
T4	aoristic analysis	Ratcliffe & McCullagh (1998)
Map & Analysis Use: *Statements about the use of maps and analysis to support law enforcement*		
U1	criminal investigative analysis	Boba (2005)
U2	intelligence analysis	Boba (2005)
U3	tactical crime analysis	Boba (2005)
U4	strategic crime analysis	Boba (2005)
U5	administrative analysis	Boba (2005)

Table 3: The Coding Scheme Applied for QDA of the Needs Assessment Study. The categories of needs and individual codes were derived from the background review.

At the end of the interview, participants were asked if there was anything else they would like to discuss before concluding or if they had any questions about the study. All interview sessions lasted between 60 and 75 minutes and were completed at the participant's work location in a private room. For consistency, the same project member acted as the interviewer for all nine interviews. The interviews were audio recorded for subsequent qualitative data analysis, as described in the following subsection.

The interview protocol for the needs assessment proceeded in six sections; a summary of the interview questions is included in **Table 2**. Each interview session began with an introduction to the project and an overview of the goals of the needs assessment; here, participants were informed that they did not have to respond to all questions, particularly if the question was irrelevant or sensitive. Participants then were asked two sets of brief, structured questions. Participants first responded to structured questions about their general background in law enforcement and their overall experience producing and using spatiotemporal information and associated information products in support of crime analysis (summarized in the previous subsection). After the background questioning, participants were asked a set of structured questions about characteristics of the geographic information that their agency collects and maintains, as well as any external geographic information sources that their agency leverages.

Following the structured portion of the interview, participants were asked two rounds of semi-structured questions. The first round of semi-structured questioning focused upon the current crime mapping practices from an information producer perspective, asking about the types of maps that are generated and the types of spatial and temporal analyses that are applied to the information. The second round of semi-structured questioning focused upon the current crime mapping practices from an information user perspective, asking about tactical and strategic uses of crime mapping, the general crime analysis workflow, and examples of successes and failures when using maps and analyses to support the mission of law enforcement.

3.3 Qualitative data analysis

Qualitative data analysis (QDA) describes the systematic interpretation of qualitative information, such as text reports, websites, photos, maps, and field observations (Dey, 1993; Miles & Huberman, 1994). A review of work using qualitative data analysis on electronic government information, government information products, and government information use is provided by Yildiz (2007), with a multitude of examples published more recently in *Government Information Quarterly* outside of the domains of law enforcement and public safety. In the most robust form of QDA, the documents in the set are decomposed to their smallest unit of analysis and a series of codes are applied to the units by several independent coders, with the coding then compared across coders to ensure reliability in interpretation of the document set.

Transcription of the audio recordings was completed using Transana, with the transcripts then unitized at the statement level in Microsoft Excel for margin coding (Bertrand et al., 1992). The above background review on the current state of science in spatiotemporal crime analysis was used to identify six key themes: geographic information (G), cartographic representation (R), cartographic interaction (I), spatial analysis (S), temporal analysis (T), and map and analysis use (U). These key themes are areas in which law enforcement agencies may have an unmet spatiotemporal analysis *need*, defined as a resource or feature required by the targeted end user to complete their work and thus represents a disconnect between the current states of science and practice in spatiotemporal crime analysis. Thirty-one individual codes then were identified from the above background review within these six needs; each code was marked during margin coding to distinguish needs that were met by existing software (+) from those that were not met (-) at the time of the interview. Table 3 lists the six higher level categories, each of the 31 codes across these categories, and the source of the individual code from the above background review; Table 4 lists the frequency of each code across the nine transcripts. A total of 515 codes identifying user needs were applied to the nine transcripts, an average of 57.2 codes per transcript.

Two coders with expertise in GIScience and training in crime analysis were hired to apply independently the same 31-part coding scheme used in the initial coding, with code reliability assessed using the inter-rater reliability score described by Robinson (2008). The two coders achieved inter-coder reliability scores of 93.2% and 87.6% against the initial margin coding, indicating a high degree of reliability in the interpretation and application of the coding scheme, particularly considering the large number of codes in the coding scheme. Differences in coding were reconciled for reporting through discussion among the coders and a third project member. Statements were sorted according to the assigned code and summarized using the synoptic style of reporting described by Monmonier and Gluck (1994) and Roth (2009). Crime analysis needs within the six higher level categories are summarized in the following section.

