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The Application of Analytic Hierarchy Process in Quantitative Research on Handwriting Examination

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ABSTRACT The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method combined with qualitative and quantitative analysis. Chinese handwriting examination too is a process of qualitative and quantitative decision-making. This paper attempts to use the AHP to quantitatively consider the process of handwriting examination and to find a convincing qualitative basis for the expert identification of handwriting.

KEY WORDS Document inspection; Chinese handwriting examination; Analytic Hierarchy Process; Quantification; Quantitative analysis; Multi-criteria decision-making method

In the field of document examination, the quantitative methods and ideas of Chinese handwriting examination are mostly based on computer mathematical models. However, it is always difficult to find an idealized model due to the complexity and variability of handwriting. The process of handwriting identification, largely based on empirical judgments, is actually a process wherein appraisers make operational decisions. In this paper, the Analytic Hierarchy Process (AHP) in operational research is used to construct a pattern that can reproduce the quantification process of appraisers' thoughts through a combination of qualitative and quantitative methods.

1. THE FEASIBILITY OF THE AHP IN QUANTITATIVE RESEARCH IN HANDWRITING EXAMINATION

1.1 The use of the AHP in the quantitative analysis of a complex decision-making process

The AHP was proposed by T. L. Saaty, an American operations expert [1]. It refers to a complex multi-criteria decision-making system. In this system, the target or a decision problem is first decomposed into a hierarchy of multiple objectives and multilevel indices through the qualitative index fuzzy quantification method. This is done to calculate hierarchical single sort (weight) and total ordering that can be used as a multi-scheme system to optimize the decision-making process. The AHP is a process in which a decision is made based on the general objective, the stated problem, and evaluation criteria after the problem is decomposed into different levels in a hierarchy. Using the eigenvector method, a judgment matrix is obtained for each element of each level to obtain the priority weights of the elements. Finally, the weighted sum method is used to obtain alternative solutions to reach the target weight, and this final weight is the optimal solution [2]. Here, the so-called "priority weight" is a relative measure, which indicates the evaluation of alternatives in specific measurement criteria or sub-goals, and of each element in the different hierarchical levels.

Its basic principle is dividing the factors involved in complex problems into several hierarchical levels, performing pairwise comparisons of the various elements of the same level according to some criteria, comparing their importance, and then calculating the weight of every element in each level. The optimal scheme is determined according to the combination and maximum weight principle.

This method is suitable for dealing with complex problems that are difficult to quantify as it involves a combination of qualitative and quantitative analysis. In the decision-making process, the qualitative thinking process is mathematical and model, and it helps maintain a consistent thought process. The method is used to construct a judgment

matrix and find its maximum eigenvalue. The corresponding eigenvector, after normalization, is the importance weight of a certain level relative to that of the previous level. In this case, if you think of the matrix as a motion, the most important features are obviously its velocity and direction, and so the eigenvalue is the velocity of the motion, and the eigenvector is the direction of the motion. Its mathematical definition is as follows: A is an n-order matrix, if the number of λ and n for non-zero vector x, relation $Ax = \lambda x$, then the number of λ is the characteristic value and a non-zero vector x is called an eigenvector of A corresponding to the eigenvalue of λ.

1.2 Handwriting is vague and inconsistent

Handwriting examination tracks the movement of writing, which is not uniform or limited to two-dimensional space. It includes, among other things, writing pressure, speed, and angle, as well as change in the rhythm of these factors. In plane and static handwriting, we can observe a three-dimensional, dynamic image. From a single stroke, multiple connected strokes, word relationships, and text layout, we can understand the writing process of Chinese characters that includes writing pressure, speed, and other characteristics [3]. However, the writing movement is not precise and mechanical; even if the same word is repeatedly written in a row, it is quite impossible to produce the same stroke length, arc, angle, and distance between strokes. Therefore, handwriting is ambiguous, and it is inappropriate to measure its absolute value.

Moreover, handwriting does not always have a fixed form. When someone is writing, the person's mood, motivation, writing tools, and environmental conditions could change, and in some cases, a person may want to deliberately disguise his/her handwriting, so even the same person's handwriting can appear varied. In addition, handwriting consists of eight basic strokes, which are the basic units of text, and they are linked through writing movements. In the process of "linking" these strokes, the writing movements are broken and punctuated, and one can transform the font or even reduce or accelerate his/her writing speed [4].

The objective of handwriting examination is to analyze the character symbol system of personal handwriting. As mentioned earlier, handwriting is ambiguous, and it is difficult to measure it accurately. These complex and random characteristics of handwriting make handwriting examination a subjective cognitive process.

1.3 Qualitative and quantitative analysis in handwriting examination

In handwriting examination practice, an examiner compares two handwriting samples to determine whether it is written by the same person. It is important to identify whether the two samples are written by the same person, and to do that, the examiner needs to identify the handwriting characteristics and then compare them. Handwriting characteristics refer to the specific signs of an individual's handwriting, which is based on personal writing skills and habits, and these signs include the features of skill level, text layout, typos, proportion, and connectedness and disconnectedness, as well as font characters, pen marks, Arabic numeral features, and symbol characteristics [5]. In handwriting examination, different handwriting characteristics should be selected to carry out a comparison according to specific cases. This process includes analyzing the handwriting, selecting and comparing characteristics, performing comprehensive evaluation, and forming conclusions. In the same recognition theory, two samples are considered the same if they contain similar differences. In the handwriting examination theory, everyone's handwriting is considered peculiar, that is, it reflects personal writing habits, which are unique as well as common. In other words, even if two handwriting samples are written by the same person, they would contain differences based on different characteristics, and if they are written by different people, the samples could still have similar characteristics. Therefore, in the comprehensive evaluation phase, it is necessary to evaluate the quality and quantity of similarities and differences [6]. Through qualitative and quantitative analysis, one can determine whether two handwriting samples are written by the same person.

For decades, people have been struggling to find a way to use computer technology for handwriting recognition, but with little success. The use of computer technology for handwriting recognition has undeniably made breakthrough progress in artificial intelligence, digital image and signal processing, feature extraction, recognition algorithms, and measurement techniques, especially in the breakthrough of the automatic segmentation and location of significant Chinese characters. However, writing is a dynamic process, which is difficult to reproduce repeatedly. First, normal writing may undergo various changes due to writing speed, environment, instruments, and a writer's physical and psychological characteristics. Second, regarding intentionally disguised handwriting, due to writers' disguising skills and different level of ability, the difficulty of identification also varies. If writers' write could be careful planning, attention to detail, and deliberate control, they can dramatically change their handwriting. Third, at present, handwriting examination is mainly based on analyzing signatures. However, signatures contain fewer words, have little features, are arbitrary, have multiple changes, and can easily be imitated. Identification of

signatures using computers to determine the characteristics of the handwriting and automatic handwriting recognition is very difficult.

1.4 The AHP is applied to quantification and decision-making in handwriting examination

The process of handwriting examination is essentially a decision-making process to determine whether two handwriting samples are written by the same person. Comparing two handwriting samples could lead to the following conclusions: written by the same person, written by different people, likely written by the same person, likely written by different people, and unable to make conclusions. When faced with a variety of options, experts need to compare, judge, and evaluate based on certain standards in order to reach a conclusion. The study of natural and social phenomena mainly uses mechanism and statistical analyses—the former analyzes the causal relationship between phenomena with classical mathematical tools, and the latter uses random mathematics as a tool to seek statistical laws through a large amount of observation data. A systematic analysis of recent developments is yet another method, and the AHP, being a practical method, is one of the mathematical tools used in systematic analysis.

2. THE CONSTRUCTION OF THE AHP IN QUANTITATIVE RESEARCH IN HANDWRITING EXAMINATION

Quantification in handwriting examination must be started with the characteristics of handwriting, including quantization of characteristic descriptions and values. The AHP's principle and method are introduced into quantitative analysis in handwriting examination, whose basic idea is to select the handwriting characteristics or extract the standard elements, to determine the value of the handwriting characteristics or conduct weight comparison of each standard element, and to perform a comprehensive evaluation or comparison of the decision-making process.

We combined the actual materials of a handwriting examination to introduce the specific application of the AHP. In the loan dispute case examined in this study, the number of words that need to be checked is large in the IOU ("I owe you"), the handwriting is normal, of sufficient quantity, close to "the condition required for inspection handwriting, and reflects that the writer's writing style is complete and stable.

2.1 Construction of a hierarchical diagram

First, a structural diagram of the AHP must be constructed. The first layer is the target layer that is, determining whether the two handwriting samples are written by the same person. The second layer is the standard layer; it involves analyzing the questioned handwriting and the sample handwriting and selecting the handwriting characteristics, for example, writing skill level, font feature, proportion feature, connectedness and disconnectedness feature, arrangement feature, etc. The third layer is the decision scheme layer that is, reaching the conclusion of handwriting examination.

2.2 Scale and pairwise comparison matrix

In order to make pairwise comparison of each scheme to get the relative weight under each standard or certain standard, we introduced the relative importance of scale, as shown in Table 1.

The reasons for choosing the 1-9 scale are as follows. Psychologists believe that too many factors of pairwise comparison will exceed the ability of people to judge; up roughly in the range of 7±2, such as the limit of 9, and 1-9 scales accurately express the difference between them [7]. The two factors in Table 1, i and j, represent two standards for comparison or two schemes for comparison under a certain standard. This pairwise comparison matrix is composed of the scale aij, and the score of the matrix should be given independently by the expert.

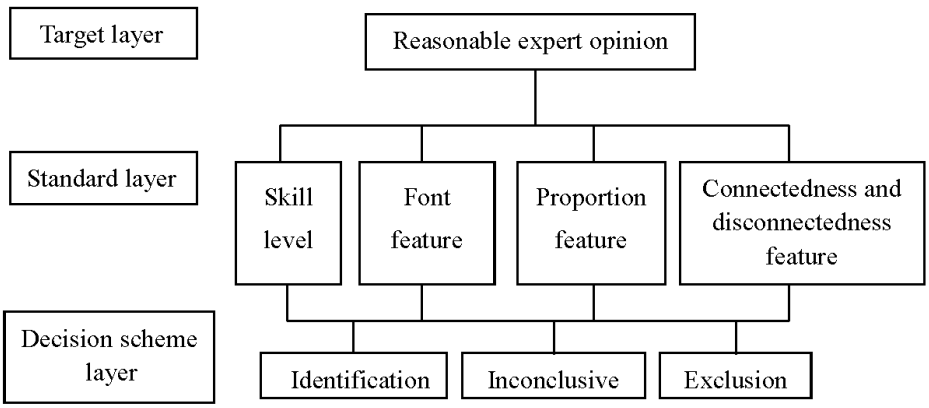

Fig. 1 Hierarchical diagram of handwriting examination

2.3 The process of calculating the weight of each factor of the standard layer under the target layer

2.3.1 Determining the standard weight

To obtain the relative importance (or relative weight) of each standard, pairs of four standards are formed for each comparison to get the pairwise comparison matrix. Table 2 shows the score of the handwriting characteristics selected by the appraiser for the case examined in this study.

The scoring rules are as follows: the appraiser selects the handwriting characteristics and, according to the 1-9 scale, scores the characteristics based on their significance, such as, when skill level vs. skill level, score is 1; when skill level is more important than font feature, score is 2; when skill level is slightly less important than proportion feature, score is 1/3; when skill level is obviously not important than connectedness and disconnectedness feature, score is 1/5. In the same way, all matrix judgments are completed.

The matrix calculation is conducted as follows:

The first step is to find the sum of each column in the comparison matrix, as shown in Table 3.

In the second step, every element of the pairwise comparison matrix is divided by the sum of the corresponding column, and the new matrix composed by the quotient is called the standard pairwise comparison matrix, as shown in Table 4.

The third step is to calculate the average of each row of the standard pairwise comparison matrix, which is the weight of each standard in the target layer, as shown in Table 5.

This method of calculating the weight of each factor is called the standard column average method, which is an approximate method for calculating weight. Other methods include the square root method, power multiplication method, *etc*. [8].

