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Conceptualising, evaluating and communicating uncertainty in forensic science: Identifying commonly used tools through an interdisciplinary configurative review

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Abstract

This study provides a set of tools for conceptualising, evaluating and communicating uncertainty in forensic science. Given that the concept of uncertainty is one that transcends disciplinary boundaries, an interdisciplinary configurative review was carried out incorporating the disciplines of medicine, environmental science and economics, in order to identify common themes which could have valuable applications to the discipline of forensic science. Critical Interpretive Synthesis was used to develop sub-synthetic and synthetic constructs which interpreted and synthesised the underlying evidence and codes. This study provides three toolkits, one each for conceptualisation, evaluation and communication. The study identified an underlying theme concerning the obstacles that would need to be overcome for the effective application of these toolkits and achieving effective conceptualisation, evaluation and communication of uncertainty in forensic science to lay-stakeholders. These toolkits offer a starting point for developing the conversation for achieving greater transparency in the communication of uncertainty. They also have the potential to offer stakeholders enhanced understanding of the nuances and limitations of forensic science evidence and enable more transparent evaluation and scrutiny of the reliability, relevance and probative value of forensic materials in a crime reconstruction.

Keywords: uncertainty conceptualisation; uncertainty evaluation; uncertainty communication; forensic science; interdisciplinary review; critical interpretive synthesis; configurative review.

1. Introduction

Every stage of the crime reconstruction process in forensic science, from the crime scene to the presentation of forensic evidence in court, must address uncertainty [1]. Uncertainty is an inherent attribute of science and therefore, of forensic science [2]. The scientific method is predicated on the testing of hypotheses and falsification [3], to draw inferences in a manner that must accommodate missing or incomplete information. In forensic science, due to the complexity of the forensic process as it operates at the nexus of science, the law, policy and government [4, 5] it is very rare to be able to establish a 'ground truth' [1] to test derived inferences which can stand in contrast to the scientific 'laws' that can be established through laboratory based experimental studies or population level studies.

Uncertainties are present when identifying, recovering, preserving and analysing traces and patterns, and also in the decision-making of experts as they interpret what those materials mean in the context of a crime reconstruction [6, 7, 4, 8]. Uncertainty needs to be considered during the collection of traces or patterns at the crime scene, particularly given their dynamics which may affect the state of those traces or patterns [9]. The impact of these dynamic events in turn influences the judgements and decisions made in terms of what is searched for, where or if a clue is recovered, how it is recovered and preserved, and how it may be analysed within the context of the specific case [7]. Expert decision-making and interpretation must take place under conditions of uncertainty which can be influenced by the contextual information that is or is not made available [2, 10], often considered extrinsic factors, in addition to the well documented intrinsic factors of human cognition [11, 12, 13, 14, 15].

Academics and professional organisations have been increasingly calling for more acknowledgement, disclosure and articulation of uncertainty. Taroni & Biedermann [2] highlighted the need to explicitly and clearly articulate uncertainties, the National Academy of Science [16] raised the issue of evaluating uncertainties in its seminal report, while the Forensic Science Regulator in England and Wales has been showing significantly greater interest in the topic of uncertainty and evaluative interpretation [17] in laboratory based sub-disciplines as well as in the evaluation and communication of uncertainty in more qualitative based sub-disciplines. Whilst the issue is highlighted the report fell short of providing any detailed or specific directions for addressing uncertainty revealing the complexity of the issue. The Government Chief Scientific Adviser in his annual report [18] also addressed the topic of evaluating and communicating uncertainties in forensic science, however, it is salient that evaluation was solely discussed in terms of measurement associated with analytical tests and results. In a more recent report the UK Forensic Science Regulator [19] stated her intention and ongoing plans to develop a calibrated interpretative framework which would also include the tackling of uncertainty issues. However, it is not clear what type of evidence base can be utilised to establish such a framework. The communication of uncertainty to stakeholders is consistently being highlighted as a prerequisite for ensuring that jurors are appropriately informed about the evidence presented to them [20] and are in a position to evaluate whether the prosecution has dismissed the burden of proof beyond reasonable doubt [21]. At the very least, it is clear that a transparent dialogue addressing the uncertainties that are inherent in science and in the forensic science process is needed and has the potential to enhance expert performance [20, 22].

Sources of uncertainty which may impact the confidence that can be placed in science findings and inferences in a forensic science context have also been identified. Significant consensus exists in the published literature that there is a lack of empirical research addressing expert analysis and interpretation of materials found at the crime scene [23, 24, 25, 26, 16, 27]. Despite the developing body of research that exists in certain disciplines, fields such as fingerprint analysis are generally considered to be based on skill and experience of examiners rather than primarily methodologies based on the scientific method [28, 29]. There are of course many reasons for this, and ongoing debate about the most appropriate way to consider fields within forensic science that rely on both explicit and tacit knowledge [30, 1], while ensuring that there is transparency in how a conclusion has been reached that is communicable to appropriate audiences [31]. This lack of consensus to date is an additional source of uncertainty, particularly in relation to the capacity of experts to make transparent evaluations of the science evidence that can assist investigators and the courts.

Despite these contributions, a common framework with a consistent language and structure capturing, evaluating and conveying uncertainty has yet to be developed [22]. Uncertainty in forensic science has traditionally been discussed in terms of being a corollary of the examination of past events [2, 32] and the unknowability of a 'ground truth' [33, 1]. More recently, efforts have been made to think of forensic science as a system made up of individual, interrelated components [4, 1, 34, 35]. There have also been calls to move focus away from the calculation of error rates [25, 36], which have been fraught with contention in terms of definitions [37, 38], the methods by which these should be calculated [39, 33, 40, 41] if at all, and considerations of whether a framework of risk assessment and management could be a more valuable pathway forward [17, 22, 42, 43]. This has led to recent considerations of how uncertainty can and should be articulated within forensic science with the use of terms, such as 'known unknowns' and 'unknown unknowns' reflecting conceptualisation trends originating in other disciplines [44, 22].

The broad body of knowledge established in a wide range of disciplines has only been applied very sparsely to forensic science to date. An extensive range of definitions and typologies have been developed over the years [45]; ranging from the Knightian uncertainty indicative of unquantifiable peril, to a more modern understanding of uncertainty associated with issues that are 'far less clear cut' [46, p.9] and of more subjective or qualitative in nature [47]. The typologies seeking to characterise uncertainty have also been as diverse, with different approaches ranging from Krupnick et al. [48] who distinguished between five types of uncertainty and Smithson [49] who identified a synthesis of 16 different types of ignorance. Therefore while there is a broad and extensive diversity of definitions and typologies of uncertainty, and a general lack of consensus due to the diversity and complexity of disparate fields, this body of knowledge offers the potential to gain insights that offer a pathway forward in forensic science for considering uncertainty and developing a conceptual construct of uncertainty that moves the discipline forward.

The absence of compatible developments between forensic science and the general body of knowledge addressing uncertainty is not only evident in the conceptualisation of the term, but also in the evaluation and communication of uncertainty. Evaluation and communication have generally been considered within the framework of probability theory [50], and in forensic science, the value of probabilities has been strongly advanced with declarations that probability theory, and specifically Bayesian approaches, represent "the only coherent logical foundation" for "reasoning in the face of uncertainty" [51, p.11]. However, the complexity and multi-faceted nature of uncertainty cannot always be reduced into a numerical formula and is not always easily quantifiable [52]. This is especially true when data are not available to help establish priors or conditional probabilities, as is often the case in forensic science. Indeed, discussions outside the discipline of forensic science have recognised this with frameworks of evaluating uncertainty embracing more qualitative elements [53, 54]. At the same time there is a growing emphasis on the need for more holistic structures that embrace all the relevant concepts and theories, and combine both qualitative and quantitative techniques for evaluating and communicating uncertainty [52, 30, 44]. Such holistic structures could potentially also allow for innovative ways of evaluating and communicating uncertainty to exist alongside, and to complement the established Bayesian paradigm.

Forensic science necessarily brings together explicit and tacit forms of knowledge and therefore frameworks for evaluating probabilities in some fields where the predominant forms of knowledge are more explicit may not always be appropriate for, or easy to directly apply into forensic science. This is particularly the case when considering how to evaluate the uncertainties associated with human, decision-making, which may not be amenable to quantification [1] due to the blend of both tacit and explicit forms of knowledge [4, 30]. One clear issue with regards to the use of probabilities in the communication of uncertainties in court has been identified in terms of the degree to which it can introduce a form of reasoning that is incompatible with the non-mathematical, inductive and even categorical reasoning of jurors [55, 56]. Empirical studies have also indicated that the use of probabilities in court may lead to fallacious juror reasoning [57, 58].

