Busca de objetividade na balística forense

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$$\frac{p(E|H_p)}{p(E|H_d)}$$

Slides

- https://geoff-morrison.net/#CongressoNacional2024

Introduction

Introduction

- Last year I presented at **InterForensics** in Brasília

- Morrison G.S. (2022). **Advancing a paradigm shift in evaluation of forensic evidence: The rise of forensic data science**. *Forensic Science International: Synergy*, 4, 100270. https://doi.org/10.1016/j.fsisyn.2022.100270

Introduction

- A **paradigm shift** in evaluation of forensic evidence is underway in which methods based on human perception and subjective judgement are replaced by methods based on **relevant data**, **quantitative measurements**, and **statistical models**; methods that:
  - are **transparent and reproducible**;
  - are **intrinsically resistant to cognitive bias**;
  - use the **logically correct framework for interpretation of evidence** (the **likelihood-ratio framework**); and
  - are **empirically calibrated and validated under casework conditions**.

Introduction

- Traditionally, **firearms examination** is based on:
    - human perception
    - subjective judgement

- Traditional conclusions:
    - identification
    - inconclusive
    - exclusion

Introduction

- Traditionally, **firearms examination** is based on:
  - human perception
  - subjective judgement
- Traditional conclusions:
  - identification
  - inconclusive
  - exclusion
- Replace with **likelihood ratios** calculated using:
  - relevant data
  - quantitative measurements
  - statistical models

Introduction

- Likelihood ratio:

$$\frac{\mathbf{p}(\,E\mid H_1\,)}{\mathbf{p}(\,E\mid H_2\,)}$$

Introduction

- Common-source likelihood ratio:

  - What is the probability of obtaining the measured properties of the two items of interest if they both came from the same source (a source selected at random from the relevant population)?

    divided by

  - What is the probability of obtaining the measured properties of the two items of interest if they each came from a different source (each a source selected at random from the relevant population)?

Introduction

- Common-source likelihood ratio:

  - What is the degree of **similarity** between the measured properties of the two items?

    divided by

  - What is the degree of **typicality**, with respect to the relevant population, of the measured properties of the two items ?

Introduction

- Basu N., Bolton-King R.S., Morrison G.S. (2022). **Forensic comparison of fired cartridge cases: Feature-extraction methods for feature-based calculation of likelihood ratios**. *Forensic Science International: Synergy*, 5, 100272. https://doi.org/10.1016/j.fsisyn.2022.100272

- Bolton-King R.S., Morrison G.S., Basu N., Zhang X.A. (2022). **E^3 database of 3D images of fired cartridge cases**. *NIST Ballistics Toolmark Research Database*. https://tsapps.nist.gov/NRBTD/Studies/Studies/Details/a023199a-b9f3-4a1a-89e8-c94054a7cf61

Acknowledgements

- This research was supported by Research England's Expanding Excellence in England Fund as part of funding for the Aston Institute for Forensic Linguistics 2019–2024.

- Thanks to the organizations and individuals who donated the fired cartridge cases.

- Thanks to ScannBI Technology Europe GmbH for the loan of the Evofinder® imaging system.

Contents

- Scenarios and hypotheses
- Database
- Preprocessing
- Feature extraction
- Statistical models
- Validation results
- Conclusion
- Future plans

Scenarios and Hypotheses

Scenario 1

- One or more firearms are fired at a crime scene and the cartridge cases are ejected.
- Crime-scene investigators later recover two fired cartridge cases.
- A forensic practitioner compares the two questioned-source cartridge cases with one another.
- The forensic practitioner draws an inference with respect to whether they were fired by the same firearm or not.

Hypotheses for Scenario 1

- H_1: The two cartridge cases were fired by the same firearm.

- H_2: The two cartridge cases were fired by different firearms from the same population.

Scenario 2

- A firearm is fired at a crime scene and the cartridge case is ejected.
- Crime-scene investigators later recover the fired cartridge case.
- Police investigators seize a firearm from a suspect.
- A forensic practitioner fires multiple cartridges from the seized firearm and collects the ejected cartridge cases.
    - 3 cartridges
    - 9 cartridges

Scenario 2

- The forensic practitioner compares:

    - the fired cartridge case recovered from the crime scene
      (the questioned-source cartridge case)

      with

    - the cartridge cases fired from the suspect's firearm
      (the known-source cartridge cases)

- The forensic practitioner draws an inference with respect to whether the questioned-source and known-source cartridge cases were fired by the same firearm or not.

Hypotheses for Scenario 2

- H_1: The questioned-source cartridge case and the multiple known-source cartridge cases were fired by the same firearm.

- H_2: The questioned-source cartridge case and the multiple known-source cartridge cases were fired by different firearms from the same population.

Hypotheses

- Relevant population:
    - Semi-automatic pistols that:
        - fire 9 mm diameter centre-fire Luger-type ammunition
        - have hemispherical firing pins
        - have parallel breech-face marks

Database

Database

- Existing databases tend to have:
  - a very large number of fires from a small number of firearms
  - a small number of fires from a moderate number of firearms
- For training a likelihood-ratio model, we need:
  - a relatively large number of fires from a relatively large number of firearms of the same class
  - representing within-source and between-source variability for that class

