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Using Bayes' Theorem in Behavioural Crime Linking of Serial Homicide

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Purpose. The study extends research by Santtila *et al.* (2008) by investigating the effectiveness of linking cases of serial homicide using behavioural patterns of offenders, analysed through Bayesian reasoning. The study also investigates the informative value of individual behavioural variables in the linking process.

Methods. Offender behaviour was coded from official documents relating to 116 solved homicide cases belonging to 19 separate series. The basis of the linkage analyses was 92 behaviours coded as present or absent in the case based on investigator observations on the crime scene. We developed a Bayesian method for linking crime cases and judged its accuracy using cross-validation. We explored the information added by individual behavioural variables, first, by testing if the variable represented purely *noise* with respect to classification, and second, by excluding variables from the original model, one by one, by choosing the behaviour that had the smallest effect on classification accuracy.

Results. The model achieved a classification accuracy of 83.6% whereas chance expectancy was 5.3%. In simulated scenarios of only one and two known cases in a series, the accuracy was 59.0 and 69.2%, respectively. No behavioural variable represented pure noise but the same level of accuracy was achieved by analysing a set of 15, as analysing all 92 variables.

Conclusion. The study illustrates the utility of analysing individual behavioural variables through Bayesian reasoning for crime linking. Feasible applied use of the approach is illustrated by the effectiveness of analysing a small set of carefully chosen variables.

Analyses of the behavioural aspects of a crime have increasingly become a part of crime investigation. One domain of this is *crime linking*; that is, drawing the conclusion that

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several crimes are committed by the same offender. Crime linking does not attempt to provide any information about the characteristics of the offender, but can still render the investigation of crimes more effective. If several crimes can be reliably linked together, the information gathered from the investigation of these separate crimes can be pooled together, permitting further conclusions and investigation methods. In addition, the efforts that would otherwise be directed at the separate crimes may now be joined together (Grubin, Kelly, & Brunsdon, 2001; Woodhams & Toye, 2007). While crime linking is most effective when based on physical evidence such as fingerprints or DNA traces, linking crimes based on behavioural variables may also be fruitful in cases where physical evidence or the economic resources to analyse it are not available (Grubin *et al.*, 2001).

The accuracy of crime-linking methods needs to be evaluated for police forces to be able to decide to what extent the investigation should be guided by such analyses (Alison, Bennell, Mokros, & Ormerod, 2002). Furthermore, behavioural crime linking analyses are sometimes presented as evidence in court (Alison *et al.*, 2002; Douglas & Munn, 1992; Woodhams & Toye, 2007). If such analyses are to be used in court, convincing empirical evidence of their accuracy should be presented (Alison *et al.*, 2002; Woodhams & Toye, 2007). For crime-linkage analyses to be usable, for any purpose, their theoretical assumptions must be shown to hold true, and the method itself needs to be shown to be effective.

In the recent years, Bayesian reasoning in statistical calculation of probability has been considered a revolutionary force in a wide range of research areas, for example in genetics (Beaumont & Rannala, 2004). In the present study, we examine if serial homicides can be reliably linked together based on behavioural variables alone using Bayesian reasoning.

Serial homicide

Murder cases are considered serial homicide when there are several independent events committed by the same perpetrator, separated by so-called emotional cooling-off periods. The cooling-off period differentiates serial homicide from mass murder and spree murder, in which several multiple victims are killed during a single event (Douglas, Ressler, Burgess, & Hartman, 1986). There are differing opinions about the definition of serial murder regarding the number of homicides: time elapsed between homicides, number of perpetrators, and motivational background (see Harbort & Mokros, 2001 for a review). In the present study, serial homicide was defined as series of homicides involving the killing of two or more persons in separate incidents with an interval of more than 24 hr between the killings.

The apparent randomness of serial homicide may cause fear among the general public, and at the same time makes the cases more difficult to solve (Douglas *et al.*, 1986). Any method that contributes to a quick apprehension of the perpetrator is, therefore, of great value.

Theoretical assumptions of behavioural crime linking

Behavioural crime linking rests on the theoretical assumptions of consistency and inter-individual variation (Alison *et al.*, 2002; Canter, 1995, 2000; Woodhams & Toye, 2007). The consistency assumption states that an offender's behaviour is consistent across crime scenes and influenced by stable characteristics of the offender, while the inter-individual

variation assumption states that the crime scene behaviour of one offender is different from that of other offenders.