There is therefore, a need to consider whether it is possible to identify and articulate a consideration of uncertainty within the forensic science process in a holistic manner that considers the entire system [1, 22, 4]. Therefore, this study considered three frameworks for uncertainty to elicit potentially valuable concepts, instruments and approaches to set the foundations for more systematically conceptualising uncertainty and more holistically evaluating and communicating it within a forensic science context. This study recognised the fruitful ground of inquiry that exists in other disciplines and sought to draw together the knowledge that has been developed in other disciplines in an organised and systematic manner to offer insights for forensic science. A configurative interdisciplinary review of the disciplines of medicine, environmental science and economics was therefore carried out, in order to assess how scientific uncertainty is conceptualised, evaluated and communicated in these disciplines (as disciplines that can be considered to be distinct from but related to forensic science in terms of interdisciplinarity and the consideration of complex systems) and whether these can be developed into an appropriate format for considering, understanding and communicating uncertainty in forensic science.

2. Method

2.1 Design

Given the lack of established methods to address uncertainty within forensic science, this study sought to establish how other disciplines with similar characteristics to forensic science deal with uncertainty by undertaking a configurative review. The principal format of the configurative review was a critical interpretive synthesis (CIS), for the analysis and synthesis of the data. CIS was selected as it is aligned with the aim of concept and theory development [59], it endorses work across multiple disciplines, and allows for the inclusion and synthesis of different forms of materials [59]. The flexible and non-reproducible nature of CIS [59, 60] also permits the use of elements from alternative methodological approaches in order to complement CIS [60, 61, 62]. Therefore, this study combined elements from other approaches throughout its various stages (see Figure 1) as enabled by the CIS approach.

2.2 Selection of Disciplines

The ‘neighbourliness’ of a discipline with forensic science constituted the primary guiding factor in selecting the disciplines that were included in the review, as ‘neighbouring domains’ often prove to be valuable sources of ideas for the resolution of problems that transgress disciplinary boundaries [63, p.3].

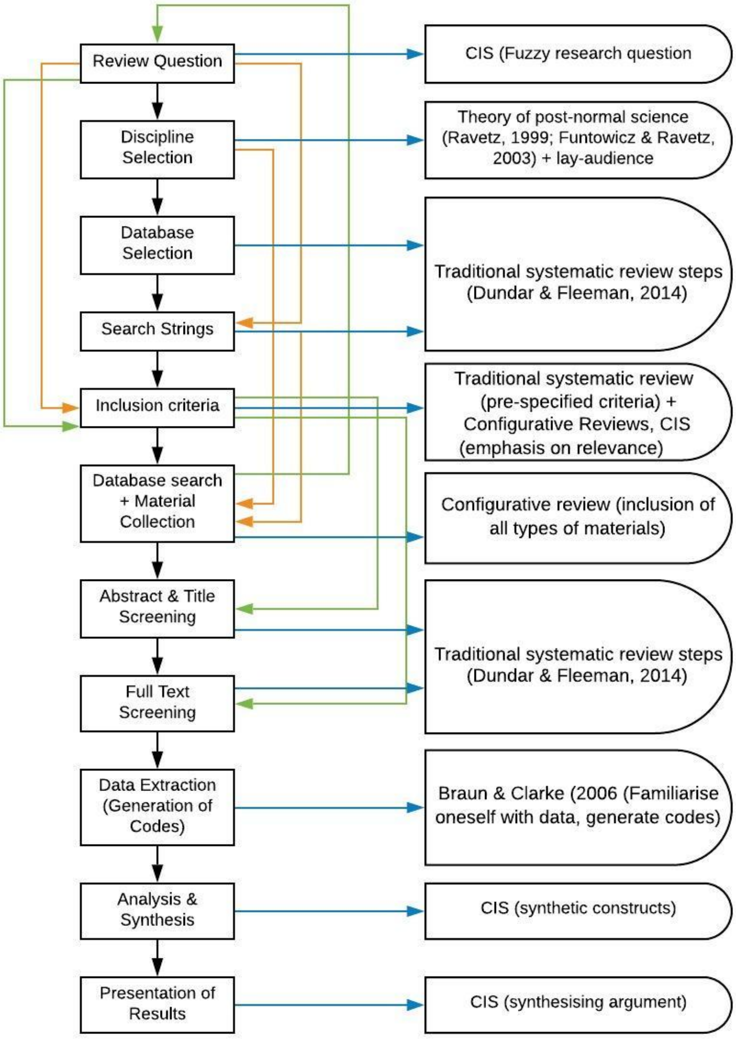

Figure 1| Orange arrows indicate influences, green arrows indicate revisions, and blue arrows indicate foundations.

The disciplinary categories on ‘Scopus’ (the largest peer-reviewed online database of published research) constituted a pool of 26 disciplines (in addition to two categories defined as ‘multidisciplinary’ and ‘undefined’) from which ‘neighbouring’ disciplines were selected. This database was chosen given its breadth and because when conducting searches disciplinary categories remain constant despite the search terms. Only the 26 clearly defined disciplines were considered for inclusion in the study.

The degree of neighbourliness of each of the 26 disciplines was judged on the basis of how closely each discipline shared two core elements of forensic science:

- Strong interaction with a lay-audience (such as that observed between expert witnesses and judges, lawyers and jurors), AND
- whether they could be described as:
    - A professional consultancy (A type of ‘issue-driven science’ where science is applied to a social context. It exhibits salient levels of decision stakes and/or uncertainties [64, 65] or
    - A post-normal science (A type of ‘issue driven science’, characterised by severe levels of decision stakes and/or uncertainties. See Figures 2 and 3 for the guidance used when determining whether a discipline was a professional consultancy or a post-normal science).

Of the 26 disciplines, nine disciplines satisfied the criteria for neighbourliness and professional consultancy/post-normal science: engineering, environmental science, meteorology, medicine, economics, genetics, pharmaceutics, veterinary science and dentistry. The disciplines of medicine and environmental science were reviewed first, as they had returned the greatest number of articles; with the exception of engineering, which encompassed an extremely large volume of articles which was beyond the capacity of this study.

Medicine was reviewed first and then environmental science. By the time the materials of environmental science had been coded and analysed thematic saturation was reached. The discipline of economics was also reviewed in order to ensure that the saturation was based on as wide a dataset as possible [66]. The rest of the disciplines were not reviewed after saturation was reached.

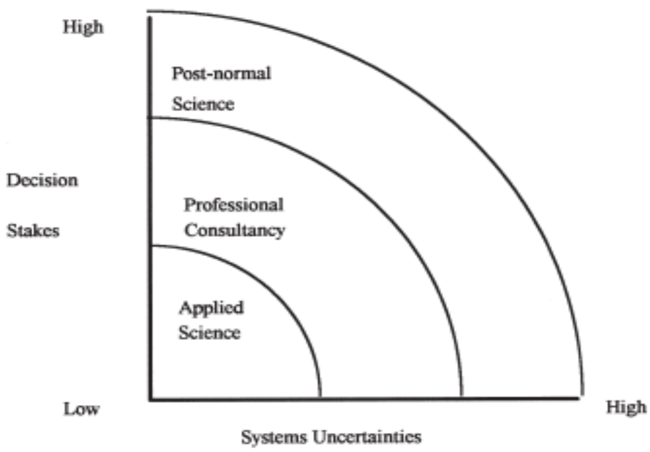

Figure 2| Spectrum of Issue-Driven Sciences (Ravetz [64])

Figure 3| Features of Professional Consultancy and Post-normal Science (Funtowicz and Ravetz [65]; Ravetz [64])

Search Strategy

The key-words found in the research question were entered into a table, along with their synonyms. This table formed the basis for the development of the search terms (see Appendix B). Boolean-operators and wildcard characters were used to combine these into search strings. A pilot was carried out on Scopus to ensure that the search string that was created (see Appendix B) returned enough relevant results. The search string that was tested in the pilot had to be adjusted in some of the databases, due to the intricacies and limitations of each of their search engines – such as failure to recognise Boolean operators [67].

Additional electronic databases were also searched for academic and grey literature in the three disciplines forming part of this review. The databases that were searched were: Scopus, UK government, Nuffield Trust Publication, MEDLINE, EMBASE, Intergovernmental Panel on Climate Change (IPCC), Georef, Greenfile, EconLit, Institute of Economic Studies, Office for Budget Responsibility, International Monetary Fund, and the National Institute of Economic and Social Research. Despite efforts to carry out a full search, the possibility that certain relevant materials were not identified as a result of database selection is acknowledged.

Material Selection

Relevance, rather than exhaustiveness, is at the heart of most configurative, interpretive reviews [59, 68]. As such, there is often no restriction on the types of materials that are included [69, 59]. This study followed this approach and included a wide range of materials, such as empirical studies, editorials, opinion articles and policy reports.

Allowing for a large range of included materials can often result in unmanageable load, so the CIS uses sampling instead of the development of pre-specified inclusion criteria (as per traditional reviews) to ensure the manageability of the contributions load and the relevance of the included materials [59]. However, this study did not follow this step of the CIS process. Instead, the development of pre-defined inclusion criteria was carried out to ensure the manageability of the contributions load, and also to minimise the potential for bias as much as possible, given that the review was undertaken by a single-reviewer.

The construction of the inclusion criteria was guided by the principle of relevance – given its prominence in configurative reviews – and the research question. Inclusion was limited to materials published in the past ten years and those that were concerned with uncertainties associated with human/subjective decision-making. These criteria were developed in order to ensure that the concepts and instruments identified would be as relevant and potentially applicable to forensic science as possible. Inclusion was also limited to materials in English for practical purposes [69, 70].