Database

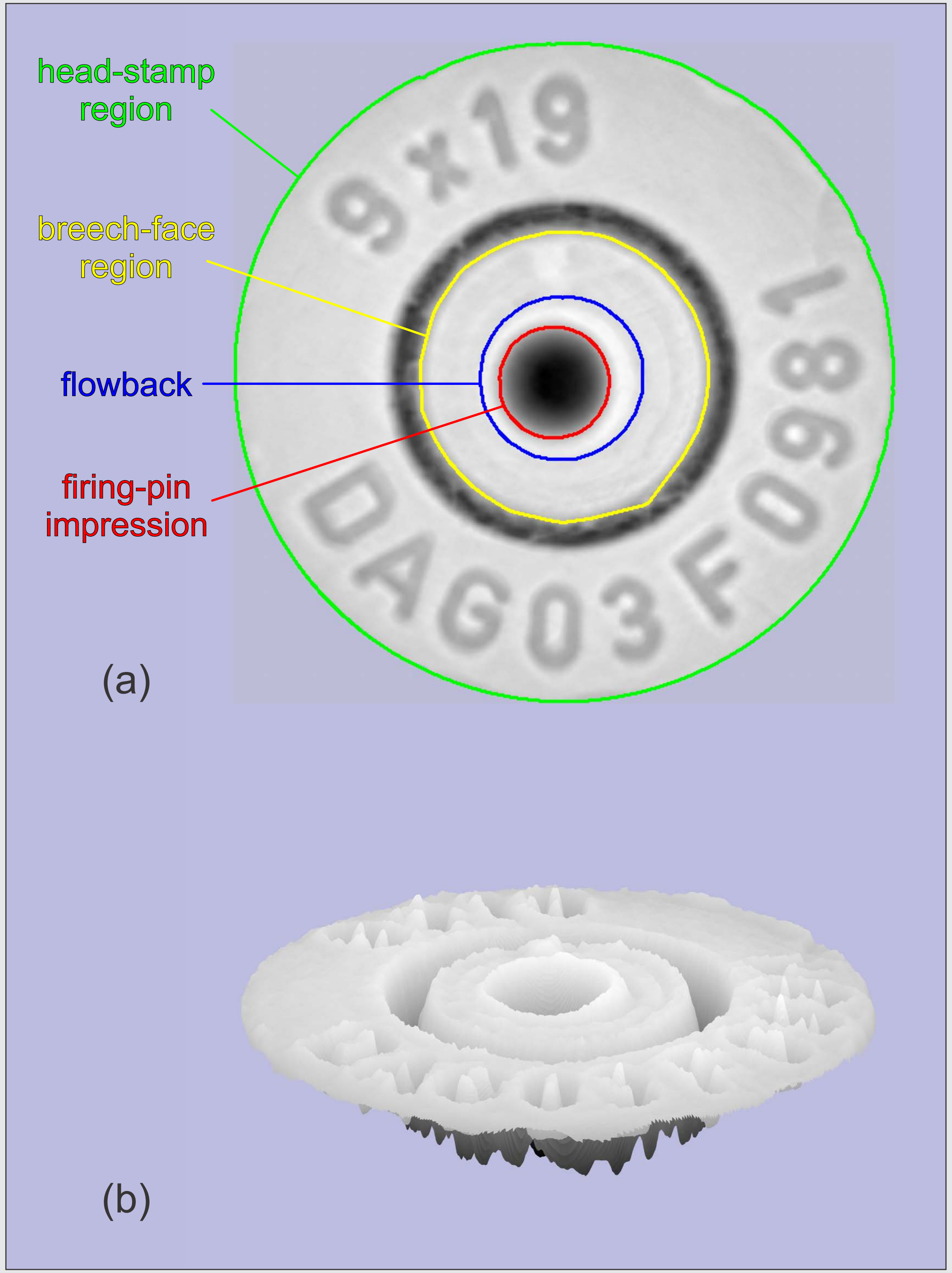
- Database of 3D digital images of the bases of fired cartridge cases:
    - ~300 firearms from relevant population
        - 10 cartridges fired from each firearm
    - Aim was 1,000 firearms, but COVID
    - Firearms were in the possession of a number of operational forensic laboratories, law-enforcement agencies, military units, and private individuals in Barbados, Canada, France, Germany, UK, and USA

Database

- Database of 3D digital images of the bases of fired cartridge cases:
  - Digitally imaged using Evofinder®
    - 3D surface topography
    - exported as a matrix of values $z(x,y)$ in x3p format

Database

- Example 3D digital image



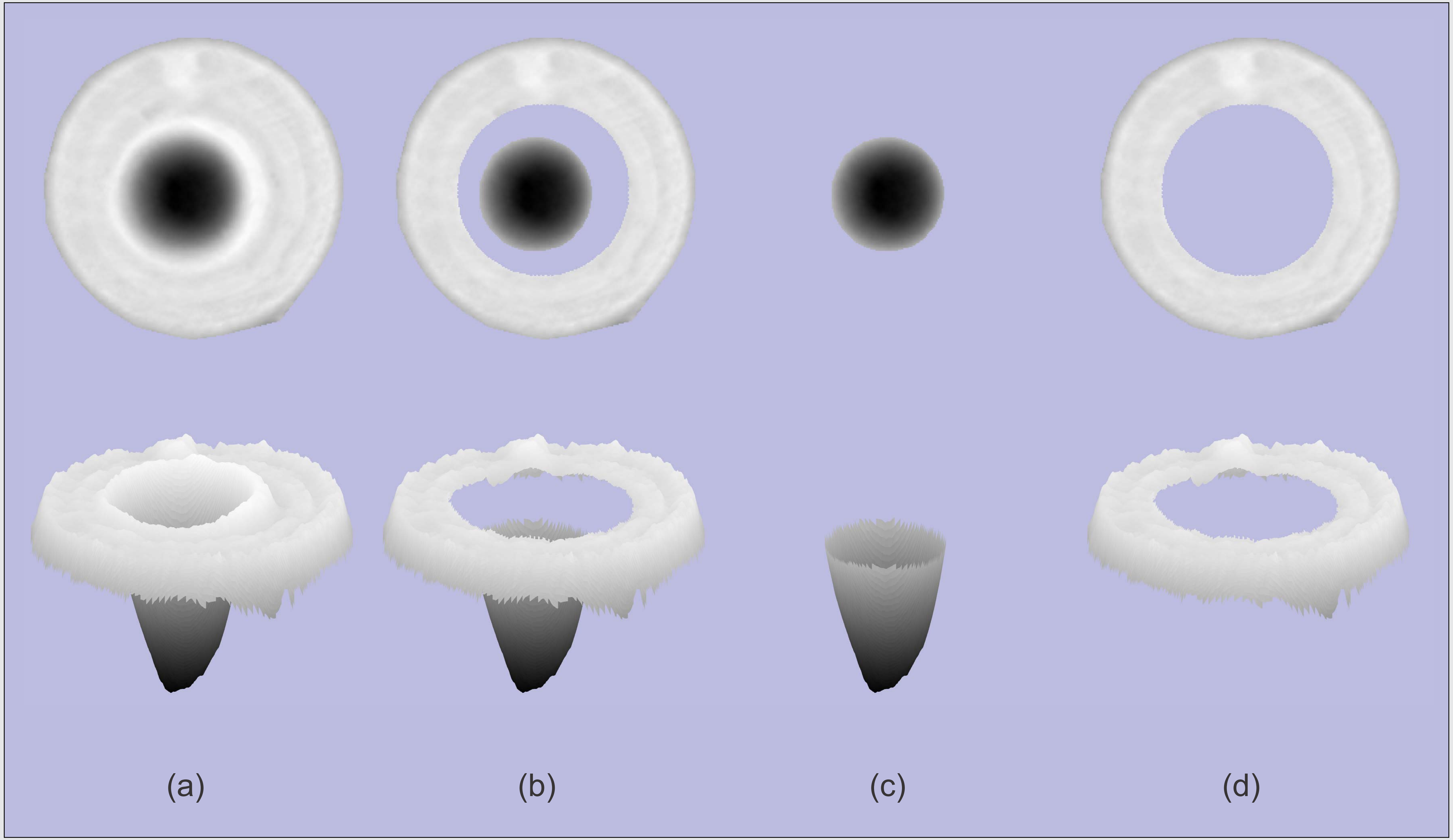
Preprocessing

Preprocessing

- Segmentation:
  - Separation of the firing-pin impression and the breech-face region from the remainder of the image and from each other.
- Illumination correction:
  - Correction for non-uniformities in illumination.
- Noise removal:
  - Removal of imaging artifacts.
- Registration:
  - Rotation and alignment.