Table 1 Scale comparison

Scale a_{ij}	Definition
1	i factor and j factor are equally important
3	i factor is more important than j factor
5	i factor is obviously more important than j factor
7	i factor is very important than j factor
9	i factor is absolutely important than j factor
2,4,6,8	The scaled value corresponding an intermediate state between the above two judgments
Reciprocal	If j and i factors are compared, the judgment value is $a_{ji}=1/a_{ij}$

Table 2 Four standard comparison matrix

	Standard			
	Skill level	Font feature	Proportion feature	Connectedness and disconnectedness feature
Skill level	1	2	1 / 3	1 / 5
Font feature	1 / 2	1	1 / 4	1 / 4
Proportion feature	3	4	1	1 / 3
Connectedness and disconnectedness feature	5	4	3	1

Table 3 The sum of the pairwise comparison matrix for each column

	Standard			
	Skill level	Font feature	Proportion feature	Connectedness and disconnectedness feature
Skill level	1	2	1 / 3	1 / 5
Font feature	1 / 2	1	1 / 4	1 / 4
Proportion feature	3	4	1	1 / 3
Connectedness and disconnectedness feature	5	4	3	1
Column sum	19 / 2	11	55 / 12	107 / 60

Table 4 Standard pairwise comparison matrix

	Standard			
	Skill level	Font feature	Proportion feature	Connectedness and disconnectedness feature
Skill level	2 / 19	2 / 11	4 / 55	12 / 107
Font feature	1 / 19	1 / 11	3 / 55	15 / 107
Proportion feature	6 / 19	4 / 11	12 / 55	20 / 107
Connectedness and disconnectedness feature	10 / 19	4 / 11	36 / 55	60 / 107

Table 5 Average of each row of the standard pairwise comparison matrix

	Standard				
	Skill level	Font feature	Proportion feature	Connectedness and disconnectedness feature	Row average
Skill level	0.105	0.182	0.073	0.112	0.118
Font feature	0.053	0.091	0.055	0.140	0.085
Proportion feature	0.316	0.364	0.218	0.187	0.271
Connectedness and disconnectedness feature	0.526	0.364	0.655	0.561	0.526

Table 5 shows the scores or weights of the four standards under the target layer, which are 0.118, 0.085, 0.271, and 0.526 respectively, and the sum of the weights is 1. The vectors 0.118, 0.085, 0.271, 0.526 are called standard eigenvectors.

2.3.2 Consistency test of comparison matrix

The elements of the pairwise comparison matrix are obtained by a comparison of two factors, and in many of these comparisons, it is often possible to draw some inconsistent conclusions.

When the importance of factors such as *i*, *j*, and *k* is very close to each other, it may be concluded that i is more important than *j* in the pairwise comparison, *j* is more important than *k*, and *k* is more important than *i*, thereby drawing contradictory conclusions. This is more likely to occur when there are many factors, so it must be tested for consistency.

The consistency test is composed of five steps:

In the first step, the tested pairwise comparison matrix is multiplied by its eigenvectors. The result is called the empowerment sum vector, as shown below:

$$\begin{pmatrix} 1 & 2 & 1/3 & 1/5 \\ 1/2 & 1 & 1/4 & 1/4 \\ 3 & 4 & 1 & 1/3 \\ 5 & 4 & 3 & 1 \end{pmatrix} \times \begin{pmatrix} 0.118 \\ 0.085 \\ 1.271 \\ 0.526 \end{pmatrix} = \begin{pmatrix} 0.483 \\ 0.344 \\ 1.14 \\ 2.269 \end{pmatrix}$$

In the second step, each component of the empowerment sum vector is divided by the component of the corresponding eigenvectors, as in the following case:

0.483/0.118≈4.093, 0.344/0.085≈4.047

1.14/0.271≈4.207, 2.269/0.526≈4.314

In the third step, the average of the results obtained in the second step is calculated, and it is recorded as l_{max} , as follows:

$$l_{max} = \frac{4.093 + 4.047 + 4.207 + 4.314}{4} = 4.165$$

In the fourth step, the consistency index CI is calculated:

$$CR = \frac{4.165 - n}{n - 1}$$

n is the number of comparison elements; in this case, there are four standards, *n* = 4, so:

$$CR = \frac{4.165 - 4}{4 - 1} = 0.055$$

In the fifth step, the consistency rate CR is calculated:

$$CR = \frac{CI}{RI}$$

In order to determine the permissible range of the inconsistent degree of matrix, we need to find out the standard that can measure the matrix of the consistency index CI and need to introduce the random consistency index RI.

For *n* = 1, ..., 9, Saaty gives the value of RI, as shown in Table 6.

The value of RI is obtained by using the random method to construct 500 sample matrices: a number from 1 to 9 and its reciprocal is extracted to construct a positive reciprocal matrix, and the average of maximum eigenvalue

λ'_{max} is obtained, which is defined as follows:

$$RI = \frac{\lambda'_{max} - \mathrm{n}}{\mathrm{n} - 1}$$

Generally, when CR $\leqslant$ 0.1, the consistency of the pairwise comparison matrix is acceptable; Otherwise, its consistency is poor, and then we must recalculate pairwise comparison judgments. In this case, we can calculate CR = $0.055/0.90 \approx 0.061 \leqslant 0.1$, so the pairwise comparison matrix of four standards satisfies the consistency requirements, and the corresponding eigenvectors are valid.

2.4 The process of calculating the weight of each factor of the decision scheme layer under the single factor of the standard layer

Under the standard skill level, the pairwise comparison method is used to judge the significance of the pairs among the three schemes, and then the pairwise comparison matrix is concluded under this standard, as shown in Table 6. According to the pairwise comparison matrix, the weight of the three schemes under this standard is calculated, and then the consistency test is performed. The specific calculation method is the same as in the above standard layer calculation.

Using the same process, under the skill level, font feature, proportion feature, and connectedness and disconnectedness feature, we can construct the pairwise comparison judgment matrix among the "affirmation, non-conclusion, and exclusion" schemes. The judgment matrices and the calculation results are shown below (Tables 7-10).

The calculation results are as follows:

Eigenvectors of skill level = (0.6196,0.1561,0.2243), CI = 0.0546, CR = 0.0942 Eigenvectors of font feature = (0.7189, 0.1127, 0.1684), CI = 0.0437, CR = 0.0754

Eigenvectors of proportion feature = (0.7903, 0.1328, 0.0769), CI = 0.011, CR =0.0189

Eigenvectors of connectedness and disconnectedness feature = (0.6232, 0.2395, 0.1373), CI = 0.0092, CR = 0.0158

These weights or eigenvectors are used to solve the sequence of each scheme.

As mentioned above, the eigenvectors of the four standards and the four eigenvectors of the three schemes under the single standard are calculated, as shown in Table 11.

These weights or vectors are used to calculate the total score of each scheme.

Under skill level, the score of the affirmation scheme is 0.6196, and the importance of skill level in the target of reasonable expert opinion is 0.118; therefore, due to its skill level, the affirmation scheme in the total target score is 0.118×0.6196. Similarly, the affirmation scheme due to its font feature in the total target score is 0.085×0.7189; the affirmation scheme due to its proportion feature in the total target score is 0.271×0.7903; and the affirmation scheme due to its connectedness and disconnectedness feature in the total target score is 0.526×0.6232. Therefore, the total score of the affirmation scheme in the total target is as follows:

$$0.118 \times 0.6196 + 0.085 \times 0.7189 + 0.271 \times 0.7903 + 0.526 \times 0.6232 \approx 0.676$$

In the same way, the total score of the non-conclusion scheme in the total target is as follows:

$$0.118 \times 0.1561 + 0.085 \times 0.1127 + 0.271 \times 0.1328 + 0.526 \times 0.2395 \approx 0.190$$

The total score of the exclusion scheme in the total target is as follows:

$$0.118 \times 0.2243 + 0.085 \times 0.1684 + 0.271 \times 0.0769 + 0.526 \times 0.1373 \approx 0.134$$

By comparison, the score of the affirmation scheme is the highest.

Table 6 The average random consistency index

Dimensions (*n*)	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Table 7 Pairwise comparison matrix of skill level

	Skill level		
	Affirmation	Non-conclusion	Exclusion
Affirmation	1	3	4
Non-conclusion	1 / 3	1	1 / 2
Exclusion	1 / 4	2	1

Table 8 Pairwise comparison matrix of font feature

	Skill level		
	Affirmation	Non-conclusion	Exclusion
Affirmation	1	5	6
Non-conclusion	1 / 5	1	1 / 2
Exclusion	1 / 6	2	1

Table 9 Pairwise comparison matrix of proportion feature

	Skill level		
	Affirmation	Non-conclusion	Exclusion
Affirmation	1	7	9
Non-conclusion	1 / 7	1	2
Exclusion	1 / 9	½	1

Table 10 Pairwise comparison matrix of connectedness and disconnectedness feature

	Skill level		
	Affirmation	Non-conclusion	Exclusion
Affirmation	1	3	4
Non-conclusion	1 / 3	1	2
Exclusion	1 / 4	1 / 2	1

Table 11 The eigenvectors of the four standards and of the three schemes under the single standard

Eigenvectors of the four standards		Eigenvectors of the three schemes under the single standard				
Skill level	0.118		Skill level	Typeface Feature	Proportion feature	Connectedness and disconnectedness feature
Typeface Feature	0.085	Affirmation	0.6196	0.7189	0.7903	0.6232
Proportion Feature	0.271	non-conclusion	0.1561	0.1127	0.1328	0.2395
Connectedness and disconnectedness feature	0.526	Exclusion	0.2243	0.1684	0.0769	0.1373

3 DISCUSSION AND CONCLUSIONS

First, the selection of skill level, font feature, proportion feature, and connectedness and disconnectedness feature in this study is based on a specific case. The different circumstances of the case are not limited to the four abovementioned characteristics. Different characteristics may be added or deleted according to specific circumstances and the standard layer. In addition, the sub-standard layer can be subdivided under the standard layer. For example, under the connectedness and disconnectedness feature, it can be subdivided into initial, connecting, and terminal strokes, and under the connecting strokes feature, it can be subdivided into slant or slope, speed, and pressure features. The three-tier structure can be extended to a four or even five-layer structure [9]. At the same time, the “affirmation, non-conclusion, and exclusion” schemes can be extended to the “affirmation, tendency affirmation, non-conclusion, exclusion, and tendency exclusion” schemes.

Using MATLAB software, the calculation of the abovementioned extended application can be realized.

Second, through a combination of qualitative and quantitative methods, this approach describes the thought process of experts using the mathematical form, that is, using data to explain identification and exclusion.

Third, the matrix judgment score was marked by analyzing the questioned and sample handwriting, and combining the appraiser's professional experience and the difference in each case. In the implementation process, it is necessary to pass the consistency test; if the consistency test fails, it needs to be rescored.

Finally, the AHP has become a mature concept and an operational method. It is applicable to the field of handwriting examination. However, the specific operational practice needs to be studied further.

The mathematical algorithm of the AHP is programmed by MATLAB software, which is convenient for finishing the operation and consistency test of the above-mentioned matrix.

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The Optimal Electrode Distance in Recording Compound Nerve Action Potentials to Study Traffic Nerve Functional Injury Mechanism

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ABSTRACT The compound nerve action potential and its conductivity characteristics can be used to study the traffic brain functional injury mechanism. The recording of compound nerve action potentials is greatly affected by the distance between the electrode tips. In order to study the optimum parameters for these recordings in the bullfrog sciatic nerve trunk, compound nerve action potential was measured at different electrode spacing. The threshold and super stimulation intensity of compound nerve action potential were first decreased slowly and then gradually increased as the distance between the tips of the two stimulation electrodes was increased. When the distance between exciting point and recording point was gradually increased, the amplitude and area under the curve were decreased, but the action potential duration was increased. The amplitude, action potential duration and area under the curve had the tendency to improve with the distance between two recording electrode tips increasing from 5 mm to 20 mm. When that spacing was larger than 20 mm, the amplitude was relatively stable. The distance of two stimulating electrodes is 5mm, the distance between stimulating and measuring electrodes is 10mm and the distance of two measuring electrodes is 20mm, which is the most suitable distance for compound nerve action potentials collecting on the bullfrog sciatic nerve trunk.

KEY WORDS Compound nerve action potential; Traffic nerve functional injury; Amplitude; Area under the curve; Action potential duration

1. INTRODUCTION

In the study of traffic brain injury, the compound nerve action potential and its conductivity characteristics were often adopted especially to help understanding the nerve functional injury mechanism. The compound nerve action potential is the sum of the potentials produced by various nerve fibers as the nerve trunk is stimulated. It was applied to the evaluation of nerve injury by some scholars [1-4]. The amplitude and area under the curve are correlated with myelinated fiber numbers [5-7]. The action potential duration is associated with synchronous excitement extent of nerve fiber [8]. The lower of synchronous excitement extent of nerve fiber is, the lower of amplitude is, and the wider of action potential duration is. The nerve structure and the injury degree of nerve function could be analyzed by measuring compound nerve action potential.