The following inclusion criteria were thereby developed:

1. Provides substantive information on the evaluation of uncertainty in relation to any stage of the decision-making or conclusions reached by scientific experts.
2. Provides substantive information on the communication of uncertainty in relation to any stage of the decision-making or conclusions reached by scientific experts, to a lay-audience.
3. Provides substantive information on the sources and/or types of uncertainty in relation to any stage of the decision-making or conclusions reached by scientific experts.
4. The uncertainty has to be related to at least some form of subjective/human decision-making process, rather than a purely laboratory or mechanical process.
5. The material has to be in English.
6. The material must have been published in the ten years up to the commencement of the database search. The majority of the database search was carried out in the end of 2018, with some searches also conducted in early 2019 – thus resulting in the inclusion of certain materials published in early 2019.

Material Collection

Once the database search was completed and all the resulting materials retrieved, EndNote was used to store the materials and delete duplicates. A title and abstract screening was carried out [71], where each article was marked as either irrelevant or potentially relevant on the basis of the inclusion criteria. Following this, the full text documents of those marked as potentially relevant were downloaded and scanned , in order to more thoroughly examine whether they satisfied the inclusion criteria. Short reasons for exclusion were noted for each of the materials on EndNote. Those articles for which the full-text could not be retrieved were excluded from the review [72].

Material selection results

The database search yielded 14,428 materials in total. Once the materials were exported to EndNote, duplicates were removed, resulting in 5,445 records for medicine, 4,177 for environmental science and 1,793 for economics. Following the screening processes (see Figure 4), 91 articles from medicine, 60 articles from environmental science and 70 articles from economics were deemed to have fulfilled the inclusion criteria and were thus included in the review.

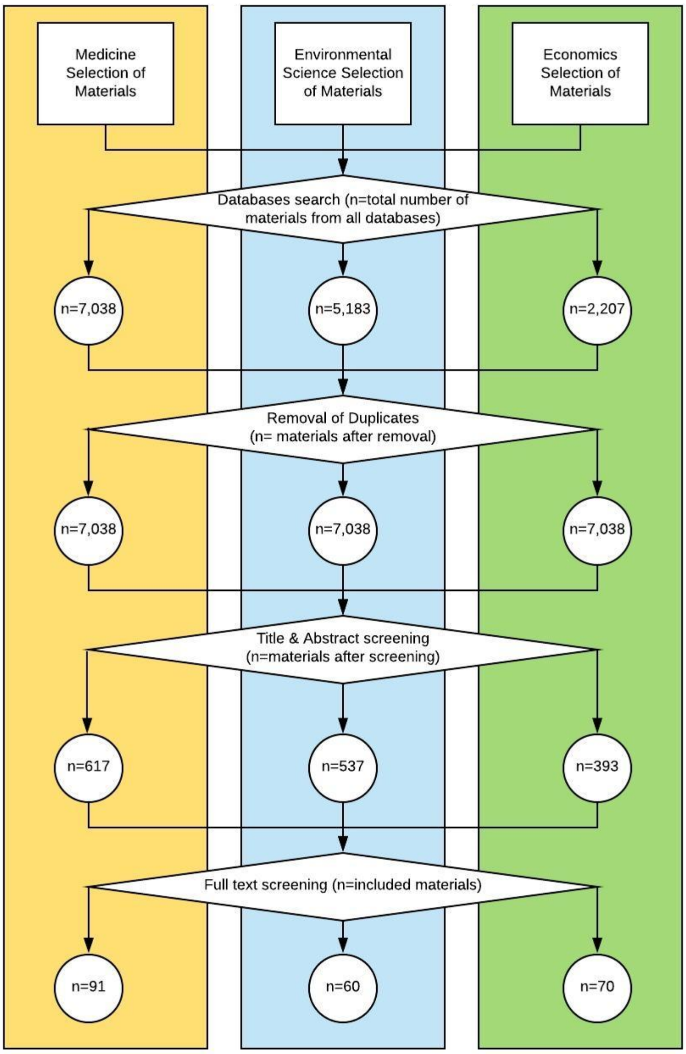

Figure 4| Material Selection process for the disciplines of medicine, environmental science and economics

Quality Appraisal

A quality appraisal was not carried out, given their contentious nature in configurative reviews [73, 59, 74, 61]. A number of configurative reviews do not carry out quality appraisals, but instead focus on ensuring relevance of materials [61, 62, 67, 60, 75]. The design of the inclusion criteria was, therefore, driven primarily by the need to ensure relevance of materials.

Data analysis and synthesis

A framework for data extraction and analysis developed by Braun & Clarke [76] was followed. The Braun & Clarke [76] method involves six steps: familiarise oneself with the data; generate codes, search for themes; review themes; define themes; and writing up.

The NVivo software was used to assist with the data extraction and analysis phases [74]. Open-coding was used to code anything of interest or relevance to the research question [77]. Free-coding was used to code words, phrases and sentences that were of interest. Once a number of initial free codes were generated, wider codes were then produced which encompassed a number of the initial free codes that had an identical or very similar meaning/topic.

The coding process yielded 876 codes (Table 2), which were organised into parent and children nodes during the analysis stage. These codes were then transcribed manually to assist with their organisation, the identification of patterns and the development of synthetic constructs and synthesising arguments. From the 876 codes, duplicates were discarded, irrelevant codes were dismissed, while codes that had the same or similar meanings but were referred to differently by the authors, were given a common term. This process resulted in the retention of 342 codes.

Following the generation of codes, sub-synthetic and synthetic constructs were developed and revised [59, 76]. The conceptual patterns identified through the codes were captured by the sub-synthetic constructs (i.e. knowledge uncertainties), while the purpose of the synthetic constructs was to represent the patterns identified among the sub-synthetic constructs (i.e. sources of uncertainty) (See figure 5). The codes informed the development of 6 overarching synthetic constructs and 29 sub-synthetic constructs (see Table 2).

Synthetic constructs, instead of themes, were developed as per the CIS process, given their emphasis on interpretation of the available evidence and codes in a more unified and explanatory manner [59].

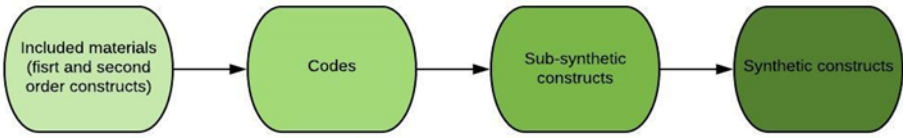

Figure 5| Process from included materials to synthetic constructs

A number of the sub-synthetic and synthetic constructs were named after some of the existing codes, such as the sub-synthetic constructs of level, location and nature borrowed from Walker et al. [78]. Other sub-synthetic and synthetic constructs were provided with original names that better represented the underlying codes and evidence [73]. For example, the sub-synthetic construct of evaluative structures was not directly taken from one of the codes, but was instead prescribed to describe a certain pattern recognised among the evaluative instruments that were collected. The final step was that of synthesising the synthetic constructs into a synthesising argument. The ‘synthesising argument’ represents the network of relationships between the synthetic constructs and seeks to explain their connection [59].

3. Results

3.1 Description of Included Contributions

The majority of the included contributions were non-empirical in nature (n=177), consisting of review and opinion articles, letters to editors, editorials, essays and commentaries. Among the non-empirical materials were 3 systematic reviews from the discipline of medicine [79, 80, 81] and 37 grey literature materials. The majority of these (n=33) were retrieved from the discipline of economics and included reports by the Office for Budget Responsibility (OBR), the Bank of England, the International Monetary Fund, the Deutsche Bundesbank Eurosystem and the European Central Bank. Four further grey literature contributions were identified in the materials of environmental science, all relating to the Intergovernmental Panel on Climate Change. The empirical articles only made up a small proportion of the 221 included materials (n=44), 21 of which were retrieved from the discipline of medicine, 20 from the discipline of environmental science and 3 from economics.

Table 1 summarises the characteristics of the included contributions, including year of publication, discipline, whether it was an empirical study or not, as well as its primary topic in relation to the three main themes. The majority of the included contributions had as their primary focus only one of the three main themes (n=151), while the rest engaged with two of the themes (n=44) or all three of them (n=26).

Characteristics of Included Materials			
Characteristics		Number	Percentage of total
Year Published	2009	16	7.2%
	2010	11	5%
	2011	22	10%
	2012	28	12.7%
	2013	24	11%
	2014	16	7.2%
	2015	21	9.5%
	2016	25	11.3%

	2017	35	15.8%
	2018	18	8.1%
	2019	5	2.3%
Discipline	Medicine	91	41.2%
	Environmental Science	60	27.1%
	Economics	70	31.7%
Empirical/ Other	Empirical	44	19.9%
	Other	177	80.1%
Primary Topic	Conceptualisation	29	13.1%
	Evaluation	59	26.7%
	Communication	63	28.5%

Table 1| Characteristics of included contributions

3.2 Analysis & Synthesis results – background information:

Of the 342 codes, only 36 codes were commonly identified in the materials of all three disciplines. The distribution of the codes according to discipline, including any overlaps, is captured in Figure 6.

