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Establishing the most appropriate databases for addressing source level propositions

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Previous papers in *Science & Justice* have described the work of the Case Assessment and Interpretation (CAI) project that has been running for several years within the Forensic Science Service (FSS). The principles of the CAI model, which have developed through casework, are the foundation of a balanced, robust and logical approach to interpretation. The question arises frequently as to what is the most appropriate database that should be available to assist in assigning a value to a given probability. In this paper we present a set of guidelines in the form of flowcharts and explore them within the context of a range of case examples.

Des articles précédents dans *Science & Justice* ont décrit le travail de l'évaluation du projet de l'évaluation des cas et leur interprétation (CAI) qui s'est poursuivi durant de nombreuses années au sein du Forensic Science Service (FSS). Les principes du modèle CAI, qui ont été développés au travers de cas sont les fondements d'une approche équilibrée, robuste et logique de l'interprétation. La question qui se pose fréquemment concerne la base de données la plus appropriée qui devrait être disponible pour aider à déterminer une valeur à une probabilité donnée. Dans cet article, nous présentons un jeu de conseils sous la forme de schémas.que nous explorons dans le contexte d'un certain nombre d'exemples de cas.

Frühere Veröffentlichungen in *Science & Justice* haben die Arbeit des seit mehreren Jahren innerhalb des Forensic Science Service (FSS) laufenden 'Case Assessment and Interpretation' (CAI) Projekts beschrieben. Die Prinzipien des durch Arbeit an konkreten Fällen entwickelten CAI-Modells bilden die Grundlage einer ausgewogenen, robusten und logischen Herangehensweise an die Befundinterpretation. Eine häufig auftretende Frage ist, welches die am besten geeignete Datenbank ist, um einer gegebenen Wahrscheinlichkeit ein bestimmtes Gewicht zuordnen zu können. In diesem Artikel präsentieren wir eine Reihe von Richtlinien in Form von Flussdiagrammen und untersuchen diese im Zusammenhang mit mehreren Fallbeispielen.

Se han descrito en publicaciones anteriores de Science and Justice el trabajo del proyecto de Valoración de casos e Interpretación (CAI) que se lleva haciendo desde hace varios años en el Forensic Science Service (FSS). Los principios del modelo CAI que se han desarrollado a través del trabajo rutinario son la base de un equilibrado, robusto y lógico enfoque a la interpretación. La pregunta que surge más frecuentemente es cual la base de datos más apropiada que debería estar disponible para ayudar a la asignación de un valor para una determinada probabilidad. En este trabajo presentamos un conjunto de directrices en la forma de gráficos y los exploramos en el contexto de un amplio rango de casos.

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Key words Forensic science, probability, statistics, likelihood ratio, Bayes, databases, glass, footwear, DNA, drugs.

Introduction

Previous papers in this journal [1,2,3,4,5] have explained the evolution of the Case Assessment and Interpretation (CAI) project within the Forensic Science Service (FSS). This paper has been prompted by the need to address an issue relating to the use of databases that has arisen in the consideration of several different evidence types. Whereas we feel that we have been able to address the issue on a case-by-case basis it is desirable to formulate some kind of generic solution. In essence, the problem is as follows. Given that some kind of correspondence has been found between material associated with a crime scene and material associated with a suspect for the crime, what is the most relevant kind of database that should be used to form an assessment of the weight of evidence? For example, would we prefer: a database of observations made on material left at crime scenes?; or a database of observations made on suspects for crimes of this nature?; or is there some other more appropriate survey?

We will approach such questions by means of three flow charts, which we explain and illustrate by a series of case examples. First, it is necessary to establish some basic notation.

Notation and preliminary evaluation

In the second CAI paper [2] we explained the concept of the *Hierarchy of Propositions* and, at that time, we adopted the broad categories of *Offence, Activity* and *Source* level propositions. For the purposes of the present discussion we will confine ourselves to the consideration of source level propositions and, in each of the case examples, A and $\bar{A}$ will denote propositions that represent prosecution and defence positions respectively. These will be of the form:

A: the two samples came from the same source

$\bar{A}$: the two samples came from different sources.

In each of the cases, the task of relating the source level propositions to the offence will be left to considerations outside the role of the scientist. Nevertheless, for the purpose of our discussion, we will assume that in each case there is other evidence to show that the crime sample is indeed closely associated with the crime that has been committed.

Much of the treatment in previous papers has centred on the likelihood ratio, in the form:

$$LR = \frac{\Pr(E|A,I)}{\Pr(E|\bar{A},I)}$$

Where: E denotes the scientific evidence; and I denotes what we have increasingly referred to as the *framework of circumstances*. For the present paper, we find it helpful to develop and change this notation somewhat. In each of the case examples, we will replace the letter E with two letters that represent sub-sets of E: we will use O_c to denote observations on a sample of material from the scene of a crime and O_d to denote observations on a sample of material from a suspect/defendant.

The letter I implies a connotation of "information" that is not strictly appropriate for the framework of circumstances. For example, the scientist might be called on to present an assessment on the basis of assumptions – put forward either by defence or prosecution – that might not be supported by formal evidence. So, in this paper, we will use the letter F to summarise the framework of circumstances and, as with O_c and O_d, we will tend to distinguish between two components:

F_c: the circumstances surrounding the crime, including evidence about the nature of the true offender;

F_d: those aspects that are relevant to the defendant.

Then we consider:

$$LR = \frac{\Pr(O_c,O_d|A,F_c,F_d)}{\Pr(O_c,O_d|\bar{A},F_c,F_d)} \qquad (1)$$

Observations and matching

It is worth digressing at this juncture to explain a little more what we mean by "observations" in the current context. Each of the two samples that the scientist examines is capable of revealing, in principle at least, an infinite amount of detail, depending on the methods of observation that are employed.

It is helpful to consider the detail as falling into two components: information and noise. The information component is that which is helpful in addressing the propositions of interest: the noise component is a nuisance that not only does not help address the proposition but may also serve to obscure the information component. In this paper we will refer to the *information content* of a sample and by this we mean its capacity to generate meaningful observations in the sense of those items of detail which the scientist will record for the purpose of comparing the two samples. Each observation, in the judgement of the scientist, will have the potential, if it can be compared with a corresponding observation in the other sample, of making a contribution to the overall LR that is greater than one (i.e. a similarity) or less than one (i.e. a difference). Ideally, we would envisage the scientist as recording sets of observations for the two samples separately, prior to the comparison stage.

