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Guidance for Information about Linking Datasets - GUILD

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Complete List of Authors:	<p>Gilbert, Ruth; University College London, Population Policy and Practice Programme Lafferty, Rose; Office of National Statistics Hagger-Johnson, Gareth; University College London, Population Policy and Practice Programme Harron, Katie; London School of Hygiene and Tropical Medicine, Health Services Research and Policy Zhang, Li-Chung; University of Southampton, Social Statistics and Demography Smith, Peter; University of Southampton, ESRC Administrative Data Research Centre for England Dibben, Chris; University of Edinburgh, School of Geosciences Goldstein, Harvey; University College London, Population Policy and Practice Programme</p>
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Full title

Guidance for Information about Linking Datasets - GUILD

Short title

GUILD Guidance

Writing committee on behalf of a wider team of linkage experts (listed in the acknowledgments).

Ruth Gilbert^{1*}, Rosemary Lafferty¹, Gareth Hagger-Johnson¹, Katie Harron², Li-Chun Zhang³, Peter Smith³, Chris Dibben⁴, Harvey Goldstein¹.

¹ Administrative Data Research Centre for England, University College London Great Ormond Street Institute of Child Health, London, UK

² Health Services Research and Policy, London School of Hygiene and Tropical Medicine, London, UK

³ Social Statistics and Demography, University of Southampton, Southampton, UK

⁴ Administrative Data Research Centre for Scotland, University of Edinburgh, UK

*Corresponding author and address for reprints:

The Administrative Data Research Centre for England, UCL Great Ormond Street Institute of Child Health, 30 Guilford Street, London WC1N 1EH, UK, Telephone: +44 (0)20 7905 2101, Fax: +44(0)20 7905 2793

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1 **Full title**

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7 Smith³, Chris Dibben⁴, Harvey Goldstein¹.

8
9 ¹ Administrative Data Research Centre for England, University College London Great Ormond Street
10 Institute of Child Health, London, UK

11 ² Health Services Research and Policy, London School of Hygiene and Tropical Medicine, London, UK

12 ³ Social Statistics and Demography, University of Southampton, Southampton, UK

13 ⁴ Administrative Data Research Centre for Scotland, University of Edinburgh, UK

14
15 *Corresponding author and address for reprints:

16 The Administrative Data Research Centre for England, UCL Great Ormond Street Institute of Child
17 Health, 30 Guilford Street, London WC1N 1EH, UK, Telephone: +44 (0)20 7905 2101, Fax: +44(0)20
18 7905 2793

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23 **Abstract**

24 Record linkage of administrative and survey data is increasingly used to generate evidence to inform
25 policy and services. Although a powerful and efficient way of generating new information from
26 existing datasets, errors related to data processing before, during and after linkage can bias results.
27 However, researchers and users of linked data rarely have access to information that can be used to
28 assess these biases or take them into account in analyses. As linked administrative data is
29 increasingly used to provide evidence to guide policy and services, linkage error, which
30 disproportionately affects disadvantaged groups, can undermine evidence for public health.

31 We convened a group of researchers and experts from government data providers to develop
32 guidance about the information that needs to be made available about the data linkage process, by
33 data providers, data linkers, analysts and the researchers who write reports. The guidance goes
34 beyond recommendations for information to be included in research reports. Our aim is to raise
35 awareness of information that may be required at each step of the linkage pathway to improve the
36 transparency, reproducibility, and accuracy of linkage processes, and the validity of analyses and
37 interpretation of results.

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40 Introduction

41 Data linkage is increasingly used to bring together electronic records containing information from
42 different sources about an individual, organisation or location. Linkage offers a relatively quick and
43 low cost means of capturing information from large administrative datasets for service planning,
44 delivery and evaluation, surveys and censuses, and research. Data linkage centres have been
45 established in many countries, building on early exemplars of linking administrative data for
46 population-based research in the Nordic countries, Manitoba, Western Australia and Scotland
47 (<http://www.ipdln.org/data-linkage-centres>). For example, the UK government has invested in
48 national networks for health informatics research (<http://www.farrinstitute.org/>) and in social
49 research using administrative data (<https://adrn.ac.uk/>).