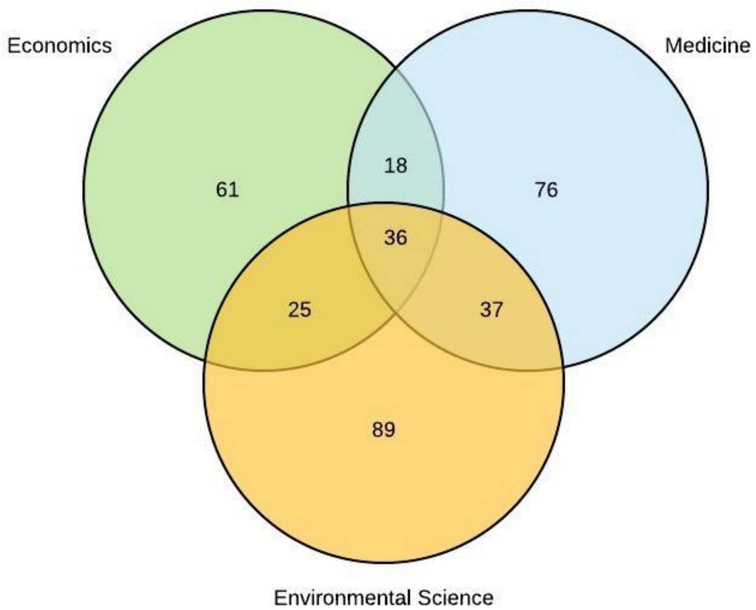

Figure 6| Codes produced by the materials of each discipline

The codes informed the development of 6 overarching synthetic constructs and 29 sub-synthetic constructs. The sub-synthetic and synthetic constructs, as well as the number of codes encompassed under each of these can be seen in Table 2.

Topic	***Synthetic & Sub-synthetic Constructs***	***No Codes***
		342
Conceptualisation		
	Sources of Uncertainty	Total = 84
	Knowledge Uncertainties	6
	Data Uncertainties	25
	Methodological Uncertainties	18 (10 of which are broadly captured under the term model uncertainty in Figure 7)
	Probability Uncertainties	5
	Expert (decision maker)-centred uncertainties	11
	Semantic Uncertainties	3
	Innate Uncertainties	16
	Characterisation of uncertainty	Total =20
	Level	6
	Location	9
	Nature	5
Evaluation		
	Instruments	Total = 68
	Mathematical or Statistical	48
	Graphical representations	3
	Qualitative instruments	5
	Structures	12
Communication		
	Elements & Approaches	Total = 117
	Format of communication	7
	Instruments & terms	42
	Forms of language	4

	Framing	12
	Mediums of communication	8
	Content	24
	Desirable characteristics	20
Effective Evaluation & Communication		
	Obstacles	Total =28
	Affective responses of lay stakeholders	9
	Cognitive responses of lay stakeholders	3
	Affective responses of expert decision makers	3
	Cognitive responses of expert decision makers	3
	Empirical	10
	Benefits	Total=25
	Lay-Audience decision makers	8
	Expert decision makers	9
	Both	9

Table 2| Codes organised in synthetic and sub-synthetic constructs

3.3 Analysis and synthesis results – the three toolkits:

A. Conceptualisation

The analysis and synthesis of the codes revealed that uncertainty was conceptualised either in terms of the sources that give rise to it, or through certain descriptions of its features (i.e. its magnitude, location or reducible or irreducible nature). Two synthetic constructs were created to reflect this distinction: 'sources of uncertainty' and 'characteristics of uncertainty'.

A model was also developed in the form of an 'Uncertainty Map' (see Figure 7) that portrays the synthetic and sub-synthetic constructs relating to the sources of uncertainty, as well as the individual codes that come under these. The individual codes are placed on the circumference of the circle. Each of these codes is connected to the centre of the circle. The different coloured connections represent the sub-synthetic constructs developed under the synthetic construct of 'Sources', which capture the patterns of the codes in terms of their main source area. Seven source areas were identified: data, knowledge, methodological, probability, semantic, innate and expert-centred.

Data constitutes one source area, as limitations in relation to the data that is available to the expert decision maker [82, 83, 84] can give rise to uncertainty. In addition, limitations can exist with regards to the knowledge base that will form the foundation of decision-making by an individual [85, 86, 87], as well as due to the methods employed [88, 89, 90], such as the precision of analytical instruments, or how the data is stored and used. Uncertainties may also arise due to probabilities, either due to the difficulty of assigning probabilities to the occurrence of events in question [91, 92] or simply because probabilities are unknown or unknowable [92]. Probabilities may also arise as a source of uncertainty relating to the precision of the probabilistic evaluations of decision makers [93, 94]. Three further source areas were identified, as those relating to the decision maker (e.g. quality of the individual, heuristics or judgment), to the semantics (e.g. conceptualisation of uncertainty) or to inherent uncertainties (e.g. back-casting, bounded expert knowledge).

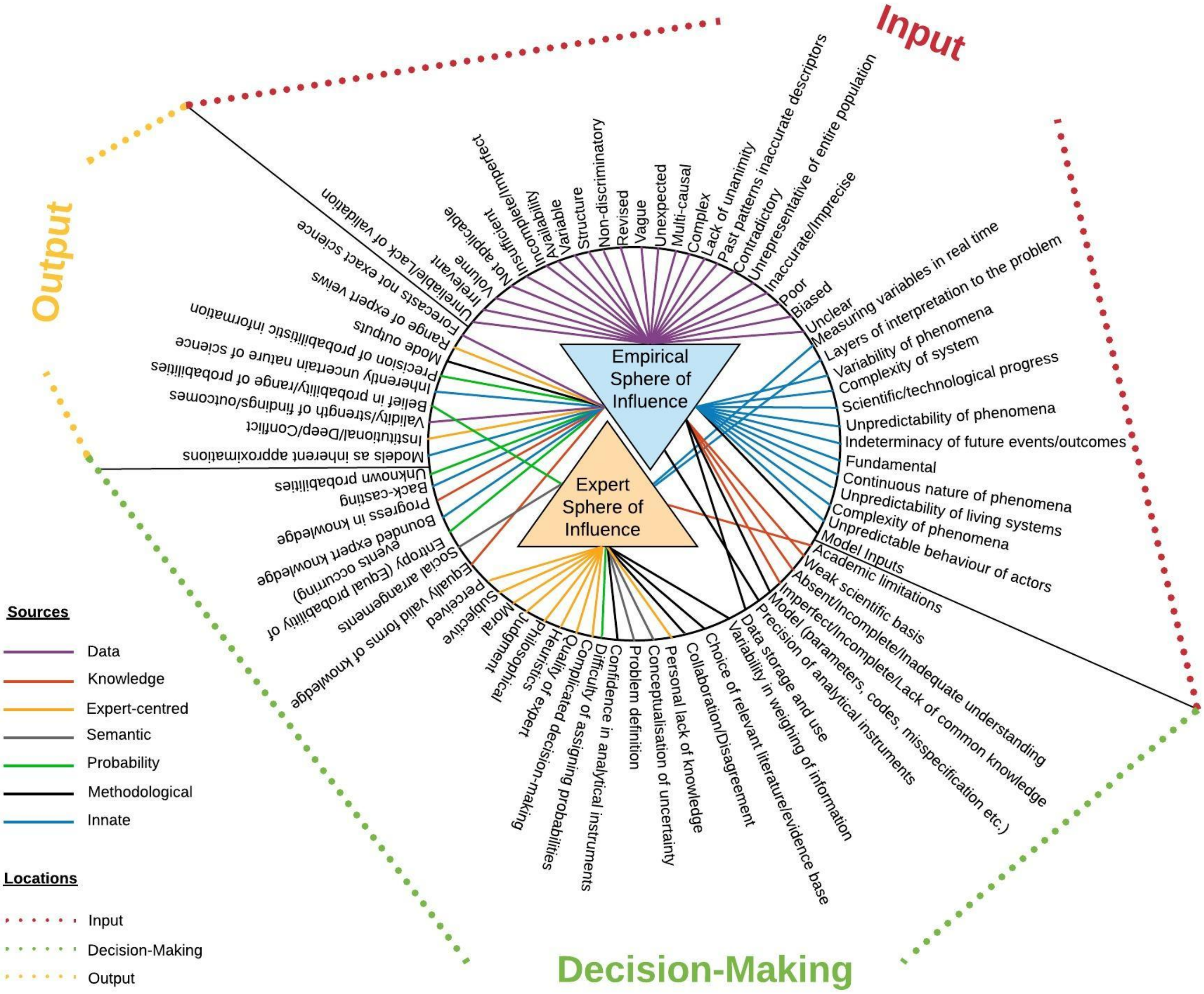

Figure 7| Uncertainty Map *[NEEDS TO BE IN COLOUR]*

The model also captures two further elements of the characterisation of uncertainty: location and nature of uncertainty (expert and empirical spheres of influence) (See Table 3).