Compound nerve action potentials have been recorded in amphibians and mammals, including bullfrogs [9, 10], rats [5], dogs [6], and humans[11]. And similar waveforms have been recorded both in vitro [12] or in vivo [13]. Due to different recording methods, different electrode positions, different distances between bipolar electrodes or stimulation intensity, there may be large differences in compound nerve action potentials measured in the same nerve trunk of the same individual [17]. In the isolated bullfrog sciatic nerve trunk, Dalkilic et al. [14] revealed that the amplitude and the action potential duration will change significantly when the distance

between the measuring electrode spacing gradually increases. Kline et al. [15] argued that the most suitable distance of bipolar recording electrodes between 3 and 5 mm. The amplitude becomes gradually smaller as the distance between stimulus and measurement points increases (from 10 to 20, 30, 40, 50 mm) [16]. The most ideal data model for compound nerve action potential measuring in rat median nerve, found in some other studies, were a distance of 5 mm between two stimulating electrodes and a distance of 10 mm between measuring and stimulating points and a distance of 5 mm between two measuring electrodes [17]. But there may be a problem that they were not able to test longer distances.

In recent years, it is common to study compound nerve action potentials or to study the effects of chemical substances on compound nerve action potentials by using bullfrog [10, 18–20]. But, as far as we know, there is no electrode spacing standard for measuring the compound nerve action potential on the bullfrog sciatic nerve trunk., that is the reason why compound nerve action potential measurement results were different in the same nerve of same species. This paper explored the influence of electrode distance on compound neural action potentials and explained the reasons, and gave the optimal distance between electrode distance.

2. MATERIALS AND METHODS

2.1 Materials

Fifteen bullfrogs(100～110g) were provided for the experiment. We tried our best to reduce the number of animals used and their suffering.

2.2 Methods

2.2.1 Sciatic nerve trunk preparation

According to the method introduced by Wang Limin [21], each bullfrog sciatic nerve specimen was prepared. It should be noted that the nerve trunk was dissected as long as possible, and nerve damage ought to be minimized during the process. In order to ensure the activity of the nerve specimen, the nerve specimen should be immersed in Ringer's solution for 20 minutes after dissection.

2.2.2 Neurophysiological measurement

Compound nerve action potentials were recorded by biomedical signal acquisition system. The waveform of compound nerve action potential sampling frequency was 10000 Hz, stimulating frequency 5 Hz, stimulus square wave duration 0.1 ms, and the filtration was lower than 1000 Hz.

The optimal distance of electrodes was explored by recording compound nerve action potentials at different distances between electrodes.

In the first case, the distance between two stimulating points was 2, 4, 6, 8 or 10 mm, the distance between two recording electrodes was maintained at 20 mm, and the distance between recording and stimulating electrodes was maintained at 15 mm. In the latter case, the distance increased from 10 to 15, 20, 25, 30, 35 mm between stimulating and recording sites, the stimulating electrode spacing and measuring electrode spacing were maintained at 5 mm and 20 mm respectively. In the third case, compound nerve action potential was measured with distances of 5, 10, 15, 20, 25, 30, 35 mm between two measuring electrodes, meanwhile the stimulating electrode spacing was fixed at 5 mm and the distance between stimulating and measuring electrodes was maintained at 15 mm. The compound nerve action potential was measured by orthodromic recording (Fig.1).

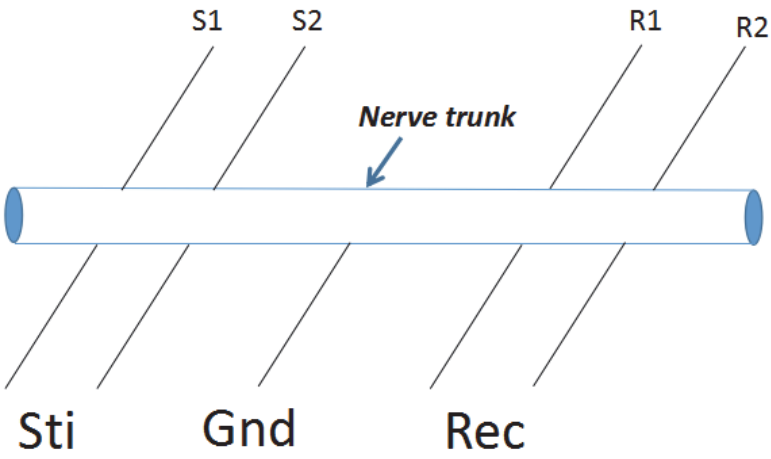

Fig. 1 The methods to compound nerve action potential measuring(S1 and S2 are stimulating electrodes, R1 and R2 are measuring electrodes.)

2.2.3 Statistical analysis

Spss26.0 was used for data analysis and the data were presented as mean ± SEM. One-way ANOVA with Least-Significant Different test was used for comparisons of threshold intensity, super stimulation intensity , amplitude, action potential duration and area under the curve between different experimental groups. The data was considered statistically significant when $P < 0.05$.

3. RESULTS

The threshold intensity(THI) and super stimulation intensity(SSI) of compound nerve action potential were first decreased slowly and then gradually increased as the stimulating electrode spacing was increased from 2 mm to 10 mm($P < 0.05$, Table 1).

When the distances between stimulating sites and measuring sites were gradually increased, the first peak amplitude(FPA), peak peak amplitude(PPA), and area under the curve(AUC) gradually decreased($P < 0.05$), while the action potential duration was increased($P < 0.05$, Table 2).

The FPA and PPA were dramatically increased when the spacing of two measuring electrodes changed from 5 to 20 mm($P < 0.05$), meanwhile the FPA and PPA were no obvious change when the measuring electrode spacing increased from 20 mm to 35 mm($P > 0.05$). As the measuring electrodes spacing increased from 5 mm to 35 mm, considerably greater AUC and APD were observed($P < 0.05$, Table 3).

Table 1 Effects of different electrode spacing on threshold intensity and super stimulus intensity

Variable	2.0mm	4.0mm	6.0mm	8.0mm	10.0mm	F	P
THI（V）	0.235±0.009	0.183±0.006	0.187±0.009	0.227±0.006	0.245±0.009	13.172	0.000
SSI（V）	0.412±0.020	0.327±0.013	0.323±0.01	0.368±0.009	0.406±0.011	10.215	0.000

Table 2 Effects of different spacing between stimulating and measuring electrodes on waveform

Variable	FPA（mv）	PPA（mv）	APD（ms）	AUC（mvms）
10mm	2.29±0.16	3.89±0.30	1.12±0.03	3.30±0.22
15mm	2.13±0.15	3.61±0.28	1.16±0.03	3.13±0.23
20mm	1.95±0.13	3.30±0.25	1.23±0.06	2.89±0.20
25mm	1.76±0.10	2.97±0.19	1.29±0.07	2.61±0.16
30mm	1.66±0.11	2.77±0.17	1.38±0.05	2.42±0.16
35mm	1.59±0.12	2.64±0.19	1.48±0.07	2.36±0.17
F	4.451	4.457	6.398	4.056
P	0.002	0.002	0.000	0.003

Table 3 Effects of different spacing between two recording electrodes on waveform

Variable	FPA（mv）	PPA（mv）	APD（ms）	AUC（mvms）
5mm	0.74±0.04	1.17±0.07	0.95±0.02	0.86±0.06
10mm	1.28±0.08	2.02±0.15	1.03±0.02	1.60±0.13
15mm	1.68±0.09	2.70±0.17	1.06±0.02	2.20±0.15
20mm	1.96±0.10	3.25±0.19	1.11±0.02	2.76±0.17
25mm	2.11±0.11	3.66±0.22	1.16±0.03	3.28±0.20
30mm	2.11±0.12	3.79±0.22	1.24±0.03	3.56±0.21
35mm	2.15±0.16	3.92±0.23	1.27±0.03	3.83±0.23
F	29.905	30.571	23.879	39.220
P	0.000	0.000	0.000	0.000

4. DISCUSSION

Neuroelectrophysiology is an important method to explore nerve function, with a long history of research [22, 23]. Compound nerve action potential recording, a classic and mature electrophysiological method, is a useful tool for assessing peripheral nerve diseases and nerve repair. Compound nerve action potential has a unique diagnostic value for the analysis of nerve function and structure[1-4, 22, 24].

Even if the same nerve of the bullfrog was measured, the waveform of the compound nerve action potential may be significantly different. Therefore, exploring the influence of electrode spacing on the waveform of compound nerve action potentials and finding the most ideal electrode spacing is of great value for experimental research.

In our study, when the distance between two stimulating electrodes was changed from 2 mm to 4mm and 6 mm, the threshold intensity and super stimulation intensity of compound nerve action potentials were gradually decreased, that was consistent with the conclusions of some scholars [17]. But, when the distance was changed from 6 mm to 8 mm and 10 mm, the threshold and super stimulation intensity were gradually increased (Fig.2). Other studies showed that the width between the two poles of the stimulating electrodes affected the waveform of the action potential [25]. The multiphase wave is more obvious with the increase of the stimulation electrode spacing. In other words, the optimal distance between two stimulating electrodes should be 4～6 mm.

Our research results demonstrated that the compound nerve action potential amplitude and the area under the curve decreased, while the action potential duration increased gradually when the distances between the stimulating or measuring points were increased from 10 to 35 mm(Fig.3, Fig.4). In the process of action potential transmission, the compound nerve action potential amplitude decreased due to the decrease of nerve fiber's number. Another reason for the decrease of amplitude is related to the dispersion of action potential velocity[8, 16]

When the measuring electrode spacing changed from 5 to 20 mm, the amplitude, action potential duration, and area under the curve were gradually increased. It was tough to record completely the waveform of compound nerve action potential when the measuring electrode spacing was less than 20 mm, that why if the distance was too short, both electrodes would be placed on the activation area of the nerve trunk and influenced by each other. Actually, biphasic action potential is the potential difference between two recording electrodes. That means the recording electrode spacing needs to be longer than the wavelength of the composite action potential. A problem in other studies was that the median nerve in rat was not long enough to be used, they were not able to test distances between the recording electrodes greater than 5 mm, hence they may not have recorded complete action potential waveforms [17]. When the spacing between the measuring electrodes changed from 20 to 35 mm, the amplitude was not found statistically significant effect, but the action potential duration and area under the curve were gradually increased (Fig.5, Fig.6).

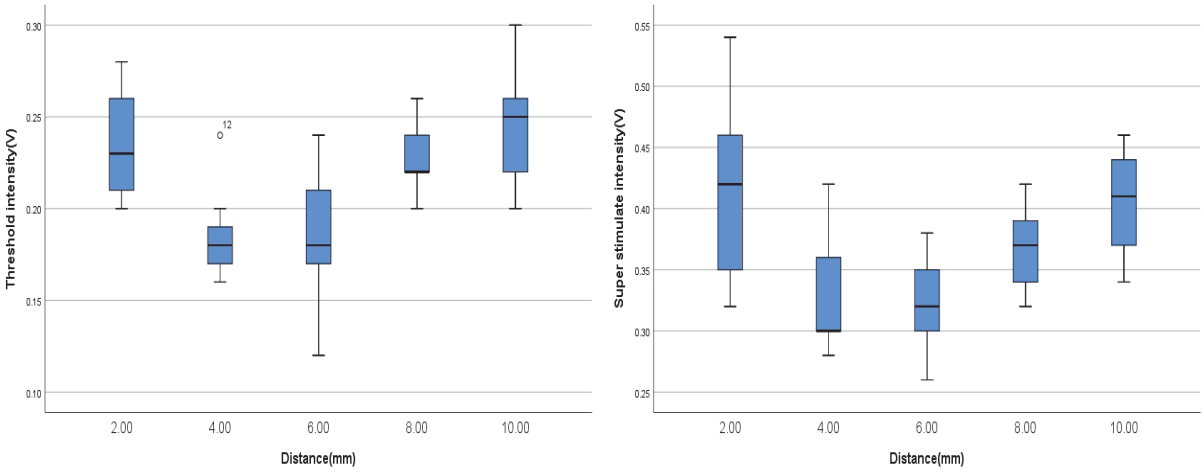

Fig. 2 Effects of different spacing between stimulating electrodes on threshold intensity and super stimulation intensity

