

1   **An LLM-based pipeline for understanding decision choices in data analysis from  
2   published literature**

3   **ANONYMOUS AUTHOR(S)**

4   Decision choices, such as those made when building regression models, and their rationale are essential for interpreting results and  
5   understanding uncertainty in an analysis. However, these decisions are rarely studied because tracing every alternatives considered  
6   by authors is often impractical, and reworking a completed analysis is generally of limited interest. Consequently, researchers must  
7   manually review large bodies of published analyses to identify common choices and understand how choices are made. In this work,  
8   we propose a workflow to automatically extract analytic decisions and their reasons from published literature using Large Language  
9   Models. Our method also introduces a paper similarity measure based on decision similarity and visualization methods using clustering  
10   algorithms. As an example, this workflow is applied to analyses studying the effect of particulate matter on mortality. This approach  
11   enables scalable and automated studies of decision choices in applied data analysis, providing an alternative to existing qualitative and  
12   interview-based studies.

13   CCS Concepts: • **Applied computing** → *Document analysis*; • **Human-centered computing** → *Empirical studies in HCI*.

14   Additional Key Words and Phrases: Large language models

15   **ACM Reference Format:**

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18   **1 Introduction**

19   TODO: need references

20   Decisions are made at every stage of data analysis, from initial data collection and preprocessing to modeling. One  
21   might expect well-trained researchers to make similar choices when faced with the same analytical task, yet evidence  
22   suggests otherwise. Many-analyst experiments show that independent analysts often arrive at markedly different  
23   conclusions, even when analyzing the same dataset to answer the same research question [8, 19, 46]. This variation in  
24   analytical decision-making, described by Gelman and Loken [18] as the “garden of forking paths,” can undermine the  
25   quality and credibility of reported results and hinder comparability across studies. For junior researchers who lack  
26   guidance, this variability may lead to over reliance on default statistical software settings or arbitrary choices made  
27   without clear justification.

28   A common approach to investigate uncertainty in decision choices is sensitivity analysis, where researchers systematically  
29   vary key decisions in their analysis to assess the robustness of their findings. Multiverse analysis extends this  
30   idea by evaluating *all* plausible combinations of analytical choices to examine how results vary across the full decision  
31   space [7, 43]. However, what an analyst consider “reasonable” is subjective and may not reflect the full range of options  
32   commonly used in practice. Even when a reasonable set of alternatives is tested, the sensitivity analysis may be of

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53 limited interest to other researchers facing a similar problem, who are seeking evidence to inform comparable decision  
54 choices and their rationale. Ideally, decision-making in applied research would be studied by following experienced  
55 analysts throughout the entire analysis process to capture their reasoning. In reality, this is rarely feasible and not  
56 scalable.  
57

58 While individual studies may not capture the full range of reasonable decision options, crowdsourcing decisions  
59 from a collection of studies on a shared theme creates a “many-analyst” setting that reveals how analysts make choices  
60 and justify them in practice. Classic research training typically involves reading through the literature to understand  
61 how decisions are made and to learn the common choices. This process now has the possibility to be automated at scale  
62 given recent LLMs’ ability to follow instructions to extract structured information from unstructured text. In this work,  
63 we propose a new approach for studying data analysis decision choices by automatically extracting decisions from  
64 scientific literature using Large Language Models (LLMs). We develop a tabular schema to record decisions, automate  
65 the extraction process with LLMs, and introduce a new paper similarity measure based on decision similarity, which  
66 serves as a distance metric for dimension reduction methods to visualize papers group according to their decision  
67 patterns.  
68

69 We apply this workflow to a set of 56 air pollution modelling studies estimating the effect of particulate matter (PM<sub>2.5</sub>  
70 or PM<sub>10</sub>) on mortality and hospital admissions. This type of studies is typically analyzed using Poisson generalized linear  
71 models (GLMs) or generalized additive models (GAMs). Analysis of the extracted decisions reveals common choices for  
72 decisions considered in this type of studies such as the number of knots or degree of freedom for smoothing methods  
73 and the temporal lags for time and weather variables. Multi-dimensional scaling on the paper similarity distance finds  
74 three distinct clusters corresponding to different smoothing methods – LOESS, natural spline, and smoothing spline –  
75 used in European and U.S. studies. These findings align with the APHENA project [28], which synthesizes research  
76 from multiple studies in Europe and North America by expert investigators.  
77

78 In this workflow, we also provide detailed documentation on the validation and standardization of LLM outputs.  
79 Because LLMs generate results probabilistically, it is not yet clear how these outputs should be validated for downstream  
80 analysis in practice. We outline the validation and standardization process, including the use of a developed Shiny  
81 application in R for reviewing decisions, the types of edits made through validation, and secondary standardization of  
82 decisions. Additionally, we conduct sensitivity across different LLM providers and assess the reproducibility of the  
83 text extraction from single LLM models. We aim to offer guidance for future studies seeking to extract structured  
84 information from unstructured text using LLMs.  
85

86 In summary, the contribution of this work includes:  
87

- 88 • A new approach to study data analysis decision choices through automatic extraction of decisions from scientific  
89 literature using LLMs,
- 90 • A new method to construct paper similarities based on the decisions and the semantic similarity of their  
91 rationale,
- 92 • A shiny GUI tool for validation LLM outputs in this context, and
- 93 • A dataset of decisions and rationale, along with metadata, compiled from 62 studies in air pollution mortality  
94 modelling.

**105 2 Related work****106 2.1 Decision-making in data analysis**

108 Data analysis involves making choices at every step, from initial data collection, data pre-processing to model specification,  
109 and post-processing. Each decision represents a branching point where analysts choose a specific path to follow,  
110 and the vast number of possible choices analysts can take forms what Gelman and Loken [18] describe as the “garden  
111 of forking paths”. While researchers may hope their inferential results are robust to the specific path taken through  
112 the garden, in practice, different choices can lead to substantially different conclusions. This has been empirically  
113 demonstrated through “many analyst experiments”, where independent research groups analyze the same dataset to  
114 address the same research questions with their own chosen analytic approach. A classic example is Silberzahn et al.  
115 [46], where researchers reported an odds ratio from 0.89 to 2.93 for the effect of soccer players’ skin tone on the number  
116 of red cards awarded by referees. Similar variability has been observed in structural equation modeling [44], applied  
117 microeconomics [22], neuroimaging [8], and ecology and evolutionary biology [19].  
118