There are three sub-synthetic constructs in total within the synthetic construct of ‘characterisation of uncertainty’: location, level and nature. The terms for these sub-synthetic constructs were taken from Walker et al. [78], whilst not an included paper in the review, it was referred to on numerous occasions by some of the included contributions [such as 95, 96, 97, 98]. It is important to note that the original meaning of these three terms have not been maintained throughout because certain patterns of concepts identified in the review fitted well under the sub-headings produced by Walker et al. [78], yet did not comply with the original meaning intended by Walker et al. [78].

The locations identified shared significant similarities with the sources of uncertainty. For example, there were codes relating to uncertainty located in the findings [98, 99], in probabilities [100, 101] and the methodologies and techniques used [102, 89]. As such, these codes were analysed in conjunction with the sources of uncertainty in developing the sub-synthetic construct of location, which would more efficiently organise the patterns of related concepts.

The forensic science process model developed by Morgan [4] was used as the basis for organising the concepts relating to the point in the process that the uncertainty is introduced. Part of the model is the recognition of the different steps of the forensic science process; crime scene, analysis, interpretation, intelligence and evidence. In order to better capture the more general nature of expertise studied through this review, 3 locations were developed. The 'crime scene' step is embodied in the first location, that of 'input'. Analysis and interpretation correspond to the location of 'decision-making', while intelligence and evidence to that of 'output'. The three locations that were developed were effective at representing the locations of the specific sources of uncertainty that were coded from the data of the included contributions, as can be seen from the 'Uncertainty Map (Figure 7).

The second sub-synthetic construct was that of the level of uncertainty. Level of uncertainty refers to the magnitude of uncertainty. The meaning of level of uncertainty remained largely unchanged from that initially intended by Walker et al. [78], with the addition of three further levels of uncertainty. These additions were made so as to represent the entirety of the evidence collected and analysed from the review. As a result a spectrum of uncertainty was produced in this study ranging from deterministic knowledge to total ignorance (Figure 5). Within that range, statistical uncertainty is the closest level to deterministic knowledge, as it refers to uncertainty that can be quantified [78]. Scenario uncertainty follows, indicating unquantifiable uncertainty which is nevertheless known and recognised [78]. Qualitative uncertainty is the uncertainty that can be expressed in qualitative terms and is as such subject to greater evaluation than total ignorance [96], upon which a value cannot be added [78]. Total ignorance marks the end of the spectrum, implying uncertainty that is so grave that "we do not even know that we do not know" [103, p.726].

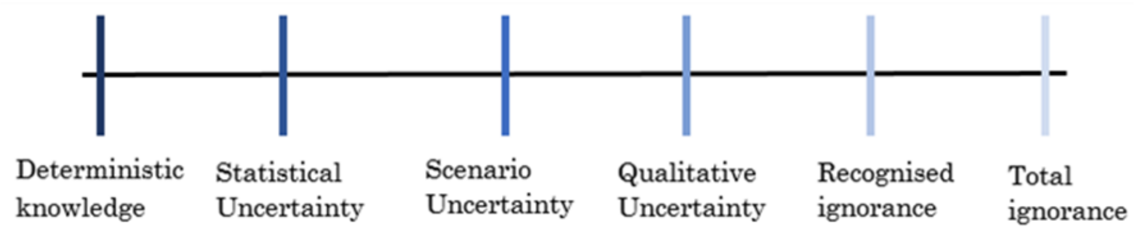

Figure 8| Level of uncertainty spectrum

The last sub-synthetic construct represents those codes taken from some of the included contributions, which refer to the nature of uncertainty. Six features of the nature of uncertainty were identified. As can be seen in Table 3, each of these features consists of two sets of opposites. Similarities are shared by the opposite features on the same column. Aleatory uncertainty refers to variability in data, behaviour, phenomena etc. Aleatory uncertainty is also irreducible, and can also be described as inherent. Of these features, only 'sphere of influences' was captured by the 'Uncertainty Map' (Figure 7).

Nature of Uncertainty - Features	
Irreducible (Cannot be reduced through further research)	Reducible (Can be reduced through further research)

Aleatory (inherent variability in phenomena)	Epistemic (Related to limitations of knowledge)
Empirical sphere of influence (uncertainties lying outside the decision-making of expert)	Sphere of influence of expert (uncertainties related to experts' decision making)
Unknown Unknowns - Black swans (unforeseeable or unforecastable rare events)	Known unknowns
Inherent	Non-inherent

Table 3| Nature of Uncertainty

B. Evaluation

Four main types of evaluative approaches were identified in the included materials: mathematical or statistical, graphical representations, qualitative instruments and evaluation structures (Figure 6).

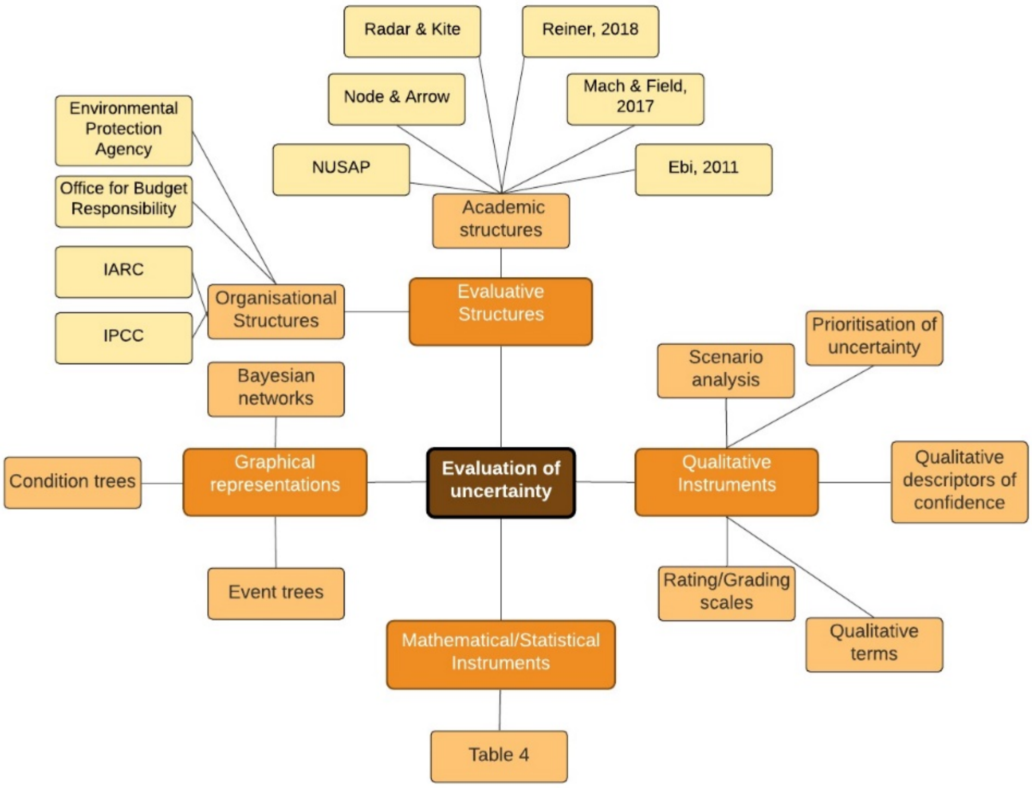

Figure 9| Evaluation Instruments

Mathematical/Statistical Instruments

Table 4 presents the mathematical and statistical instruments collected from the included contributions. Despite their quantitative nature, each of these have disparate applications; some respond better to specific sources of uncertainties, while others are designed for particular purposes. Possibility theory, for example, focuses on the uncertainties that arise due to the imprecision of language and natural systems, 'fuzzy sets' are capable of dealing with uncertainties that arise due to vagueness of the data, while rough sets and Monte Carlo simulations are model oriented.

Sensitivity analysis and Bayesian theorem are two mathematical instruments that were discussed in the included materials in all three disciplines. Both of these seek to address specific uncertainty related needs. Sensitivity analysis is used to quantify those sources of uncertainty that have the greatest impact on the results, while Bayesian theorem is used to update a set of prior beliefs in light of new data or evidence.