Preprocessing

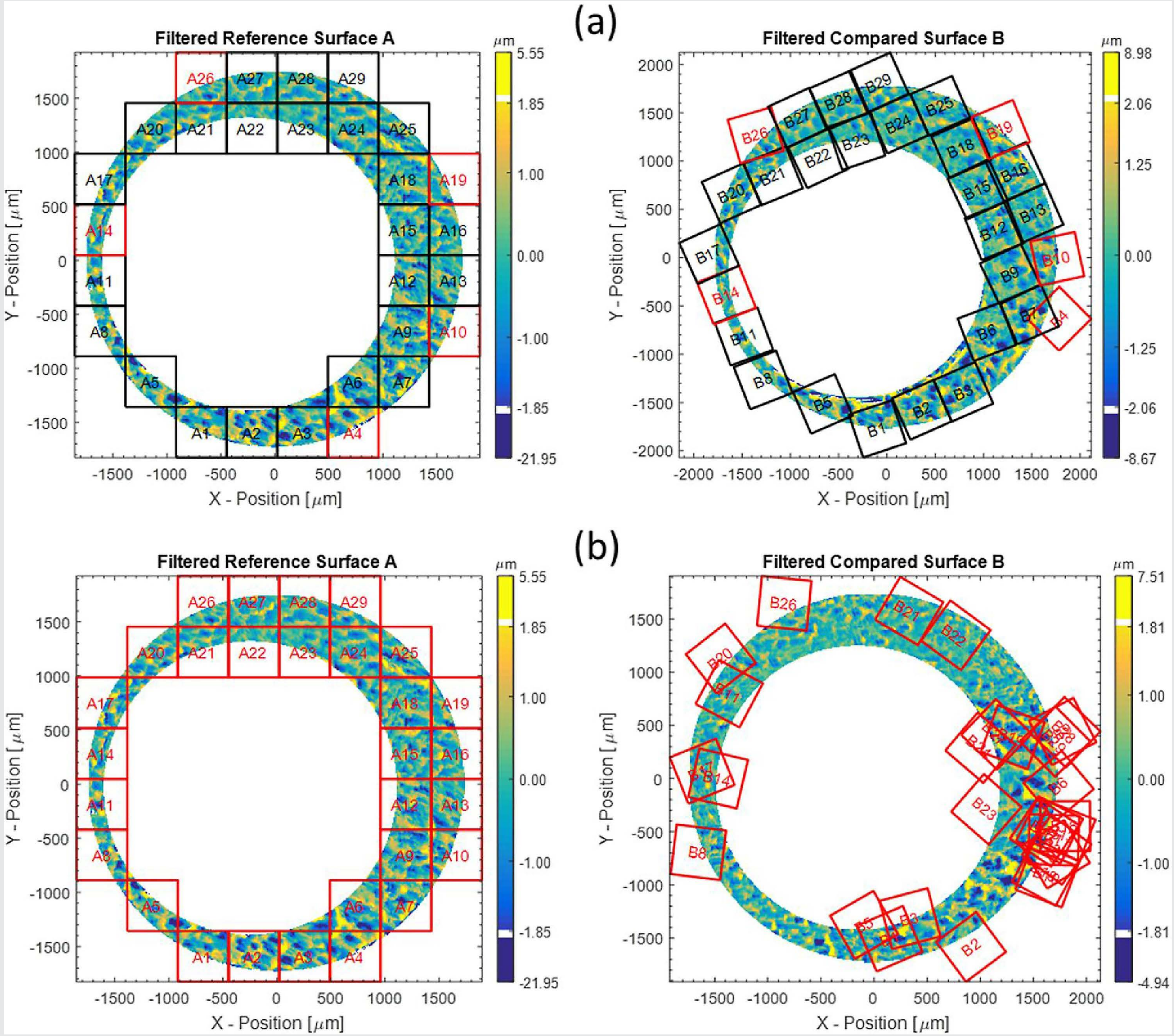
- Segment-
  ation



Feature Extraction

Similarity scores

- Previous attempt to calculate likelihood ratios for fired cartridge cases have used similarity scores, e.g., congruent matching cell (CMC) based similarity scores.

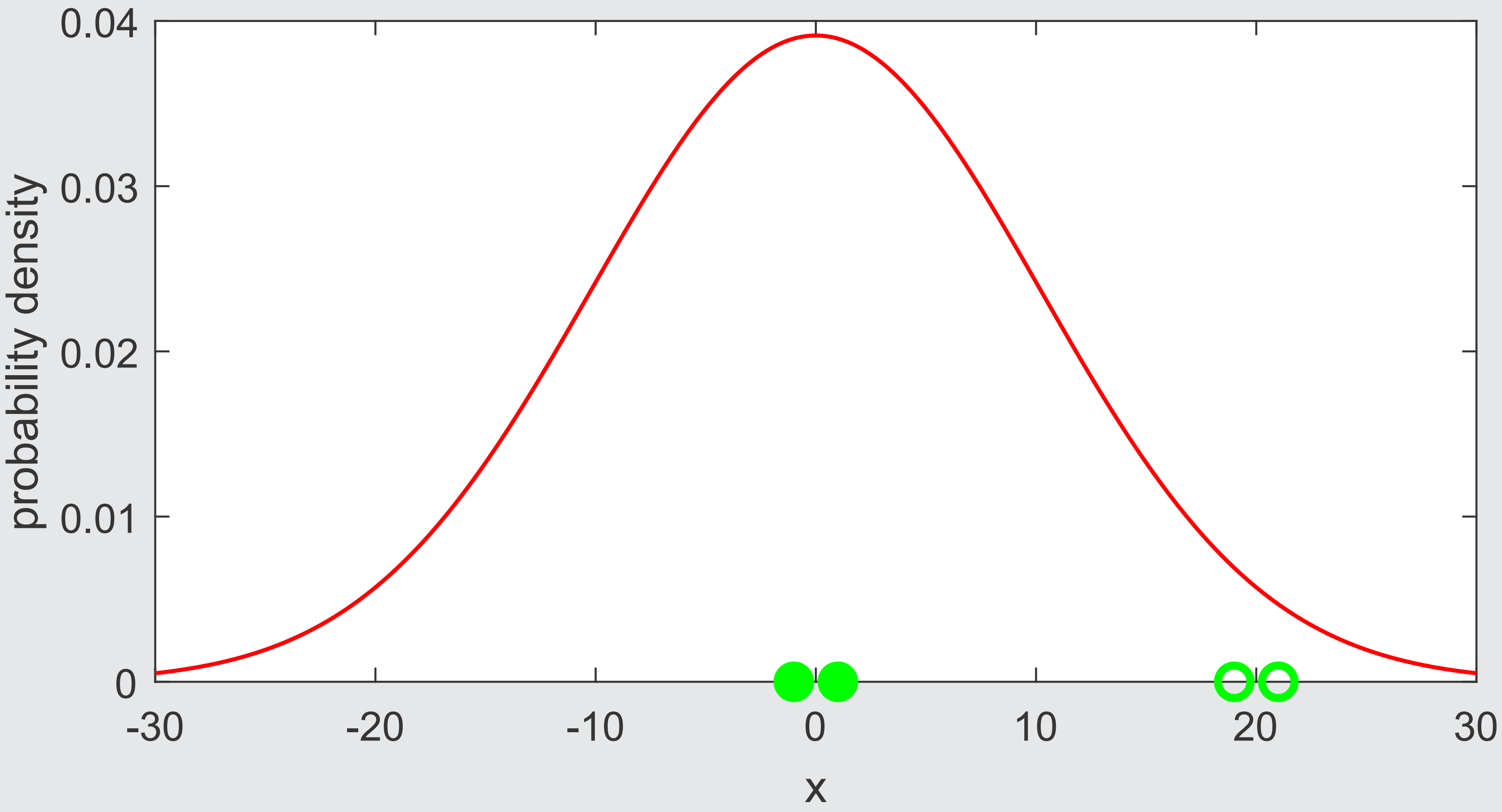


Song J., Vorburger T.V., Chu W., Yen J., Soons J.A., Ott D.B., Zhang N.F. (2018). **Estimating error rates for firearm evidence identifications in forensic science**. *Forensic Science International*, 284, 15–32. https://doi.org/10.1016/j.forsciint.2017.12.013

Similarity scores

- Previous attempt to calculate likelihood ratios for fired cartridge cases have used similarity scores.
  - Similarity scores do not take account of typicality with respect to the relevant population.
  - They are not suitable for calculating likelihood ratios addressing hypotheses of interest in a case.