So, we define "observations" as those aspects of the detail revealed from the two samples that are recorded by the scientist for the purpose of addressing the two propositions A and $\bar{A}$. We give some examples.

Glass: the samples to be compared might consist of a fragment of glass recovered from the clothing of a person suspected of breaking a particular window and a control sample of glass taken from that window. Here the observations may consist of measurements of refractive index and elemental composition.

DNA: current technology does not enable us to sequence completely a DNA molecule and our observations for each of the samples will consist of a "profile" constructed from the properties (alleles) of a small number of separate locations (loci) within the molecule. The two samples will be compared by means of their respective profiles.

Footwear: here we might compare a mark made in dust at the scene of a crime against a test print made from a shoe taken from a suspect. The observations may consist of features that represent a manufacturer's sole/heel pattern and other features related to wear and/or damage.

Fingerprints: it will most often be the case that the comparison is between a high quality inked impression of a suspect's finger and a poor quality, fragmentary scene mark, subject to movement, distortion and interfering detail from the substrate. The observations will principally consist of friction ridge features – such as ridge endings and bifurcations – and the skill of the expert consists of recognising those aspects of the scene mark that are relevant to the comparison and those that are not.

Handwriting: a passage of handwriting of unknown, or disputed origin, will be compared with specimens of handwriting from one or more known individuals. The observations will include general features, such as slope and fluency, as well as design of individual characters. Deliberate disguise may be one complicating feature of such a comparison.

There will often be an imbalance in the information content in the sense that more observations will be possible on one of the samples than on the other. For example:

Glass: if there is only one recovered fragment then it may be practical only to take one measurement of a particular property, whereas there may be an extensive control sample from the broken window on which a virtually limitless set of observations may be made.

DNA: a carefully taken and preserved sample from a suspect should reveal a full profile, whereas a degraded sample from a crime scene may reveal only a partial profile.

Footwear: the scene mark may consist of one region of the sole, whereas the test mark will be of the entire sole.

Fingerprints: here there will, typically, be far fewer ridge detail features discernible in the scene mark than in the control mark from the suspect.

Handwriting: a suspect might be prepared to furnish the examiner with copious examples of his writing but the questioned material might consist of just a few letters.

When the comparison is made, some of the observations from the sample with greater information content will not be used directly. Nevertheless, as we see in case study 7, even if not used in the comparison, such observations may still contribute to the overall assessment of the weight of evidence.

When the pairs of observations that can be compared are brought together, some kind of combined assessment must be made. In principle, this should be a single continuous process but often it is convenient to see it as falling into two stages. This is particularly the case with the DNA example where first the scientist looks for a correspondence between the alleles in the two samples and, in the event that they do correspond, carries out a calculation of the overall *LR* – with reference to the most appropriate database. In the glass case, a two stage approach incorporates some kind of statistical significance test. If there is a correspondence, in the sense of the test not proving significant, then a calculation of the *LR* will be carried out, again by reference to a database of some kind. In other cases there may not be such a clear dichotomy but, for the purpose of the present discussion, it will be helpful to discuss the problems in the sense of a two-stage approach. This will provide a justification for Assumption 3, below: this will simplify the discussion without creating a serious loss of generality.

We will, therefore, use the term "match" in the sense of a recognition by the scientist of some kind of consistency between the two sets of observations that is in accord with what would be expected if the two samples had, indeed, come from the same source. In some cases, the match will be evident even to unskilled observers; in others it may be heavily dependent on the personal judgement of the scientist. For example, a comparison between two DNA profiles might reduce simply to recognising that they have the same pairs of alleles at all of the scored loci. In a handwriting comparison, on the other hand, the assessment of all of the similarities and differences will be a matter for skilful judgement by the expert.

We must emphasise that we do not equate the notion of matching to that of concluding that two items have come from the same source: the establishment of a match is the first stage, it is in the second stage that we address the issue of identity of source. We will consider only those cases in which there is a match of some kind and our discussions will concentrate on the second stage, through evaluation of the *LR*.

It is worth emphasising that we are following this kind of two-stage approach because it will enable us to expose the issues of interest more clearly. Ultimately, we would hope to see that all forensic comparisons would be based on a continuous methodology. That developed for glass evidence interpretation and described by Curran *et al.* [6] is a model in that regard. The underlying issues relating to databases are essentially the same.

Assumptions

Any scientific model is based on a series of assumptions and there is always a trade-off to be made. Appropriate assumptions render the subsequent mathematical treatment more tractable and easier to follow; yet they inevitably restrict the scope of applicability of the model and its relevance to real life situations. For our treatment, we will make three assumptions which, we believe, will enable us to expose important key issues yet without the cost of limiting the applicability of the model too severely.

Assumption 1: if $\bar{A}$ is true then O_c and O_d are independent of each other.

This amounts to assuming that, if the two samples have, in fact, come from different sources then knowledge of one of them does not influence our uncertainty in relation to the other. For example, in a footwear case, if the mark at the crime scene was not left by the defendant, then knowing that the defendant had a pair of Reebok Classics does not affect our assessment of the probability that the crime mark would also be of a Reebok Classic.

Assumption 2: if $\bar{A}$ is true then O_c is independent of F_d and O_d is independent of F_c.

This is the assumption that, if the two samples have, in fact, come from different sources then: first, the framework of circumstances in relation to the defendant does not influence our uncertainty in relation to the observations on the crime mark; and second, the framework of circumstances in relation to the crime does not influence our uncertainty in relation to the observations on the sample from the defendant. For example, if a witness to a rape said that the offender was Afro-Caribbean, this does not influence our probability that the defendant has a particular genotype, if $\bar{A}$ is the case.

Remembering that we are considering only those cases where is a match between the two sets of observations, we make the next assumption:

Assumption 3: if A is true then the probability of the set of observations from the sample with the smaller information content, given the set of observations from the sample with the greater information content, is one.

The following examples serve to illustrate this assumption

Fingerprint comparison
The control print from the defendant may exhibit a hundred or more ridge details. The crime mark, on the other hand, might reveal only, say, 10. If these correspond to a subset of the ridge details in the control print (and if there are no unexplainable differences) then the expert will conclude a match. Assumption 3 here means saying that, if the crime mark was left by the defendant then the configuration of those 10 points is just how the expert would consider them to be.

DNA profiling
Imagine that the sample from the defendant yields a full profile whereas that from the crime sample is partial. Those features in the crime profile that can be compared, O_c, however, match those in the defendant's profile, O_d. If A is the case, then the features contained in O_c are exactly what would be expected, given O_d.