Mathematical & Statistical Evaluation Instruments			
Aggregate density forecasts	Distance between individual forecast and perfect forecast	Interval probability three valued logic	Probability distributions for model parameters
ANOVA	Shannon Entropy	Likelihood Ratio	Root Mean Squared Forecast Errors
Asymptomatic reliability analysis	Evidence theory	Markov Chain Monte Carlo	Robust optimization
Average of squared differences	Fuzzy probability	Mean and standard deviation of past errors	Rough sets
Bayes	Fuzzy set	Measure of disagreement of different forecasts	Sensitivity analysis
BKLS	Fuzzy stochastic	Model averaging	Standard Deviation
Bootstrap analysis	Identifiability Analysis	Monte Carlo simulation	Stochastic optimization
Composite indicators with uncertainty analysis	Information Gap decision analysis	Multimodel Analysis	Stochastic simulation
Compositional Fuzzy Model	Information theory	Parameter Estimation	Uncertainty Analysis
Contribution Index	Interquartile range calculation	Past forecast errors	Uncertainty propagation
Data analysis	Interval Fuzzy Robust Dynamic Programming (IFRDP)	Point forecast and density forecast	Variance of Mean Forecast Errors (using General Autoregressive Conditional Hederoskedasticity)
Dispersion	Interval mathematics	Possibility theory	Volatility estimation

Table 4| Mathematical or statistical evaluative instruments in alphabetical order

Graphical representations:

The second sub-synthetic construct of graphical representations is the most closely connected to the sub-synthetic construct of mathematical or statistical instrument. The graphical representations may be subject to probabilistic analysis, while the Bayesian theorem found in the first sub-synthetic construct appears as the basis or a component of some of these graphical representations. One of the graphical representations under this construct are Bayesian networks. These are underpinned by Bayes rule and are recognised as useful tools for their ability to provide clear representations of different causal relationships, whether quantitatively or qualitatively. Further graphical representations under this sub-synthetic construct, include event trees and condition trees. Event trees present a sequence of events so as to provide a clear understanding of the uncertainties involved, while they also often appear to be subject to Bayesian analysis [104]. The last form of graphical representation is that of the condition tree, which is considered to be a valuable tool in identifying all sources of uncertainty and avoiding oversights [105].

Qualitative Instruments

The instruments discussed so far had a significant statistical or mathematical element involved. The sub-synthetic construct of qualitative instruments captures those instruments that had a purely qualitative character. These instruments appear to be more valuable when the uncertainties are not subject to quantification [106]. Grading/rating scale was the only qualitative instrument recognised by authors of the included contributions in all three disciplines. These scales require the use of qualitative ratings with regards to different issues relating to uncertainty; such as confidence in risk estimates [107], the quality of the underlying evidence or the strength of the experts' recommendations. Qualitative descriptors of confidence, such as likely, very likely and so forth go hand in hand with rating scales [106,107].

Qualitative terms in contrast, are more ad hoc in nature, and have been found mostly in the included contributions of medicine [108; 109]. Examples of these include terms such as "suggestive of" and "possibly". Scenario analysis and prioritisation of uncertainty are not as conventional in evaluating uncertainty per se. Scenario analysis is a process through which different scenarios of outcomes are predicted. These scenarios can then be used as model inputs which can lead to a more tangible evaluation of uncertainty [98]. Similarly, prioritisation of uncertainty may not evaluate uncertainty in a traditional sense, but it does so by identifying and prioritising uncertainties according to the values and interests of stakeholders.

Evaluation Structures

The evaluation structures that were identified were either developed by academics or organisations. These structures exhibit significant similarities in the manner in which they evaluate uncertainty. The majority of these combine quantitative and qualitative metrics to evaluate uncertainty. They also use proxies of uncertainty, for some or even all of their metrics. Their common characteristics can be seen in Table 5, along with an outline of the individual properties of each structure.

Structure	Quantitative/ Qualitative	Metrics	Use of proxies	Instruments
Ebi [110]	Qualitative	1. Agreement 2. Evidence 3. Theory	Yes: all metrics are proxies of uncertainty	Qualitative descriptors/scale
IARC (as discussed by Ebi, [110])	Qualitative	1. Agreement 2. Confidence 3. Evidence 4. Theory	Yes: all metrics are proxies of uncertainty	Qualitative descriptors

Impact Matrix (Environmental Protection Agency, as discussed by [111])	Qualitative	1. Level of uncertainty 2. Level of impact	No	3x3 matrix with qualitative descriptors. Vectors = 2 metrics
IPCC TAR Guidance Note ([112], as discussed by Ebi [110])	Both	1. Identify most important factors and uncertainties 2. Document ranges and distributions in the literature 3. Determination of level of precision 4. Distribution of values of outcome/event 5. Rate and describe state of scientific knowledge informing values in step 4 6. Prepare traceable account of how estimates were constructed	Yes for step 5: type/amount of evidence and level of peer acceptance/consensus	Quantitative or qualitative evaluations for value and range; qualitative descriptors for state of knowledge
IPCC AR4 (as discussed by Mastrandrea et al. [113]; Ekwurzel et al. [106])	Both	1. Qualitative levels of understanding 2. Levels of confidence 3. Likelihood (probabilities)	Yes for qualitative levels of understanding: Amount of evidence and agreement between expert decision makers	Qualitative descriptors/scale & probabilities
IPCC AR5 (as discussed by Jones [114]; Mastrandrea et al. [113]; Ebi [110]; Mach et al. [115]; Helgeson et al. [116])	Both	1. Confidence scale 2. Likelihood scale	Yes for confidence scale: Underpinned by evidence strength (amount, type, consistency and quality) and agreement of lines of evidence	Qualitative descriptors/scale & probabilities
Mach & Field [117]	Both	1. Underlying evidence and agreement 2. Scientific Knowledge 3. Likelihood of the outcomes of interest	Yes: All metrics are proxies of uncertainty	Model to capture overall structure; qualitative descriptors for second metric; subjective probabilistic evaluations for third metric with corresponding verbal scale
Node & Arrow (Chen et al., [118]	Both	1. Identification of causes of uncertainty 2. Confidence of expert in each of the causes (nodes)	No	Confidence intervals; visual node and arrow diagram
Radar & Kite Diagram (van	Both	1. Theory 2. Method 3. Validation	Yes: all metrics are proxies of uncertainty	Numerical evaluations; confidence in

der Sluijs et al. [53])		4. Value laden 5. Proxy 6. Empirical		evaluations; visual diagram representing confidence in numerical evaluation of each metric.
NUSAP (Funtowicz & Ravetz [119] as discussed by Curry [103])	Both	1. Numerical 2. Unit 3. Spread 4. Assessment 5. Pedigree (qualitative)	Yes for pedigree: quality and pedigree of underlying data and methods.	Confidence intervals, error rate, variance for third metric; qualitative grading scale for fifth metric.
OBR EFO, March [103]	Qualitative	Total uncertainty rating	Yes: 1. Data uncertainty 2. Modelling Uncertainty 3. Behavioural Uncertainty	Qualitative descriptors/scale
Reiner [120]	Both	Characterise source of uncertainty in medical reporting and create end-user specific uncertainty profiles	Yes: 24 variables impacting the user-specific uncertainty profile	6 questions and 24 provider (physician) profile variables

Table 5| Evaluation structures

B. Communication

Seven dimensions to the communication of uncertainty were identified. These seven dimensions were captured through the sub-synthetic constructs of format, instruments and terms, form of language, framing, medium of communication, content and desirable characteristics (Figure 7).

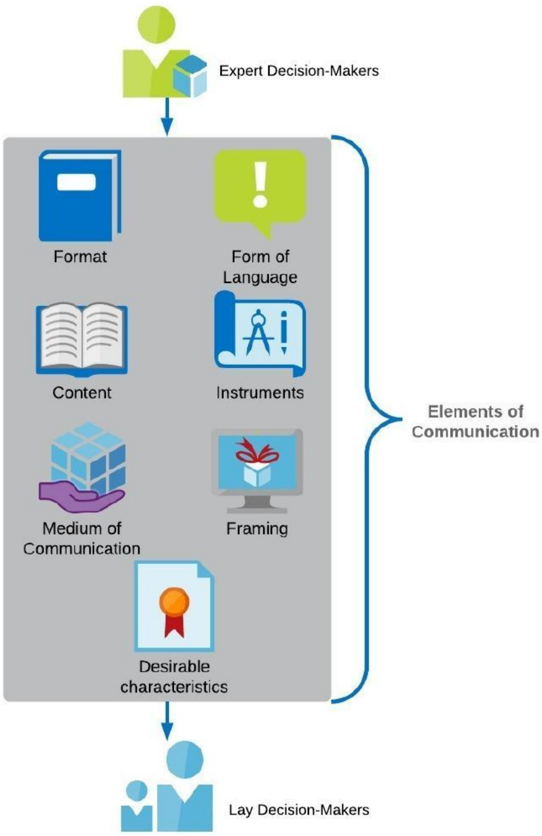

Figure 10| Communication of Uncertainty dimensions

A complete breakdown of the elements that are encompassed under each of these sub-synthetic constructs are presented in Table 6. With regards to the format of communication, the empirical evidence has indicated that even though numerical representations are preferred by participants [121; 122], the communication of uncertainty in numerical and verbal forms has been found to be more effective [122]. Among the four forms of language that were identified, natural language was the least recommended by academics, due to its vague and imprecise nature [123]. The use of narrative language or 'the power to tell stories' [124, p.317] has been argued to be particularly useful in conveying uncertainty due to its ability to bridge the gaps between expertise and non-expertise [125]. Using a translatory discourse has also been recommended as a method for balancing the inequality of arms between expert and lay-stakeholder decision makers, and ensuring that the assumptions on how the results should be interpreted and applied are consistent between the experts and lay-stakeholders [126]. The manner in which the uncertainty information is framed has been suggested to be equally important as the form and format of language [127]. The full list of framing techniques discussed by the included contributions are presented in Table 6.