4. Results and discussion: Current state of practice

4.1 Geographic information

Codes included in the geographic information (G) category indicate statements about the geographic information sets leveraged to support crime analysis. Five codes were included under the geographic information (G) category based upon the above background review: (G1) crime reports (incidents plus arrests), (G2) calls for service, (G3) vehicle recoveries, (G4) field interviews, and (G5) any external information sources not collected or maintained by the law enforcement agency itself. The most frequently discussed geographic information sets include crime reports (average=6.6) and external information sources (average=6.3), with participants identifying external information sources as an unmet need (average=1.9) slightly more frequently than crime reports (average=1.8). Participants rarely discussed calls for service (average=1.6), vehicle recoveries (average=0.8), and field interviews (average=0.2).

Overall, participants indicated that crime reports are the primary geographically-referenced information collected and used at their law enforcement agencies. Discussion centered almost exclusively on crime

reports describing incidents, rather than arrests. The number of crime incident records collected per year by the interviewed agencies ranges from approximately 7,000 to 2.5 million, indicating a need for user interfaces to scale to increasingly large and complex information sets. All participants described a similar set of core attributes captured in their crime incident reports: crime type (by UCR code), address, date and time (often with precision to the minute, except in the cases of burglary when a time range is given), MO, suspect and victim description, and a text narrative. Surprisingly, one participant noted that his/her agency did not regularly geocode (i.e., convert the listed address to spatial coordinates) their crime incident reports for mapping and analysis, instead geocoding only a small grouping of crime incident reports if an association is suspected. One participant also noted that his/her agency also captures information on *location type*, such as "parking lot, convenience store, restaurant, street, sidewalk"; while this information is not geographic in the sense of absolute coordinates, it is highly relevant to spatiotemporal crime analysis as it provides important geographic context for understanding the crime setting.

ID	Name	Have		Need		All	
		total	avg	total	avg	total	avg
G1	crime reports	43	4.8	16	1.8	59	6.6
G2	calls for service	9	1.0	5	0.6	14	1.6
G3	vehicle recoveries	5	0.6	2	0.2	7	0.8
G4	field interviews	2	0.2	0	0.0	2	0.2
G5	external information sources	40	4.4	17	1.9	57	6.3
Total Geographic Information (G)		**99**	**11.0**	**40**	**4.4**	**139**	**15.4**
R1	push pin maps	26	2.9	6	0.7	32	3.6
R2	choropleth maps	13	1.4	3	0.3	16	1.8
R3	proportional symbol maps	7	0.8	2	0.2	9	1.0
R4	hot spot maps	15	1.7	2	0.2	17	1.9
R5	multivariate symbolization	1	0.1	1	0.1	2	0.2
R6	buffer maps	11	1.2	0	0.0	11	1.2
R7	maps representing time	33	3.7	9	1.0	42	4.7
R8	reference or basemap symbolization	29	3.2	8	0.9	37	4.1
Total Cartographic Representation (R)		**135**	**15.0**	**31**	**3.4**	**166**	**18.4**
I1	focusing/filtering	18	2.0	10	1.1	28	3.1
I2	viewpoint manipulation	5	0.6	1	0.1	6	0.7
I3	brushing	11	1.2	1	0.1	12	1.3
I4	sequencing	3	0.3	2	0.2	5	0.6
I5	colormap manipulation	1	0.1	0	0.0	1	0.1
I6	assignment	3	0.3	0	0.0	3	0.3
Total Cartographic Interaction (I)		**41**	**4.6**	**14**	**1.6**	**55**	**6.1**
S1	spatial autocorrelation measures	0	0.0	2	0.2	2	0.2
S2	spatial scan statistics	4	0.4	1	0.1	5	0.6
S3	journey-to-crime analysis	7	0.8	2	0.2	9	1.0
Total Spatial Analysis (S)		**11**	**1.2**	**5**	**0.6**	**16**	**1.8**
T1	temporal & spatiotemporal cluster analysis	3	0.3	0	0.0	3	0.3
T2	trend analysis	23	2.6	5	0.6	28	3.1
T3	predictive analysis	4	0.4	0	0.0	4	0.4
T4	aoristic analysis	3	0.3	0	0.0	3	0.3
Total Temporal Analyses (T)		**33**	**3.7**	**5**	**0.6**	**38**	**4.2**
U1	criminal investigative analysis	3	0.3	2	0.2	5	0.6
U2	intelligence analysis	8	0.9	3	0.3	11	1.2
U3	tactical crime analysis	34	3.8	3	0.3	37	4.1
U4	strategic crime analysis	19	2.1	7	0.8	26	2.9
U5	administrative analysis	20	2.2	2	0.2	22	2.4
Total Map & Analysis Uses (U)		**84**	**9.3**	**17**	**1.9**	**101**	**11.2**
Total		**403**	**44.8**	**112**	**12.4**	**515**	**57.2**

Table 4: Frequency of Codes Applied for QDA of the Needs Assessment Study. *Total* describes the total number of statements given the code, while *Avg* divides this total by the sample size (n=9).