Simplification of the LR

If the three assumptions are valid then we show in Appendix 1 how the *LR* simplifies to one of the following two forms, depending which of the two sets of observations has the greater information content.

$$LR = \frac{1}{\Pr(O_c|\bar{A},F_c)} \cdot \frac{\Pr(O_d|A,F_c,F_d)}{\Pr(O_d|\bar{A},F_d)} \qquad (2a)$$

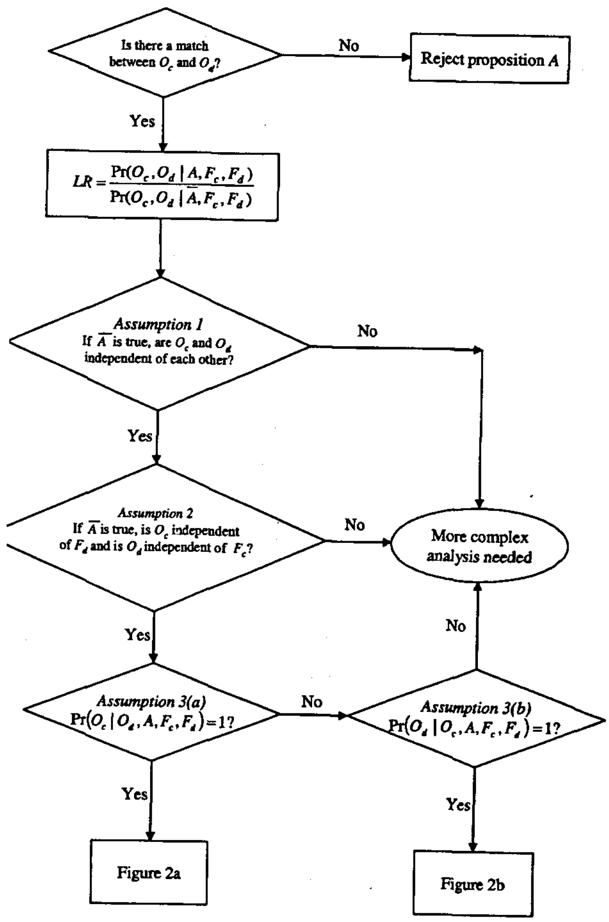
$$LR = \frac{1}{\Pr(O_d|\bar{A},F_d)} \cdot \frac{\Pr(O_c|A,F_c,F_d)}{\Pr(O_c|\bar{A},F_c)} \qquad (2b)$$

The choice depends on which, if either, of the two sets of observations contains the greater amount of information. If they both contain the same amount, then one can proceed using either. We note that they correspond to what has been referred to as the *suspect* and *scene* anchored approaches, respectively – note, in particular, Stoney [7].

Databases

The probabilities in (2a) and (2b) suggest, in principle, the relevance of the following kinds of surveys and consequent databases.

Figure 1 Consideration of the validity of the assumptions.



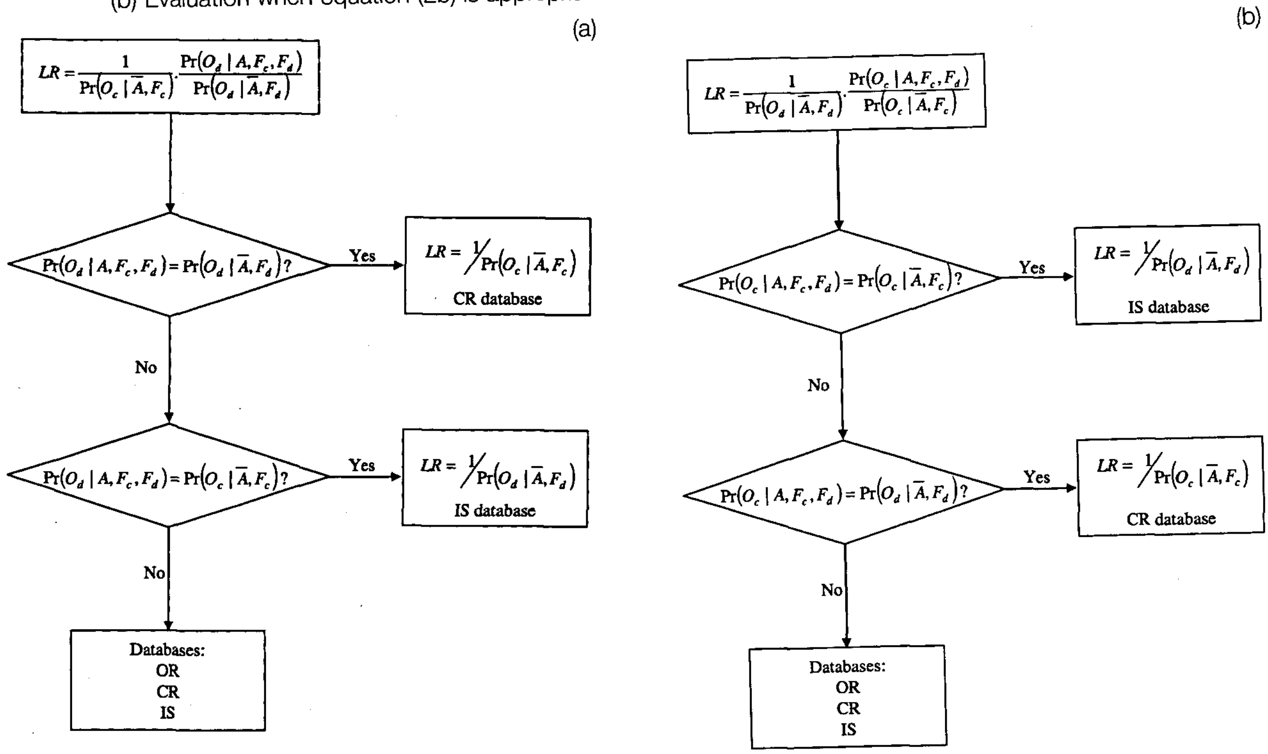
$Pr(O_d|A,F_c,F_d)$: the probability that the observations O_d would be made in relation to the defendant given: A that the crime and suspect materials have the same source; F_c, what we know about the crime; and F_d, what we know about the defendant. This would imply the relevance of surveys made on people who are known to have some kind of association with a crime scene of the relevant kind. Such a survey would form the basis of an "offender related" (OR) database.