Similarity scores



- $x_q = -1 \quad x_k = 1 \quad \Lambda_{\text{common-source}} = 2.9 \quad \Lambda_{\text{similarity-score}} = 4.1$
- $x_q = 19 \quad x_k = 21 \quad \Lambda_{\text{common-source}} = 19 \quad \Lambda_{\text{similarity-score}} = 4.1$

Feature extraction

- Extract fixed-length feature vectors:
  - One feature vector from each image
  - Suitable for calculating common-source likelihood ratios

Feature extraction

- Feature sets:
  - central moments
  - circle-moment invariants
  - Legendre moments
  - coefficients of Fourier series fitted to concentric circles
  - **Zernike moments**

Feature extraction

- Orthogonal Zernike polynomials

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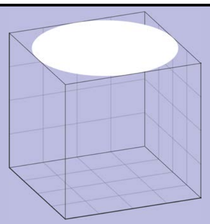
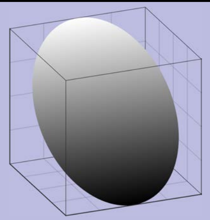
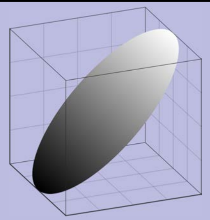
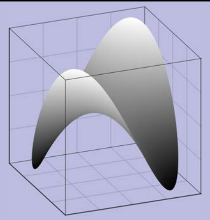
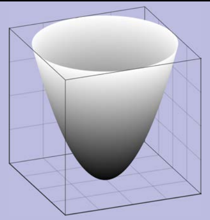
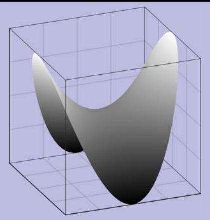
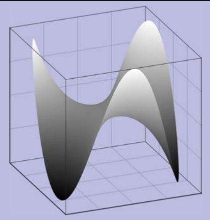
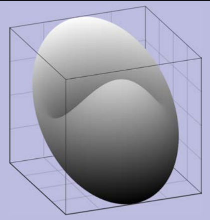
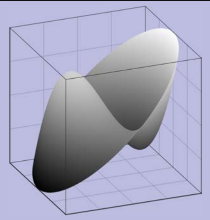
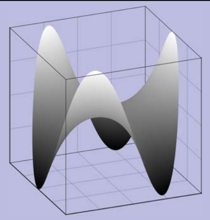
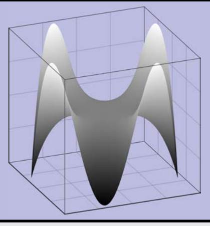
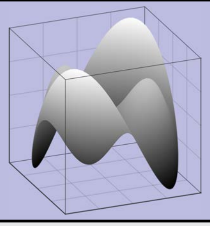
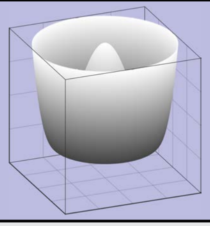
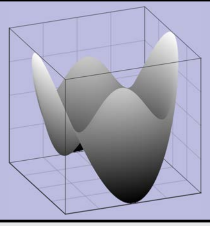
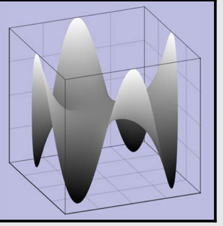
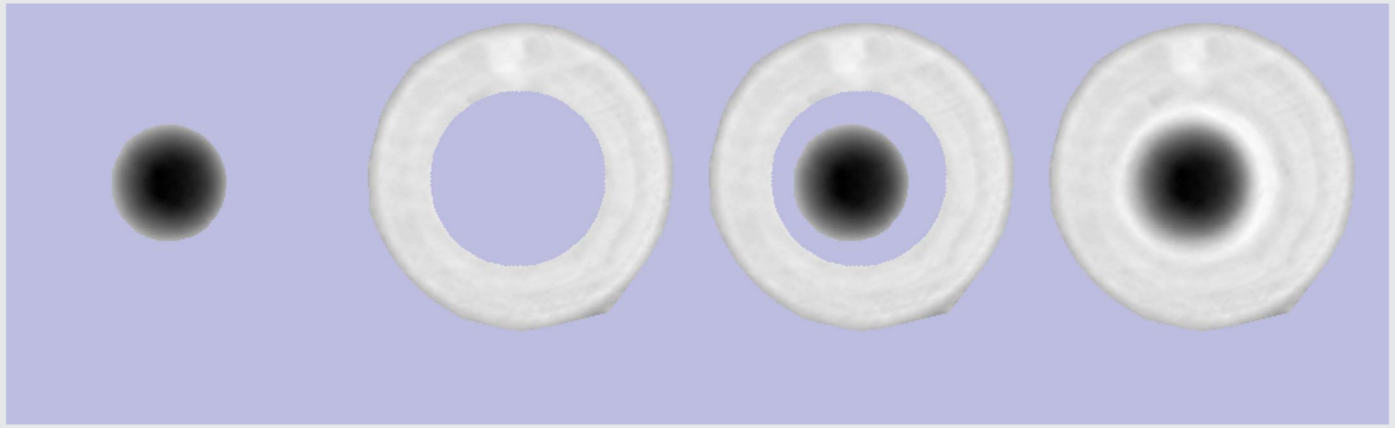
0									
1									
2									
3									
4									

Feature extraction

- Extracted from different segmentations:



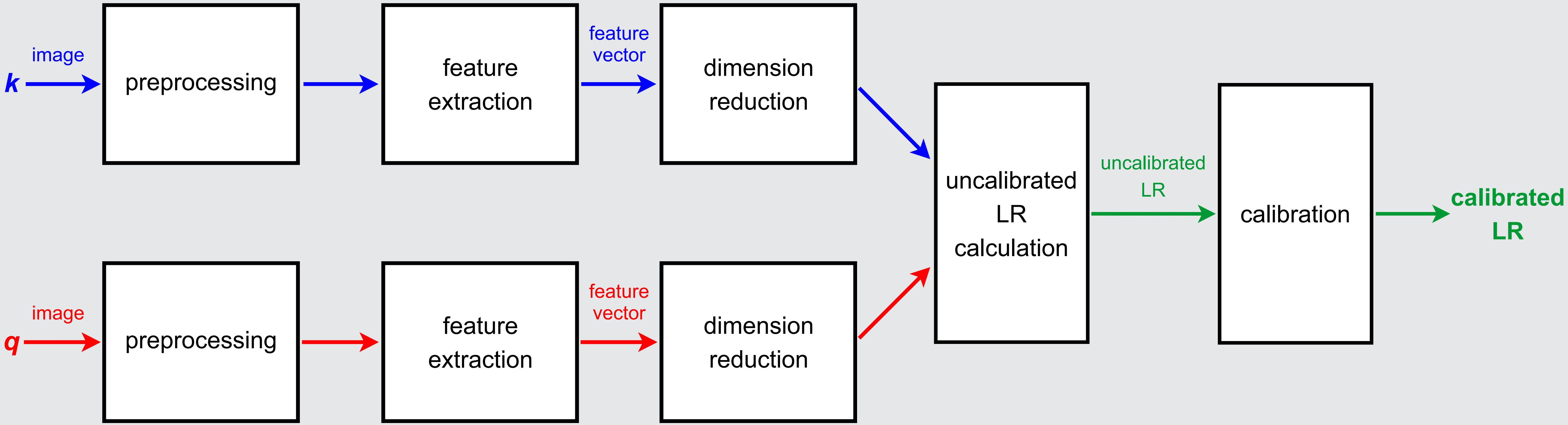
  - firing-pin impression [66]
  - breech-face region [231]
  - whole region of interest (excluding flowback) [297]
  - firing-pin impression + breech-face region (feature concatenation) [297]
  - firing-pin impression + breech-face region (score-level fusion) [66]+[231]
  - **whole region of interest (including flowback)** [297]

[number of Zerinke moment magnitude and phase features extracted]

Statistical Models

Statistical models

- Based on pipeline used in forensic voice comparison.



Statistical models

- Dimension reduction methods:
    - Principal component analysis
    - Linear discriminant functions
- Resulting number of dimensions:
    - 10 for firing-pin impression
    - 20 for breech-face region
    - 30 for whole region of interest

Statistical models

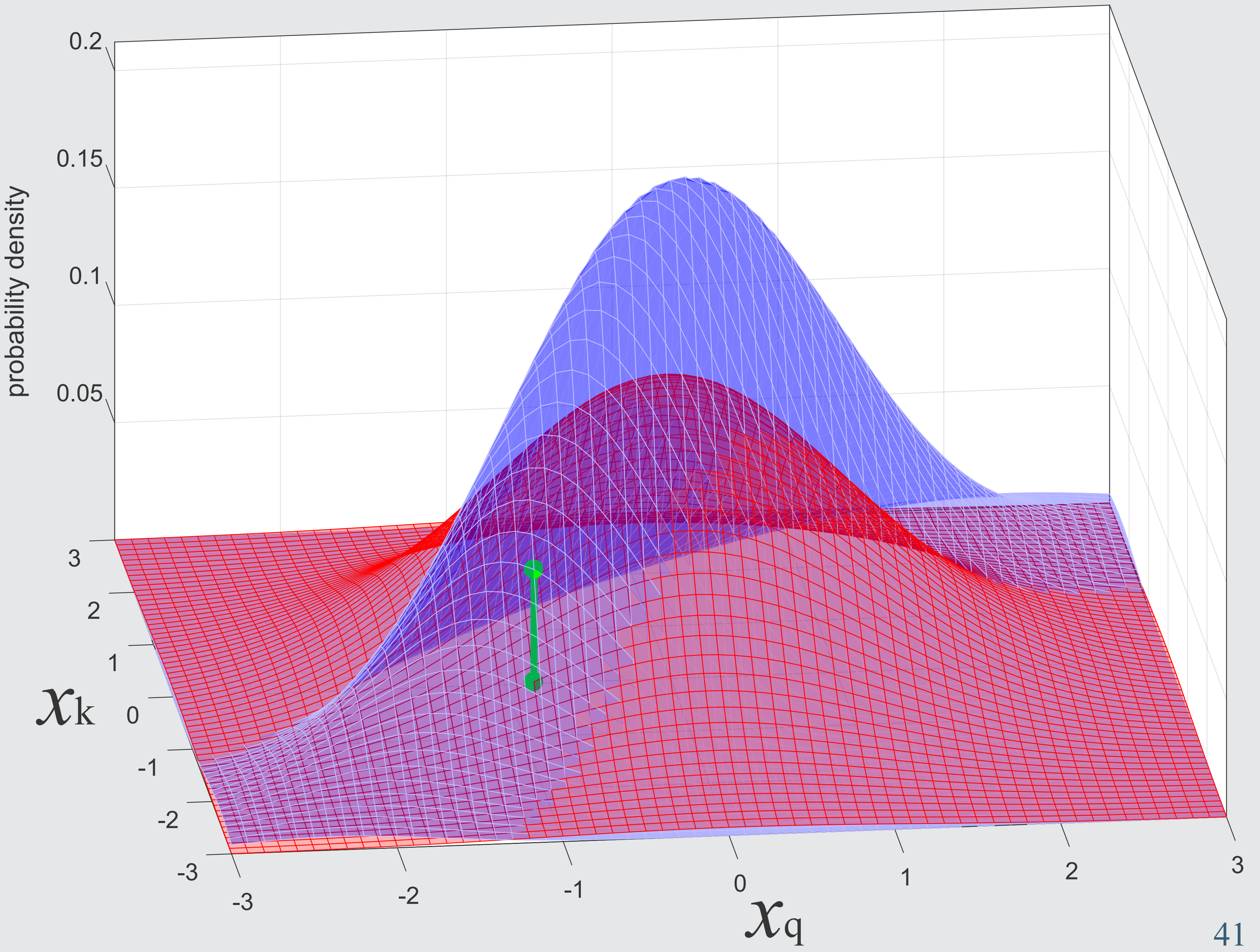
- Calculation of uncalibrated likelihood ratio:
  - Common-source likelihood-ratio model:

$$\lambda = \frac{f\left(\begin{bmatrix}\boldsymbol{v}_{\mathrm{q}} \\ \boldsymbol{v}_{\mathrm{k}}\end{bmatrix} \middle| \begin{bmatrix}\widehat{\boldsymbol{\mu}}_{\mathrm{r}} \\ \widehat{\boldsymbol{\mu}}_{\mathrm{r}}\end{bmatrix}, \begin{bmatrix}\widehat{\boldsymbol{\Sigma}}_{\mathrm{w}} + \widehat{\boldsymbol{\Sigma}}_{\mathrm{b}} & \widehat{\boldsymbol{\Sigma}}_{\mathrm{b}} \\ \widehat{\boldsymbol{\Sigma}}_{\mathrm{b}} & \widehat{\boldsymbol{\Sigma}}_{\mathrm{w}} + \widehat{\boldsymbol{\Sigma}}_{\mathrm{b}}\end{bmatrix}\right)}{f\left(\boldsymbol{v}_{\mathrm{q}} \middle| \widehat{\boldsymbol{\mu}}_{\mathrm{r}}, \widehat{\boldsymbol{\Sigma}}_{\mathrm{w}} + \widehat{\boldsymbol{\Sigma}}_{\mathrm{b}}\right) f\left(\boldsymbol{v}_{\mathrm{k}} \middle| \widehat{\boldsymbol{\mu}}_{\mathrm{r}}, \widehat{\boldsymbol{\Sigma}}_{\mathrm{w}} + \widehat{\boldsymbol{\Sigma}}_{\mathrm{b}}\right)}$$