Most participants indicated that their agency leverages externally maintained geographic information sources. One participant stated that "we have gone out and tried to collect as many datasets as we can find that may or may not be useful to us, just so we know where they are at and what we have access to." Two important geographic information sets mentioned repeatedly were parole/probation records and registered sex offender records maintained at the state level, both of which include the home address of the offenders. Departments that have access to this information emphasized its utility and those that do not have access acknowledged their desire to acquire it. Other information sets include DMV (Depatment of Motor Vehicle) records and infrastructure information from the City's GIS department. One external geographic information set that is not used regularly is the federal census, with one participant stating that "I had to jump through hoops just to break it down by district and section within the police department" and a second stating that "the census data is about nine years old now [and] just isn't accurate...the census doesn't really mean much of anything to us." This contradicts descriptions of crime analysis in the literature, where the integration of census information for strategic crime analysis is highly recommended (e.g., Cahill & Mulligan, 2007); the recent release of the 2010 census may alleviate the latter participant's concern, at least for the small window of time that the census is current enough for the purpose of crime analysis. Many of the participants stated that their agencies use volunteered geographic information collected from social networking websites such as Facebook and MySpace, primarily for link analysis; none of the participants recalled using volunteered geographic information posted to microblogging websites like Twitter, but stated that they would like to do so if simple methods were available. While most law enforcement agencies appear willing and able to synthesize a large amount of external information sources, it is important to note that participants knew little about if or how their internally maintained information are shared with other agencies within their municipality or other law enforcement agencies in neighboring cities.

4.2 Cartographic representation

Codes included in the cartographic representation (R) category indicate statements about the way in which the collected geographic information are represented in map form to support crime analysis. Eight codes are included under the cartographic representation (R) category based upon the above background review: (R1) push pin maps (i.e., one-to-one dot or single-symbol maps), (R2) choropleth maps (i.e., graduated maps by color), (R3) proportional symbol maps (i.e., graduated maps by size), (R4) hot spot maps (i.e., density or surface maps), (R5) multivariate maps, (R6) buffer maps, (R7) maps representing time, and (R8) aspects of the underlying basemap. On average, cartographic representation was the most mentioned of the six key themes, indicating that the design of the map remains as important—or more so, as suggested by the code frequency—as more technically complex spatial and temporal analyses. The most frequently discussed cartographic representation forms include maps representing time (average=4.7), basemaps (average=4.1), and push pin maps (average=3.6). Less discussion was elicited concerning hot spot maps (average=1.9) and choropleth maps (average=1.8). Participants infrequently identified buffer maps (average=1.2), proportional symbol maps (average=1.0), and multivariate maps (average=0.2) as key needs, either met or unmet.

Of the set of crime map types identified by Boba (2005), push pin maps were by far the most commonly identified as a core need by participants. Participants indicated that the primary explanation for the frequent employment of push pin maps was their simplicity, but their simplicity in interpretation by map users rather than their simplicity in creation by mapmakers. One participant stated that "for the most part, simpler is better for the [officers] on the street" and second stated that "a lot of times we want to do more fancy and sophisticated analytical maps, but [high ranking officials] want to see pin maps, so of course we have to do pin maps." Such statements suggest that a large number of the information users at law enforcement agencies currently are incapable or unwilling to utilize more complex cartographic representations in support of criminal investigation and resource allocation. Interestingly, at least one

agency still commonly adds push pins to printed wall maps manually for serial tracking and collaborative decision-making.

Despite its relatively small amount of overall discussion within the cartographic representation (R) category, participants identified the hot spot map (i.e., density or surface map) as the preferred cartographic representation technique for large volume crimes where aggregation is necessary. Several participants noted that the generation of hot spot maps is growing in popularity, with one participant stating that "the latest and greatest thing that people like to see is a hot spot map" and a second stating that "it was something that my analysts saw at a conference, [so] we started making hot spot maps." Several of the participants responsible for producing hot spot maps indicated that they primarily use the *kernel density estimation* (KDE) function in the 3D Analyst extension to Esri's ArcGIS, which uses a moving window (i.e., a kernel) or multiple pixels to generate a crime estimation for the central pixel. However, several participants were cautious about inappropriately using hot spot maps, fearing that officers and detectives "don't understand them." One agency specifically avoided the use of KDE because they considered it misleading, as their map users did not realize that the shading is a smoothed result of a search window and not an aggregate of crime incidents within the specific pixel. Interestingly, several participants identified hexagons, rather than squares, as the preferred tessellation (i.e., cell shape), as the representation leads to naturally shaped hot spots that are easier to interpret and use for allocating patrol.