$Pr(O_d|\bar{A},F_d)$: the probability that the observations O_d would be made in relation to the defendant given: $\bar{A}$, that the crime and suspect materials do not have the same source; and F_d, what we know about the defendant. This would imply the relevance of surveys made on people who are known not to have an association with a crime scene of the relevant kind but yet have come to the notice of the police. Such a survey would form the basis of an "innocent suspects" (IS) database.

$Pr(O_c|\bar{A},F_c)$: the probability that the observations O_c would be made in relation to the crime given: $\bar{A}$, that the crime and suspect materials do not have the same source; and F_c, what we know about the crime. This would imply the relevance of surveys of material associated with crimes of the appropriate nature. Such a survey would form the basis of a "crime related" (CR) database.

$Pr(O_c|A,F_c,F_d)$: the probability that the observations O_c would be made in relation to the crime given: A, that the crime and suspect materials have the same source; F_c, what we know about the crime; and F_d, what we know about the defendant. Depending on the relative dominance of the two classes of circumstantial information this may imply reference to either a CR database or an OR database.

Figure 2 (a) Evaluation when equation (2a) is appropriate.
(b) Evaluation when equation (2b) is appropriate.



Assistance by flow charts

We present three flow charts that represent a generic approach to the class of cases that satisfy the assumptions that have been made. The main purpose of Figure 1 is to provide an aide memoire for the assumptions.

First, we check that a match exists between the two sets of observations and assume that, following a two stage approach, if there is no match then proposition A is rejected. Otherwise, it is necessary to evaluate the LR, equation 1. The first two assumptions are in the first two diamond shaped nodes and, if either cannot be made then some other kind of analysis, not covered in this paper, will be needed. The next two diamond nodes incorporate the third assumption and direct us to equation 2a or 2b, depending on which of O_c, O_d has the greater information content.

The next two figures guide us through the evaluation, depending on which of equations 2a or 2b is the more appropriate. We will illustrate the process by means of the following case examples.

Case example 1

A sample of DNA has been recovered from the scene of a crime and the defendant has provided a control sample. Both crime and defendant samples are found to be the same genotype G; i.e. $O_c = O_d = G$. For simplicity, we assume that there is no suggestion of there being any close relatives of the defendant as potential alternative suspects for the crime. The defendant is Caucasian and an eyewitness said that the offender was Caucasian. We take it that the circumstances are such that there is no doubt that the DNA was left by the offender.

We consider the following propositions:

A: the DNA from the crime scene came from the defendant

$\bar{A}$: the DNA from the crime scene came from some unknown person.

F_d in this case is the information that the defendant is Caucasian. F_c is the information that the eyewitness said that the offender was Caucasian.

We start at the top of Figure 1 and, given that there is a match, we proceed to the first question, which relates to the validity of assumption 1.

Assumption 1: We can rephrase the question for this particular case as follows: if $\bar{A}$ is the case, can we assume that knowledge that the defendant is genotype G (O_d) does not influence our uncertainty as to whether DNA from some unknown person would be genotype G (O_c)? Actually, this is only approximately valid and the current accepted method for calculating the match probability in DNA profiling cases (see, for example, Evett and Weir [8]) is based on the premise that, if the defendant and the "unknown person" should be considered as coming from the same population subgroup then the knowledge of the defendant's genotype influences, albeit in a small degree, the uncertainty relating to the genotype of the unknown person. The principles of the present discussion, however, will emerge more clearly if we adopt the assumption.

We now proceed down the flowchart to:

Assumption 2: this appears quite reasonable in this case. If $\bar{A}$ is true, then knowledge about the defendant's ethnic group (F_d) does not influence our uncertainty with regard to the genotype of the crime stain (O_c). Furthermore, knowledge about the ethnic group of the person who left the crime stain (F_c) does not influence our uncertainty with regard to the genotype of the defendant (O_d).

We now come to a question that relates to assumption 3.

Assumption 3: if the defendant left the crime stain, are we certain that both the defendant and the crime stain would be found to be the same genotype? This is the case, if we assume a zero chance of a laboratory profiling error. In other words, if A is the case then, given that $O_d = G$, we would expect O_c to be G with probability 1. So the answer to this question is "Yes" and we are directed to Figure 2a. (In this particular case, because the information contents of the two sets of observations are the same, we would reach the same final answer if we followed Figure 2b.)

We can write the LR in the first box of Figure 2a as:

$$LR = \frac{1}{\Pr(O_c=G|\bar{A},F_c)} \cdot \frac{\Pr(O_d=G|A,F_c,F_d)}{\Pr(O_d=G|\bar{A},F_d)}$$

Consider the first question, in the first diamond of the flowchart. We need to address two probabilities. We can express the first as follows:

$\Pr(O_d=G|A,F_c,F_d)$ What is the probability that the defendant would be genotype G given: F_d, that he is Caucasian; A, that he was the person who left the crime stain; and the eyewitness evidence F_c that the person who left the crime stain was Caucasian?

Once we know that the defendant is Caucasian and that he left the crime stain, then the eyewitness evidence that the person who left the crime stain was Caucasian becomes redundant. So we rewrite the question as:

$\Pr(O_d=G|A,F_d)$ What is the probability that the defendant would be genotype G given: F_d, that he is Caucasian; and A, that he was the person who left the crime stain?

The second question is:

$\Pr(O_d=G|\bar{A},F_d)$ What is the probability that the defendant would be genotype G given: F_d, that he is Caucasian; and $\bar{A}$, that he did not leave the crime stain.

These two probabilities suggest the need, in principle, for two different kinds of database:

For the first, a database from a survey of people of similar characteristics to the defendant who have been known to leave crime stains. This would be what we have called an "offender related" (OR) database.

For the second, a database from a survey of people of similar characteristics to the defendant who have come to police notice, but are innocent of the crimes of which they are suspected. We would be what we have called an "innocent suspects" (IS) database.

For the present case, we know that it is widely believed that there is no association between "tendency to commit crime" or "tendency to come to police notice" and DNA profiling genotype. We therefore consider it reasonable to accept that the equality in the first diamond Figure 2a holds and we are directed via the "Yes" arrow to:

$$LR = \frac{1}{\Pr(O_c=G|\bar{A},F_c)}$$

To evaluate this, we use a database that is relevant to genotypes in the population that is implied by the information about the crime: in this case it would be based on a survey of crime scene stains that were known to be left by Caucasians. This is what we have referred to as a "crime related" (CR) database.

Case example 2

This case is the same as case example 1 in all respects save that the eyewitness who saw the person who committed the crime (and left the crime stain) said that the person he saw was Afro-Caribbean: the defendant is Caucasian, as before.