The question of behavioural consistency across situations has been a major controversy in psychology for several decades. It is, however, now widely accepted that cross-situational consistency is low but non-zero. Mischel and Shoda (1995) proposed a cognitive–affective system theory to explain this phenomenon. According to this theory, people differ in how they interpret and respond to different situations. This interaction between person and situation makes an individual's behaviour somewhat inconsistent. However, taking this interaction into account, a person's behaviour follows a consistent pattern when the circumstances are similar since the person responds to a certain situation in a predictable way.

When it comes to criminal behaviour there is some empirical evidence for consistency, even if all offender behaviours are not considered equally consistent (Woodhams, Hollin, & Bull, 2007). It has been suggested that behaviours that are more offender initiated and less situation-dependent show greater consistency (Bennell & Canter, 2002; Woodhams *et al.*, 2007). In homicide cases connected to the same offender, there are various degrees of interaction between the offender and the victim (Bateman & Salfati, 2007), which can lead to quite different realizations of the actual crime situations (Alison *et al.*, 2002). The offenders thus find themselves in different situations from crime to crime, and this has been suggested to lead to inconsistency in behaviours that are not offender initiated (Bateman & Salfati, 2007).

Another suggested source of inconsistency is that an offender may learn new behaviours from experiences in previous crimes (Bateman & Salfati, 2007; Douglas & Munn, 1992). There is a distinction between *Modus Operandi* (MO) and *signature behaviour* and it has been argued that MO behaviours, that is, behaviours that the offender uses to effectively complete the crime, are easily influenced by previous experience. Signature behaviours, on the other hand, are behaviours that go beyond what is necessary for completing the crime, such as sexual behaviours with the victim's dead body. It has been hypothesized that these behaviours spring from the offender's psychopathological needs and are not to the same extent learned. While signature behaviours may evolve, it has been proposed that they would remain a more consistent part of the offender's behaviour at the crime scene (Douglas & Munn, 1992; Hazelwood & Warren, 2003).

Some supporting evidence for the assumptions of consistency and inter-individual variation comes from effective crime linking. Behavioural variables have successfully been used to link cases of burglary (Bennell & Canter, 2002; Bennell & Jones, 2005; Goodwill & Alison, 2006; Green, Booth, & Biderman, 1976), rape (Canter, 1995; Grubin, Kelly, & Ayis, 1997; Grubin *et al.*, 2001; Santtila, Junkkila, & Sandnabba, 2005), and arson (Santtila, Fritzon, & Tamelander, 2004). Regarding serial homicide, there have also been studies supporting the consistency of offender behaviours (Bateman & Salfati, 2007; Lundigran & Canter, 2001; Salfati & Bateman, 2005). To our knowledge only one study, however, has so far examined specifically the effectiveness of linking serial homicide. With a factor analysis based approach, Santtila *et al.* (2008) identified seven dimensions of crime scene behaviours in 116 cases of Italian serial homicide and used summary scores for these dimensions in a discriminant function analysis to link offences. They were able to assign 62.9% of the cases to the correct series in a cross-validation scheme,

where the chance expectation of the correct assignment was 5.3%.[1] No previous study has to our knowledge examined the effectiveness of linking cases of serial homicide based on individual behaviours.

Themes of behaviour versus individual behaviours

Since variation in crime situations and the possible novel MO behaviours learned by the offender can be expected to cause some inconsistency in the individual offender behaviours, it has been hypothesized that analysing dimensions of offender behaviour (e.g., several behaviours indicating preplanning) would be more effective in linking crime than analysing individual behaviours. Different circumstances might cause the offender to avoid a particular behaviour but instead employ another behaviour within the same dimension, making the offender's position on the dimension more consistent than the individual behaviours (Bateman & Salfati, 2007).

There are, however, also reasons why individual behaviours, rather than behavioural dimensions, might be fruitful to consider for crime linking. First of all, the dimensional approach is based on the assumption that the offender's personality or psychopathological needs are inevitably expressed through one behaviour or another, which in turn causes behavioural consistency. This is an assumption that is not necessary for crime linking and may not even be correct (Alison *et al.*, 2002; Mokros & Alison, 2002). Consistency in MO behaviours can also be due to external circumstances, for example, the consistent availability rather than a personality driven preference of a certain type of weapon. Behaviours guided by external circumstances rather than the offender personality are most likely specific, rather than dimensional.