Participants generally considered choropleth maps as inferior to hot spot maps for crime analysis, as choropleth maps aggregate crime information to political or jurisdictional units that have little impact on patterns of criminal activity. Only one law enforcement agency regularly generated choropleths instead of hot spot maps for tactical crime analysis. However, choropleth maps are generated regularly for strategic and administrative crime analysis; one participant stated that "with more strategic or long-term maps, then we will do a choropleth map" and a second stated that choropleth mapping is "more of the administrative work" that he/she does. Other maps that were created on occasion by a subset of departments include

graduated symbol maps (graduated by point locations and, at one department, by line segment), flow maps (primarily to connect the location of vehicle thefts versus recoveries, but also to connect crime incidents in a serial; never scaled to show the volume of flow), and buffer maps. Most mapmaking is completed using Esri's ArcMap, although one agency exclusively uses the Microsoft MapPoint software to produce push pin maps.

Surprisingly, cartographic representation of time was the most discussed of the themes included in the cartographic representation (R) category; maps representing time also were the most frequent cartographic representation form listed as a need that currently is unmet. Coloring the pins on a push pin map according to the date of the incident—a separable coincident technique—was identified by participants as the primary method for representing time on maps. One participant stated that "I will have 28 days in color, the previous 28 days in grey, and the current 7 days will be in purple", a second participant stated that he/she will use "a color ramp to show thirty incidents over a two month period...the initial incident may be a white dot and it progresses to red over time", and a third participant stated that he/she would produce "a map of the last 30 days, [with] halos around the different periods of times." Participants identified the last seven days, the last month, and the last two months as common time periods used for temporal colored push pin maps. Several departments also apply color to represent cyclical temporal patterns, such as different days of the week (e.g., 'Monday', 'Tuesday', 'Wednesday') or shifts ('8am-4pm', '4pm-12am', 6pm-2am', '12am-8am'). Several participants also remembered isolated times that they had created animations when specifically prompted in the interview, with frames typically forwarded manually using Microsoft Powerpoint; one participant did report using Adobe Flash once to generate an animation. While these participants stated that the animations were extremely well received, they also stated this was not an approach they typically completed due to the perceived time-consuming nature of constructing the animation, making animation a key unmet cartographic representation need.

Participants agreed that a street network with labels is the primary basemap or reference information included on their crime maps. Other infrastructure information like building footprints and parcels may be included for large scale maps. Participants noted that points of interest (e.g., schools, parks, police stations, bars, restaurants, bus stops) may be included, but typically only upon special request or for the generation of buffer maps. Most agencies have access to aerial imagery, but generally only include it upon special request (particularly for court maps).

4.3 Cartographic interaction

Codes included in the cartographic interaction (I) category indicate statements about the way in which the generated cartographic representations are manipulated through user interfaces. Six codes are included under the cartographic interaction (I) category based upon the above background review: (I1) focusing/filtering, (I2) viewpoint manipulation, (I3) brushing, (I5) colormap manipulation, and (I6) assignment. Focusing/filtering was identified as the biggest need (average=3.1) among the MacEachren et al. (1999) cartographic interaction operators, with brushing (average=1.3) also garnering some discussion. Viewpoint manipulation (average=0.7), sequencing (average=0.6), assignment (average=0.3), and colormap manipulation (average=0.1) were discussed infrequently.

Participants stated that most of the exploratory crime analysis leveraging cartographic interaction is completed with desktop GIS software designed for other purposes. While some law enforcement agencies have generated customized interface widgets providing some cartographic interaction in real-time, this still is limited to a subset of interaction operators and a subset of agencies. Across the nine participants, cartographic interaction was performed only by the crime analysts responsible for producing crime maps and analyses. Participants from agencies that hold CompStat meetings noted that high-ranking officers may include interactive maps in their presentations, manipulating the cartographic representation in real-time; however, in all reported examples "analysts are in the back driving that." Thus, a transparently usable interface, providing a subset of core interaction operators through an intuitive interface design,

may fill a key unmet need for the consumers of crime maps, such as administrators, detectives, supervisors, and other decision makers.

Participants identified focusing/filtering as the most needed cartographic interaction operator, with one participant acknowledging that crime analysts "filter continuously, every time they make a map they filter." Most participants have to perform focusing/filtering queries using a series of *nested dialog windows*, which hide interface features in a set of windows that must be activated in sequence by users, limiting the *usability* (i.e., ease-of-use) of the application and making exploratory crime analysis difficult. One recommended solution is the inclusion of *persistent dialog windows* housing focusing/filtering controls that remain visible until minimized by the user; this was deemed particularly appropriate for common filtering attributes such as UCR and MO. Participants also identified brushing as a commonly employed cartographic interaction operator, noting that brushing typically is provided on digital push pin maps in order to retrieve additional information about the selected crime incident. Only one participant described an application currently in use at his/her agency that uses brushing for linked highlighting across multiple information graphics (a desktop mashup between ArcGIS and the ATAC system).