The two propositions to be addressed are as in the previous case. Clearly, the eyewitness' evidence will influence the prior odds of the jury in relation to the two propositions. The extent of the influence will depend on how reliable the jury consider the eyewitness to be. We do not consider that issue here and concentrate solely on evaluating the LR. First we need to consider the validity of the core assumptions, referring to Figure 1.

> *Assumption 1*: this is clearly valid: if $\bar{A}$ is the case then knowledge that the Caucasian defendant is genotype G (O_d) does not influence the uncertainty in relation to whether or not the crime stain would be genotype G (O_c).

> *Assumption 2*: once again, if $\bar{A}$ is the case then knowledge about the defendant's ethnic group (F_d) does not influence our uncertainty with regard to the genotype of the crime stain (O_c). Furthermore, knowledge about the ethnic group of the person who left the crime stain (F_c) does not influence our uncertainty with regard to the genotype of the defendant (O_d).

> *Assumption 3*: this is the same as the corresponding (reasonable) assumption in the first case study.

Once again, we are led to Figure 2a. The question in the first diamond directs us to considering the following probability:

> $\Pr(O_d=G|A,F_c,F_d)$ What is the probability that the defendant would be genotype G given: F_d, that he is Caucasian; A, that he was the person who left the crime stain; and the eyewitness evidence F_c, that the person who left the crime stain was Afro-Caribbean?

This is an interesting question because of the apparent contradiction that is embodied in its conditioning. We can resolve it as follows. It will simplify the notation in our analysis if we define Caucasian as ethnic group 1; and Afro-Caribbean as ethnic group 2. For simplicity, we assume that the population contains only these two ethnic groups – but the principles of the analysis can be extended to wider diversity.

The eyewitness may, or may not, be correct and, to reflect this, it is helpful at this stage to introduce two additional propositions that represent the true, though unknown, state:

R_1: the person who left the stain was ethnic group 1

R_2: the person who left the stain was ethnic group 2.

Then we can write out the probability of interest, using the "law of total probability", as follows:

$$\Pr(O_d=G|A,F_c,F_d)=\Pr(O_d=G|R_1,A,F_c,F_d)\Pr(R_1|A,F_c,F_d)+\Pr(O_d=G|R_2,A,F_c,F_d)\Pr(R_2|A,F_c,F_d)$$

But, if A is the case, then the person who left the crime stain (the defendant) must have been ethnic group 1. So $\Pr(R_1|A,F_c,F_d)=1$ and $\Pr(R_2|A,F_c,F_d)=0$ and the probability we seek is $\Pr(O_d=G|R_1,A,F_c,F_d)$. Now, if R_1 is true, the eyewitness evidence in F_c is irrelevant and we can simplify this to $\Pr(O_d=G|A,F_d)$:

> What is the probability that the defendant would be genotype G given: F_d, that he is Caucasian; and A, that he was the person who left the crime stain? In principle, we would refer to a Caucasian OR database.

The second probability to be addressed in relation to the first diamond is $\Pr(O_d=G|\bar{A},F_d)$:

> What is the probability that the defendant would be genotype G given: F_d, that he is Caucasian; and $\bar{A}$, that he did not leave the crime stain. In principle, we would refer to a Caucasian IS database.

These are exactly the same two questions as in Case example 1 and, as in that example, we argue that it is reasonable to proceed as though their answers are the same. So, once again, we arrive at:

$$LR = \frac{1}{\Pr(O_c=G|\bar{A},F_c)}$$

However, there is the important difference that F_c includes the information that the eyewitness said that the offender was Afro-Caribbean. Presumably, given that the defendant did not leave the crime stain, it would be appropriate to accept that the eyewitness was correct and use a CR database, where the crime stains had been left by Afro-Caribbeans. In case example 1, as we have seen, we would use a database of crime stains left by Caucasians.

Case example 3

A person has been stabbed by an unknown assailant. A man is arrested on suspicion of the offence. There were no eyewitnesses and the suspect gives a "no comment" interview: the limited nature of the framework of circumstances means that activity level propositions are not, at present, feasible for the scientist to address. A bloodstain is found on the suspect's outer clothing that yields a partial DNA profile which matches those components that can be compared in the full profile of the victim. We consider the evaluation of the evidence at the stage where the suspect has become the defendant at court proceedings, still maintaining a "no comment" defence.

We address the following propositions:

A: the bloodstain came from the victim

$\bar{A}$: the bloodstain came from some unknown person.

In this case, O_c represents the profile of the victim and O_d represents the partial profile from the bloodstain on the defendant's jacket.

If we work down the flowchart in Figure 1 we come to the question relating to assumption 3(a). The answer to this must be "No" because there are additional components in O_c that are not in O_d. In relation to assumption 3(b), however, it appears reasonable to answer "Yes". In the first diamond of Figure 2(b) we consider the question:

> Are our observations on the genotype of the victim, O_c, dependent in any way on whether or not the stain on the defendant's clothing came from the victim – but without knowing what the observations O_d on the stain are?

The answer to this question would appear to be "no" and so the answer to the question in the first diamond is "yes" and we are led to:

$$LR = \frac{1}{\Pr(O_d = G|\bar{A}, F_d)}$$

Where G denotes the genotype of the partial profile from the stain on the defendant's clothing. There is one key question, then: "what is the probability of observing that profile from a stain found on the clothing belonging to the defendant, if that stain had not come from the victim?" The need is for a IS database. It is important to realise here that what we are interested in is the distribution of DNA profiles on clothing of people like the defendant. So if, for example, the victim were Caucasian, and the defendant Afro-Caribbean, we would be interested in considering the distribution of DNA profiles on the clothing of *Afro-Caribbeans*. Of course, this may be no different from the distribution of DNA profiles on the clothing of Caucasians but it is the principle that is of interest here. Note also that we are interested in the distribution on the clothing of those who were not involved in crime.

In this case, where the transfer of material was away from the crime scene, it seems fairly reasonable to assert that there is need for only one database. In the first two cases – where the transfer of material was from offender to crime scene – there is, in principle, the need for three databases. In practice, because these are DNA profiling cases we believe that we can make reasonable assumptions based on the principles of genetics that reduce our need to one database. In later cases, we see that this reduction is more problematic.