Second, even if offenders cannot perform a certain behaviour every time, they might choose to perform it whenever possible. This is especially true for behaviours that could be defined as signature behaviours. The offender may be particularly consistent regarding such behaviours and if they are pooled together with other behaviours in a statistical analysis, it is likely to lead to a loss of valuable information.

Bayesian reasoning

Bayesian reasoning (Bernardo & Smith, 1994) can be interpreted as a process where observations are used to update the probability that a hypothesis is true given *a priori* characterization of its plausibility. In the present context, this task corresponds to the assessment of whether a particular homicide is linked to a previously known series of homicides. Several arguments in favour of utilizing Bayesian reasoning as an approach to crime linking can be put forward, especially if individual behaviours are to be considered. First, basing the analysis on Bayesian reasoning allows for a large number of variables to be analysed simultaneously in a sensible manner even in the presence of sparse data. Second, within a series there will inevitably be both consistencies and inconsistencies when a large number of individual behaviours are investigated. One of the key strengths of the Bayesian reasoning lies in its ability to create more honest representations of uncertainty as well as more appropriate handling of missing data compared to traditional statistical inference. Bayesian reasoning provides a coherent framework for handling uncertainty, within which the individual behaviours can be weighed against each other to reach a conditional probability of any particular crimes being linked.

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[1] *Chance expectancy was reported to be 6.2% due to different calculation methods.*

The assumptions of consistency and inter-individual variation in linking are an inherent part of Bayesian reasoning. Any behaviour with high enough consistency and inter-individual variation will provide information that contributes to a more accurate assessment of whether particular crimes are linked. Therefore, a Bayesian approach to crime linking can also be used to evaluate the usefulness of separate individual behaviours.

An important characteristic of the Bayesian framework is also its ability to coherently handle missing information concerning particular behaviours, as such tend to be present in real data. This is in a strong contrast to the traditional frequentist statistical methods, where missing data are often either ignored or artificially re-labelled to represent a category already present in the data. Both such approaches handle incorrectly the decrease in the actual amount of information available for making predictions, however, the latter approach is more harmful in the sense that it forces confounding information into the observations, when the true behaviours are different from the artificially created labels. Instead of coherently judging the degree of information lost by missing observations as done in a Bayesian framework, these are then converted into fake knowledge. Nevertheless, it should be noted that appropriate statistical handling of missing observations typically requires that their pattern of occurrence is random. It would in principle be possible to handle non-randomly missing information by introducing a statistical model for the expected deviations from total randomness, but this would require rather detailed knowledge about the data-gathering process.

A Bayesian approach has previously been used for crime linking based on behaviours in databases of burglary (Ewart, Oatley, & Burn, 2005; Oatley, Ewart, & Zeleznikow, 2006; Yokota & Watanabe, 2002). However, these previous studies have made use of so-called *empirical Bayesian* approaches that are unable to coherently deal with the uncertainty of unknown prior probabilities. The present study made use of a *fully Bayesian approach*, where the marginal data likelihoods can appropriately take into account the presence of missing data concerning some behaviours and cases. A Bayesian approach has also successfully been applied to the related field of profiling of offender characteristics (Baumgartner, Ferrari, & Palermo, 2008).

Aims of the study

The present study aims to examine the usefulness of linking cases of serial homicide by analysing individual behaviours through Bayesian reasoning. First, the present study examines whether this suggested approach can be more effective than previously used statistical methods, with the same data, in linking serial homicide. Santtila *et al.* (2008) analysed these data by first identifying seven dimensions of behaviour and used these dimensions to link cases. Following the reasoning above, the present study, approaches crime linking through analysing the behaviours individually and uses Bayesian statistics to do so. Second, under the hypotheses that this approach will result in higher classification accuracy, the present study explores what individual behaviours are useful for crime linking of serial homicide.