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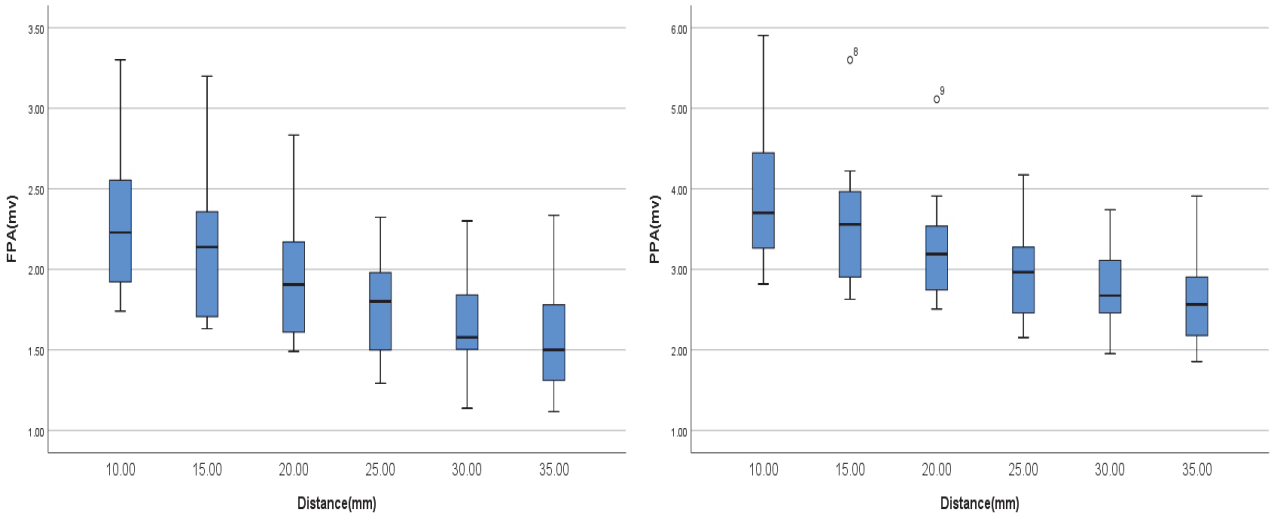

Fig. 3 Effects of different distances between exciting and measuring electrodes on the amplitude

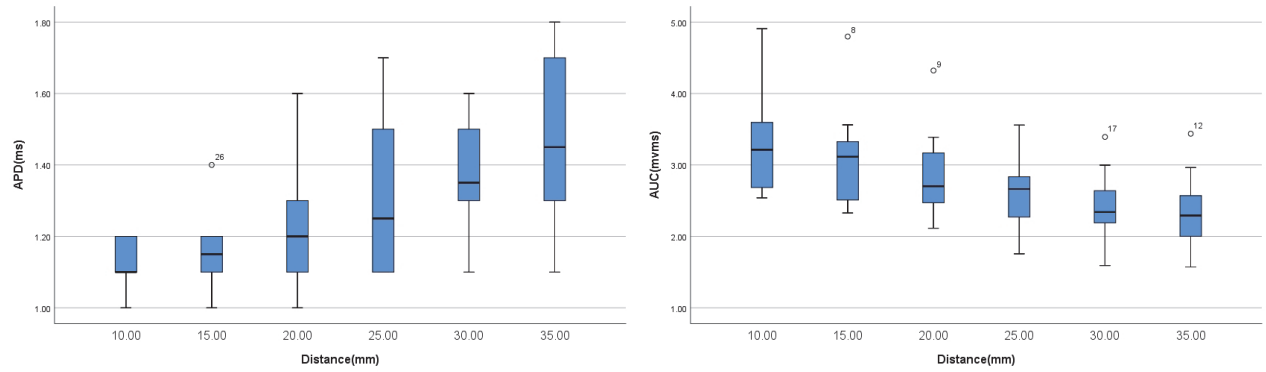

Fig. 4 Effects of different distances between exciting and measuring electrodes on the APD and AUC

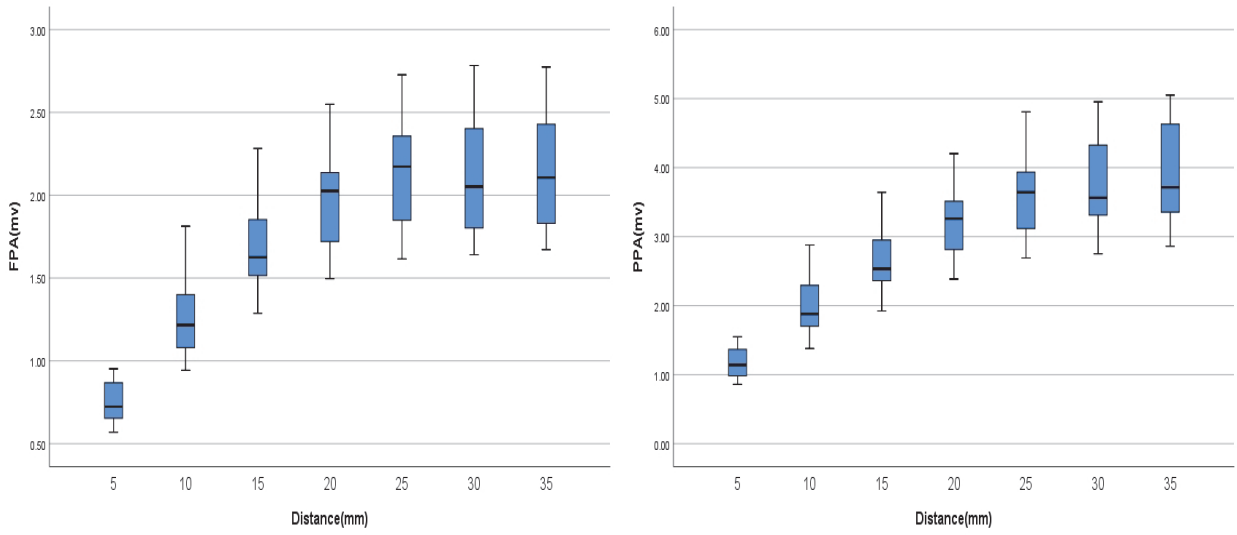

Fig. 5 Effects of different distances between measuring electrodes on the amplitude

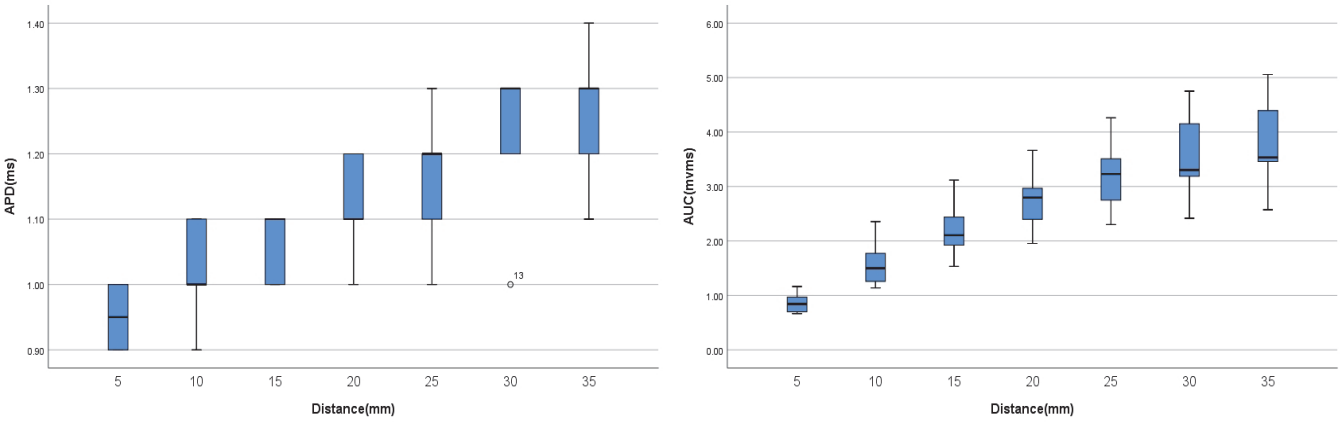

Fig. 6 Effects of different distances between measuring electrodes on the APD and AUC

The nerve trunk is composed of different diameters and types of nerve fibers, so the conduction velocity and wavelength of action potential are different from each nerve fiber. Our results further showed that the action potential synchronization of different nerve fibers decreased, while the action potential duration become longer when the distance between stimulating and recording electrodes or recording electrodes got longer. Therefore, in order to reduce the influence of the electrode spacing on the waveform and record complete information of the compound nerve action potential as much as possible, a distance of 5 mm between two stimulating electrodes, a distance of 10 mm between stimulating and measuring electrodes and a distance of 20 mm between two measuring electrodes were revealed to be optimum for compound nerve action potential measuring in the bullfrog sciatic nerve trunk.

The optimal parameters revealed in the study can provide experimental references and data support for accurate recordings of compound nerve action potential of bullfrog sciatic nerve. It could be used in related research fields (evaluation of nerve functional injury severities and healing effects after traffic accidents, evaluation of the results of drugs or chemicals in nerves and so on).

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Conflicts of interests

None declared.

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Communicating Forensic Genetics: 'Enthusiastic' Publics and the Management of Expectations

Nina Amelung, Rafaela Granja, Helena Machado

ABSTRACT Exploring Science Communication brilliantly demonstrates how Science Communication can be enhanced and elaborated through an engagement with Science and Technology Studies. Analytically and empirically, the volume traces the complex roles of Science Communication in the making and doing of science, publics and politics. Essential reading for both analysts and practitioners., Science communication emerges as much more than getting new knowledge 'out' to larger society. Through a series of insightful contributions, science communication is revealed as shaping both science and society, re-imagining our socio-technical futures and creating narratives of governance, responsibility and change. Seen from an STS perspective, science communication 'matters' in important, challenging and unexpected ways.

1. INTRODUCTION

'One of the most important problems in forensic medicine', write forensic geneticists Angel Carracedo and Lourdes Prieto, 'is the so-called "CSI effect"' (Carracedo & Prieto 2018: 4). Their description of the threat posed by TV shows such as Crime Scene Investigation (CSI) to their discipline runs as follows: '[m]ost TV series present forensic evidence as infallible – one hundred percent reliable, with no margin for doubt – when reality is very different: the scientific validity of forensic tests is variable' (ibid.). When looking at the communication of forensic science, we therefore seem to be confronted with an interesting paradox. While researchers and policy makers tend to complain about public disinterest in science and see this as threatening its cultural authority, in the case of forensic science we encounter the exact opposite. It is the prominence of forensic science in popular culture which seems to have raised expectations to a degree which might actually have negative consequences for the use of this knowledge in the context of criminal investigations and in the judicial system.

Indeed, forensic genetics, as a specialisation of genetics and forensic science, is communicated and negotiated in particular settings. On the one hand, its identity is generally negotiated in and structured by the physical and social space of the forensic genetics laboratory, a space that is important in the chain of custody for producing DNA evidence that can be used for police criminal investigation and in the courtroom. On the other hand, the results of forensic genetic science are always eventually communicated in the courtroom, which becomes 'a theatre' (Felt and Davies, in Chapter 3, referring to Jasanoff) in which evidence needs to be demonstrated in a manner legible to the common sense of judges and jurors. In recent decades, public understandings of forensic genetics – publics including here also judges and police officers – have been understood as being strongly shaped by media representations in prominent TV series. As a consequence, forensic geneticists have had to reflect on the views of publics they encounter and to develop communication strategies to protect and defend their profession's identity, including the provision of guidance about 'good communication'.

In the present chapter we explore forensic geneticists' perceptions of how they carry out science communication to their specific publics in the criminal justice system. More particularly, we examine how forensic geneticists reconstruct their self-conception and relations to their publics when performing the presentation of DNA evidence in court. The research questions guiding our investigations are the following: What are the particularities of communicating forensic genetics? How do forensic geneticists cope with these particularities? And how do imaginaries of publics shape forensic geneticists' experiences of communication?

In what follows we will reflect on two strands of Science and Technology Studies (STS) debates that inform our study. After presenting our material and the methods we use, we present our analysis along three lines and draw concluding remarks.

2. SCIENCE COMMUNICATION AS BOUNDARY-WORK: PROTECTING SCIENCE'S IDENTITY AND DELEGATING RESPONSIBILITIES

Science communication scholars have highlighted that STS can offer relevant perspectives to understand how science and publics are co-produced in science communication practices (Davies & Horst 2016: 204). Indeed, there is a quite large body of literature pointing to the fact that publics are not simply out there waiting to be informed about science, but are actively made through the precise settings and the spaces in which science communication happens (Felt & Fochler 2010; Lezaun & Soneryd 2007). In this context it is also useful to consider the distinction introduced by Mike Michael (2009) between 'publics-in-particular' – namely specific, situated publics with identifiable stakes and interests – and 'publics-in-general', a rather undifferentiated vision of 'people out there'. Thus, we have to consider that the criminal justice system, and in particular the courtroom, are specific spaces (see Chapter 3) in which forensic geneticists communicate about DNA evidence. This gives form to specific kinds of publics, and shapes the roles that can be taken on, how these are distributed, and the kinds of knowledge that can and need to be communicated.