119 Examples like above have rendered decision-making in data analysis as a subject to study in human computer  
120 interaction. To understand how analysts making decisions during data analysis and navigating the garden of forking  
121 path, researchers have conducted qualitative interviews with analysts on data analysis practices [2, 24, 31]. Visualization  
122 tools have also been explored to communicate the decision process through analytic decision graphics (ADG) [32]. In  
123 fairness machine learning literature, Simson et al. [47] contributed a reusable workflow that supports participatory input  
124 to democratize decisions in machine learning algorithms related to fairness, privacy, interpretability and performance.  
125 Conducting qualitative studies through interviews to study how assumptions and decisions are made in data analysis  
126 practices takes a significant amount of time and effort, and the findings may not generalize to other contexts. While  
127 published research papers may not provide a complete picture of the decision-making process, they do contain valuable  
128 information about the choices made by analysts and the rationale behind them. With recent advances in Large Language  
129 Models (LLMs), it has become possible to automatically extract structured information from unstructured text. This  
130 could provide a scalable way to study decision-making practices in data analysis.  
131

132 On top of qualitative studies, software tools have also developed to incorporate potential alternatives in the analysis  
133 workflow. The DeclareDesign package [7] introduces the MIDA framework for researchers to declare, diagnose, and  
134 redesign their analyses to produce a distribution of the statistic of interest, which has been applied in the randomized  
135 controlled trial study [6]. The multiverse package [33, 43] provides a framework for researchers to conduct multiverse  
136 analysis to systematically explore how different choices affect results and to report the range of plausible outcomes that  
137 arise from alternative analytic paths.  
138

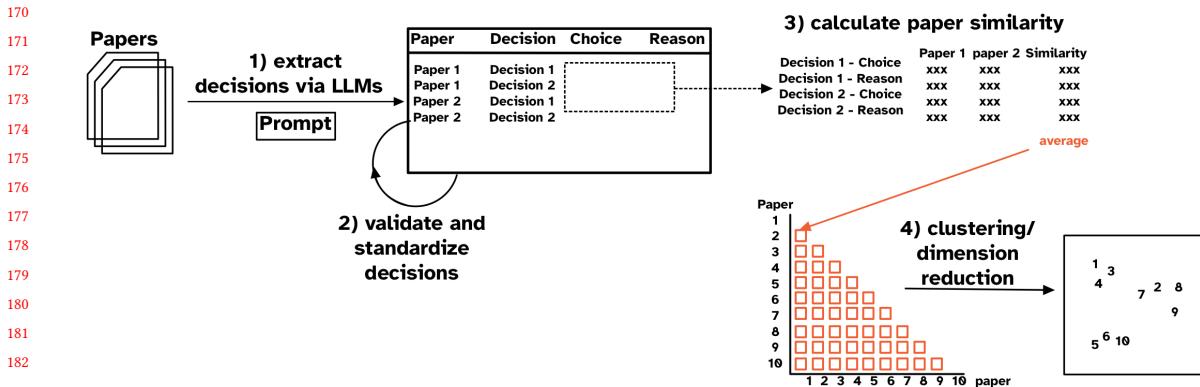
**144 2.2 Visualization on scientific literature**

145 With the growing volume of scientific publications and the difficulty of navigating the literature to stay informed,  
146 there is increasing interest in developing tools to visualize and recommend scientific papers. These systems link papers  
147 based on their similarity and relevance, typically determined by keywords [23], citation information (e.g. citation list,  
148 co-citation) [13], or combinations with other relevant paper metadata (e.g. author, title) [5, 14, 17, 20]. Recent approaches  
149 incorporate text-based information using topic modelling [1], argumentation-based information retrieval [48], and  
150 text embedding [39]. While metadata and high-level text-based information are useful for finding relevant papers,  
151 researchers also need tools that help them *make sense* of the literature rather than simply *locating* it. In applied data  
152 analysis, one interest is to understand how studies differ or align in their analytical approaches. Capturing the decisions  
153

157 and reasoning expressed in analyses on a shared theme enables the calculation of similarity metrics based on these  
 158 choice and their underlying rationale, which supports clustering and visualizing paper to identify common practices in  
 159 the field.  
 160

### 161 3 Methods

162 In this section, we will present the workflow for extracting decisions from published literature using Large Language  
 163 Models (LLMs). We will begin with an explanation of the data structure for recording decisions and then each step of  
 164 the workflow: 1) Extract decisions automatically from literature with LLMs, 2) Validate and standardize LLM outputs,  
 165 3) Calculate paper similarity and visualization, and 4) visualization with clustering or dimension reduction methods. An  
 166 overview of the workflow is illustrated in Figure 1.



184 Fig. 1. The workflow for extracting decisions from published literature using Large Language Models (LLMs) and analyzing the  
 185 extracted decisions. The workflow consists of four main steps: (1) Extract decisions automatically from literature with LLMs, (2)  
 186 Validate and standardize LLM outputs, (3) Calculate paper similarity and visualization, and (4) visualization with clustering or  
 187 dimension reduction methods.  
 188

#### 190 3.1 Record decisions in data analysis

192 In the study of the health effects of outdoor air pollution, one area of interest is the association between short-term,  
 193 day-to-day changes in particulate matter air pollution and daily mortality counts. This question has been studied  
 194 extensively by researchers across the globe and in the US, it serves to provide scientific evidence for to guide public policy  
 195 on setting the National Ambient Air Quality Standards (NAAQS) for air pollutants. While individual modelling choices  
 196 vary, these studies often share a common structure: they adjust for meteorological covariates such as temperature and  
 197 humidity, apply temporal or spatial treatments, like including lagged variables and may estimate the effect by city or  
 198 region before combining results. This naturally forms a “many-analyst” experiment setting where different researchers  
 199 analyze similar data to address the same scientific question and the analyses are documented in published papers.  
 200

202 Consider the following excerpt from Ostro et al. [40] that describes the modelling approach to provide evidence of  
 203 an association between daily counts of mortality and ambient particulate matter (PM10):

205 Based on previous findings reported in the literature (e.g., Samet et al. 2000), the basic model included a  
 206 smoothing spline for time with 7 degrees of freedom (df) per year of data. This number of degrees of  
 207 freedom controls well for seasonal patterns in mortality and reduces and often eliminates autocorrelation.

209 This sentence encode the following components of a decision:

- 210 • **variable**: time  
 211 • **method**: smoothing spline  
 212 • **parameter**: degree of freedom (df)  
 213 • **reason**: Based on previous findings reported in the literature (e.g., Samet et al. 2000); This number of degrees of  
 214 freedom controls well for seasonal patterns in mortality and reduces and often eliminates autocorrelation.  
 215 • **decision**: 7 degrees of freedom (df) per year of data

216 To record these decisions in a tabular format, we follow the tidy data principle [51], which states each variable should  
 217 be in a column and each observation in a row. For our purpose, each row represents a decision made by the authors  
 218 in a paper and an analysis often include multiple decisions. To retain the original context of the decision, we extract  
 219 the original text in the paper, without paraphrase or summarization. The decision choice above is a parameter choice  
 220 of a statistical method applied to the variable. Analyses also include other types of decisions, such as temporal and  
 221 spatial treatments, for example, the choice of lagged exposure for certain variables or whether the model is estimated  
 222 collectively or separated for individual locations. These decisions don't have a specific method or parameter, but should  
 223 still be recorded with the variable, type (spatial or temporal), reason, and decision fields.