Materials and Method

Data collection

As previously reported by Santtila *et al.* (2008), to identify cases of serial homicide, the most important daily Italian newspapers were checked for serial homicides, the Internet

was searched with keywords related to serial homicide, and microfilms of journals in libraries were inspected. Also, Italian criminological literature was consulted in order to identify cases of serial homicide. The search was limited to serial homicides taking place between 1970 and 2001. The study at hand relies mostly on data from year 1980 through 2001. In a majority of the cases court files were available, whereas for eight of the killers, criminological literature and newspaper articles were consulted. All the cases included in the present study were cases in which the offender had been convicted in a court of law.

In total, our sample consisted of 116 homicides belonging to 19 separate series of homicides. In 26 of these homicides, the victims in the analysis were killed in situations involving another victim as well. Sixteen of the series were committed by a single offender, in two of the series there were two, and in one series there were three offenders.

All offenders were male, while 55.1% of the victims were female and 44.0% were male. For one of the victims (0.9%), gender remained unknown. The age of the offenders varied during the series but their average age at the midpoint of their series (defined as the median of the offenders age at the time of the separate crimes) was 35.0 years (SD = 13.6). The youngest offender commenced his series when he was 18 years old and the oldest offender committed his last murder when he was 72 years old. Age was known for 91 victims. The age ranged between 4 and 84 years such that eight victims were under 18 years old and the mean was 35.1 years (SD = 19.2).

The homicide series in this sample differed in terms of the number of victims as well as the time period during which the offences were committed. The median number of victims in the 19 series was 5 (M = 6.1, SD = 4.2); the most extensive series included 17 victims (n = 1) while the shortest series encompassed two victims (n = 3). The median duration of a series was 3 years (M = 4.83, SD = 5.11). In the case of the longest time period, the time between the first and the last killing was 16 years, while the killings in the most rapidly evolving series took place within a single year. Descriptive information about the series, including the number of victims in the different series as well as the duration of the different series in years is presented in Table 1.

Because of this variability, the homicides could be put into categories depending on different definitions of serial homicide or how difficult they are to investigate. However, for the purpose of crime linking, it is useful to apply a wide definition of serial homicide. Examining the probability that a new crime is linked to previous crimes becomes of potential value as soon as there is one previous case committed by the same offender, and remains of value as long as the offender is not apprehended.

Content analysis of the cases

The pre-trial investigation protocols, ranging between 100 and 300 pages, were coded for each case. The variables used in the present study were developed by Santtila *et al.* (2008) based on research by Salfati (1998). Usually, the case files contained socio-demographic information on the victim and the offender as well as the charges against the suspect. Also, descriptions of the facts of the case by the court and the conclusions derived from these that had indicated the guilt of the accused were incorporated. This description of the facts contained, among other things, a summary of the findings of the pathologist, the witness statements, and interrogations with the suspect. Thus, the variables included offence-related information, victim characteristics as well as situational variables. These variables constituted the individual behaviours to be analysed in the linkage analyses. All

Table 1. The number of victims and the duration of the series

Series	Number of victims	Duration of the series in years
1	17	1
2	14	12
3	11	16
4	9	3
5	8	6
6	7	2
7	7	1
8	6	5
9	6	0
10	5	7
11	4	15
12	4	0
13	3	3
14	3	3
15	3	1
16	3	0
17	2	1
18	2	1
19	2	0
	116	$M = 4.1$

variables and their presence in the data in percentage are presented in Table S1 available online (ordered according to results reported below). With the purpose of assuring anonymity for the victims and their families, identity information of the offenders and the victims were excluded from the data file. However, general information such as the age of the offender and victim was included.

Access to the court transcripts was limited so that only one researcher could read the transcripts of a particular series. The inter-rater reliability of the coding scheme was examined by comparing the coding of public material, where the data coding was conducted by two research assistants under the supervision of a senior researcher with prior experience of the coding format. The inter-reliability of the coding scheme is good with a coder-wise kappa of 0.72 (Pakkanen, Santtila, Mokros, & Sandnabba, 2008).

The recorded behaviours of a single crime i ($i = 1, \ldots, n$) were coded as a d-dimensional ($d = 92$) binary vector X^i, where each value corresponds to the presence or absence of a behaviour. Some of the vectors contained missing values, as the presence of certain behaviours was unknown in these crimes. This was the case, for example, when the protocol was insufficient and did not include the variable or the coding researcher did not find the variable in the protocol. Such missing values are coherently taken into account in the Bayesian model used under the assumption of randomly missing observations. As stated earlier, this is in contrast to the earlier used non-Bayesian methods, where the missing values of important behaviours would lead to a statistical bias, when, for example, coded arbitrarily into some category of observations.