We also suggest reading our case in the light of the dominant sense-making narratives used by science communication scholars and practitioners today, such as the so-called 'deficit model' (Davies & Horst 2016: 37–39; Irwin 2014; McNeil 2013). The reference to the 'deficit model' usually serves as an established classification to describe certain ways of performing science communication (in particular one-way instead of two-way science communication; Davies & Horst 2016: 37–39). This model has been used instrumentally, in the sense that it serves as a justification to argue for increasing scientific literacy or for excluding lay publics from some types of decision making. The 'deficit model' is thereby a manifestation of broader imaginations of what scientific governance should look like (Irwin & Wynne 1996). In this chapter we will explore an additional, quite different, notion of the 'deficit model', applied not only to publics, but also to science/scientists. For our particular case, we will argue that the deficit model, as applied to science within forensic geneticists' discussions about science communication, serves as a gateway to renegotiate the responsibilities within forensic genetics and the use of forensic genetics' findings beyond its own communities.

Approaching science communication as relational and emergent also means paying attention to how imaginaries of publics prefigure science communication practices and to the role that communication plays in performing boundary-work (Gieryn 1983). Such boundary-work contributes on the one hand to maintaining the authority, credibility, and integrity of a specific scientific community (Jasanoff 1993, 2004), but on the other hand it also allows the performance of specific distributions of duties and responsibilities. As we will show, in this case, science is framed as being responsible for demonstrating the reliability and veracity of research results, while those who apply the results in the criminal justice system are presented as being responsible for the appropriate use of these results.

3. DNA DOESN'T SPEAK – PEOPLE DO: COMMUNICATING DNA EVIDENCE IN THE CRIMINAL JUSTICE SYSTEM

Particularly significant characteristics of forensic genetics derive from its specific epistemic culture (Cole 2013), which is distinct from other forensic science cultures as well as from science in general, and which impacts upon the particularities of communicating it. Forensic genetics differs from other forensic sciences by being celebrated as the 'gold standard' (Lynch 2003) among forensic sciences, suggesting a higher level of certainty and reliability due to its quantifiable estimations. Another important distinction comes from the type of work undertaken by forensic geneticists: these professionals tend to produce a specific type of scientific knowledge, designed to contribute to the investigation of a single criminal incident, and specifically to aid convictions or exonerations. Forensic genetic science's temporally limited nature within legal truth-finding processes thus comes from the specificity of knowledge claims and data produced (Cole 2013: 39).

Most relevant, in terms of impact on the particularities of communicating forensic genetics, is forensic geneticists' specific target audience, comprising police officers, prosecutors, judges, jurors – the so-called 'law-set' (Edmond 2001). The members of the criminal justice system that we will regard as forensic geneticists' publics-in-particular (Michael 2009) are specific and situated publics with identifiable stakes and interests in specific aspects of DNA evidence, which in turn helps them to fulfil their duties. By contrast, publics-in-general (Michael 2009) – or 'wider publics' as they are often referred to – are for most forensic geneticists an undifferentiated mass, who largely take their knowledge of forensic genetics from TV media.

One other particularity of communicating forensic genetics relates to how courts have emerged as democratising agents in disputes over the control and deployment of new DNA technologies, thereby advancing and sustaining a public dialogue about the limits of forensic genetics' expertise (Jasanoff 1995; Lynch & Jasanoff 1998). Following the work of Michael Lynch and Sheila Jasanoff on that topic, a growing body of literature has addressed how the field of forensic genetics evolved and has been constructed through a complex series of practices and procedures that functioned to close down initial controversies and to guarantee the credibility and reliability of forensic DNA evidence in

criminal justice systems worldwide (Aronson 2007; Derksen 2003; Lazer 2004; Lynch et al. 2008).

Although foundational controversies involving DNA evidence have been resolved, standardisation and legal acceptance does not mean the end of controversies surrounding the uses and interpretation of DNA evidence in court. Within the forensic genetics community, negotiations about diverse issues involving the uses and interpretation of DNA evidence mean that there is a continual need to seek common agreements in order to stabilise the field. Among these issues is a lack of protocol for dealing with diverse forms of reporting DNA evidence to non-experts (such as those found in courtrooms; Howes et al. 2014), and the challenges of communicating probabilistic results and likelihood ratios in typical identification cases (Amorim et al. 2016). Finally, the interpretation of complex DNA profiles, such as partial or mixed profiles, is also portrayed as being notably prone to reporting inconsistencies due to subjective decisions about whether a result is probative or inconclusive (Gill et al. 2008).

STS literature on forensic genetics has also explored one other important dimension affecting the communication of DNA evidence in the criminal justice system: the so-called 'CSI effect', a concept employed by scholars, and increasingly also by practitioners and public media, to capture the assumption that members of the criminal justice system, and the public-in-general, confuse the idealised portrayal of DNA evidence on television with the actual capabilities of forensic genetics in the criminal justice system (Cole & Dioso-Villa 2009; Kruse 2010; Podlas 2009). The CSI effect, together with a lack of literacy on the probabilistic framework involved in the interpretation of DNA evidence, is considered by many forensic geneticists to be the major obstacle in their task of communicating the results of DNA analysis to members of the criminal justice system (Amorim 2012; Amorim et al. 2016). Although there is no consensus in social science studies about whether or not a CSI effect really does exist and what exactly it would consist of (see Ley et al. 2010), as we will show it is nevertheless an important element of forensic geneticists' narratives about the challenges of communicating forensic genetics analysis in courtrooms.

4. METHODS

This chapter draws on qualitative data derived from nine interviews conducted with forensic geneticists who work in forensic laboratories and/or university departments of forensic sciences based in different countries in Europe. Taking into consideration the diversity of the forensic genetics community (Cole 2013; Lynch et al. 2008), we adopted the following selection criteria to recruit participants in this study: they needed to hold a degree in disciplines directly connected to forensic genetics (Biology, Genetics and Medicine) and be the head of or employed by a forensic laboratory that provides DNA analysis for presentation as evidence in criminal cases. In line with Cole's proposal, our sample therefore aggregates forensic genetic scientists and research scientists (Cole 2013). Although the interview sample is small, for the purpose of pointing at the diverse argumentative repertoires that are the core interest of this chapter the diversity was large enough.

Recruitment was conducted by sending an invitation letter by email. Prior to the interviews, all the interviewees signed a written informed consent form and agreed to be audio-recorded. All the interviews were digitally recorded, transcribed verbatim, and anonymised. The script for the interviews covered the following themes: views and experiences of the expansion of criminal forensic DNA databases in different European jurisdictions, and of the transnational exchange of DNA data; opinions about the challenges of the uses of DNA technologies in the criminal justice system; perceptions on DNA technology development and innovation; and opinions about ethical issues and public engagement with forensic genetics.

In order to avoid narrow framings of 'science communication' and 'public', for analysis purposes we use terms such as 'public(s)' but also others which appear to be used synonymously, such as 'citizens', 'collectives', 'lay groups', 'communities', 'society', or 'people'. Relevant quotations pertaining to the communication of DNA evidence were coded and subjected to multiple readings to develop in-depth understandings of prevalent notions of forensic genetic science communication and the relations between forensic genetics and society. These quotations were systematically compared, contrasted, synthesised, and coded by theme and by thematic category following the principles of grounded theory (Charmaz 2006), and interpreted using a qualitative content analysis approach (Mayring 2004).

5. EMPIRICAL ANALYSIS

5.1 The CSI effect and the 'threat' of enthusiastic publics

The particularities of communicating forensic genetics are understood by forensic geneticists as being shaped by the CSI effect and media coverage of high-profile cases, which they perceive as responsible for publics' beliefs in the alleged 'superior role' of DNA evidence (Lynch et al. 2008). This CSI effect is framed as having two interrelated consequences on publics. On the one hand, it has helped to foster public interest in forensic genetics, and to make citizens aware of the existence and evolution of DNA technologies. On the other hand, it disseminates exaggerated understandings of the alleged power of DNA to solve criminal cases. One of our

interviewees explains this juxtaposition of implications:

> The CSI effect has been significant, and the positive side of it is how young people have grown to be much more curious about the field. … That's the good thing. The downside to CSI [effect] is presenting the tests as infallible, [as if it] always works…. [C01]

Forensic geneticists thus accuse the media of providing an incomplete picture of DNA technologies. By exaggerating the possibilities, the speed, and the certainty of outcomes of DNA technologies, media narratives do not provide an adequate description of inherent limitations of genetic evidence: 'There is this famous CSI thing. But they [the publics] are not really educated about the pitfalls and limitations [of DNA evidence]' [O01]. Entertainment media narratives are represented as focusing on dramatic and emotionalised events in the portrayal of fictionalised representations of forensic science (Machado & Santos 2011), standing in direct contrast to the efforts of accurately communicating 'sound science' (Hansen 2016). The emphasis on uncertainties in forensic geneticists' explanation of DNA evidence is framed as incompatible with mainstream forms of communication. As such, as noted by the following interviewee, forensic geneticists struggle with media representations of DNA evidence, which are portrayed as being assured facts:

> [The main challenge of communicating science is] the information that people receive from television programs and the media and the sort of impression that science is about certainty: 'scientist says this and therefore it must be true' and, in fact, science is full of uncertainties. People do not understand that, they do not appreciate it. … Uncertainties do not make good … audience. [D09]

Consequently, forensic geneticists tend to portray their publics as overly 'enthusiastic' and as holding what they perceive to be unrealistic views about the possibilities of DNA technologies in criminal justice systems. However, these inflated perspectives on the potential contributions of DNA analysis to criminal investigation processes are not only present in forensic geneticists' views of lay publics, but also in framings of the publics-in-particular that are active members of the criminal justice system. Several of our interviewees outlined how police officers, prosecutors, and judges also attribute too much importance to DNA technologies when addressing criminal cases. In their opinion, DNA is generally considered to be 'a sort of priority type of evidence' [E01] which plays a decisive role in how criminal cases are presented in court:

> This public perception is that if you have the DNA, that's it! That's all you need! And if you don't have the DNA, we'll have prosecutors [saying] 'You can't make a case with this, with no DNA!' [laughs]. [E01]

Not being immune to representations that portray DNA as infallible, stakeholders directly involved in the criminal justice system are thus perceived as being strongly influenced by overly bright prospects fostered by the entertainment media: 'The CSI effect is a very common phenomenon, and therefore it shapes police officers' expectations about what is possible' [C04].

This poses several challenges to an adequate use of forensic genetic science in criminal investigations. Members of the criminal justice system are described as not being very well informed about the kind of information that can(not) be obtained from DNA technologies, and under what conditions such information can be retrieved. As a consequence, forensic geneticists often describe how they are confronted with frustration and disappointment on the part of members of the criminal justice system when they are unable to provide clear results – namely, a match or non-match – on the basis of a DNA profile:

> It is so popular the perception that it [DNA] is infallible and there is a fairly substantial lack of scientific education in most inspectors who work with DNA. … They will have either questions or issues with the results. … You get back a mixed result, or a negative result, and they say 'We sent you a DNA analysis, so where is my result?' and we say 'Well, this is why we couldn't get a result', and they can't understand that. [E01]

The repercussions of overly positive expectations about the possibilities of DNA technologies are wide-ranging. A major concern, in the view of forensic geneticists, is that 'misrepresentations' might lead to miscarriages of justice, especially in cases where DNA technologies play a relevant role in deliberations in court. Forensic geneticists also voice their dissatisfaction with judges when the latter ignore the potential risks and the unintended consequences of overstating DNA evidence. One interviewee would put it as follows:

> Evidently, it [DNA evidence] is given much more importance by judges than it should. They must be aware that it's a clear mistake, they should be much more careful. … Do judges know that 30% of incorrect rulings are linked to wrong identification of testimonies? Do judges know the real value behind each specific piece of scientific forensic evidence? They don't. And they make a barbaric number of mistakes because of that. [C05]

By pointing to a lack of knowledge among members of the criminal justice system and to the need to tackle their 'misconceptions', forensic geneticists engage in a standard 'deficit model' narrative. At the same time, they underline that this is a serious issue that touches on the shared responsibilities of members of the criminal justice system. Such a lack of awareness has potentially serious consequences, such as a possible miscarriage of justice. According to this view, one of the key types of DNA-related errors therefore results from misunderstanding the 'real value' of DNA evidence in court settings, rather than from

errors that occur in the process of DNA analysis in the lab. Such a position also performs important boundary-work focused on constructing distinctions between the tasks of different professional groups in making use of DNA analysis: carrying out an analysis in the lab is the responsibility of forensic geneticists, while its final interpretation is the responsibility of judges in courts (Machado & Granja 2018). According to forensic geneticists' views, the final (and therefore decisive) instance of interpretation of the evidence in order to reach a decision about guilt or innocence must be enacted by judges. As the following quotation illustrates, from such a perspective, forensic geneticists see their role as presenting and explaining DNA evidence, while also outlining the ambiguity involved in its interpretation:

> I think that sometimes the expectation of the court [is] that they are going to be provided with some unambiguous scientific evidence of fact that is just going to allow them to come to the right conclusion in terms of guilt or innocence. I think there is a general difference in the perspective of the scientist, who will say: 'Well, we found this profile and it is up to the court to decide what its significance is, particularly in regard to the guilt or innocence of the accused person'. [D11]

Forensic geneticists represent themselves as confronted by publics-in-particular that they feel have too strong expectations of DNA evidence, namely that it should provide a 'result' that forms a clear basis for deciding whether the accused is 'guilty' or 'innocent'. Members of the criminal justice system are regarded as having a specific 'deficit': one of being overly optimistic about the capacity of DNA analysis, which is seen as synonymous with their lack of scientific literacy for understanding the 'real value' and the probabilistic framework of DNA evidence. These forensic geneticists clearly subscribe to a 'deficit model', and with it to a particular vision of the publics-in-particular they encounter in the criminal justice system. This vision is instrumental in the sense that it reifies the boundary between the worlds of science and of non-science. On the one hand, their use of this 'deficit model' stabilises forensic genetics' authority over understanding DNA evidence; on the other hand, it constructs an enthusiastic, yet ignorant, public who have idealised views of DNA evidence, and thus who could potentially become a threat to the credibility of forensic genetics' epistemic authority (Marris 2015).