224 Given the writing style and the quality of the analysis itself, multiple decisions may be combined in one sentence  
 225 and certain fields, e.g. decision and reason, may be omitted. Consider the following excerpt from Ostro et al. [40]:

226 Other covariates, such as day of the week and smoothing splines of 1-day lags of average temperature  
 227 and humidity (each with 3 df), were also included in the model because they may be associated with  
 228 daily mortality and are likely to vary over time in concert with air pollution levels.

229 This sentence contains four decisions: two for temperature (the temporal lag and the smoothing spline parameter)  
 230 and two for humidity and should be structured as separate entries:

Paper	ID	variable	method	parameter	type	reason	decision
ostro	1	temperature	smoothing spline	degree of freedom	parameter	3 degree of freedom	NA
ostro	2	relative humidity	smoothing spline	degree of freedom	parameter	3 degree of freedom	NA
ostro	3	temperature	NA	NA	temporal	1-day lags	NA
ostro	4	relative humidity	NA	NA	temporal	1-day lags	NA

250 Notice in the example above, the reason field are recorded as NA. This is because the stated rationale ("and are  
 251 likely to vary over time in concert with air pollution levels") only supports the general inclusion of temporal lags but  
 252 does not justify the specific choice of 1-day lag over other alternatives, for example, 2-day average of lags 0 and 1 and  
 253 single-day lag of 2 days. Similar scenario can happen when a direct decision is missing while a reason is provided  
 254 ("done by minimizing Akaike's information criterion"), as in Katsouyanni et al. [27]:

255 The inclusion of lagged weather variables and the choice of smoothing parameters for all of the weather  
 256 variables were done by minimizing Akaike's information criterion.

### 261    3.2 Extract decisions automatically from literature with LLMs

262  
 263 Manually extracting decisions from published papers is labor-intensive and time-consuming. With Large Language  
 264 Models (LLMs), it has become possible to automatically extract structured information from unstructured text by  
 265 supplying a set of PDF documents and a prompt for instruction. Text recognition from PDF document relies on Optical  
 266 Character Recognition (OCR) to convert scanned images into machine-readable text – capability currently offered by  
 267 Anthropic Claude and Google Gemini. In the prompt, we assign the LLM a role as an applied statistician and instruct it  
 268 to generate a markdown file containing a JSON block that extract decisions from the PDF in the format described in  
 269 Section 3.1. We also provide a set of instructions and examples on the potential missing of reason and decision fields.  
 270 Prompt engineering techniques [12, 54] are used to optimize the prompt script. The full prompt feed to the LLM is  
 271 provided in the Appendix. We use the `chat_PROVIDER()` functions from the `ellmer` package [53] in R to obtain the  
 272 output with Gemini and Claude API.  
 273

### 276    3.3 Validate and standardize LLM outputs

277  
 278 The LLM outputs need to be validated and standardized before further analysis. Validation focuses on ensuring the  
 279 correctness of the extracted decisions by LLMs, while standardization aims to ensure consistency in variable and model  
 280 names across papers, given authors may express the same concept in different ways. For example, “mean temperature”,  
 281 “average temperature”, and “temperature” all refer to the same variable, which can be all standardized to “temperature”  
 282 for consistency. To help with the validation and standardization process, we developed a Shiny application that provides  
 283 an interactive interface for users to review and edit the LLM outputs. A Shiny application takes a CSV of extracted  
 284 decisions as input and allows three types of edits: 1) *overwrite* – modify the content of a particular cell, 2) *delete* –  
 285 remove a particular irrelevant decision, and 3) *add* – manually enter a missing decision. Figure 2 illustrates the *overwrite*  
 286 action for standardizing the variable NCtot (The number concentration of urban background particles <100 nm in  
 287 diameter) to “pollution”: the user enters a predicate function in the filter condition box on the left panel, and the filtered  
 288 data will appear interactively in the right panel. The user can then specify the variable to overwrite and the new value  
 289 and the corresponding cells in the right panel will be updated. This change need to be confirmed by pressing the “Apply  
 290 changes” button to update the full dataset. The corresponding `tidyverse` [52] code will then be generated in the left  
 291 panel to be included in an R script, and the edited table can be downloaded for future analysis.  
 292

### 296    3.4 Calculate paper similarity and visualization

297  
 298 Once the output has been extracted and validated, the decisions can be treated as data for further analysis. In this  
 299 section, we construct a distance metric between pairs of papers based on the similarity of their decision choices. This  
 300 metric can then be used as a distance matrix among papers for clustering, dimension reduction, and visualization.  
 301

302    For each paper pair, a decision is considered comparable if the papers share the same variable and decision type, for  
 303 example, a parameter decision on temperature or the temporal decision on humidity. For two decisions to be considered  
 304 similar, both the decision choice and the rationale are taken into account. A similar choice indicates a similar final  
 305 decisions are made in the analysis, whereas a similar reason reflects a shared rationale or justification for the choice,  
 306 even when the choices themselves differ, potentially due to differences in the underlying data. To assign numerical  
 307 value for measuring the similarity, we use the semantic similarity from text model, using the `text` package [29]. We  
 308 first obtain the text embedding for all the reason and decisions and calculate the cosine similarity between the matched  
 309 reason and decisions. For parameter type decisions, the statistical method used also contributes to the similarity of the  
 310

Edit decision table output									
Initial view									
paper	id	model	variable	method	parameter	type	reason	decision	reference
andersen2008size	1	generalized additive Poisson time series regression model	temperature	smoothing spline	degrees of freedom	parameter	NA	4 or 5 df	
andersen2008size	2	generalized additive Poisson time series regression model	dew-point temperature	smoothing spline	degrees of freedom	parameter	NA	4 or 5 df	
andersen2008size	3	generalized additive Poisson time series regression model	calendar time	smoothing spline	degrees of freedom	parameter	to control for long-term trend and seasonality	3, 4, or 5 df/year	
andersen2008size	4	generalized additive Poisson time series regression model	NCTot	NA	NA	temporal	to include days with the strongest lag effects	4-day pollutant average (lag 0-3)	
andersen2008size	5	generalized additive Poisson time series regression model	NCTot	NA	NA	temporal	to include days with the strongest lag effects	5-day average (lag 0-4)	
andersen2008size	6	generalized additive Poisson time series regression model	NCTot	NA	NA	temporal	to include days with the strongest lag effects	6-day average (lag 0-5)	
Upon pressing the "Apply changes" button, the data panel will update to reflect the edit									
paper	id	model	variable	method	parameter	type	reason	decision	reference
andersen2008size	4	generalized additive Poisson time series regression model	pollutant	NA	NA	temporal	to include days with the strongest lag effects	4-day pollutant average (lag 0-3)	NA
andersen2008size	5	generalized additive Poisson time series regression model	pollutant	NA	NA	temporal	to include days with the strongest lag effects	5-day average (lag 0-4)	NA
andersen2008size	6	generalized additive Poisson time series regression model	pollutant	NA	NA	temporal	to include days with the strongest lag effects	6-day average (lag 0-5)	NA
Upon confirmation, the changes will be applied to the full dataset									
paper	id	model	variable	method	parameter	type	reason	decision	reference
andersen2008size	1	generalized additive Poisson time series regression model	temperature	smoothing spline	degrees of freedom	parameter	NA	4 or 5 df	
andersen2008size	2	generalized additive Poisson time series regression model	dew-point temperature	smoothing spline	degrees of freedom	parameter	NA	4 or 5 df	
andersen2008size	3	generalized additive Poisson time series regression model	calendar time	smoothing spline	degrees of freedom	parameter	to control for long-term trend and seasonality	3, 4, or 5 df/year	
andersen2008size	4	generalized additive Poisson time series regression model	pollutant	NA	NA	temporal	to include days with the strongest lag effects	4-day pollutant average (lag 0-3)	
andersen2008size	5	generalized additive Poisson time series regression model	pollutant	NA	NA	temporal	to include days with the strongest lag effects	5-day average (lag 0-4)	
andersen2008size	6	generalized additive Poisson time series regression model	pollutant	NA	NA	temporal	to include days with the strongest lag effects	6-day average (lag 0-5)	