Among the instruments and terms used to convey uncertainty, two of these were identified in the materials of all three disciplines: confidence intervals and sensitivity analysis. Confidence intervals have been noted as more suitable to audiences that are numerate [128], while sensitivity analysis is considered best when there is a need to show that the variation in the input can cause output uncertainty [111]. Empirical research casting light on the effectiveness of communication instruments and terms, include those by Budescu et al. [122], Milne et al. [128], Gibson et al. [129] and Han et al. [130]. According to these empirical studies, verbal presentation of frequencies was found to achieve greater consistency of understandings among participants, rather than verbal representations of probabilities [122]. Box-plots and shaded arrays are preferred by participants who work in the government and policy, while histograms were found to be the most confusing graphical representation [128]. Histograms were also found to decrease the odds of correctly reporting probability of harm, similarly to summaries, while stacked bar graphs doubled the odds of doing so [129]. Colour coding of tables was found not be of assistance in enhancing the understanding of a lay-audience [128]. In addition, the use of blurred/solid edges confidence interval bar graphs alongside texts did not have any impact on worry, perception of risk or perceived credibility of the information, in comparison to the perceptions of the participants who were exposed to the textual information only [130].

A range of content features to be disclosed when communicating uncertainty, as well as additional desirable characteristics for the overall communication were also elicited from the included contributions. The details of these can be found in Table 6.

Instruments & Terms				
Ad hoc drawings	Contribution index	Icon arrays	Percentile Range	Sensitivity analysis
Blurry-Solid edges confidence interval bar graphs	Credibility interval	Likelihood and confidence scales	Pictographs	Shade around median
Box plots	Diagnostic Diagram	Likelihood ratio	Probabilities	Shaded arrays
Box Whiskers	Dot diagrams	Loops	PDF, MPDF, CDF, CCDF, GLF	Stacked bar graphs
Certainty terms	Error bands	Mean Absolute Error Table	Probability Distribution	Summaries
Colour coding	Evidence base	Natural frequencies	Range of baseline forecasts and their error rates	Tables
Confidence interval	Fan chart	Numerical Ranges	Robustness function	Uncertainty interval
Confidence terms	Histograms	Opportunity function	Scatter plot	Verbal representation of frequencies
Verbal representations of probabilities	Visual Timelines			

Desirable Characteristics				
Accessible	Avoid recipe based approach	Consistency of terms	Exhume expert competence	Succinct
Accurate	Avoid superfluous information	Depth of language	Honest	Use of parenthesis
Avoid mid-range category use	Careful consideration of order	Economy of words	Readable manner	Vocabulary that is understood by lay-audience
Avoid poor structure	Clear	Engaging	Simple statements	Well organised

Content of communication				
Address common misinterpretations and misperceptions	Depth of analysis	Knowledge gaps	Rationale	Scope
Baseline forecast + error rates	Full range of uncertainties	Knowns and Unknowns	Relatability	Source and impact of uncertainty
Belief in conclusion	Hidden assumptions	Literature	Relevant contextual factors	Underlying expert judgment
Confirmed and dependable knowledge	Inadequacies in knowledge	Maturity of findings	Research gaps	Underlying theory
Deference to other sources	Inevitability of uncertainty	Range of expert views	Research process	

Mediums of Communication
Briefing notes
Interactive media
Leaflets
Presentation
Short orienting overviews
Videos
Written material
Online tools

Format of Communication
Numerical
Numerical and Verbal
Verbal
Verbal & Visual
Visual
Visual & Textual
Written

Form of Language
Narrative
Natural
Technical
Translatory

Framing of Uncertainty Information	
Aligning with mental models of audience	Responsibility
Contrasting	Subjectification
Emphasis on robust elements	Trustworthiness
Explicit	Urgency
Goal framing	
Hedging	
Implicit	
Positive~Negative context	

Table 6| (Set of tables) The seven dimensions of communicating uncertainty with their underlying codes

D. Efficacy of Conceptualisation, Evaluation and Communication of uncertainty:

A number of obstacles and benefits were further identified through this review (figure 11). The obstacles were subdivided into 5 sub-synthetic constructs, broadly capturing three different types of obstacles: affective responses, (e.g. denial, decision paralysis, worry and concern), cognitive responses (e.g. lack of understanding of statistics, confusion and misunderstanding), as well as empirical issues. The first two types of obstalces related to the experience of both expert and lay decision-makers, even though the specific obstacles that each set of actors would have to overcome differed. The third type of obstacles are more empirical in nature and often more innate and perhaps harder to overcome. These include: questions that are unanswerable, the diversity of audiences, as well as inherent uncertainties associated with the nature of language and the process of heuristics.

However, if obstacles can be overcome or at least mitigated, a great number potential benefits can arise both for expert and the lay decision-makers. Some of the benefits that were identified were directly related to the the expert decision-maker, others were linked to the lay decision-makers, while a third sub-synthetic construct captured those benefits experienced by both. Some of the benefits include: strenghtening the respect and trust between expert and lay-audiences, the empowerent of lay decision-makers and their encouragement to engage in public debates, as well as enhanced humility and avoidance of errors. The details of the obstacles and benefits are captured in Figure 11.

Figure 11| Obstacles and Benefits of Uncertainty Conceptualisation, Evaluation & Communication [NEEDS TO BE IN COLOUR]

4. Discussion

4.1 Summary of findings

The aim of this study was to identify the conceptual, evaluative and communicative tools that are utilised in the disciplines of medicine, environmental science and economics for addressing uncertainty. Three hundred and fourty-five codes were produced which constituted bit-size information addressing some aspect of the research question. Sub-synthetic and synthetic constructs captured common patterns in these codes. The majority of these constructs were further organised under the three main themes to which they contributed – conceptualisation, evaluation, communication.

Conceptualisation of uncertainty revolved around two main synthetic constructs – sources and characterisation, while the evaluative instruments identified were organised in the sub-synthetic constructs of qualitative approaches, evaluation structures, graphical representations and mathematical or statistical instruments. The sub-synthetic constructs that were developed to organise the body of knowledge on the communication of uncertainty included, the format of communication (e.g. verbal, visual, etc.), the instruments and terms used (e.g. confidence terms), the form of language (e.g. narrative), the manner in which the information is framed (e.g. hedging, contrasting), the medium of communication (e.g. videos, interactive media), the content of communication (e.g. research gaps, rationale) and lastly a set of desirable characteristics (e.g. clear and succinct communication). An additional theme was identified, underpinning all three main themes, concerned with the efficacy of the conceptualisation, evaluation and communication of uncertainty. This theme encompassed as its synthetic constructs the obstacles that would need to be overcome, as well as the benefits that can be gained from evaluating and communicating uncertainty.

4.2 Disciplines and their uncertainty:

Each discipline provided a different perspective on how uncertainty arises, how it is experienced by its expert decision makers, as well as the approaches that are utilised to evaluate and communicate it to its stakeholders. Uncertainty was reported to exist at every aspect of the decision-making process of doctors [131, 132, 133], whether that is relating to diagnosis [133], end of life care [134] or treatment selection [135]. Authors in medicine have highlighted the difficulties of conceptualising and defining uncertainty, as well as the absence of a coherent framework for its measurement [133,136]. Hence, the majority of the evaluative instruments identified from the materials of medicine belong predominantly to the synthetic construct of qualitative instruments. Challenges regarding the communication of uncertainty are also highlighted in medicine, due to the diversity of values and characteristics among the plethora of physicians and patients that interact on a daily basis. The legal principle of informed consent was seen to underpin a lot of the discussions in medicine regarding the communication of uncertainty. A legal and ethical responsibility is placed on physicians to step away from a paternalistic approach and enhance the agency of their patient and the ability of the patient to reach an informed decision regarding their health [93,137].

Uncertainties are also inherent and pervasive in environmental science [122,124], as is evident from a consideration of the IPCC assessment reports. The uncertainty frameworks developed and revised as part of the IPCC's annual reports indicate that scientific uncertainty associated with climate change projections and assessments is worthy of international attention. The greater attention that has been drawn to the issue of scientific uncertainty in environmental science may be the reason behind the apparent less severe struggles within environmental science to evaluate uncertainty, in comparison to medicine. A greater variety of approaches were identified in the included contributions in this study from environmental science, spanning across the four evaluative synthetic constructs. A significant amount of information was also drawn from the included contributions of environmental science with regards to the seven dimensions of communicating uncertainty. Communication of uncertainty in environmental science does not serve the purpose of informed consent per se, as in medicine, but it rather intends to assist its lay stakeholders with reaching informed decisions [138] and engaging in public debates [139].

The included materials from the discipline of economics exhibited a predominant concern with the evaluation of uncertainty, and more specifically its quantification. This does not come as a surprise, given that the strategy to manage uncertainty in economics has been one of "tam[ing] and domesticat[ing]" it [140, p. 195]. The central role played by quantification in the discipline of economics may be considered at odds with the fact that one of the leading definitions for uncertainty originates in the discipline of economics, where uncertainty is distinct from risk on the basis of its non-quantifiable nature [141], with this definition being observed in the included contributions of all three disciplines considered in this study. Nevertheless, evaluations of uncertainty featured heavily in the included contributions, particularly model-based ones. The role of expert decision making heuristics in the constructions of these models and thus in the existence of uncertainty was also highlighted by a number of published research papers, as well as domestic and international financial organisations [142; 143; 144; 145].