5.2 Boundary-work along 'deficits': Establishing risk communication to delegate responsibility

In order to cope with the particular challenges of communicating their work, forensic geneticists develop coping strategies within their epistemic community, strategies which attempt to counterbalance excessive expectations towards DNA technologies. Among these is the emergence of what can be called a 'proactive ethos of public responsibility' (Bliss 2012: 166–172; Machado & Granja, 2018). This means that they aim to perform (forensic genetic) science in a way that is committed to and engaged with its wider social implications and the ways that its results are taken up in different arenas. One of the dimensions of this ethos is active communication of the limitations associated with DNA analysis within the criminal justice system, therefore deconstructing dominant visions that associate forensic science with a 'truth machine' (Lynch et al. 2008) that is able to provide certainty with regard to results. The adoption of such an idiom of uncertainty, one that addresses and attempts to manage the risks and uncertainties underlying forensic science, seems to have become part of the epistemic culture of forensic geneticists, as illustrated by the following quotation:

> So, it is a question of trying to give as much genetic data as we can, but at the same time not offering a service that makes exaggerated claims about the accuracy or the precision of the tests from very small amounts of DNA. So, I think it is important that we are realistic about the limitations. [C04]

Here we can detect a type of boundary-work that frames the identity of 'responsible' forensic genetics experts as characterised by a felt need to reflect on and clearly communicate the limitations of the evidence they can provide. Therefore, as a response to the high expectations present in the public arena, science communication is often preoccupied with caution concerning what forensic genetics cannot provide. Against the high expectations of its publics, the propagated approach for science communication here emphasises the responsibility for fully disclosing the limits and uncertainties, for example the deficits inherent to 'their science'. This is a new twist in applying a 'deficit model', this time to science (and scientists' responsibilities to cope with science's deficits).

A certain degree of formalisation and standardisation of such 'risk communication' has been established in protocols for using quantitative probabilistic value descriptions for reporting the results of DNA analysis when reaching out to members of the criminal justice system. Although being transparent about the limitations and risks of DNA results has become a routine part of reporting, it remains essential to make a distinction from 'messy' laboratory practices and to maintain the appearance of technical order (Lynch 2002) in producing evidence. The need to communicate that the uncertainties of DNA evidence are tamed and under control therefore also derives from the need to protect the epistemic community's credibility from becoming 'fodder for impeachment' (Cole 2013: 41) when exposed to potential fallibility. More recently, additional strategies for addressing such transparency-oriented approaches to risk communication have emerged. Some examples of this trend include providing concrete models for good practice for evaluative expert reporting and suggesting standards for

evaluative reporting within professional networks, such as the European Network of Forensic Science Institutes (ENFSI) (Biedermann et al. 2017). According to several forensic geneticists, this type of risk communication is increasingly important as more sensitive methods of DNA analysis are being developed and, as a consequence, sensitivity to issues such as contamination has also risen (Gill et al. 2008). Some participants in our study therefore advocate the adoption of an even more careful strategy of interpretation and communication:

> Now we are getting weak profiles, partial profiles, from contact stains, there may be secondary transfer, and all of these other things, and this also has to be taken into consideration for the interpretation of the evidence. And the awareness of this situation is not very widespread. This is something that we need to promote and to make public, that there are limits of testing that … we are victims of our own success. … Because we have made it [DNA technologies] very sensitive, and now we have to live with the consequences. [O01]

Although some forensic geneticists might be committed to communicating the limitations and uncertainties of DNA analysis, judges and other members of the criminal justice system might not be willing to interpret, understand, engage with, or even accept such 'uncertain' premises. However, in the end, forensic geneticists partly delegate responsibility for managing the difficulties of interpreting DNA evidence to members of the criminal justice system. These types of tensions therefore illustrate the boundaries and tensions between the rationalities that guide the different epistemic cultures at work – those of science and the criminal justice system. This was addressed in the following quote:

> In order to be successful in this interplay, of course we have the right to try to explain [DNA evidence], but the other guys, judges and lawyers, also have the duty of trying to understand. And unfortunately, as the society is organized, they prefer not to. Because the judges, most of them … prefer that the DNA speaks for itself, they do not realise that they are deciding. And they go mad when I resist their pressing on me to state a probability or something like that. Which is misunderstanding everything I am trying to do. [N01]

In adopting risk communication strategies anchored to policies of transparency, forensic geneticists thus attempt to leave the 'black box' of forensic evidence deliberately open, leaving uncertainty and the limitations of DNA technologies visible (Amorim 2012). However, this creates friction in as much as the intent of the criminal justice system – especially in decision-making spaces such as the courts – is to search for factual certainty in order to ensure that justice is done in each individual case (Jasanoff 2006), while the science system is quite used to handling a reasonable degree of uncertainty and error.

Besides delegating responsibility for interpreting DNA evidence to members of the criminal justice system, forensic geneticists also enact other kinds of boundary-work by defining what makes a good scientist (Machado & Granja 2018) – that is, the one who communicates limitations – and delineating those who don't accept the same norms. Such individuals are framed as what Jasanoff (1993: 78) has called 'misfits, deviants, charlatans, or outsiders' to the enterprise of science. Several forensic geneticists demonstrate this pattern of othering 'bad behaviour', that is, attributing certain behaviours to colleagues who are seen as less committed to these norms of humility when it comes to the capacity of producing evidence with certainty. They are quite sceptical, doubting whether other colleagues stick to the ideal of communicating the limitations of DNA evidence:

> When I am testifying in court I always try also to make clear where the limits of this evidence are. … But I am not quite sure about my other colleagues. … So basically, my impression is that there may be cases … where the DNA was overstated, already in the report; there was no quality check because there was nobody in the court asking questions. Everyone just accepted that as a given fact, there was no criticism. [O01]

Our findings suggest that these coping strategies of risk communication, and particularly the emphasis on limitations of forensic genetics' capacity to deliver unquestionable evidence, is not yet mainstream among forensic geneticists. It is, however, perceived as a reasonable approach to render the all-too-easily black-boxed aspects of uncertainty accompanying statistical interpretation of DNA evidence more explicit and visible (Amorim 2012; Biedermann et al. 2017). One way of stabilising the field of forensic genetics against criticism and keeping its authority is thus presented as the use of its own understanding of DNA evidence, with all its limitations made explicit, while delegating responsibility for binary decisions to other members of the criminal justice system.

5.3 Communicating and mobilising a forensic genetics' understanding of DNA evidence

While the previously described coping strategies of forensic genetics mainly address how forensic geneticists redefine their self-conception and presentation of forensic genetics, this section explores how imaginaries of publics impact upon actual communication experiences with members of the criminal justice system. Most of the venues and material structures for communicating forensic genetics to publics-in-particular are pre-formatted by the criminal investigation and judicial settings. These routine practices entail, for instance, the production of written reports and the provision of expert testimony in courts at the request of judges or lawyers. Nevertheless, some forensic geneticists also use alternative spaces and formats to respond to what they perceive as being the needs of publics, for instance the need to clearly understand the potential and limitations of DNA evidence.

Based on the premise that members of the criminal

justice system are not properly informed about forensic genetics and DNA evidence, many of our interviewees claim that there is a need for training designed to fill knowledge gaps, as the following quotation illustrates:

> The investigators are often not the people who do the work in the laboratory and they may not have learned the same kind of knowledge. So, one of the problems is the collection of samples, for example, doing this properly. So there needs to be an educational program, which makes sure that everybody is aware of what they should be doing. [Q01]

By attempting to construct a shared knowledge base about DNA analysis, forensic geneticists take on the role of public educators. In doing so, they are therefore delineating hierarchies of knowledge, attempting to assure their epistemic authority (i.e., their role as experts), protecting the autonomy of forensic genetics, and creating new forms of scientific legitimation and consolidation of expertise claims (Gieryn 1983; Kruse 2016).

The narratives of most of the forensic geneticists we interviewed highlighted the belief that, by occasionally engaging with members of the criminal justice system through educational courses and direct interactions – at least in more exceptional criminal cases, they might reduce the overall risk of potential misinterpretation of certain DNA evidence. This is illustrated by the following quotation:

> I think it is important to educate the police officers about your own work. … We are doing it because we are offering educational workshops, trainings, where we invite police to give them an update about our work. … Normally [when] we are involved in a major case, like a capital crime, then we have direct contact with … police officers. They like this very much because they can come to our institute and then we can discuss the case, and we can demonstrate what we have found and what it means. [O01]

When addressing publics-in-particular, forensic geneticists thus occasionally attempt to actively engage them in training, education, and joint discussion. Such moments enrich forensic geneticists' imaginaries of their publics by giving them access to the needs of publics-in-particular, as articulated by those publics themselves. They further provide an opportunity to actively share forensic geneticists' understanding of DNA evidence, thereby somewhat (re)distributing responsibility for (correctly) interpreting DNA evidence.

However, the willingness of forensic geneticists to engage directly with their publics-in-particular remains limited. Entertainment media is generally understood as limiting their capacity to reach out to wider publics and to influence exaggerated views about the potential of DNA technologies. In this sense, although forensic geneticists acknowledge the need to provide education and information, some may in fact contribute to the power of the CSI effect by overlooking the influence of their own claims to shape public opinion. Feeling unable to compete with media impact on audiences, some forensic geneticists end up demonstrating a certain resignation about challenging dominant perceptions:

> And we need to make improvements, and all roads lead to education and information. I worry about living in a world where everything is part of the news, not a world where we value education, instead everything becomes breaking news, everything ends up on newspapers or television. It's all CSI. But where's the education? [C05]

Beyond communication experiences with members of the criminal justice system, publics-in-general are, at least to a certain extent, perceived as being 'out of reach': 'We are interested in public perception, but it is not as important to us as police perception' [C04]. Consequently, forensic geneticists tend to give priority to communication with their publics-in-particular, who are in principle the greater threat to the credibility of forensic genetics.

6. CONCLUSION

This chapter has addressed the particularities of communicating forensic genetics and shown how forensic geneticists respond to these particularities. It has also elaborated on forensic geneticists' imaginaries of public audiences, and how these imaginaries shape their experiences of communication.

Forensic geneticists feel that the conditions under which they communicate DNA evidence in the criminal justice system are shaped by widely shared media representations of the capacities of DNA technologies. These representations are understood as being beyond their control, producing considerable 'misconceptions' among both publics-in-particular and publics-in-general. Consequently, confronted with what they describe as overly 'enthusiastic publics', communication of forensic genetics is frequently framed by a deficit model approach. Forensic geneticists' imaginaries of their publics-in-particular – judges, the police, or jury members – not only highlight their lack of knowledge, but also construct them as a potential threat to forensic expertise. Public misunderstanding of the nature of DNA evidence is framed as potentially putting into jeopardy both the credibility of forensic genetics and, ultimately, the ability of the criminal justice system to deliver justice.

As we have described, forensic geneticists develop coping strategies to manage these challenges. They emphasise the need to communicate the limitations of forensic genetics, and particularly the potential risks and uncertainties in the interpretation of quantitative probabilistic frameworks for forensic DNA analysis. They also point to the fact that interpretation frameworks can differ substantially: binary conventions of interpretation inherent in the criminal justice system are very different from the interpretation principles prevalent among forensic geneticists. Importantly,

forensic geneticists work to (re)align the distribution of responsibility for the interpretation of DNA evidence. While they suggest that it is the responsibility of (good) forensic geneticists to highlight the contingencies of DNA evidence, and that of other parts of the criminal justice system to make final judgements concerning justice, they also propose educational initiatives for their publics-in-particular. Again, work is done here to outline the boundaries between the practices of forensic geneticists and members of the criminal justice system in the interpretation of DNA evidence and judicial decision making.