Statistical models

- Common-source likelihood-ratio model:

$$\Lambda = \frac{f\left(\begin{bmatrix}x_\mathrm{q}\\ x_\mathrm{k}\end{bmatrix} \middle| \begin{bmatrix}\mu_\mathrm{r}\\ \mu_\mathrm{r}\end{bmatrix}, \begin{bmatrix}\sigma_\mathrm{w}^2+\sigma_\mathrm{b}^2 & \sigma_\mathrm{b}^2\\ \sigma_\mathrm{b}^2 & \sigma_\mathrm{w}^2+\sigma_\mathrm{b}^2\end{bmatrix}\right)}{f\left(\begin{bmatrix}x_\mathrm{q}\\ x_\mathrm{k}\end{bmatrix} \middle| \begin{bmatrix}\mu_\mathrm{r}\\ \mu_\mathrm{r}\end{bmatrix}, \begin{bmatrix}\sigma_\mathrm{w}^2+\sigma_\mathrm{b}^2 & 0\\ 0 & \sigma_\mathrm{w}^2+\sigma_\mathrm{b}^2\end{bmatrix}\right)}$$



Statistical models

- Calibration (and score-level fusion):
    - Regularized logistic regression
        - regularization weight equivalent to one source (i.e., one firearm)

$$\log(\Lambda) = \beta_0 + \beta_1 \log(\lambda)$$

$$\log(\Lambda) = \beta_0 + \beta_1 \log(\lambda_1) + \beta_2 \log(\lambda_2)$$

- Cross-validation
    - leave-one-source-out / leave-two-sources-out

Statistical models

- Models trained:
  - **Scenario 1:**
    - 1 questioned-source v 1 questioned-source
  - **Scenario 2:**
    - 1 questioned-source v 3 known-source
    - 1 questioned-source v 9 known-source

Statistical models

- Data split:
  - ⅔ training (dimension reduction and uncalibrated likelihood ratio model)
    - ~200 firearms
  - ⅓ calibration & validation
    - ~100 firearms

Validation Results

Validation results

- Validation metric and validation graphic commonly used in forensic voice comparison:
  - log-likelihood-ratio cost (C_{llr})
  - Tippett plot

Morrison G.S., Enzinger E., Hughes V., Jessen M., Meuwly D., Neumann C., Planting S., Thompson W.C., van der Vloed D., Ypma R.J.F., Zhang C., Anonymous A., Anonymous B. (2021). **Consensus on validation of forensic voice comparison**. *Science & Justice*, 61, 229–309. https://doi.org/10.1016/j.scijus.2021.02.002

Validation results

- C_{llr}
  - **Scenario 1:** 1 questioned-source v 1 questioned-source

Feature Set	Segmented Region					
	whole region of interest		breech face	firing pin	breech face + firing pin	
	including flowback	excluding flowback			feature concatenation	score-level fusion
Zernike moments magnitude & phase	**0.52**	0.65	0.69	0.84	0.61	0.64

Validation results

- C_{llr}
  - **Scenario 2:** 1 questioned-source v 3 known-source

Feature Set	Segmented Region					
	whole region of interest		breech face	firing pin	breech face + firing pin	
	including flowback	excluding flowback			feature concatenation	score-level fusion
Zernike moments magnitude & phase	**0.38**	0.50	0.55	0.73	0.45	0.48

Validation results

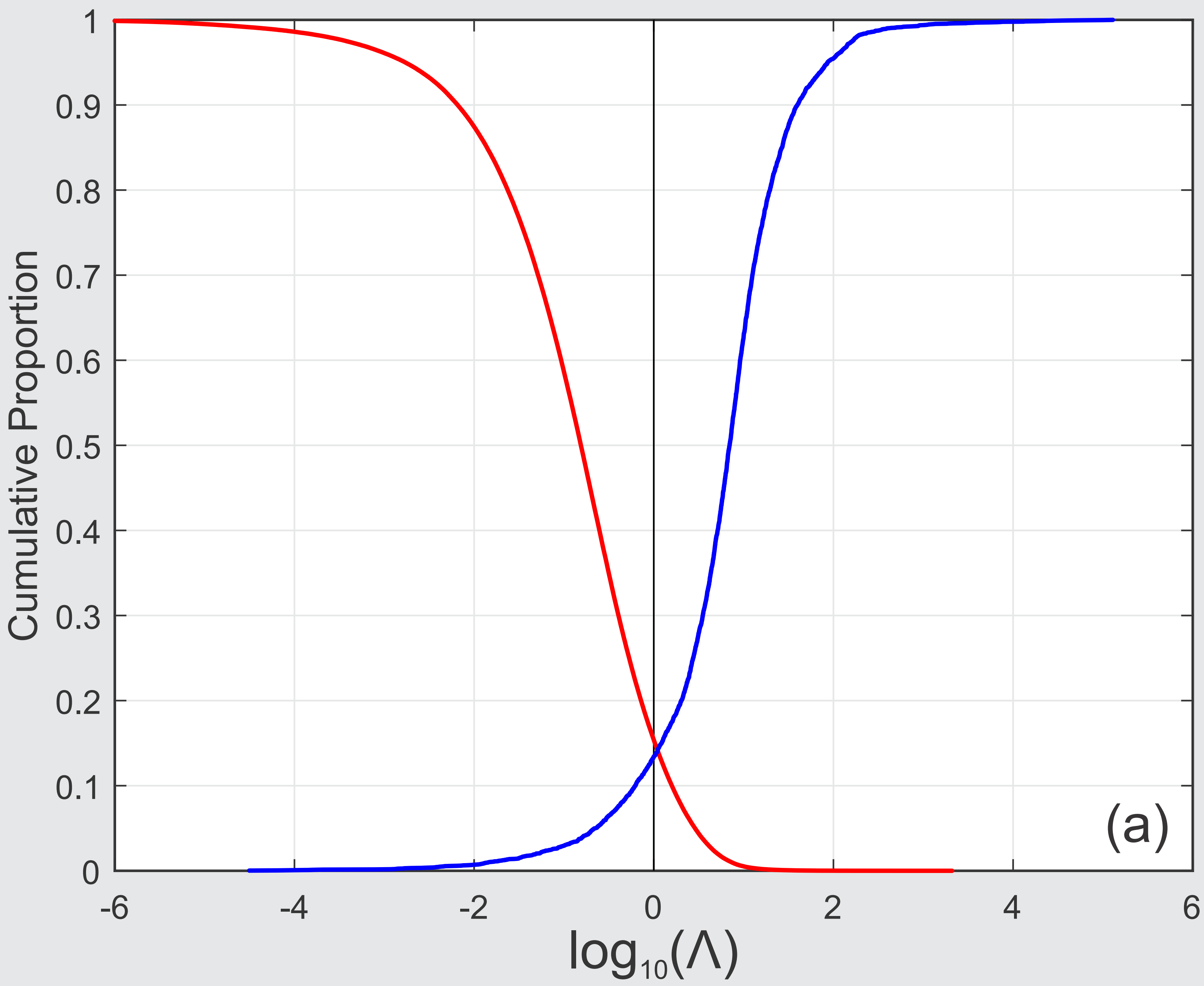
- $C_{\mathbf{llr}}$
  - **Scenario 2:** 1 questioned-source v 9 known-source