Fig. 2. The Shiny application interface to validate and standardize Large Language Model (LLM)-generated output. (1) the default interface after loading the input CSV file. (2) The table view will update interactively to reflect the edit: for paper with handle “andersen2008size” and id in 4, 5, 6, replace the variable NCtot with “pollutant”. (3) After clicking the Confirm button, the corresponding tidyverse code is generated, and the table view returns to its original unfiltered view with the edits applied. The edited data can be downloaded by clicking the Download CSV button.

365 decision. Since semantic similarity cannot fully capture the difference betweenit statistical methods (the difference  
 366 between smoothing spline and natural spline is not well represented by the textual difference of “smoothing” and  
 367 “natural”), method similarity is encoded as binary: 1 if the two papers used the same method, and 0 otherwise. The  
 368 paper similarity is then computed as the average similarity across all the matched methods, decisions, and reasons. The  
 369 resulting paper similarity metric can be interpreted as a distance measure to cluster and visualize papers based on their  
 370 decision choices.  
 371

372 Because analyses vary in the decisions they report, the number of matched decisions differs across paper pairs. In  
 373 practice, some studies may not fully report the decision and reason for every choice made, leading to missing data for  
 374 the matched decisions. Although paper similarity can be calculated based on all available matched decisions, cares  
 375 should be taken for pairs with only a small number of matches, as the paper similarity may be overly influenced by one  
 376 or two decisions. To address this, users may focus on a set of decisions shared across papers and on papers that report a  
 377 minimal number of these decisions when calculating paper similarity.  
 378

## 380 4 Results

381 From the 56 studies examining the effect of particulate matters ( $PM_{10}$  and  $PM_{2.5}$ ) on mortality and hospital admission,  
 382 we focus on the baseline model reported in each paper, excluding secondary models (e.g. lag-distributed models) and  
 383 sensitivity analysis. We also exclude decisions on other pollutants, such as nitrogen dioxide ( $NO_2$ ). This yields 242  
 384 decisions extracted using Gemini, averaging approximately 4 decisions per paper.  
 385

### 386 4.1 Validation and standardization of LLM outputs

391 Table 2. Summary of validation and standardization edits made during the review process.  
 392

393 Reason	394 Count
395 Remove decisions out of scope: other pollutants and sensitivity analysis	50
396 Edit made to recode smoothing parametser unit to per year	45
397 Duplicates	9
398 Fix incorrect capture	9
399 Edit made due to decisions are too general, e.g. minimum of 1 df per year was required	6
400 Remove decisions related to definition of variables, e.g. season	5
401 Total	124

405  
 406 Table 2 summarizes the number of edits made during the review process using the Shiny application. These edits  
 407 fall into two main categories: 1) correcting LLM outputs and 2) standardizing extracted decision. The first category  
 408 includes fixing incorrect captures, removing non-decision (e.g. definition of variables), removing duplication, excluding  
 409 irrelevant decisions (e.g. sensitivity analyses), and excluding decisions whose stated reasons reflect general guidelines  
 410 rather than actual choices (e.g. “minimum of 1 degree of freedom per year is required”).  
 411

412 Standardization addresses variation in how authors express variable names and decisions. For example, variable  
 413 names such as “mean temperature” and “average temperature” refer to the same variable and should be aligned for  
 414 comparison for later decision similarity calculation. Variable names are manually standardized into four main categories:  
 415  
 416 Manuscript submitted to ACM

417 Table 3. Missingness of decision and reason fields in the Gemini-extracted decisions. Most decisions report the choice (35.5 + 57.1 =  
 418 92%), but 57.1% lacks a stated reason.

Reason	Decision	
	Non-missing	Missing
Non-missing	90 (37.2%)	14 (5.8%)
Missing	134 (55.4%)	4 (1.7%)

- **temperature:** “mean temperature”, “average temperature”, “temperature”, “air temperature”, “ambient temperature”
- **humidity:** “dewpoint temperature” and its hyphenated variants, relative humidity”, “humidity”
- **PM:** “pollutant”, “pollution”, “particulate matter”, “particulate”, “PM10”, “PM2.5”
- **time:** “date”, “time”, “trends”, “trend”

Notice that “dewpoint temperature” is standardized under humidity because it serves as a proxy for temperature in achieving a 100% relative humidity.

Decisions themselves also require standardization. For example, the smoothing parameter (number of knots and degree of freedom) may be expressed *per year* or *in total*, and temporal lag decision may be expressed in different formats (e.g. “6-day average”, “mean of lags 0+1”, “lagged exposure up to 6 days”). Smoothing parameter units are manually recoded to a *per year* basis for consistency, as reflected in Table 2. Temporal decision show a wider variety, generally falling into two categories:

- **multi-day average lags**, such as “6-day average”, “3-d moving average”, “mean of lags 0+1”, “cumulative lags, mean 0+1+2” and
- **single-day lags**, such as “lagged exposure up to 6 days”, “lag days from 0 to 5”.

This variability makes manual standardization impractical, hence we apply a secondary LLM process (claude-3-7-sonnet-latest) using the ellmer package to convert temporal decisions into a consistent format: multi-day: lag [start]-[end] and single-day: lag [start], . . . , lag [end]. For instance, “6-day average” is converted to “multi-day: lag 0-5” and “lagged exposure up to 6 days” is converted to “single-day: lag 0, lag 1, lag 2, lag 3, lag 4, lag 5”.