Uncertainty is a phenomenon that is inherently polytopical. It transgresses disciplinary boundaries and a multitude of perspectives have been voiced over the years with regards to its conceptualisation, evaluation and communication. Despite the diversity in the experiences of uncertainty between disciplines and even within disciplines, two transcendent themes that capture the essence of uncertainty were identified. First, the innate and inescapable existence of uncertainty in nearly all scientific endeavours. Uncertainty was often conceptualised as a form of deficiency or incompleteness. Fisher & Ridley [134] highlight the impossibility of achieving complete certainty, Domen [146] notes the incompleteness of scientific knowledge, while Martinez [131] makes references to philosophers who argued against the existence of deterministic knowledge and objective truth. Second, the open acknowledgment and recognition of uncertainty. Openly recognising uncertainty was advocated by a number of authors [121,147,85,100,134,148,95,139,149,132,150, 151] as a prerequisite for the effective treatment and management of uncertainty [117, 132]. This concept of openness seems to be in line with the current trends which have seen scientific uncertainty acknowledgement being on the rise [152], as well as with the open science movement, encouraging greater participation by the public in scientific matters [153].

4.3 This study and forensic science: Three toolkits

The objective of this interdisciplinary configurative review was to identify and synthesise the approaches and evidence that are currently in place when conceptualising, evaluating and communicating uncertainty in the neighbouring disciplines of medicine, environmental science and economics. The result was the development of three toolkits to assist and guide with each of these three aspects of uncertainty management.

Conceptualisation toolkit:

Speaking of uncertainty in explicit terms [2] and presenting it to the decision-makers [154] has been highlighted on several occasions. This, however, cannot be achieved unless a coherent, organised framework is in place that will provide the requisite vocabulary that will enable open communication and discussion of uncertainty.

The conceptual framework developed as part of this study has provided the requisite vocabulary to transpose some of the existing concepts to the discipline of forensic science. For example, even though Taroni & Biedermann [2] and Jackson et al. [32] refer to the uncertainty tied to the examination of past events, in the discipline of environmental science, the term 'back-casting' was identified [139], which can provide a more precise and solid term to the phenomenon described by the authors in forensic science. The lack of empirical research to support the findings and conclusions reached by expert decision makers was also discussed as a potential source of uncertainty by scholars in forensic science [23, 24, 25, 26, 16] (see section 2.2). The conceptual framework identified the appropriate term to describe this source; namely weak scientific basis as part of the sub-synthetic construct of knowledge uncertainties. The sub-synthetic construct of data uncertainties can also encompass – once applied to forensic science – the uncertainties that have as their source the incomplete and missing data which have been argued to be pervasive in forensic science [2], as well as the absence of data in relation to the frequency of concurring features experienced in some forensic sub-disciplines [25].

The map of uncertainty (Figure 3) is not only helpful in highlighting and mapping those sources of uncertainty that have already been discussed explicitly or implicitly in forensic science, but it may also draw further attention to sources of uncertainty that have not been identified or discussed yet by academics or practitioners in the field. Semantic sources of uncertainty are significant examples of these. The manner in which uncertainty is conceptualised and understood both personally by the forensic examiner, and collectively through the social institutions that develop and reinforce the disciplinary structural understandings of the concept have not been part of the discussions of uncertainty in forensic science. Yet, the absence of the plurality of perspectives that may exist with regards to the understanding what is meant by uncertainty is in itself a source of uncertainty that should not be overlooked.

Evaluation toolkit:

Perhaps the greatest benefit of the evaluation toolkit for forensic science has been its departure from placing the Bayesian theory at the core of the uncertainty evaluation discussion. The identification of a plethora of instruments ranging from fully quantitative to purely qualitative, demonstrated the complexity and multifaceted nature of uncertainty, which is not amenable to evaluation through a singular 'one-size fits all' approach. Equally important has been the recognition of the highly interwoven elements of conceptualisation and evaluation. Gaining an understanding of the uncertainties involved in the decision-making and final conclusions of expert decision makers is a necessary precondition to the initiation of a process of evaluating these uncertainties and communicating them to the relevant stakeholders [154,150].

When it comes to forensic science, it will be necessary to identify the predominant sources and characteristics of uncertainty that are of most interest to expert decision makers and stakeholders, before being able to determine which uncertainties are subject to quantification, which should be evaluated on a purely qualitative basis (when they are not subject to quantification) and which would benefit from a structure of instruments to capture their complexities. Factors such as the ability of expert decision makers to carry out statistical or mathematical uncertainty analyses, as well as the feasibility of cooperating with experts in the fields of statistics and mathematics will have to be taken into account prior to deciding on the best approach. The evaluation and communication of uncertainty are also resource and commitment intensive [155], therefore developing a simple and standardized framework is crucial.

Given the multiplicity of fields encompassed under the discipline of forensic science, as well as the diversity of sources and characteristics of uncertainty that exist, an evaluative framework which combines quantitative and qualitative elements may be the best approach towards achieving a more holistic evaluation of uncertainty in forensic science [52]. The evaluation toolkit comes as particularly valuable in the pursuit of a holistic and nuanced evaluation of uncertainty in forensic science, due to the large number of approaches that have been identified. The identified evaluative approaches are not only plentiful, but are also diverse in terms of their forms and applications; some are mathematical or statistical, while others use qualitative scales to assess factors such as the underlying evidence or the agreement of expert decision makers, as proxies to assessing uncertainty when uncertainty is not subject to [103, 111].

Communication toolkit:

The benefits of the communication toolkit for forensic science are similar to the benefits identified above in relation to the evaluation of uncertainty. A number of the synthetic and sub-synthetic constructs that were developed to organise and represent the patterns regarding the communication of uncertainty have not yet been discussed in the forensic science literature. The forensic science literature emphasises heavily on the use of probabilities to convey the findings of expert decision makers [57; 58], the use of the likelihood ratio [55; 156] as well as conveying uncertainty through verbal scales [51,157].

The literature on the communication of uncertainty as discerned from the disciplines of medicine, environmental science and economics constituted a much more fertile ground from which insights and ideas were drawn. Seven dimensions to be considered when communicating uncertainty where identified, while a wide range of instruments to convey such information were identified; spanning from pictographs and fan charts, to scatter plots and blurry edge confidence interval bar graphs. A number of empirical studies testing various dimensions of the communication of uncertainty and their efficacy were also discovered, which could provide inspiration for similar experiments to take place in the context of forensic science and the legal system. Examples include the study by Budescu et al. [122] which examined the influence of different presentation methods on the motivated interpretation of participants.

5. Conclusion

"Generalizable and holistic approaches" to addressing uncertainty have yet to be developed in the discipline of forensic science [1]. Yet, a myriad of approaches to conceptualise, evaluate and communicate scientific uncertainty exist in the total body of knowledge on the topic of uncertainty. This study has identified and mapped out the most prominent conceptualisation, evaluation and communication tools in disciplines neighbouring with forensic science, which can be used as a guide by all stakeholders involved in criminal trials. The three toolkits may be a useful starting point for forensic scientists who are interested in developing approaches for increasing the transparency of their testimonies or reducing the uncertainties in their decision-making. The conceptualisation toolkit more specifically may also be important to judges and lawyers, as it explicitly highlights the existence of uncertainties, and may assist them in identifying areas in the decision-making of experts that could be subject to greater scrutiny during trial.

Characterising, evaluating and communicating uncertainty are challenging tasks [133, 136]. However, even when the acknowledgement of uncertainty does not consist of a formal identification and evaluation of its nuanced features, the toolkits are still an important first step towards enhancing transparency in the reporting and presentation of forensic evidence in a way that is clear about what is known, can be known and what is not known or can not be known. The toolkits produced by this study can raise stakeholder awareness around the limitations of forensic science [146] and offer a starting point for developing the common language necessary for more creative discussions on how uncertainty can best be communicated to take place.

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Appendix A

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Appendix B

Search Terms Table:

Synonyms	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**
	Uncertain*	Decision-mak*	Finding$	Assess*	Communicat*
		Determin*	Conclusion$	Evaluat*	Disclos*
			Prognos*	Estimat*	Report*
			Diagnos*	Quant*	Present*
			Forecast*		
			Predict*		

Search Strings

Main search string for evaluation of uncertainty, as used in Scopus:

1. Medicine:

uncertain*W/4 ("decision mak*" OR conclusion* OR finding* OR prognos* OR diagnos* OR determin* OR assess* OR evaluat* OR estimat* OR quant*)

2. Environmental Science & Economics:

uncertain*W/4 ("decision mak*" OR conclusion* OR finding* OR forecast* OR predict* OR determin* OR assess* OR evaluat* OR estimat* OR quant*)

Main search string for evaluation of uncertainty, as used in Scopus:

uncertain*W/4 ("communicat*" OR “disclos*”)