50 Research using linked data is fast becoming a powerful source of evidence to drive policy, practice
51 and biomedical and social sciences.(1) For example, the US recently passed legislation to mandate
52 sharing of administrative and survey data with the US Census Bureau for research for evidence-
53 based policy.(2, 3) However, there is growing evidence that important elements of data processing
54 before, during and after linkage, can introduce error and lead to biased results.(1, 4, 5) The recent
55 RECORD statement and an earlier framework for reporting recommend information relevant to
56 linkage that should be included in reports of research based on routinely-collected health data.(6,
57 7)(1) In practice however, such information is rarely available to researchers. Lack of information is
58 partly because different processes along the data linkage pathway are performed by different
59 agencies (Figure 1). Such fragmentation creates barriers to sharing of information about data
60 processing, prevents analyses that take linkage error into account and can limit understanding of the
61 impact of data quality and linkage error on the results of analyses.

62 The GUILD guidance addresses this lack of understanding by recommending information that could
63 be made available at each step of the data linkage pathway, by data providers, data linkers, analysts
64 and those writing reports. GUILD guidance does not set minimum standards or criteria for
65 information that should be provided nor is it a checklist or protocol. The aim is to set out principles,
66 to raise awareness, and empower data linkers, analysts, researchers and users of evidence to
67 request and use information to assess linkage error and its impact on results. Linkage error is just
68 one of the consequences of poor data quality or missing data. Analysts have a range of methods for
69 dealing with data quality issues, including linkage error, provided they are made aware of the
70 problem.

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3 72 ***Linkage error***
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5 73 Errors in linkage typically occur where there is no unique identifier across different datasets. In the
6 74 UK for example, education, health and tax records use different personal identifiers: a pupil ID,
7 75 National Health Service (NHS) number and National Insurance (NI) number respectively. Linkage
8 76 between these data sources therefore relies on other common or quasi-identifying characteristics
9 77 such as name, sex, date of birth and postcode. There is considerable potential for linkage error as
10 78 some individuals share the same identifying characteristics, identifiers may be entered incorrectly,
11 79 or different identifiers may be used across datasets (and over time) for the same person. Linkage
12 80 error occurs in two ways: false-matches are made where two records are linked but do not belong to
13 81 the same individual, and missed-matches occur when two records that do belong to the same
14 82 individual fail to link (see appendices 1 and 2).(8) Even small amounts of false- or missed-matches
15 83 can produce substantially biased results, particularly in data belonging to specific sub-groups of the
16 84 population, for example, young people, ethnic minorities or the homeless.(9-14)

17 85 Fragmentation of data processing can make it hard for data linkers and analysts to have the
18 86 information needed to assess or take into account the impact of linkage error on results. It is
19 87 common practice for data linkers to keep identifiers (e.g. NHS number or date of birth), separate
20 88 from attributes (such as information on health, finance or education). This 'separation principle' is
21 89 used to avoid disclosure during the linkage process (Figure 1). The identifying characteristics are
22 90 used only for linkage, which may be done by a separate agency (or third party). The attribute data
23 91 are linked for analysis using an artificial identifier that cannot be used to identify individuals in the
24 92 real-world (Figure 1).

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41 93 While the separation principle might reduce the risk of identification, it can increase the risk of
42 94 biased analyses.(14) Linkers and analysts may be unaware of important groups who are
43 95 disproportionately affected by linkage error if information is not shared between them. For example,
44 96 when linking mother and baby data to study infant mortality, babies who die in the first day or two
45 97 of life may be less likely to be linked because their name or NHS number had not been allocated
46 98 before death (15, 16). Data linkers will be unaware of this problem as death is an attribute that is not
47 99 included with the identifiers used for linkage. Unless information on linkage error is shared with the
48 100 analyst and incorporated into results, mortality rates could be underestimated. Another example is
49 101 the calculation of readmission rates for monitoring performance of hospitals. Incorrect or missing
50 102 patient identifiers are likely to lead to underestimated readmission rates: hospitals with poor quality
51 103 identifiers will appear to perform better. Provided information on data quality indicators associated
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3 104 with missed-matches or false-matches is made available, linkage error can be mitigated by
4 105 adaptations to the linkage method, analyses or both.(13, 14) The GUILD guidance highlights
5 106 elements of the linkage pathway when error can be introduced and recommends information that
6 107 can be used to assess or account for linkage error without breaching privacy.
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10 108 ***Guidance development***