Statistical methods

We examined the data using a Bayesian model that assigns different probabilities on observing specific behaviours depending on the series to which the crime belonged.

Based on these probabilities, the decision can be made to link a new crime to the series for which a shared offender is most likely. To allow a directly comparable evaluation of the accuracy of our approach with respect to the earlier results (Santtila *et al.*, 2008), we analysed the accuracy of the model using a so-called *leave-one-out cross-validation* (LOOCV) method, where we classified each crime case separately to a series using the rest of the crimes as training data in a supervised classifier.

We investigated the effect of the individual behaviours on the classification accuracy using two different approaches. In the first method, we tested each behaviour variable for whether it represented purely *noise* with respect to the classification. In the second approach, we removed the behaviours one by one from the model, by always choosing the behaviour that had the smallest effect on the classification accuracy, as measured by LOOCV. The model and the related computational methods are described in detail in Appendix S1.

Results

Classification accuracy

Using all behaviour variables as evidence, the Bayesian model classified correctly 83.6% of the cases in the LOOCV scenario. This is notably higher than what would be expected by chance (5.3%). It is also higher than correct classification of 62.9% reached by Santtila *et al.* (2008) using dimensions of behaviour to link the same offences.

The above rate of classification was reached when single homicides were excluded from the full-length series. (The median number of victims in the series was 5.) Linking crimes would be especially valuable while the number of victims is still low. At the same time, linking would be more challenging as fewer known cases translates into less information about what behaviours are typical for a certain series. Therefore, the level of LOOCV accuracy was also tested with data sets where only one or two crimes from each series were present in the training data. Since the possible number of such data sets is astronomic, we simulated 10,000 sets for scenarios of both *one previous case* and *two previous cases* available in the training data. This simulates crime linking in the early stages of a series, where investigators know of only a single previous homicide that might be linked to a new offence, or where investigators are confident that two previous homicides are linked and want to determine if a new homicide also might have been committed by the same offender.

In the one previous case scenario, that is when only one crime was present in the training data, 59.0% of the cases were correctly classified by the Bayesian model. When two previous homicides were allowed as available training data, the correct classification rate increased to 69.2%. Note that for the series to be included in the two-case scenario, it has to contain a minimum of three cases. Since three series in the data contain only two cases, then the number of possible series to which a case can be linked to decreases correspondingly and the chance expectation of correct assignment is elevated to 6.3%.

Effect of individual behaviours

The effect of the individual behaviours on the classification accuracy was investigated using the full-length series. As a whole, no variables were judged to be pure noise with respect to the prediction of the correct series. All variables thus, provided information useful for the linkage analysis.

Table 2. The 15 variables to be excluded last from the model when the variable affecting correct classification least was excluded at every step

Removed as number	Variable	Presence in valid observations (%)	Number of missing observations	Correctly assumed links before exclusion (%)
92	Offender had acted, during or after the offence, to reduce evidence	58.6	0	21.6
91	Point of fatal encounter and murder scene were the same place	58.6	0	29.3
90	Victim had injuries to the throat	38.1	3	44.0
89	Body found at the scene of the murder	74.1	0	54.3
88	Body found in an inner city area	32.5	2	59.5
87	Victim found with genitals exposed	12.1	9	64.7
86	Victim had injuries to several parts of the body	14.9	2	66.4
85	Firearm used in the killing	47.8	1	69.0
84	Victim forcibly moved while still alive	7.8	1	73.3
83	Victim had injuries to only one part of the body	14.0	0	73.3
82	Body found outside	63.8	0	73.3
81	Body covered with something	8.6	0	75.9
80	Victim strangled using bare hands	3.5	3	77.6
79	Killing occurred in association with a rape	15.5	1	80.2
78	Vaginal penetration achieved or attempted	19.3	2	83.6

Figure 1 presents the percentage of correctly assumed links as the behavioural variables that had the smallest effect on the classification accuracy were removed one by one. The LOOCV accuracy remained constant, and at some points even increased slightly (highest accuracy was 87.9%), until only 15 variables were present in the model. When 15 variables were used, the classification accuracy was equal to the starting accuracy (83.6%) and a consistent decrease in accuracy occurred only as the 15 last variables were removed. The results indicate that while most of the behaviours contain relevant information for classification purposes, they are overlapping in the sense that approximately 15 behaviours contain most of the information needed for obtaining the correct classification. These behaviour variables are presented in reverse order of exclusion in Table 2, so that the variables to be excluded last are reported first. It should