## 4.2 Exploratory analysis of decision choices

As raised in Section 3.1, not all decisions reported in the literature include both the decision choice and the rationale. Some decisions may only report the choice without a stated reason, while others may provide a reason without specifying the exact choice made. Table 3 summarizes the missingness of the decisions and reason for the extracted decisions. While 2% of decisions are complete for both decision and reasons, 55% of decisions lack a stated rationale for the choice. This reflects a common reporting practice in the field, where authors often present the decision itself without providing a justification, e.g. “We decide to use  $x$  degree of freedom for variable  $y_1$  and  $y_2$ ”. This also includes cases where authors provide general guidelines for selecting the parameter, but the rationale is too broad to justify the specific choice made (hence validated as NA in Section 4.1).

469 Table 4. Count of variable-type decisions in the Gemini-extracted decisions. The most commonly reported decision are the parameter  
 470 choices and temporal lags for time, PM, temperature, and humidity.

Variable	Type	Count
time	parameter	44
PM	temporal	39
temperature	parameter	35
humidity	parameter	25
temperature	temporal	23
humidity	temporal	19
PM	parameter	9
time	temporal	3

485 Table 4 lists the eight most frequently reported decision: parameter and temporal choice for time, PM, temperature,  
 486 and humidity. While a wider list of variables have been used in the analysis, these four variables are most commonly  
 487 included in baseline models. Parameter choices for time, temperature, and humidity are typically made on the use of  
 488 smoothing parameter for the smoothing method (natural spline and smoothing spline), whereas temporal choices are  
 489 commonly reported for PM, temperature, and humidity for the number of lag to consider in the model.  
 490

492 Table 5. Options captured for parameter choices for time, humidity, and temperature variables in the Gemini-extracted decisions.  
 493 The choices for natural spline knots are generally less varied than the degree of freedom choices for smoothing spline. Choices for  
 494 temperature and humidity tend to be close, given they are both weather related variables, while the choices for time are more varied  
 495 inherently.  
 496

Method	Variable	Decision
natural spline	humidity	3, 4
natural spline	temperature	3, 4, 6
natural spline	time	1, 1.5, 3, 4, 6, 7, 8, 12, 15, 30
smoothing spline	humidity	2, 3, 4, 6, 8, 50% of the data
smoothing spline	temperature	2, 3, 4, 6, 8, 50% of the data
smoothing spline	time	1, 3, 4, 5, 6, 7, 7.7, 8, 9, 10, 12, 30, 100, 5% of the data

508 Table 5 presents the parameter-related decisions extracted for spline methods (natural and smoothing spline) applied  
 509 to variable time, humidity and temperature. These decisions concern the number of knots or degree of freedom, with all  
 510 values standardized to a *per year* scale for consistency. The selection of knot for natural spline has less variation than  
 511 the degree of freedom choices for smoothing spline. Choices for temperature and humidity are generally similar, given  
 512 they are both weather related variables, whereas choices for time are more varied. This tabulation provides a reference  
 513 set for common parameter choices for future studies and help to identify anomalies and special treatment in practice.  
 514 For example, the choice of 7.7 degree of freedom reported in Castillejos et al. [11] may prompt analysts to seek further  
 515 justification. By cross comparing with other reporting, some decisions appear ambiguous. For example, in Moolgavkar  
 516 [37] and Moolgavkar [38], the reported value of 30 and 100 degrees of freedom for time may be understandable for  
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experienced domain researcher, it could be unclear for junior analysts as to whether they apply to the full 9 year period or on a per-year basis. We also observe a different report style from Schwartz [45], where smoothing spline parameters are expressed as a proportion of the data (“5% of the data” and “5% of the data”) rather than fixed numerical value.

Table 6. Options captured for temporal lag choices for PM, temperature, and humidity variables in the Gemini-extracted decisions. Both single-day lags and multi-day average lags are commonly used, generally considering up to five days prior (lag 5).

Lag type	Variable	Decision
multi-day average	PM	lag 0-1, 0-2, 0-3, 0-4, 0-5, 0-6
multi-day average	humidity	lag 0-1, 0-2, 0-3, 0-5, 1-5, 2-4
multi-day average	temperature	lag 0-1, 0-2, 0-3, 0-5, 2-4
single-day lag	PM	lag 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
single-day lag	humidity	lag 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
single-day lag	temperature	lag 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13

Similarly, Table 6 summarizes the temporal lag choices for PM, temperature, and humidity. For single-day lags, the lags are considered up to 13 days (approximately two weeks). For multi-day averages, 3-day and 5-day averages are most common, although other choices such as 2-4 day average are also observed as in López-Villarrubia et al. [35]:

In particular, lags 0 to 1 and lags 2 to 4 averages of temperature, relative humidity, and barometric pressure were considered as meteorological variables.

### 4.3 Paper similarity and clustering

Given the number of decisions reported in Table 4, we focus on the six most common variable-type decisions for calculating paper similarity: parameter choices for time, temperature, and humidity, and temporal lag choices for PM, temperature, and humidity. We also restrict our analysis to papers that report at least three of these six decisions, resulting in 48 papers for the similarity analysis. This ensures that the paper similarity metric is based on a sufficient number of comparable decisions. We use the default text embedding model (BERT) in the text package and cosine similarity to compute the similarity score. Sensitivity analysis on different text embedding model is checked in Section 4.4.3. Paper similarity is then calculated as the average of decision similarity for each paper pair. The resulting distance matrix is then used for hierarchical clustering in ?@fig-hc and multi-dimensional scaling (MDS) in Figure 3. The two MDS dimension reveals three clusters correspond to the three smoothing methods used in these analyses: LOESS, natural spline, and smoothing spline. This grouping aligns with the modelling strategies seen in large-scale analysis, such as the U.S. NMMAPS study [42] and the European APHEA [26] and APHEA2 [27] project.

To reconcile these differences, the APHENA project [28] was launched with the aim to “assess the consistency across Europe and North America when estimated using a common analytic protocol and to explore possible explanations for any remaining variation”. While multi-dimensional scaling in Figure 3 shows the match of three clusters with three smoothing methods, this is not inconsistent with the APHENA project [28] that the amount of smoothing to have a more important role than the method of smoothing for estimating the effect of PM on public health variables. The similarity metric we proposed focuses on the variation of choices across analyses, without directly assessing how those choices influence results. By pooling decision choices from multiple studies with LLMs, it becomes much easier to reveal common practices and difference in research practices, highlighting decisions that require further sensitivity