Participants indicated that the other cartographic interaction operators are employed infrequently. Participants from agencies that hold CompStat meetings noted that the sequence operator sometimes is applied during the meeting, as they have to bin their crime incident information across multiple attributes for each weekly or bimonthly meeting. However, the generated maps almost never are animated across the temporal bins generated by the sequence operator. Participants stated that viewpoint manipulation often is available only in a discrete fashion (i.e., no continuous panning across the map extent or zooming across scales), as analysts have the extent of each district preset in ArcMap and toggle between individual districts and the full extent. Participants indicated that assignment and colormap manipulation are applied rarely.

Interestingly, participant discussion on cartographic interaction revealed a split on the potential utility of web maps and web mapping services, such as Google Maps. One participant was excited about the potential of such services, stating that "a lot of folks are looking at the Google Maps...I think Google Maps has been really useful in getting law-enforcement to use these types of things because prior to Google Maps, agencies didn't even know these things were accessible" while a second was concerned not about the interactivity of these services, but about the underlying information quality, stating that "if you go to Google Maps, or something like that, you don't know how old those maps are or what actually changed, so some of that information when you physically get out there could be bad information." Interestingly, one participant stated that he/she had experimented with using Google Earth because of the potential for sharing interactive maps via .kml files; this participant stopped doing this, however, because the intended users did not have Google Earth installed on their work machine (and did not have security permission to do so) and therefore could not access the maps.

4.4 Spatial analysis

Codes included in the spatial analysis (S) category indicate statements about the spatial statistics and geocomputational routines that are applied in support of crime analysis. Three broad codes were included under the spatial analysis (S) category based upon the above background review: (S1) measures of spatial autocorrelation, (S2) spatial scan statistics, and (S3) journey-to-crime analysis; other spatial analyses were considered in the original coding scheme, but were dropped because they were not identified during the interviews. Spatial analysis was by far the least identified need during the transcript analysis, with an overall average of only 4.2 statements per transcript; journey-to-crime analysis was identified most frequently as a spatial analysis need (average=1.0), followed by spatial scan statistics (average=0.6) and spatial autocorrelation measures (average=0.2).

The overall low amount of discussion on spatial analysis needs revealed a large and unexpected disconnect between practice and science, where the application of spatial transformations and spatial models is frequently reported and highly recommended. One possible explanation for this disconnect that

came up in several of the interviews was that there is a lack of relevant expertise within the municipal law enforcement agencies in terms of both understanding how to apply the spatial analysis techniques and how to interpret their results. There were only two total references to spatial analysis by sworn officers, with one participant stating that he/she "leave[s] that up to the analyst to do because they are a lot more familiar with those type of things that I am." There also was a general notion communicated by many of the participants that crime analyst units are undermanned and even misused, forcing the crime analysts to respond to specific, often basic requests rather than providing them with the autonomy to complete more advanced spatial analyses. One participant noted his/her agency "is very short on manpower...so it becomes very difficult [to complete such analyses]." This participant went on to add that "I don't want to say it's a waste of time, but they just don't have the time to focus on this."

The two most commonly applied spatial analyses—kernel density estimation and buffering—are completed to generate an output map. Interestingly, participants from two different agencies commonly apply these two spatial analyses upon request during their CompStat meetings, illustrating the potential of providing cartographic interfaces to computational processes in support of exploration and reasoning in real-time. Several participants stated that they occasionally conduct journey-to-crime analyses using the geographic mean calculation in the CrimeStat application (Levine, 2006) or the animal movement extension in ArcGIS. None of the participants calculated spatial autocorrelation statistics, with most participants seeing limited value in metrics that do not provide local indicators of crime clusters. One participant had applied the spatial scan statistic routines provided in SaTScan (Kulldorff, 2010) and the LISA statistics provided in GeoDa (Anselin et al., 2006) several times, but noted that such application "is unusual...[crime analysts] don't use GeoDa, they don't even use SaTScan." While other participants hinted at the need to automate the identification of crime incident clusters, no other participants were aware of spatial scan statistics or other methods of spatial cluster analysis, stating that cluster identification is completed visually at their agencies.