Case example 4

A window pane has been smashed in a house in an unsuccessful attempt to gain entry. There were no witnesses. As a result of a tip-off from an informant a suspect is arrested, who is well known to the police for committing this kind of offence. He gives a "no comment" interview and the scientist judges that he has insufficient information to address activity level propositions. Nevertheless, examination of the suspect's jacket is carried out and a group of glass fragments is recovered that is found to match in refractive index a control sample from the broken window.

We address the following propositions:

A: the glass on the clothing came from the broken window

$\bar{A}$: the glass on the clothing came from some other source of broken glass.

We proceed through the questions in Figure 1 as follows:

> *Assumption 1*: if $\bar{A}$ is true the observations on the recovered group, O_d, are independent of the observations on the control sample, O_c. This seems entirely reasonable.
>
> *Assumption 2*: if $\bar{A}$ is true the observations on the control sample, O_c, are independent of anything we know about the defendant F_d; and the observations on the recovered group, O_d, are independent about anything we know about the crime, F_c. Again, this seems entirely reasonable.
>
> *Assumption 3(a)*: in principle, there will be the capacity to generate more observations from the control sample than from the recovered sample. So we answer "no" to this and proceed to:
>
> *Assumption 3(b)*: given our assumption of a two-stage approach and that the result is a "match" in this case we answer "yes" to this question and proceed to Figure 2b.

We can address the first question in 2b by considering the following question:

> Are our observations on the sample from the broken window, O_c, dependent in any way on whether or not the glass on the clothing came from that window (but without knowing what the observations on the glass on the clothing are)?

The answer to this question would appear to be "no" and, if this is the case, then the answer to the question in the flow chart is "yes", directing us to:

$$LR = \frac{1}{\Pr(O_d|\bar{A}, F_d)}$$

The most relevant survey for assigning a value to the probability of interest would be that of glass found on clothing from people of a similar background to that of the defendant. This establishes the relevance of databases such as that of non-matching glass found on the clothing of people arrested during the investigation of crimes involving broken windows that was created by Lambert, Satterthwaite and Harrison (LSH) [9].

As in case example 3 we have need of only one database. As in case example 3, the direction of transfer is away from the scene.

Case example 5

As a result of an arrest, a person is found to be in possession of a cocaine drug deal that is wrapped in transparent film – known in the UK as "clingfilm". Assume, for the purpose of discussion that the clingfilm has a distinctive blue colouring. Later, the premises of a suspected drugs dealer are raided and, among other things, a partially used roll of clingfilm with a similar blue colouring is recovered. The suspect, later the defendant, denies involvement in any form of drugs dealing but offers no explanation for the presence of the roll of clingfilm

The two propositions to be considered here are:

A: the drugs wrap came from the defendant's roll of clingfilm.

$\bar{A}$: the drugs wrap came from some other roll of clingfilm

We assume that, in the judgement of the scientist, there are no observations – such as striations or physical fits – that assist in addressing these two propositions other than that the wrap and roll are indistinguishable with regard to the blue colouration.

Considering the assumptions in Figure 1.

Assumption 1. If the drugs wrap came from some other roll of clingfilm then knowledge of the colour of the roll does not influence our judgement in relation to the colour of the wrap (and *vice versa*). This assumption is valid.

Assumption 2. If the drugs wrap came from some other roll then the circumstances relating to the defendant do not influence our judgement in relation to the colour of the wrap; neither do the circumstances in relation to the seizure influence our judgement in relation to the colour of the roll. This assumption is valid also.

Assumption 3(a). If the drugs wrap came from the defendant's roll then we would expect it to be of the same blue colour as the roll. In principle, we have a situation where there is the capacity to generate more observations from the roll (O_d) than from the wrap (O_c) so it is appropriate to proceed to Figure 2a.

Let B denote the observations made on the colour of the wrap and roll. F_c includes the information that the wrap was part of a drugs seizure; F_d includes the information that the roll was found at the defendant's home and the defendant's assertion that he is not a drug dealer. Then the first question in the flowchart Figure 2a is addressed by considering the following two probabilities:

$\Pr(O_d=B|A,F_c,F_d)$: the probability that the roll would be blue given: F_d, that it was found at the defendant's home; A, that it was the source of the wrap; and F_c, that the wrap was part of a seizure.

$\Pr(O_d=B|\bar{A},F_d)$ the probability that the roll would be blue given: F_d, that it was found at the defendant's home; and $\bar{A}$, that it was not the source of the wrap.

The critical difference in the conditioning of these two is that, for the first, the roll had been used to make a drugs wrap, whereas for the second it has not been used to make a drugs wrap. It may well be that blue is a colour favoured for the production of drugs wraps and so it would not seem reasonable to assume that these two are equal. So, we pass down the "No" arrow to the next question.

For the second, we consider the following two probabilities:

$\Pr(O_d=B|A,F_c,F_d)$: as before, the probability that the roll would be blue given: F_d, that it was found at the defendant's home; A, that it was the source of the wrap; and F_c, that the wrap was part of a seizure.

$\Pr(O_c=B|\bar{A},F_c)$: the probability that the wrap would be blue given: F_c, that it was part of a drugs seizure; and $\bar{A}$, that it was not made from the roll at the defendant's home.

Here, too, there is a critical difference in the conditioning: the first relates to a *roll* and the second to a *wrap*. It would seem unsafe to assume the same probability distribution for wraps as for rolls used to make wraps. If that is the case then the answer to the second question, like the first, is "no" and so we proceed to the bottom box of the flowchart, corresponding to an unchanged *LR*:

$$LR=\frac{1}{\Pr(O_c=B|\bar{A},F_c)}\cdot\frac{\Pr(O_d=B|A,F_c,F_d)}{\Pr(O_d=B|\bar{A},F_d)}$$

There is one small simplification that can be made with regard to the numerator of the second ratio: we argue that it is the information that the roll is the source of a drugs wrap (A and F_c combined) that dominates the conditioning. In which case:

$$LR=\frac{1}{\Pr(O_c=B|\bar{A},F_c)}\cdot\frac{\Pr(O_d=B|A,F_c)}{\Pr(O_d=B|\bar{A},F_d)}$$

Let us consider the sort of surveys that would assist us in assigning values to these three probabilities.

$\Pr(O_c=B|\bar{A},F_c)$: the probability that a single clingfilm drugs wrap would be blue. This would best be informed by a survey of seizures of single drugs wraps – a CR database.

$\Pr(O_d=B|A,F_c)$: the probability that a roll of clingfilm would be blue given that it had been used to make a drugs wrap. This would appear to be best informed by a survey of clingfilm rolls that had been used to make drugs wraps – an OR database.