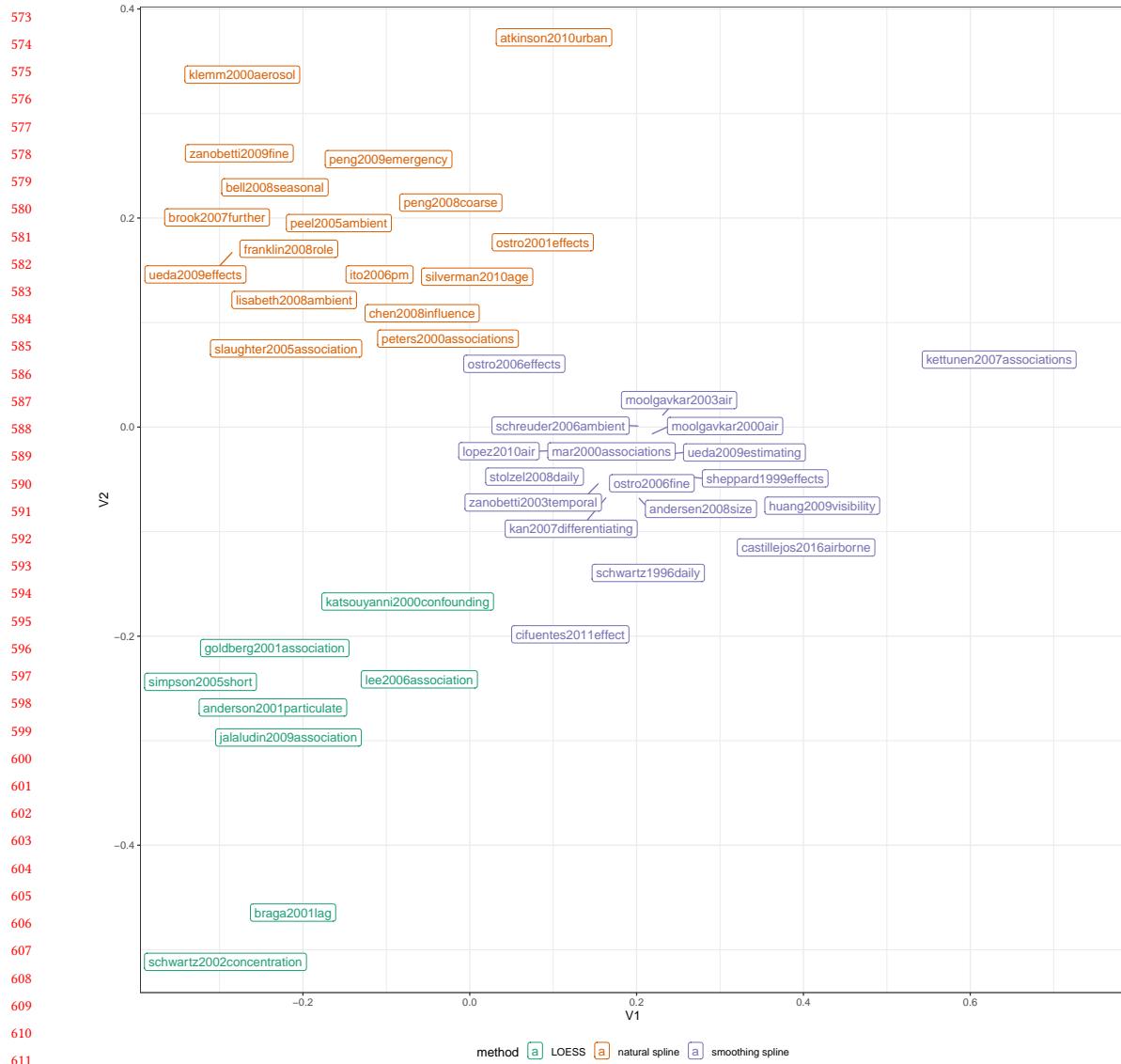


Fig. 3. The multi-dimensional scaling (MDS) based on paper similarity distance for `length(good_pp)` air pollution mortality modelling papers, colored by the smoothing method used. The MDS reveals the three distinct groups of papers, corresponds to LOESS, natural spline, and smoothing spline. These groups corresponds to the different modelling strategies debated in the European and U.S. studies, as documented in the APHENNA project [28].

analyses to assess their impact. The different smoothing methods revealed in Figure 3 are consistent with the analysis by Peng et al. [41] and Touloumi et al. [49] that compares different smoothing methods and rationale for selecting smoothing parameters.

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#### 625 4.4 Sensitivity analysis

626 A series of sensitivity analysis has been conducted to explore the reproducibility for using LLMs for text extraction  
 627 tasks (Section 4.4.1), discrepancies in decision extraction between different LLM models: Gemini (gemini-2.0-flash)  
 628 and Claude (claude-3-7-sonnet-latest) (Section 4.4.2), and the sensitivity of text model for computing the semantic  
 629 decision similarity (Section 4.4.3).

630 4.4.1 *LLM reproducibility.* We assess the reproducibility of Gemini’s text extraction (gemini-2.0-flash) by repeating  
 631 the task five times for each of the 62 papers and perform pairwise comparison between runs. This generates  $5 \times 4 / 2 \times 62 =$   
 632 620 possible comparisons for both “reason” and “decisions” fields. Comparisons where the runs produced a different  
 633 number of decisions were excluded, as this would require manual alignment. After filtering, 449 out of 620 (72%)  
 634 remained. Table 7 prints the decisions in Andersen et al. [3] across two runs and all the four decisions are identical with  
 635 no difference.

636 640 Table 7. Example comparing Gemini’s text extraction for Andersen et al. [3] across two runs. The extracted decisions are identical in  
 641 both runs.

644 Variable	645 Run1	646 Run2
647 NCtot	6day average (lag 05)	6day average (lag 05)
648 calendar time	3 4 or 5 dfyear	3 4 or 5 dfyear
649 dew-point temperature	4 or 5 df	4 or 5 df
650 temperature	4 or 5 df	4 or 5 df

651 654 Table 8. Number of differences in the reason and decision fields across Gemini runs for papers with consistent number of decisions  
 655 across runs.

657 658 Num. of difference	659 Count	660 Proportion (%)
661 0	358	79.73
662 1	12	2.67
663 2	8	1.78
664 3	0	0.00
665 4	24	5.35
666 5	12	2.67
667 6	3	0.67
668 7	0	0.00
669 8	10	2.23
670 9	6	1.34
671 10	10	2.23
672 11	6	1.34
673 Total	449	100.00

Table 8 summarizes the number of differences observed in each pairwise comparison. Among all comparisons, 80% produce the identical text in reason and decision. The discrepancies come from the following two reasons: 1) Gemini extracted different length for the same decision, e.g. in Kan et al. [25], some runs may extract “singleday lag models underestimate the cumulative effect of pollutants on mortality 2day moving average **of current and previous day concentrations** (lag=01)”, while others extract “singleday lag models underestimate the cumulative effect of pollutants on mortality 2day moving average (lag=01)”. Similarity, for decisions, some runs yield “10 df for total mortality”, while other runs yield “10 df”. 2) Gemini fails to extract reasons in some runs but not others, e.g. in Burnett et al. [9], the first run generates NAs in the reasons, but the remaining four runs are identical. In Ueda et al. [50] and Castillejos et al. [11], runs 1 and 5 fail to extract the reasons and produce the same incomplete version, whereas runs 2, 3, and 4 produce accurate versions with reasons populated.