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13 109 The GUILD guidance was developed by a core group of UK data linkage experts. In March 2015, we
14 110 held a meeting with eight experts from the Office for National Statistics and from four academic
15 111 institutions, chosen for their expertise and experience in data linkage across multiple disciplines
16 112 including social statistics, health care, demography and education. A core group of four experts
17 113 reviewed previous guidance, reviews of linkage accuracy studies, and other studies reporting sources
18 114 of bias along the data linkage pathway,(1, 4, 5, 7) and drafted initial statements, which were revised
19 115 following discussion at three face-to-face meetings with the UK expert group. The group debated the
20 116 steps in the linkage pathway that can increase or mitigate linkage error and its impact on results. No
21 117 formal process was used to achieve consensus. The main item of contention related to the
22 118 acceptability of statistical disclosure controls that degrade the quality and utility of the data prior to
23 119 analysis (see S1 text).(17, 18)
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32 120 Drafts of the recommendations were reviewed by a wider team of UK linkage experts in June 2016
33 121 (24 UK experts). We also presented the guidance at an international workshop on data linkage in
34 122 September 2016 and subsequently held a face-to-face meeting of 6 international and 3 UK experts
35 123 to discuss revisions to the guidance (all contributing experts are listed in the
36 124 acknowledgements).(19)
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41 125 In the next section and in Table 1 we propose items of information prioritised by the linkage experts
42 126 for sharing at each step of the linkage pathway (Figure 1). Such information could be included in
43 127 reports of analyses using linked data, or as supplementary material (e.g. online appendices).(20)
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48 129 **Step 1. Data Provision – the generation, processing and quality control of the source data for** 49 130 **linkage**

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52 131 The data provider should publish or otherwise share information to explain how the dataset was
53 132 created and maintained (Table 1, step 1a, 1b(i-iv)). In some cases, data providers may need to obtain
54 133 this information from the service that generated the data. The way data are collected, cleaned, and
55 134 standardised can influence the accuracy of the data and any subsequent linkage.(21) Data providers
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3 135 should share information about how unique identifiers (e.g. NHS number, NI Number, driving license
4 136 number) were generated and validated. Transcription errors, misspellings and missing data in
5 137 particular can cause false- and missed-matches.(13, 22, 23) Information about data cleaning rules
6 138 and the extent of missing data or errors in identifiers can help identify common scenarios that cause
7 139 linkage error.(13) Information should also be provided about any preprocessing of source datasets
8 140 involving internal linkage of multiple records to the same entity or to remove duplicate records
9 141 (Table 1, step 1, 1b(iii)). For example, in Hospital Episodes Statistics (HES) for NHS hospital contacts
10 142 in England, an algorithm links repeated contacts over time for the same patient.(13, 24) False-
11 143 matches and missed-matches occurring during this internal linkage can compound subsequent
12 144 linkage errors when the HES is linked externally to another dataset, such as primary care
13 145 records.(25) Provided information is shared about internal linkage errors within one or more of the
14 146 source datasets, data linkers may be able to develop linkage algorithms that minimise the
15 147 problem.(14) In addition, information on the rates of false- and missed-matches can be used to
16 148 adjust results of analyses or to undertake sensitivity analyses.(5)(5)

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19 149 Data providers or data linkers can replace real-world identifiers with artificial identifiers, i.e.
20 150 numbers or codes that cannot be traced to the individual or unit (Table 1, step 1, 1b(iv), or step 2,
21 151 2a(ii)). The aim is to reduce the risk of identification during linkage. A variety of methods can be
22 152 used, referred to as privacy preserving techniques.(26, 27) For example, the UK Office of National
23 153 Statistics replaces real-world names and numbers with an artificial identifier after cleaning and
24 154 standardisation of data received from data providers but prior to linkage (Table 1, step 2, 2a(ii)). This
25 155 process is irreversible as the artificial identifier cannot be decoded to regenerate the real-world
26 156 identifiers.(4, 28) Replacement with artificial identifiers prior to linkage is controversial because it
27 157 makes it difficult to quantify or take into account linkage errors related to certain characteristics,
28 158 such as names, postcodes or dates.(29)

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47 160 **Step 2. Data Linkage –bringing together records belonging to the same individual, place or**
48 161 **organisation**

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51 162 The first part of the guidance about data linkage (Table 1, step 2, 2a-b) relates to the information
52 163 that should be shared when undertaking linkage of two or more datasets for a specific study or
53 164 analysis. Data linkers should describe and justify the identifying characteristics (e.g. name, postcode,
54 165 sex, ethnicity) used in the linkage algorithm. In addition to the data cleaning and validation
55 166 undertaken by data providers (Table 1, step 1b, 2ai), data linkers may undertake further cleaning
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3 167 and validation of identifying characteristics used for linkage (Table 1, step 2, 2ai). Cleaning the data
4 168 by removing spaces in postcodes or editing dates by imputing information where there are
5 169 inconsistencies, makes it more likely that two identifying characteristics will agree. Care must be
6 170 taken; whilst data cleaning could enable data linkage to capture more true matches, it could also
7 171 make it more likely that two records will falsely link.(25) The rules used to standardise data should
8 172 therefore be reported in detail, because they influence linkage error.(13) It is also important to
9 173 report the proportion of missing data before and after cleaning, and the number of records excluded
10 174 or changed, for example because of duplicate records, improbable characteristics (e.g. date of death
11 175 before birthdate), or not meeting study criteria (Table 1, step 2, 2a(i), 2a(ii)).