$\Pr(O_d=B|\bar{A},F_d)$: the probability that a roll of clingfilm found at the defendant's home would be blue, given that it had not been used to make a drugs wrap. This would apparently be best informed by a survey of clingfilm rolls found at the homes of people who, like the defendant, have come to police notice, yet are not involved in drugs dealing – an IS database. (This would be different if, for example, the defendant admitted to being a drugs dealer but denied supplying the particular wrap in question)

As we have seen, in the DNA profiling case examples, it was knowledge of the population genetics of DNA profiles (first diamond in Figure 2a) and the assumption that we have equality between the distributions of genotypes at crime scenes and those of offenders (second diamond in Figure 2a) that reduced our requirements to only one database. If we cannot make similar assumptions in the present case we see that we need three separate databases for a quantitative assessment of the weight of evidence.

Case example 6

Premises have been burgled and the offender left a footwear mark on a window ledge at the point of entry. A 20 year old unemployed male from the locality has been arrested and his shoes – a pair of size 8 Reebok Classic trainers – are taken for comparison with the mark from the scene. The suspect denies any involvement in the burglary but otherwise makes no comment. We assume that there are no particular individualising features such as wear and cuts but the pattern of the crime mark is that which would be expected from a Reebok Classic of size 8.

The propositions to be considered here are:

A: the scene of crime mark was left by the defendant's shoe

$\bar{A}$: the scene of crime mark was left by some other shoe.

Here F_d includes: the suspect's age; that he is unemployed (this may, or may not, be relevant); and the locality where he lives. F_c includes the information about the type of crime and the locality where it occurred. O_c denotes the observations made on the footwear mark at the scene and O_d denotes the observations on test prints from the defendant's shoes.

Considering first the questions in Figure 1. We note that there is a match between the two sets of observations and proceed to the three key assumptions:

> *Assumption 1*: if $\bar{A}$ is the case, then it is reasonable to assert that the observations on the crime mark are independent of those on the defendant's shoe.

> *Assumption 2*: if $\bar{A}$ is the case then the observations on the crime mark are not influenced in any way by the information about the defendant; and the observations on the defendant's shoe are not influenced in any way by the information about the crime.

> *Assumption 3a*: we note first that the observations on the shoe will, in principle, have greater information content than observations on the crime mark. In the present context, this assumption amounts to saying that, given that the defendant's shoe is a Reebok Classic size 8, the probability that the mark would be found to be a Reebok Classic size 8 is one. This assumption is highly case dependent and is very much a function of the quality of the crime mark. We accept the validity of the assumption here for the sake of discussion, but do not claim that it is automatically realistic for general footwear cases. We thus proceed to Figure 2a.

Writing *RC8* to denote the observation "Reebok Classic size 8", the first question in 2a directs us to consider:

> $Pr(O_d=RC8|A,F_c,F_d)$: the probability that the defendant's shoes would be *RC8* given: *A*, that they left the crime scene mark; F_d, what we know about the defendant; and F_c, what we know about the crime.

> $Pr(O_d=RC8|\bar{A},F_d)$: the probability that the defendant's shoes would be *RC8* given: $\bar{A}$, that they did not leave the scene mark; and F_d, what we know about the defendant.

The consideration of whether the defendant's shoes left the scene mark is important here. On the one hand, they need to be viewed as the kind of shoes that are used to leave scene marks; on the other they need to be viewed as the shoes of someone unconnected with crime. It is not obvious that there would be an equivalence here so we proceed down the "No" route to the next question, which directs us to:

> $Pr(O_d=RC8|A,F_c,F_d)$: (as before) the probability that the defendant's shoes would be *RC8* given: *A*, that they left the crime scene mark; F_d, what we know about the defendant; and F_c, what we know about the crime.

> $Pr(O_c=RC8|\bar{A},F_c)$: the probability that the scene mark would be *RC8* given: $\bar{A}$, that it was not left by the defendant; and F_c, what we know about the crime.

The first of these, as we have seen, directs us to think about the kind of shoes that leave scene marks. The second directs us to think about marks left at scenes of crimes. It may be unrealistic to believe that there is a one-to-one correspondence between crime marks and the shoes used to make them and so we reply "no" to the question. Consequently, we are unable to simplify the expression for the *LR* in the first box of 2a. We can write it as follows:

$$LR = \frac{1}{Pr(O_c=RC8|\bar{A},F_c)} \cdot \frac{Pr(O_d=RC8|A,F_c,F_d)}{Pr(O_d=RC8|\bar{A},F_d)}$$

Once again, there are, in principle, three different databases that would provide guidance in assigning these probabilities:

> $Pr(O_c=RC8|\bar{A},F_c)$ would be informed by a CR database of footwear marks left at burglary crime scenes.

> $Pr(O_d=RC8|A,F_c,F_d)$ would be informed by an OR database of the footwear of people who leave footwear marks at crime scenes in the relevant locality. Note that this is not the same as the first database because there is not necessarily a one-to-one relationship between items of footwear and footwear marks.

> $Pr(O_d=RC8|\bar{A},F_d)$ would be informed by an IS database of footwear of people from the locality who, like the suspect, come to police notice during the investigation of crime.

We note that Hicks Champod [10] came to a similar conclusion in the context of interpreting the evidential value of glass found on clothing.

Case example 7

A robbery has been carried out at a petrol filling station. One of the offenders was recorded on a security video. His facial details are indistinct, but he can perceived to be of Afro-Caribbean ethnic appearance. He is wearing a brown jacket of the style known as a "flight jacket". Acting on information received, on the following day the police arrest an Afro-Caribbean suspect.

They search his home and find, hanging behind his bedroom door, a brown flight jacket, made of leather, that they take for comparison with the video.

We will consider the following propositions:

A: the jacket in the video is that taken from the defendant's home

$\bar{A}$: the jacket in the video is not that taken from the defendant's home.

The scope of the comparison between the jacket and the video is limited by the image quality of the latter. Clearly, it will be possible to characterise the jacket in far more detail than the image. For example, it can readily be observed that the jacket is made of leather, whereas the material of the jacket of the offender cannot be determined from the video image. There are other features of the defendant's jacket – such as the lining – which will be readily observable, in contrast to the jacket in the video. We will reflect this in our notation, using J to denote the observations on the jacket and j, those on the image. We assume that there is nothing in j that is in conflict with the appropriate components of J.

Starting at the top of Figure 1, we note that there is a "match" between j and part of J and proceed to the first assumption.