<table>
<tr><th rowspan="3">Feature Set</th><th colspan="6">Segmented Region</th></tr>
<tr><th colspan="2">whole region of interest</th><th rowspan="2">breech face</th><th rowspan="2">firing pin</th><th colspan="2">breech face + firing pin</th></tr>
<tr><th>including flowback</th><th>excluding flowback</th><th>feature concatenation</th><th>score-level fusion</th></tr>
<tr><td>Zernike moments magnitude & phase</td><td>0.35</td><td>0.45</td><td>0.51</td><td>0.68</td><td>0.40</td><td>0.43</td></tr>
</table>

Validation results

- **Tippett plot**

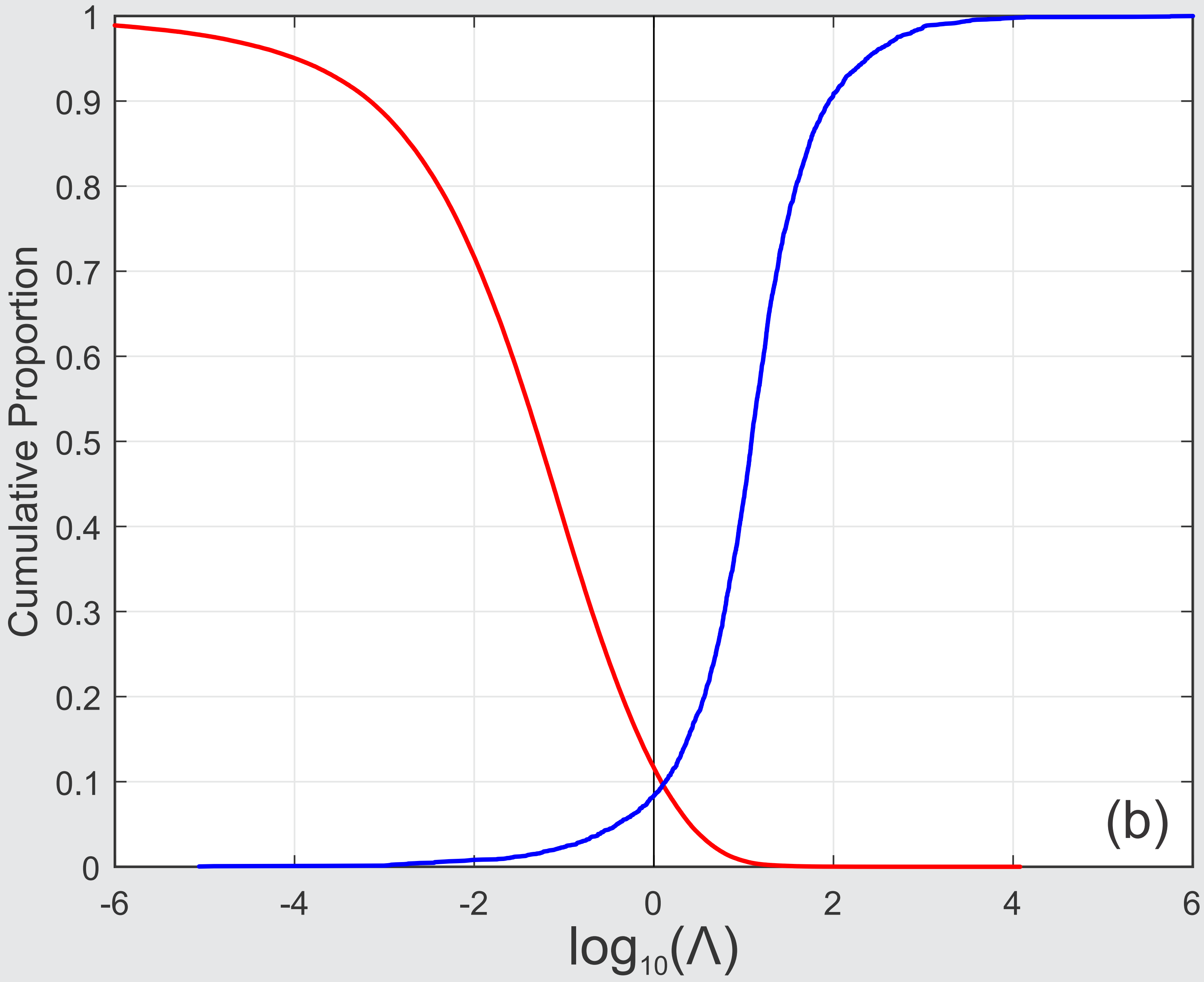
- **Scenario 1:**
  - 1 questioned-source v 1 known-source
  - $C_{\mathrm{llr}} = 0.52$



Validation results

- **Tippett plot**

- **Scenario 2:**
  - 1 questioned-source v 3 known-source
  - $C_{\text{llr}} = 0.38$