**4.4.2 LLM models.** Reading text from PDF document requires Optical Character Recognition (OCR) to convert images into machine-readable text, which currently is only supported by Anthropic Claude (claude-3-7-sonnet-latest) and Google Gemini (gemini-2.0-flash). We compare the number of decisions extracted by Claude and Gemini across all 62 papers in Figure 4. Each point represents a paper, with the x- and y-axes showing the number of decisions extracted by Claude and Gemini, respectively. The dashed 1:1 line marks where both models extract the same number of decisions. While both models extract decisions irrelevant to our analysis, such as sensitivity analyses and secondary analyses, Claude’s extractions tend to include more of these irrelevant decisions, examples of these include 1) the definition of “cold day” and “hot day” indicators in Dockery et al. [16] (“defined at the 5th/ 95th percentile”), 2) decisions relate to other pollutants: NO<sub>2</sub>, O<sub>3</sub>, and SO<sub>2</sub> using a “24 hr average on variable” in Huang et al. [21], and 3) the definition of black smoke and in Katsouyanni et al. [27] for secondary analysis (“restrict to days with BS concentrations below 150  $\mu\text{g}/\text{m}^2$ ”). While Gemini also capture these irrelevant decisions, such as “0-4 lag days” for air pollution exposure variables (CO, EC, K<sub>S</sub>, NO<sub>2</sub>, O<sub>3</sub>, OC, Pb, S, SO<sub>2</sub>, TC, Zn) in Mar et al. [36]. However, these cases are less frequent than Claude’s extraction and has been validated and standardized in Section 4.1.

For both Claude and Gemini, we find they fail to link the general term “weather variables” to the specific weather variables (e.g. Dockery et al. [16] and Burnett et al. [10] for Gemini and Dockery et al. [16] and Katsouyanni et al. [27] for Claude). Although our prompt specified that some decisions may require linking information across sentences and paragraphs to identify the correct variable, this instruction doesn’t appear to be applied consistently.

**4.4.3 Text model.** We have conducted sensitivity analysis on the text model for obtaining the decision similarity score from the Gemini outputs. The tested language models tested include 1) BERT by Google [15], 2) RoBERTa by Facebook AI [34], trained on a larger dataset (160GB v.s. BERT’s 15GB), 3) XLNet by Google Brain [55], and two domain-trained BERT models: 4) sciBERT [4], trained on scientific literature, and 5) bioBERT [30], trained on PubMed and PMC data.

Figure 5 shows the distribution of the decision similarity and the corresponding multi-dimensional scaling visualization, where distance are calculated from the paper similarity for each text model. At decision level, the BERT model produces the widest variation across all five models, while the similarity scores from XLNet are all close to 1. While the raw scores are not directly comparable across models due to the difference in the underlying transformer architecture, the multi-dimensional scaling (MDS) based on paper similarity scores shows a similar clustering pattern corresponding to the three main smoothing methods (LOESS, natural spline, and smoothing spline).

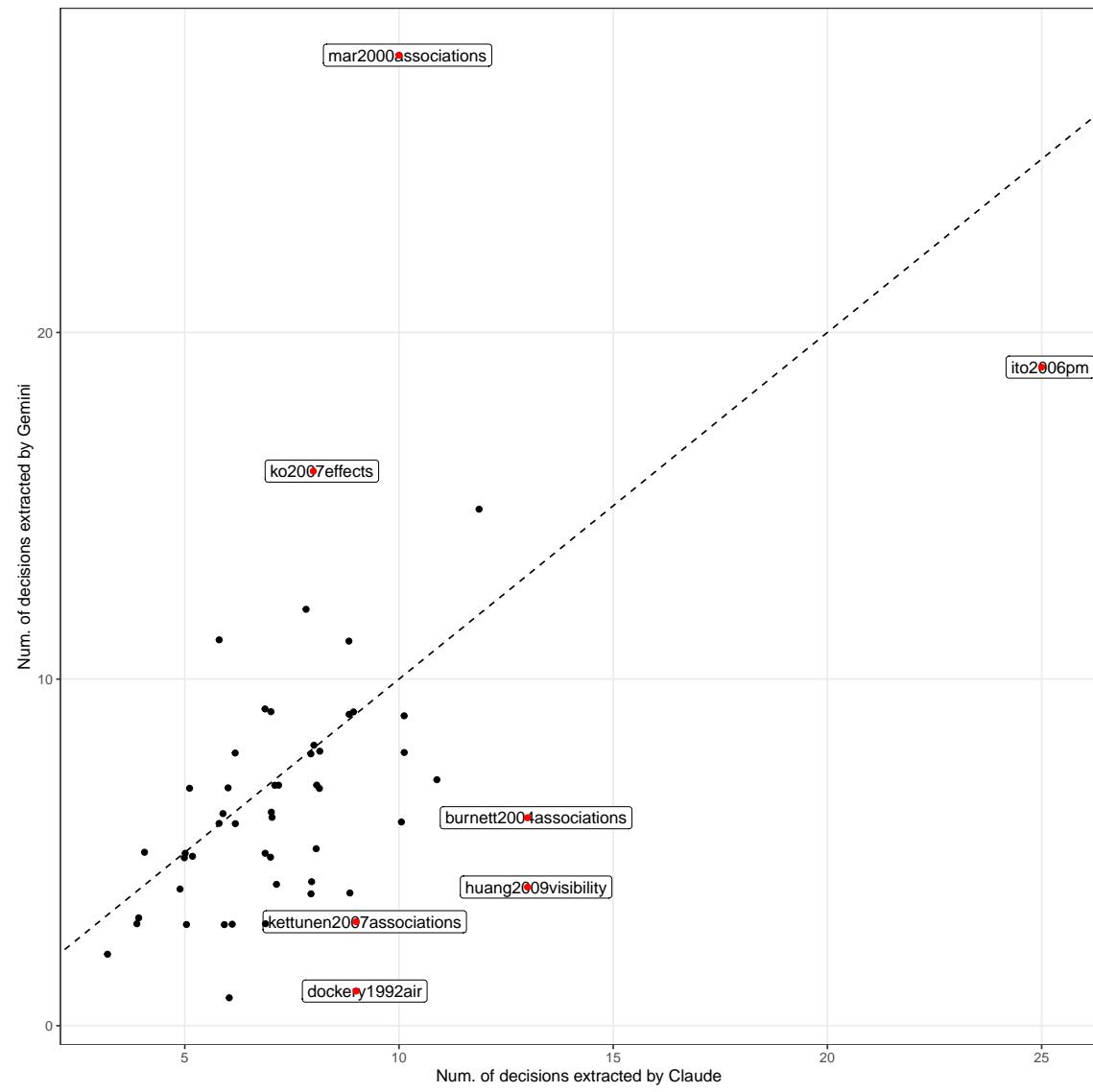


Fig. 4. Comparison of decisions extracted by Claude and Gemini. Each point represents a paper, with the x- and y-axes showing the number of decisions extracted by Claude and Gemini, respectively. The dashed 1:1 line marks where both models extract the same number of decisions. More points fall below this line, suggesting Claude extracts more decisions – often including noise from data pre-processing or secondary data analysis steps – which requires additional manual validation.