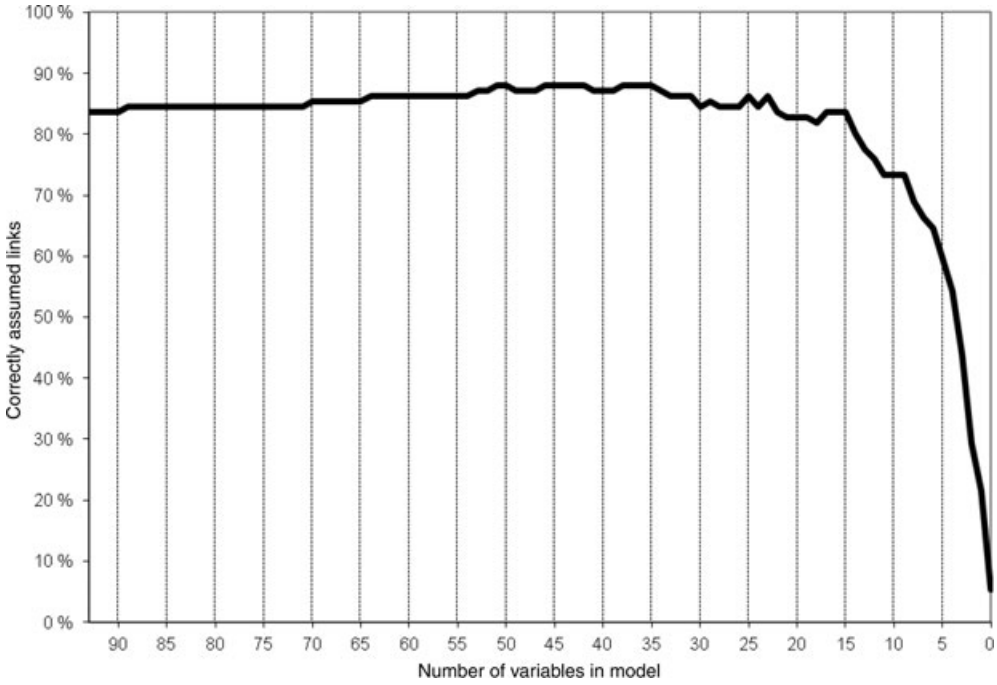

Figure 1. Correct classification as a function of number of behavioural variables in the model. At every step, the variable affecting correct classification least is excluded.

not be concluded that the order of their exclusion corresponds to an absolute inverted order of their utility for crime linking. The amount of contribution of a variable to the classification accuracy depends partially on the overlap in the information content with other used variables. This means that a number of different sets of linking variables could be considered.

However, even when interpreted cautiously, the variables excluded last in Table 2 do represent individual behaviours that appear particularly useful in crime linking. Table 2 also lists the number of missing observations in the sample for the respective variable. It may be noted that with the exception of the variable *victim found with genitals exposed* (nine missing observations), none of the variables listed among the 15 variables to be excluded last, had more than three missing observations. The average number of missing observations for all variables in the sample was 7.7 ($SD = 10.7$). The possible effect of the number of missing observations on the contribution to linking effectiveness is considered in the discussion.

Discussion

Classification accuracy

The results are encouraging when it comes to the usefulness of behavioural crime linking of serial homicide. The model presented here had a very high rate of classification accuracy of 83.6%. It has to be born in mind that the chance expectancy is as high as 5.3%. In real-world application of crime linking the number of possible links is much higher; and as the chance expectancy drops, the classification accuracy is also likely

to drop somewhat. Nonetheless, these results strongly suggest that adequately analysed individual behaviours provide information that is useful in behavioural crime linking. We can conclude that Bayesian reasoning provided an adequate approach to analysing individual behaviours and to linking cases of homicide. Furthermore, the model had a high rate of classification accuracy at scenarios that represented early stages of the series, which highlights the usefulness of the linking model. Solving the case early is paramount, and early in the series is also when the added information provided from a crime-linking analysis is most helpful.