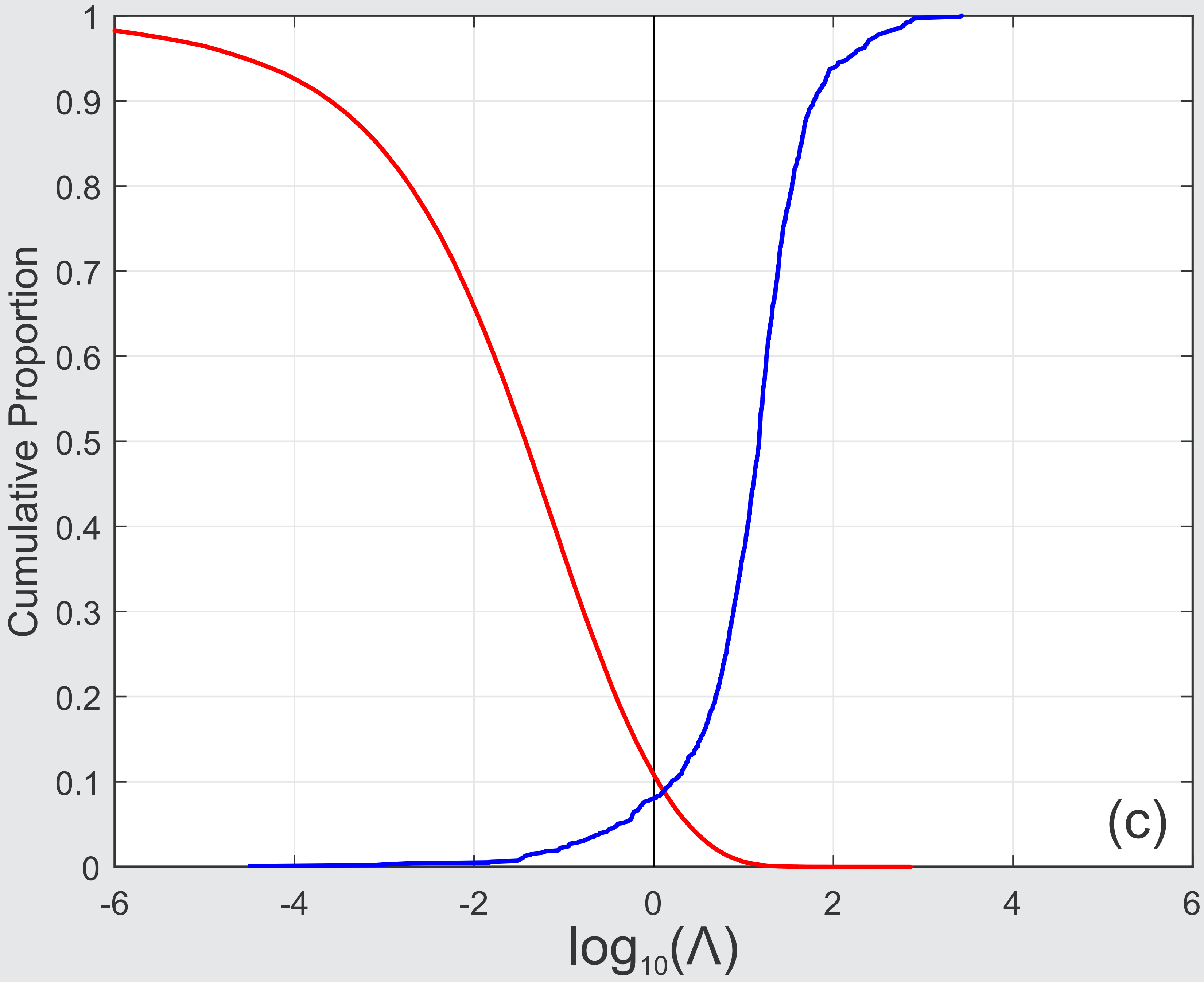
Validation results

- **Tippett plot**

- **Scenario 2:**

  - 1 questioned-source v 9 known-source

  - $C_{\mathrm{llr}} = 0.35$



Validation results

- Preprocessing **including rotation** versus **not including rotation**:
  - Zernike moment magnitude & phase features extracted from the whole region of interest including flowback
  - C_{llr} values less than 1% different

Conclusion

Conclusion

- Best feature set:
  - Zernike moment magnitude & phase
- Best segmentation:
  - whole region of interest including flowback
- Rotation not necessary
- In Scenario 2:
  - 3 is probably a sufficient number of cartridges to fire from the seized firearm

Future Plans

Future plans

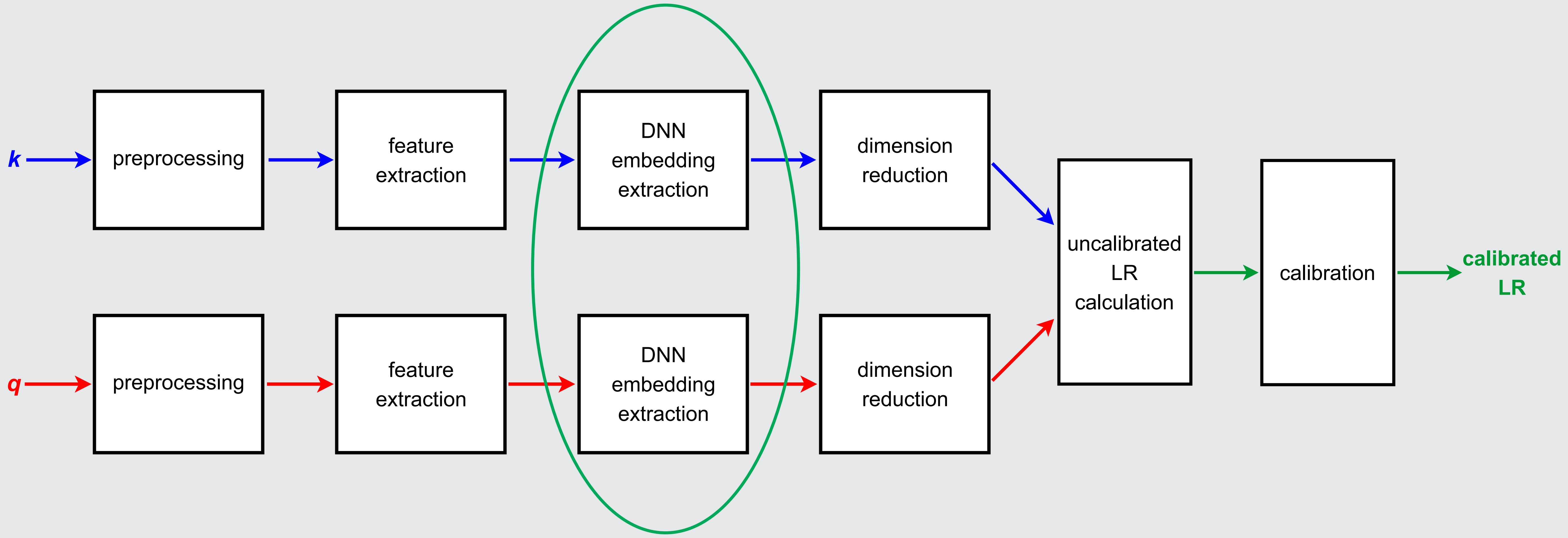
- We have submitted a grant application to fund more research:
    - Geoffrey Stewart Morrison, Aston University
    - Lehi Sudy dos Santos, Polícia Federal do Brasil
    - Flávio de Barros Vidal, Universidade de Brasília
    - Rachel S Bolton-King, Nottingham-Trent University

Future plans

- Data collection:
  - Cartridges fired from 1,000 firearms (9 mm Luger ammunition)
  - 7 cartridges with “V” mark (CBC ammunition), 7 without
  - 3D imaged using IBIS (14,000 images)
  - Also using IBIS, re-image 3,000 fired cartridges from E^3 database
  - Maybe you can help: Talk to Lehi

Future plans

- Statistical models:
  - Deep-neural-network (DNN) embeddings



Future plans

- Comparison with traditional human-based methods:
  - 24 practitioners
  - Scenario 2 (1 questioned-source v 3 known-source)
  - 36 sets of images
  - Virtual comparison microscope
  - Maybe you can help: Talk to Rachel

Future plans

- End-user testing:
    - 4 practitioners
    - Training in likelihood-ratio framework and in use of system
    - Use system in ~10 real cases and provide feedback
    - Based on feedback, make improvements to system
    - Maybe you can help: Talk to Lehi

Future plans

- If validation and end-user-testing results are favourable:
    - SINAB's Management Committee may develop standard operating procedures and training
    - Incorporate the system into SINAB member-laboratories' casework practice
    - Promote adoption elsewhere in world

Thank You

https://forensic-data-science.net/firearms/