4.5 Temporal analysis

Codes included in the temporal analysis (T) category indicate statements about the temporal transformations and models that are applied in support of crime analysis. The temporal analysis (T) category includes four codes drawn from the above review: (T1) temporal and spatiotemporal cluster analysis, (T2) trend analysis, (T3) predictive analysis, and (T4) aoristic analysis. Trend analysis using information graphics was identified by participants as the largest temporal analysis need (average=3.1). Predictive analysis (average=0.4), temporal and spatiotemporal cluster analysis (average=0.3), and aoristic analysis (average=3.1) were discussed infrequently.

There was extreme variation in the temporal analyses applied to the crime information across the participating law enforcement agencies. Most of the participants indicated that their agencies apply very little temporal analyses in support of crime analysis. These participants primarily rely upon trend analysis that does not have a linked cartographic component to it. Participants stated that the temporal information graphics used for trend analysis typically are generated as one-offs in Microsoft Excel or Crystal Reports and are restricted to incidents in the past one or two months, indicating an emphasis on tactical over strategic crime analysis (see the following subsection). Interactive integration of these temporal graphics with map views was identified as a key unmet need. Participants noted that there is little systematic interpretation of the time-series graphics, with one participant saying "there is quite a bit of qualitative feel to it." Most participants stated that their agencies generate temporal composite graphics that show cyclical crime patterns, such as peaks by day of the week or time of the day; at several agencies, however, these graphics only are created when a crime analyst notices a potential cyclical pattern when reading the individual crime reports, rather than generating the composite graphics regularly to identify patterns without sifting through the full incident narrative. For these agencies, the application of temporal or spatiotemporal clustering analysis, temporal prediction algorithms, and aoristic analysis was minimal.

In contrast, participants from two of the law enforcement agencies indicated that they regularly apply sophisticated temporal analyses, offering initial insight into potential use case scenarios of spatiotemporal

crime analysis. One agency takes full advantage of the ATAC software (Bair, 2000). ATAC automates the generation of temporal information graphics for trend analysis and provides a suite of statistics to help with the interpretation of these graphics. ATAC also has an aoristic analysis feature that provides a time split for incidents logged with a time interval. Further, ATAC includes a temporal prediction feature, although the participant using ATAC stated "I don't understand the [technique] very well" and that "this technique didn't seem to work very well for me." Finally, as mentioned above, the ATAC software is fully linked with ArcMap, allowing for real-time, interactive exploration of criminal activity in both space and time.

A second agency employs the HunchlLab/Crime Spike Detector software developed by Azavea (Cheetham, 2010), referred to internally as SpikeStat. The purpose of SpikeStat is to automate the identification of spatiotemporal hot spots of criminal activity. The participant reported that the software uses a spatiotemporal scan statistic to identify crimes spikes in both space and time. Interestingly, the implemented spatiotemporal scan statistic uses different window sizes based upon the type of crime under investigation because, as the participant noted, "you want to have a smaller search radius for thefts and a bigger one for homicide." The locations of these spikes then are compared against the set of police jurisdictions in order to send an alert to the appropriate commanding officer. The crime analyst using SpikeStat was pleased with the results, stating that it works "like an early warning system."

4.6 Map and analysis use

Codes included in the map and analysis use (U) category indicate statements about the way in which spatiotemporal mapping and analysis techniques are used in support of crime analysis. The map and analysis use (U) category includes a code for each of Boba's (2005) five types of crime analyses reviewed above: (U1) criminal investigative analysis, (U2) intelligence analysis, (U3) tactical crime analysis (U4) strategic crime analysis, and (U5) administrative analysis. Support for tactical crime analysis was identified by participants as the overall largest need (average=4.1), but strategic crime analysis was identified as the largest unmet need (overall average=2.9; unmet average=0.8). Participants also identified

support for administrative analysis as an important need (average=2.4); support for intelligence analysis (average=1.2) and criminal investigate analysis (average=0.6) were less frequently discussed.

An interesting characteristic of the current practice of crime analysis was revealed when comparing discussion on tactical versus strategic crime analysis. Most of the participating law enforcement agencies primarily conduct tactical crime analysis, applying spatiotemporal analyses and producing output crime maps in order to react to the most recent crime spikes. One participant stated that "tactically is probably how we most often use our maps" and went on to say "a lot of what we do is more just support of day-to-day functions of the police department, so you don't see [strategic crime analysis] a lot...we are more tactical." A second participant stated that "currently the way that we are utilizing [crime analysis] is to attack specific problems" and went on to say "by the time we start gathering the clustering, we have attacked the clustering, and once that clustering is eradicated, we then move on; we do not have the time or luxury to see if the clustering started nine months ago." Participants indicated that the purpose of the tactical analysis is to adjust blue force patrolling in response to recent criminal activity; one participant stated that the "most common use [of tactical crime analysis] is for patrol deployment" while a second stated "we do tactical analysis for patrol." However, at least one participant lamented this focus of crime analysis, stating "that is why we play catch-up most of the time, because it is all reactionary."