This case thus offers us an unusual approach to science communication: that of stressing science's limitations. This invites us to apply the deficit model in a new way. Studying the communication of forensic genetics means investigating a case in which the deficit not only applies to publics, but is applied by scientists to science itself (and other scientists). This emphasis on deficiencies becomes constitutive of a communication strategy for responding to what is perceived by the science community as 'too enthusiastic publics'. As such, this case study might reveal insights relevant to other situations where publics may be too 'enthusiastic', for instance in the context of 'breakthrough' medical knowledge, or space science imagined as realising utopian dreams of life beyond the Earth.

While the deficit model of publics is instrumental in the sense that it serves as a justification to argue for increasing scientific literacy or for excluding lay publics from some types of decision making, the deficit model, as it is here applied to science, serves as a gateway to renegotiate responsibilities for the non-trustworthy and illegitimate use of scientific findings. In the case of forensic genetics, the misuse of scientific findings may turn into miscarriages of justice. Therefore, when forensic geneticists emphasise the need to take the process of appropriately interpreting scientific results for criminal investigation purposes or judicial decisions seriously, at the same time they underline the fact that the responsibility to interpret all evidence so as to reach decisions – about investigative strategies, or about guilt or innocence – lies beyond the boundaries of the responsibility of forensic geneticists.

Forensic geneticists thus aim to renegotiate the meanings of forensic genetics that circulate in the courtroom and beyond. They seek to deconstruct the notions about DNA technologies conveyed by the media and to clarify the contingencies of DNA evidence. Forensic geneticists reaffirm what has been called the 'CSI effect' in relation to publics-in-particular present in the courtroom. Yet interestingly, the reference to 'the CSI effect' barely even refers to the television programme anymore. Instead, it has become a sense-making category for forensic geneticists to delineate any understanding of DNA evidence that is different from their own – and thereby a tool to create a unified identity for forensic geneticists.

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A Call for More Science in Forensic Science

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ABSTRACT Forensic science is critical to the administration of justice. The discipline of forensic science is remarkably complex and includes methodologies ranging from DNA analysis to chemical composition to pattern recognition. Many forensic practices developed under the auspices of law enforcement and were vetted primarily by the legal system rather than being subjected to scientific scrutiny and empirical testing. Beginning in the 1990s, exonerations based on DNA-related methods revealed problems with some forensic disciplines, leading to calls for major reforms. This process generated a National Academy of Science report in 2009 that was highly critical of many forensic practices and eventually led to the establishment of the National Commission for Forensic Science (NCFS) in 2013. The NCFS was a deliberative body that catalyzed communication between nonforensic scientists, forensic scientists, and other stakeholders in the legal community. In 2017, despite continuing problems with forensic science, the Department of Justice terminated the NCFS. Just when forensic science needs the most support, it is getting the least. We urge the larger scientific community to come to the aid of our forensic colleagues by advocating for urgently needed research, testing, and financial support.

KEY WORDS Forensic science; Justice; DNA; Crime; Investigation

Forensic science is at a crossroads. It is torn between the practices of science, which require empirical demonstration of the validity and accuracy of methods, and the practices of law, which accept methods based on historical precedent even if they have never been subjected to meaningful empirical validation. The field is in dire need of deep and meaningful attention from the broader scientific community. Without such guidance, forensic science and law enforcement risk withholding justice from both defendants and crime victims. The scientific community must step forward to promote, defend, and advocate for science in forensic science.

The issue is of particular importance in light of the decision by the Department of Justice (DOJ) in April 2017 to terminate the National Commission on Forensic Science (NCFS), a group (on which we served) that was charged with advising the federal government on improving the parlous state of the forensic science. Remarkably, the DOJ took this step despite recent reports from the National Academy of Science (NAS) and the President's Council of Advisors on Science and Technology (PCAST) that highlighted many problems, including the fact that some forensic methods have never been validated. Some of these methods are clearly invalid. The most egregious case is bite mark identification, which has been discredited by both scientific studies and false convictions based on the method. However, bite marks continue to be accepted in United States courts as a matter of precedent: that is, not because they are valid but because they were accepted in the past. As science—and forensic science more specifically—continues to advance, it becomes increasingly absurd to ask or expect lawyers, judges, and juries to take sole responsibility for critically evaluating the

quality and validity of scientific evidence and testimony.

The structure of the field of forensic science inhibits vital reforms. Almost all publicly funded laboratories, whether federal, state, or local, are associated with law enforcement. At the very least, this creates an inherent conflict-of-interest and leads to legitimate concerns of objectivity and bias. The linkage of forensic laboratories with prosecutorial entities dates back as far as 13th century China, was pervasive in Europe in the mid-late 19th century, and spread from there to the United States (1–14).

Some forensic methods have been rooted in science. Medicolegal death investigation emerged from medical science, because death investigation was connected to the protection of public health. Techniques of analytical chemistry were applied to the certain types of evidence, such as seized drug analysis, toxicological analysis, and aspects of instrumental analysis applied to trace evidence. More recently, molecular biology gave rise to DNA typing to forensic applications.

The evolution of other forensic disciplines, particularly those related to pattern evidence, followed a different course, having been developed primarily within law enforcement environments or at the behest of law enforcement. Disciplines, such as fingerprints, firearms, and tool marks, blood-stain pattern analysis, tread-impression analysis, and bite mark analysis matured largely outside of the traditional scientific community during a time when admissibility standards for scientific evidence had yet to be formulated. Thus, admissibility of such evidence rightly or wrongly created judicial precedent in decisions that often did not—or could not—involve the level of research that would today be needed to establish scientific validity.

The adaptation of DNA typing methods to forensic casework, a pivotal event in forensic science, catalyzed a reassessment of the scientific validity of other methods used in forensics. In the 1980s, Alec Jeffreys of the University of Leicester discovered that segments of repetitive DNA were tremendously variable among individuals and coined the term “DNA fingerprinting” (15). The rapid embrace of DNA typing, beginning in the late 1980s and continuing through the turn of the century, had far-reaching implications in the judicial system. The probabilistic nature of DNA evidence and its acceptance by the courts also played a role in shaping modern views on scientific validity. Before DNA typing, analysis of blood evidence relied on ABO blood group and secretor status, which could afford population frequencies on the order of n-in-100. DNA typing allowed a person to be linked to a sample with frequencies of less than one across the population of the world (i.e., less than one in eight billion). The use of rigorously estimated probabilities as a tool to weigh the relative importance of the data marked a critical turning point in forensic science.

During the same time, fingerprint analysis was also used to identify individuals as the source of impressions, but without either population data (on the similarity among fingerprints) or empirical studies (on the performance of examiners) providing estimates of the probability for false-positive matches. In retrospect, it is clear that DNA evidence and its success changed our views and expectations of forensic science.

In the 1990s, three critical Supreme Court rulings in civil cases provided guidance regarding the admissibility of evidence in federal cases. In Daubert v. Merrell Dow Pharmaceuticals, Inc., 509 US 579 (1993), the judge was assigned a gatekeeping role to ensure that expert scientific testimony was found to be reliable before it could be admitted as evidence. In General Electric Co. v. Joiner, 522 US 136 (1997), the Court made clear that scientific testimony must be relevant to the case at hand to be admissible. Finally, the decision in Kumho Tire Co. v. Carmichael, 526 US 137

(1999) broadened the scope of expert testimony to include all types of technical evidence, while holding fast to the reliability and relevancy requirements. These three cases, often referred to as the Daubert trilogy, generated a two-pronged test for the admissibility of evidence ruling, namely that scientific evidence used in court must be both reliable and relevant.

The Daubert trilogy represents a critical milestone in the intersection of science and the law by demanding that admissibility decisions rely on contemporaneous scientific standards. Although the admissibility of DNA evidence slightly preceded the Daubert trilogy, it provides a good model for how modern scientific advances should be integrated into the justice system: namely, scientific validation should precede admissibility.

Additionally, DNA typing has had a significant impact on forensic science through exonerations of false convictions. As noted in a recent summary report (16), for convictions in the 1974– 2016 period, DNA evidence has overturned more than 100 false convictions. Causes of false convictions are mistaken witness identification, perjury or false accusations, false confessions, official misconduct, inadequate legal defense, and false or misleading forensic evidence. In those cases where forensic science was cited as a primary cause of the false conviction, the most common methods used were forensic biology (serology), hair examinations, and bite marks.

This does not mean that all previously admitted types of evidence are necessarily invalid, but it does require, at the

very least, that validity be now established by appropriate scientific standards before they can continue to be used. This requirement poses a dilemma to prosecutors—and to some extent to law enforcement—who face an inherent risk and disincentive in arguing for scientific validation studies that could call into question past convictions based on methods that no longer pass muster. Even when scientific studies clearly debunk a methodology, some prosecutors appeal to past legal precedent to persuade courts to admit evidence, as seen in the case of bite mark evidence. The scientific community must step up to counter this pressure.

The NAS has been at the forefront of these efforts since the early 2000s (17). In November 2005, the Science, State, Justice, Commerce, and Related Agencies Appropriations Act of 2006 called upon the National Research Council (NRC) to conduct a study of forensic science. The exhaustive study resulted in the 2009 publication of Strengthening Forensic Science in the United States: A Path Forward (18), which concluded that "with the exception of nuclear DNA analysis.. .no forensic method has been rigorously shown to have the capacity to consistently, and with a high degree of certainty, demonstrate a connection between evidence and a specific individual or source." The 2009 report (18) recommended the creation of a "new, strong, and independent entity that could take on the tasks that would be assigned to it in a manner that is as objective and free of bias as possible—one with no ties to the past and with the authority and resources to implement a fresh agenda designed to address the problems found by the committee and discussed in this report." Notably, the NRC report was unambiguous that this entity be outside of the jurisdiction or control of the DOJ.

Rather than establishing such an independent entity, the government created the NCFS, which was established by the DOJ in partnership with the National Institute of Standards and Technology (NIST). The NCFS functioned from 2013 to 2017, during which time it held 13 meetings. It was a diverse body composed of representatives of several stakeholder communities, including forensic scientists, law enforcement, judges, attorneys, and independent scientists not associated with forensic science. The 49 commissioners served over two terms, heard presentations from 140 invited presenters, and approved 43 documents and summary reports. Given its heterogeneous composition and expertise, the NCFS took time to function efficiently. Only one document was approved before its fifth meeting, compared with eight at the September 2016 meeting alone. This timeline shows evidence of the learning curve commissioners were on as they began a deliberative process to achieve consensus on reports and summary documents.

As examples, the NCFS recommended the creation of postdoctoral training programs in forensic science to encourage the emergence of an inquisitive and investigative scientific culture, which the National Institute of Justice (part of the DOJ) quickly embraced. One practical recommendation was the abandonment of language the Commission found to be meaningless and misleading, such as claims by experts that their conclusions were correct to a "reasonable scientific certainty." Of significance was the commission's recommendation that forensic techniques be subjected to independent validation before being introduced into common use and that the NIST should be responsible for such oversight. Beyond its recommendations, the NCFS provided a first-ever national-level venue for communication and understanding among the many disciplines represented. During NCFS discussions, it became clear that the scientific and legal communities often had different interpretations of what constituted "error" in forensic analysis, with the former recognizing error as an intrinsic aspect of any measurement process and the latter often viewing error as synonymous with a mistake: that is, the inappropriate application of a procedure or technology. Although NCFS recommendations do not have the force of law, the fact that they emerged from a commission composed of such different stakeholders gave them moral force. Unfortunately, all of the hard work needed to forge such a heterogeneous group into a body that had learned to reach consensus was lost when the DOJ declined to renew the NCFS in early 2017.

In late 2016, a PCAST report (19, 20) highlighted why bodies like the NCFS are needed. PCAST based its conclusions on a review of more than 2,000 papers in the forensic science literature, as well as interviews with forensic scientists and stakeholders in the legal community. The report identified two gaps requiring attention: (i) a need for clarity about the scientific standards required to establish the validity and reliability of forensic methods, as well as to measure their accuracy; and (ii) a need to scientifically establish the validity and reliability of particular forensic methods that had never been properly validated. Providing an independent confirmation of many of the findings of the prior 2009 NRC report, the PCAST report concluded that empirical testing is not merely one among various alternative ways to establish scientific validity; rather, it is the only scientific basis for doing so. Furthermore, the PCAST report established that, in the 7 y since the 2009

NRC report, little progress had been made to address the criticisms raised in that report. The sole exception was latent-finger-print analysis, which had been subjected to validity testing. A key issue is how to extend this one example to other forensic methods.