It needs to be pointed out that the Bayesian model was only allowed to identify the most likely series for the particular crime. That means for high accuracy to be obtained the model has to be able to differentiate between the correct series and other rivalling series with potentially high behavioural similarity to the crime in question. As shown by the results, the Bayesian model was able to do so.

The increased linking effectiveness by the introduced Bayesian method is noteworthy. This approach allows for accounting for even minor variations in behaviour and judging joint information automatically in a probabilistic classification framework. Such an effective merging of information might explain the apparent superiority of this approach over the earlier used dimensional approach. The additional uncertainty introduced by missing observations could here be appropriately accounted for, which was not possible with the statistical methods used by Santtila *et al.* (2008). While the linking effectiveness reached in the present study exceeds considerably the linking effectiveness by Santtila *et al.*, it is still possible that themes of MO behaviours could under some circumstances prove to be more useful in crime linking than individual behaviours. Dimensions with higher reliability than those used by Santtila *et al.* might possibly be even more effective in linking crimes. Also, a considerable strength of the approach in this study is the ability to account for the information that is specific for these training data. If reliable dimensions are captured these might prove more effective when trying to link cases in a different setting or even as new homicides are committed.

The high linking effectiveness might also be explained by the possibility that cases of serial homicide are particularly suitable for crime linking. The linking effectiveness in the present study as well as in the study by Santtila *et al.* (2008) is much higher than that obtained in a similar study by Santtila *et al.* with serial stranger rapes (Santtila *et al.*, 2005). That study demonstrated a correct classification rate of 26%. The differences in linking effectiveness might be explained by a more consistent behaviour among serial killers (Santtila *et al.*, 2008). The higher consistency, in turn, might be due to a more severe psychopathology, reflected in compulsive behaviour. Personality disorders have been found to be more prevalent in serial killers than offenders in single homicide cases (Harbort & Mokros, 2001). Another suggested reason for higher consistency in cases of serial homicide is a lesser degree of offender–victim interaction (Santtila *et al.*, 2008). A suggested source of inconsistency in criminal behaviour is the unpredictable acts of the victim (Alison *et al.*, 2002). Since the victim is often killed early in the course of events, the offender has more degrees of freedom for applying the behaviours that will stay similar from crime to crime.

Effect of individual behaviours

While a Bayesian model adequately handles a large number of variables, for crime linking to have maximum usability for investigators, the number of recorded variables needs to be limited. The results show that there is considerable overlap in the relevant

information the behaviour variables provide, and consequently, very minor gains in linking effectiveness were obtained by using more than 15 behaviours in the analysis. In relation to the task, to choose the most likely out of 19 possible series, a model of 15 variables is still quite complex. However, the results suggest that the information gathered does not have to be massive for crime-linking purposes. Linking analyses may prove to be very effective when based on a relatively small number of carefully selected behaviour variables.

The results suggest that a large number of generic behaviour variables may be considered for crime linking, and the variables in Table 2 should not be considered a definite list. A selection criterion that might prove to be fruitful is reliability of coding. Only one of the behavioural variables among the 15 variables to be excluded last had more than 3 missing observations. Furthermore, the behaviour variables were almost exclusively crime scene observations on which there is unlikely to have been disagreement between two distinct investigators. There is only one exception to this rule, which corresponds to whether or not the offender had acted, during or after the offence, to reduce evidence. It could be expected that the presence or absence of this behaviour is difficult to code by an observer, since it contains a certain amount of subjective judgement. In the present study, the applied coding scheme seemed thus to work well for this behaviour and no observations had to be coded missing.

Limitations

A potential explanation for the high linking effectiveness and a limitation of the study that needs to be considered is the effect of the data material. Two studies have now shown considerable linking effectiveness with the same data material. The collection of data is affected by the fact that it is done *post hoc*. Both studies have been explorative in nature and the suggested effectiveness of the approaches to link cases of serial homicide should be confirmed by replicating the results with other data sets. A possible source of error in the collection and coding of the data is that investigators could not be made unaware of the fact that homicides were committed by the same killer. In the present study, this was made impossible by the fact that only one person could read the court transcripts of a particular series. This has to be considered, since the feasible effect of investigators having this awareness is higher consistency. Objectivity in this regard is not easily achieved when collecting crime scene data and data sets lacking this potential source of error are therefore difficult to obtain. Therefore, Zappalà, Santtila, Bosco, Mokros, and Pakkanen (2010) investigated this type of coding bias and found it not threatening the conclusions of studies where coders could not be unaware of the true links between cases.