Assumption 1: if the jacket in the video is not that taken from the defendant's home, then are the observations j and J independent of each other? It seems reasonable to believe so.

Assumption 2: if $\bar{A}$ is the case then the observations on the jacket in the video are not influenced in any way by the information about the defendant; and the observations on the defendant's jacket are not influenced in any way by the information about the crime. Again this seems reasonable.

Assumption 3a: we note that the observations J will, in principle, have greater information content than those on the jacket in the video, j so it is appropriate to answer "yes" to this question. (Note that the answer to *3b* would be "no".)

In figure 2a we address the first question by considering the two probabilities:

$\Pr(O_d{=}J|A,F_c,F_d)$: the probability of the observations on the defendant's jacket given: A, that it is the jacket in the video; F_c, what we know about the crime; and F_d, what we know about the defendant.

$\Pr(O_d{=}J|\bar{A},F_d)$: the probability of the observations on the jacket given: $\bar{A}$, that it is not the jacket in the video; and F_d, what we know about the defendant.

In the first of these we need to consider the jacket as one that has been worn by a petrol station robber; in the second, we must consider it as the jacket of someone who is not a petrol station robber. It appears unsatisfactory, therefore, to regard these two as necessarily equal. In the next box we address:

$\Pr(O_d{=}J|A,F_c,F_d)$: as before, the probability of the observations on the defendant's jacket given: A, that it is the jacket in the video; F_c, what we know about the crime; and F_d, what we know about the defendant.

$\Pr(O_c{=}j|\bar{A},F_c)$: the probability of the observations on the jacket in the video given: $\bar{A}$, that it is not the defendant's jacket; and F_c, what we know about the crime.

Again, it would appear unrealistic to accept these two as being equal and so we are left with the unsimplified expression:

$$LR = \frac{1}{\Pr(O_c{=}j|\bar{A},F_c)} \cdot \frac{\Pr(O_d{=}J|A,F_c,F_d)}{\Pr(O_d{=}J|\bar{A},F_d)}$$

To assign values to the three probabilities in this expression, we would be assisted by surveys as follows:

$\Pr(O_c{=}j|\bar{A},F_c)$: this would be informed by a CR database based on a survey of jackets in videos of people of Afro-Caribbean appearance who commit crimes of this nature.

$\Pr(O_d{=}J|A,F_c,F_d)$: this would be informed by an OR database from a survey of the jackets of Afro-Caribbean males, of similar age and background to that of the defendant, who are known to commit crimes of this nature.

$\Pr(O_d{=}J|\bar{A},F_d)$: this would be informed by an IS database from a survey of jackets of Afro-Caribbean males of similar age and background to the defendant, who have not committed crimes of this nature, but who have come to police notice.

There is an interesting corollary to this formulation of the problem. Imagine a feature, a purple lining, perhaps, that could be observed on the jacket, and thus contained in J but not contained in j because the lining of the jacket in the video cannot be seen. If a purple lining were more common in the OR database than in the IS database, it would make a contribution to the LR – even though it cannot be seen in the image of the offender. On reflection, this is not unreasonable. It amounts to saying that, if some observations are made in relation to the defendant that are more likely to be found in people who commit the given kind of offence than among innocent suspects, then this has probative value.

Discussion

In case examples 3 and 4 we found that, when the direction of transfer of possible evidential material is away from the scene, it seems reasonable to rationalise the need for only one database – an IS database. In the remaining examples, where the direction of transfer is towards the scene, we saw that there is the need for three different kinds of database to address probabilities as follows:

$\Pr(O_c|\bar{A},F_c)$: a CR database from a survey of materials recovered from crimes similar to that considered in the given case, e.g. footwear marks recovered from burglary scenes.

$\Pr(O_d|\bar{A},F_d)$: an IS database from a survey of materials from people (suspects) who, while innocent of the crime for which they were arrested, have nevertheless come to police notice (e.g. the LSH survey [9]).

$Pr(O_d|A,F_c,F_d)$: an OR database from a survey of materials from people (suspects) of given characteristics who are known to have left materials at the scenes of crimes similar to that in the given case (e.g. a survey of footwear from known burglars).

We have seen that, in the DNA profiling examples, it appears to reduce the need to a single database. However, that is because of the existence of established genetic models; with other evidence types, such a simplification may not be reasonable.

We also note that contributions can be made to the *LR* from observations made on the suspect that cannot be made on the crime sample.

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Appendix 1
Considering the denominator of equation 1, we invoke the third law of probability to write:

$$Pr(O_c,O_d|\bar{A},F_c,F_d) = Pr(O_c|O_d,\bar{A},F_c,F_d)\ Pr(O_d|\bar{A},F_c,F_d)$$

Invoking assumption 1, the right hand side simplifies to:

$$Pr(O_c|\bar{A},F_c,F_d)\ Pr(O_d|\bar{A},F_c,F_d)$$

Assumption 2 then leads to the following expression for the denominator:

$$Pr(O_c|\bar{A},F_c)Pr(O_d|\bar{A},F_d) \qquad (A1)$$

We now turn our attention to the numerator of equation (1) and consider the two ways in which it can be written, from application of the third law of probability:

$$Pr(O_c,O_d|A,F_c,F_d) = Pr(O_c|O_d,A,F_c,F_d)\ Pr(O_d|A,F_c,F_d) \qquad (a)$$

or

$$Pr(O_c,O_d|A,F_c,F_d) = Pr(O_d|O_c,A,F_c,F_d)\ Pr(O_c|A,F_c,F_d) \qquad (b)$$

Assumption 3 amounts to one of the following alternatives:

Either: $Pr(O_c|O_d,A,F_c,F_d) = 1$

Or: $Pr(O_d|O_c,A,F_c,F_d) = 1$

Or: $Pr(O_c|O_d,A,F_c,F_d) = Pr(O_d|O_c,A,F_c,F_d) = 1$

So, combining these with the expression for the denominator (A1), gives two different versions of the *LR*, to be chosen depending on the conditions in the individual case:

$$LR = \frac{1}{Pr(O_c|\bar{A},F_c)} \cdot \frac{Pr(O_d|A,F_c,F_d)}{Pr(O_d|\bar{A},F_d)} \qquad (A2a)$$

$$LR = \frac{1}{Pr(O_d|\bar{A},F_d)} \cdot \frac{Pr(O_c|A,F_c,F_d)}{Pr(O_c|\bar{A},F_c)} \qquad (A2b)$$

These are equations (2a) and (2b) in the main text.