While all but one participant could think of at least a single example of strategic mapping completed at their agency, only three of the interviewed agencies considered themselves positioned to complete strategic crime analysis on a regular basis. One key barrier to strategic analysis identified by the participants is that many agencies are undermanned, a similar barrier preventing more sophisticated spatial analyses. With regard to conducting strategic crime analysis, one participant stated that "allocating resources is a big deal" while a second participant stated "if they are overloaded with requests they won't have time to do [strategic analysis]", and a third stating that his/her agency conducts strategic analysis "whenever they get grant money or extra money." Thus, it appears as though law enforcement agencies

currently are in need of a cartographic interface that supports rapid and straightforward strategic analyses in addition to tactical analyses.

A second, and likely related, barrier to strategic analysis identified by several of the participants is accountability, as enacting intervention programs based on strategic analysis requires a long-term commitment from decision makers. As one participant noted "with strategic projects, it is a lot easier to ignore them than actually go out and initiate projects with them because it takes a lot of time and effort to do a [strategic] project ... if we are not being held accountable, it is a lot easier for some people not to do it." The best examples of cartographic representations, and associated user interfaces, that support strategic crime analysis were provided by participants whose agencies hold regular CompStat meetings; four of the seven participating agencies hold CompStat meetings, with three of these four agencies conducting regular or semi-regular strategic crime analysis. These participants noted that the primary purpose of the CompStat process is to increase accountability, which has a direct tactical goal of reacting to recent crime spikes, but also should support the long-term strategic goal of improving the quality of life of a community

Beyond Boba's (2005) tactical and strategic forms of crime analysis, participants also were able to provide numerous examples of administrative analysis. Almost all participants indicated that their agencies generate maps for court proceedings, with several agencies balancing their budgets by charging for the preparation of these maps. Many participants also described map-based reports or simple online mapping websites that are maintained by their agency for the public consumption of spatiotemporal crime information. Participants provided few examples of criminal investigative analysis and intelligence analysis during the interviews. Examples of criminal investigative analysis primarily referenced applications of the journey-to-crime analysis described above. Examples of intelligence analysis primarily referenced the extraction of geographic information from social networking applications to identify the location and relationships of a gang or other organized crime syndicate.

5. Conclusion and Outlook: Unmet needs for spatiotemporal crime analysis

This article provides a snapshot and comparison of spatiotemporal crime analysis science and practice, with the aim of revealing major disconnects and currently unmet needs. This research contributes to our knowledge of spatiotemporal crime analysis in two ways. We first completed a comprehensive background review across the domains of Criminology/Crime Analysis and GIScience/Cartography in order to characterize the current science of spatiotemporal crime analysis. We then conducted a set of interviews with seven law enforcement agencies in order to compare our background review to the current practice of spatiotemporal crime analysis; again, the insights elicited from the interviews are specific to intermediate- to large-size law enforcement agencies located in the Northeastern United States. The comparison between science and practice was completed across six themes relevant to spatiotemporal crime analysis: (1) geographic information, (2) cartographic representation, (3) cartographic interaction, (4) spatial analysis, (5) temporal analysis, and (6) map and analysis use. Importantly, the comparison between the background review and interview responses revealed several broad, unmet needs for spatiotemporal crime analysis in United States law enforcement agencies, each of which span across several or all of these six themes:

(1) **Expand and combine geographic information sources:** All of the participating law enforcement agencies indicated the need to acquire geographic information from additional sources. Participants noted two internal or government information sources, which are compiled in a consistent and top-down manner: parole/probation records and registered sex offender records. However, many intriguing comments were offered from participants with regards to external information sources. Law enforcement personnel need applications that allow for fast and flexible combination of internal and external information sources, an approach described in information science as a *mashup*

or, regarding online applications, *Web 2.0* technologies (O'Reilly, 2007; Roth et al., 2008). They also require cartographic representations and cartographic interactions that scale to the growing size of these information sets, particularly volunteered geographic information sources such as Facebook and Twitter. Further, participants indicated that they are not fully aware how their internally maintained information sets are used by other agencies at the municipal, state, or federal level. Greater coordination across agencies involved in law enforcement and public safety would act to refine the database schema to better support diverse information uses, promote transparency and collaboration across agencies, and remove overlap in collection and maintenance efforts.