## 5 Discussion

While the extraction of decisions from literature could be largely automated with LLMs, manual validations remains essential to ensure the quality of the extracted decisions for further analysis. The quality from the LLM output directly affects the amount of manual effort needed for validation and standardization. Using a default temperature of 1 and

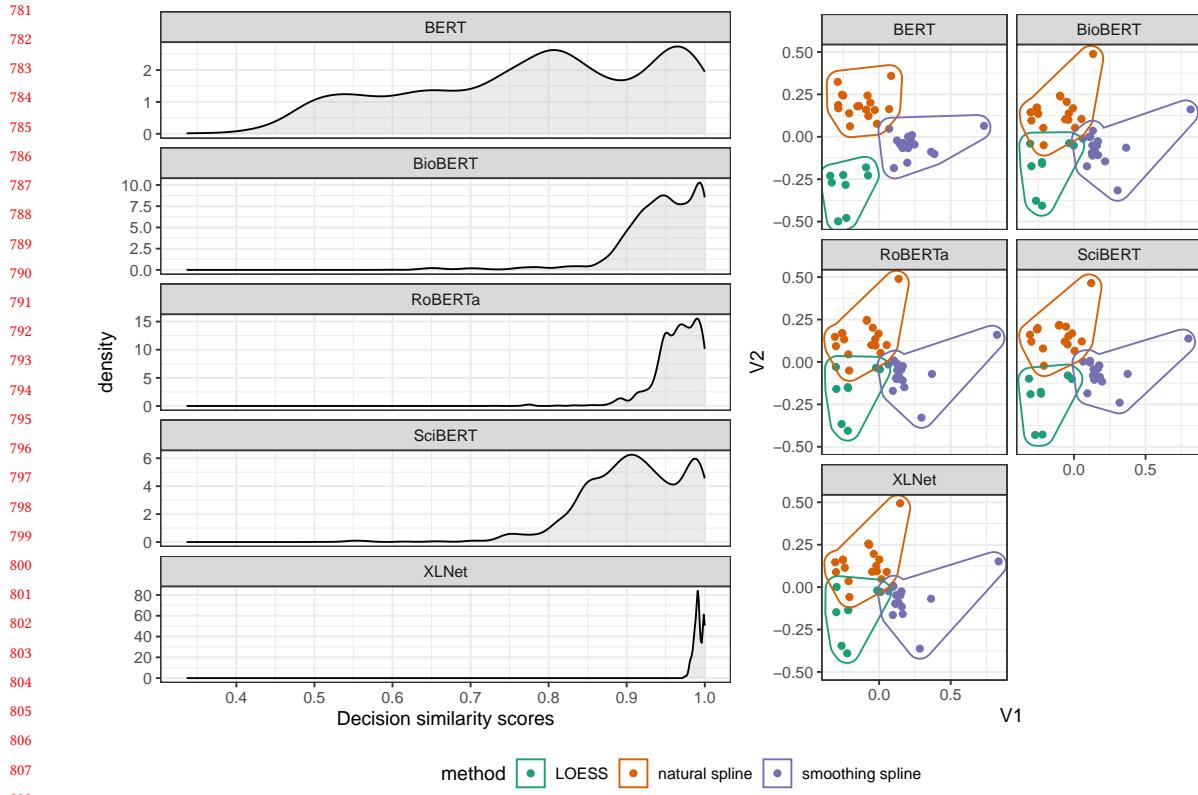


Fig. 5. Distribution of decision similarity (left) and multi-dimensional scaling (MDS) of the paper similarity scores (right) computed for five different text models (BERT, BioBERT, RoBERTa, SciBERT, and XLNet). The default language model, BERT, produces the widest variation across the five models, while the similarity scores form XLNet are all close to 1. The model BioBERT, RoBERTa, and SciBERT yield decision similar scores mostly between 0.7 to 1. All the text models shows a similar clustering structure based on the three main smoothing methods (LOESS, natural spline and smoothing spline).

instructing the model to extract original text rather than paraphrase, we find hallucination is not a major issue with Claude and Gemini for this application. While prompt engineering is used in this work to optimize the prompt for decision extraction, an alternative is to fine-tune a local model to improve LLM performance. Such approach could be beneficial for a systematic literature review, although it would require a labelled decision dataset for training and significantly more training efforts.

As a demonstration, we focus on the modelling decision for the baseline model in the air pollution epidemiology literature. Analyses in this fields often fit multiple models for different health outcomes. Other models, such as distributed lag models and multi-pollutant models are also commonly used to estimate relative risks and the interaction among pollutants. These factors increase the complexity of the decision extraction for LLM, as for additional models, authors often describe only the differences from the baseline model specification, assuming other decisions remain unchanged. The LLMs will need to be able to link the decisions across different models and identify the full set of decision for each

model for cross-comparison among papers. Apart from modelling choices, other decisions in data pre-processing are also worth comparing. This would include how variables are defined and computed from the raw data.

With the advocacy for reproducibility in science, it is expected that more papers will share their code and data. Code availability can serve as a supplementary source for understanding the choices made in the analysis and cross-check against the description in the manuscript. However, decision choices could be extracted from the scripts, but the rationale behind these choices may not be easily discernible given the lack of comments in the current practice.

## 6 Conclusion

In this paper, we aim to study how analysts make decisions in their data analysis practice. While classic interviews are often conducted in small scale with toy examples, we developed a pipeline for automatically extracting decisions using LLMs (Claude and Gemini) from scientific literature. We also introduced a method for calculating paper similarity through comparing the similarities among decisions and the similarity metric can be used as a distance to cluster papers by their decision choices and visualization with dimension reduction algorithms, such as multidimensional scaling. We applied this pipeline to a set of air pollution modelling literature that associates daily particulate matter and daily mortality and hospital admission. From the extracted modelling decisions, we identify the most common decision choices in this type of analysis and the paper similarity score calculation revealed the three clusters of paper corresponding to different modelling strategies. These findings are all consistent with the general understanding of the field, as documented in the APHENA project [28] and other methodological comparison studies [41, 49].

While sensitivity analyses are commonly used to assess the robustness of findings to different analytical choices, the set of choices tested is often limited and selected subjectively by the authors. Our approach offers a new perspective by pooling decisions made in analyses across studies in the fields. This allows for a holistic account on the alternatives in the field and identification of both consensus and divergence within the field, providing insights for future research and methodological development.

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