After terminating the NCFS, in April 2017, the DOJ proposed opening a new office for forensic science within the department and named a prosecutor to lead this effort. This new proposal is highly problematic. Specifically, it goes against the recommendations of the 2009 PCAST report, which strongly suggested that the DOJ not be involved in evaluating the use of forensic science. Although the NCFS was not entirely independent, it did include some independent stakeholders: scientists outside the realm of forensic science. Putting a prosecutor in charge of forensic science perpetuates an irreconcilable conflict-of-interest and reinforces the dominance of the prosecutorial perspective. Prosecution entities, by the nature of our adversarial legal system, have little incentive to embrace scientific advances that could risk undermining past convictions and current prosecutions. Conversely, defense entities have incentives to constantly question and raise doubts regarding scientific results that do not support their desired outcome. The role of prosecutors and defense attorneys is to win cases through competing arguments (i.e., the adversarial system). Neither "side" can or should be expected to evaluate scientific integrity on its own merits. The need for an independent and dedicated champion of forensic science has never been clearer.

The limitations of some forensic science methods have been exposed, often by forensic scientists themselves. The larger scientific community must now come to the aid of our forensic colleagues in advocating both for: (i) the research and financial support that is so clearly needed to advance the field and (ii) the requirement for empirical testing that is so clearly needed to advance the cause of justice. Vocal and continual advocacy for scientific independence is needed, along with policy recommendations and a concerted effort to ensure that this issue stays in the public conscience. Independent review efforts should be launched and supported. Forensic scientists have long complained that their work is not always valued by their scientific colleagues because of its applied nature; it is time for the scientific community to move beyond that conceit. Research and academic scientists should become educated about forensic science and take active steps to welcome the discipline into the larger scientific community. A broad effort can help illuminate the causes of failures, help predict when failure is likely to occur, and aid in the development of strategies to mitigate or circumvent those conditions. Because it represents the wide gamut of scientific disciplines that are essential to forensic science, the NAS remains in a prime position to continue the dialogue between the academic and forensic science communities. If we are unwilling to confront the issue of accuracy in our justice system, what cause is worthy?

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A Call for More Science in Forensic Science

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Imagine you're in court, accused of a crime that you know you didn't commit. Now imagine a scientist takes the stand and starts explaining to the court how your DNA is on the murder weapon.

Forensic science is nothing short of a technological success story; it is possible to detect and identify forensic traces at greater levels of resolution and accuracy than ever before, and we can capture, retain and search more data than at any other time in history. These capabilities are transforming what forensic science can do. However, at the same time, forensic science is facing a huge challenge.

WHAT CRISIS?

Forensic science sits at the intersection of science, law, policing, government and policy. It is a complex ecosystem that has competing demands and drivers to deliver science to assist the justice system. A recent inquiry by the House of Lords Science and Technology Select Committee in the UK recognized that forensic science is in a state of crisis, to such a degree that it is undermining trust in our justice systems. This crisis is multifaceted, and while some of the results of the crisis have been reported, such as miscarriages of justice, instances of malpractice, and failures of quality standards, there is an aspect of the crisis that has been overlooked. A recent study in the UK identified all the cases upheld by the Court of Appeal where criminal evidence was critical in the original trial over a seven-year period. In 22% of those cases, the evidence was misinterpreted. These cases are only the tip of the iceberg and indicate a broader root cause of the crisis forensic science is facing.

The crisis is a result of a deep-seated and systemic issue of how science is used in the justice system. It is not enough to be able to detect critical forensic traces (whether they are physical traces like DNA or digital traces like GPS data), we need to be able to interpret what those traces mean in the context of a crime reconstruction. If we find gunshot residue on a jacket, it's not enough to be able to accurately detect that those particles are gunshot residue. We need to know whether the person wearing the jacket fired the gun, and if they did, if it was fired during the crime.

At the moment, we don't always have the data that we need to be able to do that. This isn't only about understanding how and when a trace is transferred. For example, a study from the US in 2018 found that when 108 crime labs received the same complex DNA mixture, 74 of the labs correctly included two reference samples as contributors to the mixture, but they also incorrectly included a reference sample from an innocent person. That is 69% of the labs interpreting the profile erroneously. This is an issue for every type of forensic science evidence from fingerprints and DNA to fibres, gunshot residue and digital evidence, and it is an issue that strikes at the heart of how we use science in the justice system, and the fabric of our communities. We can detect traces better than ever before, but for robust forensic science, we need to know what those traces mean.

HOW HAVE WE GOT HERE?

The recent House of Lords inquiry asked probing questions across the whole remit of forensic science (from crime scene, investigation, lab analysis, to the presentation of evidence in court), in a way that also brought together the voices from all the relevant domains (the police, advocates, judiciary, scientists, researchers, government ministers and policy-makers). As a result, the committee revealed the root causes of the crisis in forensic science in England and Wales, and their findings offer valuable insights for forensic science all over the world. They found that the piecemeal approach to forensic science, where different parts of forensic science are distributed between law enforcement (who address the collection of exhibits and samples and some analysis), forensic services (who undertake the analysis and interpretation) and the courts (who seek to establish the

significance and evidential weight of those materials), has led to a devastating lack of strategic oversight and accountability for forensic science.

This fragmentation has led to a situation where the value of forensic science has not been effectively articulated or appreciated, which in turn has led to a situation where forensic science has not been a strategic priority. For example, it is not (yet) possible to effectively demonstrate the true value of detecting the source of a material that leads to a confession of guilt. A confession during an investigation may save advocate and court time down the line.

But despite the clear importance of forensic science within the justice system, demonstrating the value and strategic value of forensic science has been elusive. This is in part due to the lack of connections between the investigation and prosecution phases of the forensic science process, which makes it difficult to connect an outcome in one part of the process with an action in another part of the process. There is also the thorny issue of finding an accepted approach to equate the value of societal good on the one hand and economic cost on the other – arguably, in the justice system value should not only be considered as a fiscal issue.

This situation is exacerbated in the UK where a market has been created for forensic science services where private companies can compete for tenders to provide forensic analyses of samples and exhibits. The financial value of the market has been reduced in the last 10 years from £120m a year. to c.£50-55m a ,year and the remaining market suffers from a lack of sustainability (in part due to a procurement process that can value cost over quality) and regulation. At the same time, the main procurers of these services (usually the police) have been contending with significant budget cuts, and this has led to significant instability in the market with severe challenges for ensuring solvency of providers and preserving the integrity of evidence.

There are also serious issues around the science itself, and the evidence base that underpins forensic science. Forensic science has historically fallen between the cracks of major funders due to its interdisciplinary and applied nature. Where there has been funding available, the focus has been on equipping the industry with tools that aid the detection of materials more quickly, more accurately, at greater degrees of sensitivity and in a context of creating economic value within the market. This has meant that "… the interpretation of forensic evidence is not always based on scientific studies to determine its validity" (National Academy of Sciences 2009), which the Lords report found to still be the case in 2019. The focus on detecting forensic materials over the interpretation of what they mean, has led to a lack of funding for foundational research that can produce the evidence base that is needed to understand how (and when) your DNA got on the murder weapon.

A PATH TO JUSTICE?

The crisis in forensic science is a complex global challenge. These kinds of challenges rarely have simple solutions and require engagement across many disciplines and sectors to find the pathways that will offer progress. For forensic science, it is clear that addressing individual "symptoms" (such as a quality standards failure in a lab, or creating better technologies for real time intelligence at a crime scene) will at best offer short-term solutions to specific problems in isolation. Instead, the future of forensic science lies in tackling the root causes of the crisis in a way that keeps both technology and people at the heart of reform.

Looking forward, forensic science needs to establish a holistic vision that ensures meaningful connectivity between the investigation and the courts. There needs to be strategic oversight to set priorities for current operational approaches, to establish sustainable markets for the provision of forensic science services, and set the agenda for research to underpin each part of the forensic science process (crime scene to court). This will need to be a collective corporate strategy that provides a voice for all the key stakeholders.

A key part of addressing the crisis in the UK will be stabilizing the market, particularly in terms of addressing the procurement processes, quality standards and equitable access to forensic science services for both the prosecution and defense. But to address the core issues in forensic science globally, it will also be critical that the science being used is underpinned by excellent research.

Research in forensic science needs to be harnessing the emerging capabilities in technology, AI, and machine learning to develop novel technological tools to address the emerging challenges that are arising in the detection and identification of traces and individuals. But it must also develop the foundational underpinning needed for reliable, transparent and reproducible evaluative interpretation of what those materials that are detected mean in a specific crime investigation. This will require a stepwise change in the current funding structures at the international and national levels, and dedicated funding streams. There is a long way to go – in the UK 2009-2018 less than 0.03% of the total research funding at the national level was devoted to forensic science, and less than 0.003% on foundational research.

Given how the justice system shapes our societies, the stakes are far too high to ignore the crisis in forensic science. The integrity of the forensic science system is critical to the delivery of justice and public trust, and so this is an urgent challenge for the global community. Like plastics in our oceans, this is a problem that has gone under the radar for far too long. The time for action is now.

Conflicts of interests

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To see the data on the current forensic science research funding situation in the UK see:
https://www.sciencedirect.com/science/article/pii/S2589871X19301457

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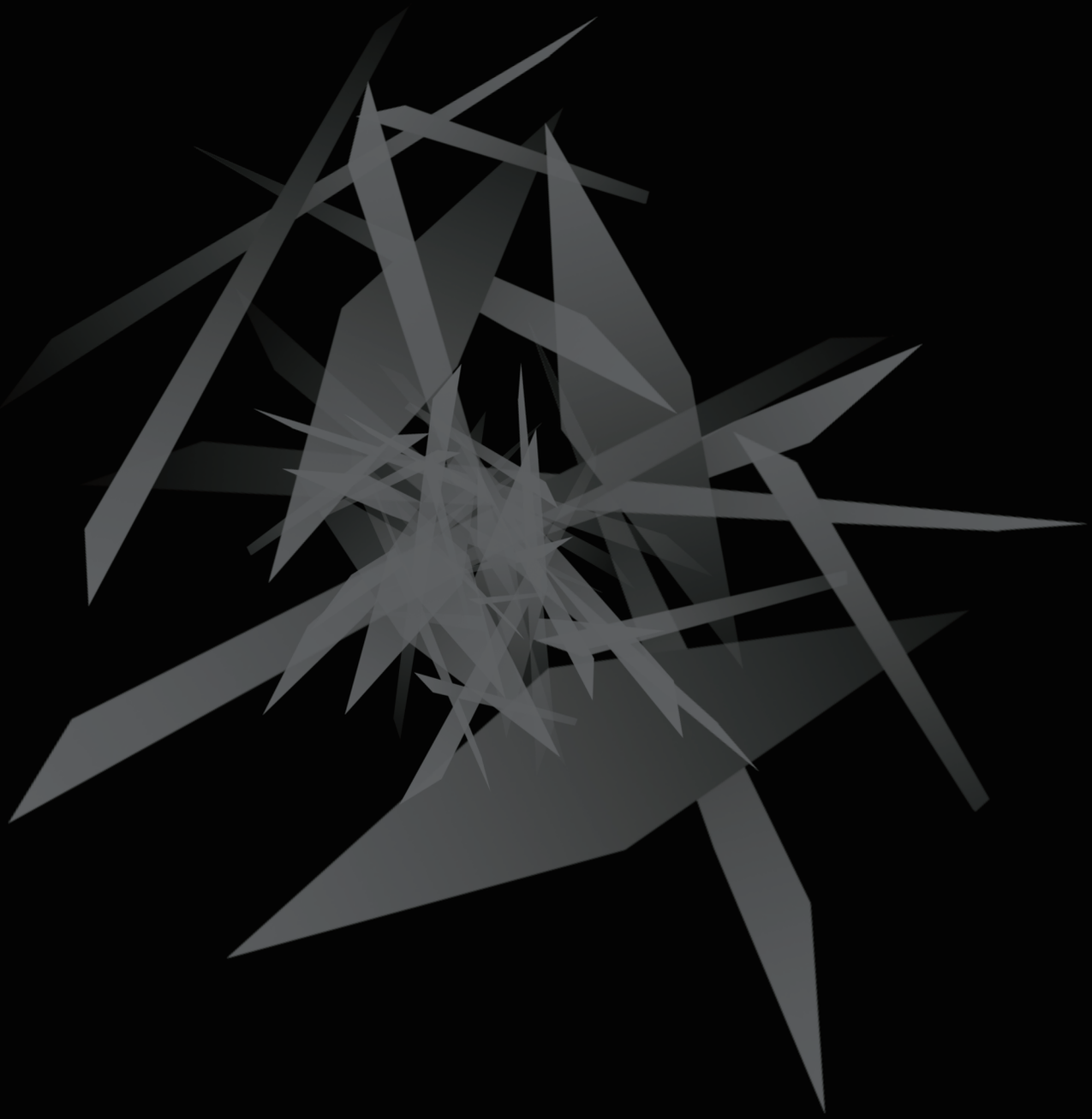

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