(2) Improve the usability of crime mapping and analysis tools: Acquisition of additional information sources means little if this information cannot be made usable through mapping and analysis techniques that are both easy to perform and comprehend. The above background review yielded a large number of techniques regarding crime mapping and analysis that support the mission of law enforcement. However, based on our empirical results, only a portion of this spatiotemporal crime analysis toolkit regularly is put to use in intermediate- to large-size law enforcement agencies; cartographic representation is limited primarily to pushpin and hotspot maps, cartographic interaction is limited primarily to the focusing/filtering and brushing, spatial analysis is surprisingly limited altogether, and temporal analysis exhibits a large amount of variation across agencies. Rather than continuing the pursuit of novel spatiotemporal crime mapping and analysis tools and techniques to add to those reviewed above, researchers perhaps instead should be investigating how to make existing tools and techniques *transparently usable* (i.e., immediately can be used by law

enforcement with little training) (Robinson et al., 2011). The topic of usability is one that has received minimal attention within crime analysis and spatial criminology, but one that is of fundamental importance considering that most-to-all law enforcement personnel are not formally trained in spatiotemporal crime analysis and have little experience interpreting complex cartographic representations and spatiotemporal analytical results. By placing an emphasis on the design of the user interfaces to the mapping and analysis techniques—rather than the techniques themselves, and perhaps even limiting their sophistication depending on the use case scenario—a greater number of law enforcement personnel can integrate spatiotemporal analysis into their workflows. Pervasive use of highly usable interfaces to simplified spatiotemporal mapping and analysis techniques also may promote buy-in within the agency to allow dedicated crime analysts to spend their time performing more sophisticated mapping and analysis techniques.

(3) Integrate geographic and temporal representations and analyses: Criminal activity has prominent spatial and temporal components that must be treated in concert during the analysis of crime information in order to glean the maximum amount of insight in to the identified pattern. Feedback elicited from the interview study supports Ratcliffe's (2009: 12) assessment that "At present, the most under-researched area of spatial criminology is that of spatio-temporal crime patterns." Across the seven participating law enforcement agencies, there were numerous positive examples of crime analysis treating the geographic (at least regarding mapping; less so for spatial analysis) or the temporal component individually. However, the representation of time on maps was identified as the primary unmet need regarding cartographic representation, with participants indicating the need for cartographic animation in particular. Further, only a

single law enforcement agency described a use case scenario that considered both space and time together (the ATAC-ArcGIS desktop mashup). Research on representation, interaction, and analysis techniques that are explicitly spatiotemporal appears to be the most fruitful avenue for crime analysis moving forward, again with a mind towards development of transparently usable interfaces to these spatiotemporal techniques.

(4) Improve support for strategic crime analysis: An emphasis on tactical crime analysis of recent criminal activity, while understandable from a practical perspective, privileges the victim of the crime, as the goal is to ameliorate the damages incurred quickly and ensure that justice is served. However, strategic crime analysis across longer time periods is needed to better understand the offenders participating in the criminal activity, the second condition under routine activity theory required for the occurrence of a crime (the law enforcement guardian being the third). All participating law enforcement agencies emphasized that it only is through such long-term, strategic spatiotemporal analysis of criminal activity that institutionalized criminal activity may be mitigated and blighted communities may be revitalized. Such an emphasis ultimately requires and reinforces better public safety policymaking and administration as well. Yet, participants noted that resources, tools, and training for strategic spatiotemporal analysis are lacking. In a period during which resources towards law enforcement and public safety are in decline, it is increasingly important to provide law enforcement agencies with crime mapping and analysis tools that are affordable, intuitive, and useful so that these agencies can improve the efficiency of their spatiotemporal crime analysis work and therefore dedicate additional time towards strategic crime analysis.

As stated in the introduction, the interview study acted as the needs assessment stage for design and development of a spatiotemporal crime mapping application called *GeoVISTA CrimeViz* (http://www.geovista.psu.edu/CrimeViz), a project completed in collaboration between the Penn State GeoVISTA Center and the Harrisburg (PA, USA) Bureau of Police. The key unmet needs identified through the interviews directly informed the conceptual design of the *GeoVISTA CrimeViz* application, providing positive evidence for speaking with the targeted end users about their core needs prior to development. Important design elements of *GeoVISTA CrimeViz* drawn from the interviews include: a web-based architecture for real-time loading of internal and external information sets, persistent interface controls and help documentation to improve the transparent usability of the application for use by all personnel within the Harrisburg Bureau of Police, multiple geographic and temporal representations that are live-linked for coordinated interaction, and contextual geographic information layers and advanced spatiotemporal analyses oriented towards strategic crime analysis. Since the initial needs assessment interview study reported here, we have completed several interface evaluation-refinement loops with the Harrisburg Bureau of Police following a user-centered design approach. The application was transitioned into use by the Harrisburg Bureau of Police for spatiotemporal crime analysis in 2012.

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