Yet another potential source of error that might have a positive effect on linking effectiveness is the fact that only solved cases can be included in the analyses. Bennell and Jones (2005) pointed out that it is possible that solved cases show higher levels of consistency and inter-personal variation in behaviour since these are characteristics that hypothetically make the cases easier to solve.

There are also potential sources of error that would add noise to the data rather than producing higher linking effectiveness. Homicide investigation protocols usually constitute massive amounts of paperwork and, as a result, are subjected to the risk of making unintentional errors. Furthermore, the data were collected for other purposes than research, mostly investigative. Potential errors in the original reporting of the data have to thus be considered. Homicides are generally investigated thoroughly but the

lack of standardized police protocols might damage the reliability of the data. Bennell and Jones (2005) pointed out that while these kinds of sources of errors reduce the probability of finding significant results it also has its benefit. Data extracted from genuine police records would likely demonstrate better validity as they are "based on forms of information upon which the police actually operate" (p. 30). Finally, it should also be kept in mind that even if all offenders were convicted in court, the verdict is always a legal judgement and does not entirely exclude the possibility of the suspect being innocent.

Conclusions and suggestions for future research

All the above limitations taken into consideration, the results should not be underestimated. In the absence of any physical evidence or witness statements, using behavioural information in order to explore possible linkages between homicides may be of great value in practical police work. Linking crimes successfully increases the likelihood of catching the offender as well as ruling out innocent suspects, thus making investigations more effective (Grubin *et al.*, 2001). The results in the present study show that analysing individual characteristics of a murder using Bayesian reasoning can provide a useful basis for crime-linkage analyses.

Several approaches could be taken to examine the generalizability of the study. First, the method could be tested with a different data set, as mentioned earlier. One of the benefits with the method developed in the present study is that it is easily replicated in a different context. It is possible that there can be different levels of consistency and inter-individual variation for the behaviours among offenders in other parts of the world than what was observed in this Italian sample. These differences can be circumvented by using the area-specific data set as training data. The generalizability of the study could also be examined by choosing not to circumvent such differences. Instead, the distributions for the individual behaviours discerned from this study can be used as training data for a linkage analyses in a different context. Through this approach, it would be possible to examine if there exist some behaviours that have high levels of consistency and inter-individual variation among serial killers cross-culturally. It would also allow for examining whether training data from one data set can be used in a context where an extensive data set has not yet been collected.

The present study could also be replicated with a new data set also including single homicides that do not belong to a series. In the Bayesian linking model, the probability of a homicide case not belonging to any considered series can be taken into account to avoid incorrect linking, which would result from forcing a case to some of the existing series. The utility of the model in an even more realistic scenario could thereby be examined. The use of Bayesian reasoning also allows for a further development of the model to include information provided by physical evidence in the cases where physical evidence is not complete. Finally, the utility of the model for other categories of crime could be examined.

Most of all, further research, on what individual behaviours best link serial homicide, should be conducted. The results of the present study suggest that the observation of roughly 15 individual behaviours provide most of the useful information that can be obtained by recording individual behaviours. Careful identification of which particular behaviours tend to best link offences would facilitate any attempt to create a standardized form for collecting and recording crime scene data. This, in turn, is very likely to increase the reliability of the collected data, and thereby, increase linking effectiveness.

Furthermore, it would enable the use of a computerized database to which various Bayesian models could be applied. A number of computerized databases on offences and offenders have been established, ViCLAS (Violent Crime Linkage Analysis System) being the most recognized and internationally used (Collins, Johnson, Choy, Davidson, & MacKay, 1998; Grubin *et al.*, 2001). However, because databases such as ViCLAS lack a theoretical basis, they have not advanced our knowledge as far as they otherwise might have done, and thus serve mainly as information management tools. The use of standardized forms in conjunction with a centralized database is likely to considerably facilitate police investigations. The results from the present study and the suggested future studies have the potential of contributing significantly to such developments.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:
Table S1. All behavioral variables in the study in order of exclusion from the model.
Appendix S1. Bayesian model and the related computational approach.
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