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19 176 Information about methods used to link data should be shared with analysts and where feasible, this
20 177 information should be published, including details of the linkage algorithm (Table 1, step 2, 2a(iii)). A
21 178 common method for data linkage is to first use rule-based matching (e.g. deterministic or exact
22 179 matching) followed by score-based matching (e.g. probabilistic linkage) to link any remaining
23 180 records.(30) Despite evidence that probabilistic linkage produces less biased results than
24 181 deterministic linkage alone,(31, 32) probabilistic linkage is rarely used for linking administrative data
25 182 in the UK. However, data linkers in Wales (SAIL), Scotland (eDRIS), Australia, the US and Canada,
26 183 demonstrate that probabilistic linkage is feasible at scale.(23, 33, 34)

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33 184 Data linkers using score-based methods should report how they grouped records that could
34 185 potentially link – referred to as blocking. (Table 1, step 2, 2a(iv)). Blocking means that only those
35 186 records with some degree of similarity are compared, e.g. only those where date of birth agrees.(4)
36 187 Blocking aims to reduce processing time, but can cause missed-matches.

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40 188 The data linker should share record-level information that enables the analyst to take linkage
41 189 uncertainty into account in analyses (Table 1 Step 2, 2b). This can be done by attaching indicators of
42 190 match certainty to each comparison pair of matched records. In rule-based linkage, indicators might
43 191 reflect the step in the algorithm at which the records were linked (e.g. pass-identifier). In score-
44 192 based linkage, record-level indicators include match-scores (e.g. match weights, probabilities or
45 193 ranks). The group or block indicator adds information on how uncertainty varies across groups.
46 194 When score-based linkage is used, information on the optimum threshold for designating links as
47 195 matches should be shared, and, where possible, a matrix that shows all possible links for each record
48 196 above the threshold. These record-level indicators can be used to adjust linked datasets, for example
49 197 by including or excluding links based on the uncertainty of the match as defined by the match-
50 198 score.(5, 35)

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3 199 Following the production of a linked dataset, the data linker should provide a description of linkage
4 200 accuracy at the aggregate level (Table 1 step 2, 2c(i-iv)). This could include a comparison of
5 201 aggregate counts of age, sex and other attributes, and reports of the uniqueness and independence
6 202 of identifying characteristics used for linkage.(36, 37)
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10 203 Data linkers should provide generic information reflecting regular quality assessments of their
11 204 linkage processes (Table 1 step 2, 2d-f), where these are large-scale, ongoing linkages (e.g. all
12 205 hospitalisations and deaths nationally). In this situation, regular comparisons of samples of linked
13 206 data to a reference dataset where true- and false-matches are known, may be sufficient provided
14 207 information is reported for important subsections of the population (e.g. infants, elderly) for whom
15 208 linkage accuracy may vary.(14) Measures include precision or positive predictive value (PPV, a
16 209 measure of false-matches), sensitivity/recall (a measure of missed-matches), and the F-measure (S 2
17 210 text).(4)
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24 211 Data linkers should publish their methods for disclosure control of linked data before transmission of
25 212 linked data to the analyst. For example, data linkers sometimes require grouping of detailed values
26 213 into broader groupings (e.g. changing exact ages to age bands), suppression of outlying values, or
27 214 addition of random noise to minimise disclosure risks (Table 1, step 2, 2e).(17, 18, 38) Making
28 215 information about the linkage processes publicly available can help to develop rigorous methods
29 216 throughout the data linkage pathway. Data linkers can support transparency, quality and
30 217 reproducibility of studies and encourage collective learning about linkage error by publishing details
31 218 of linkages undertaken with links to subsequent study reports (Table 1, step 2, 2f).
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39 220 **Step 3. Analyses of the linked data – taking account of linkage error**

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42 221 So far, the guidance has focused on providing the data analyst with the information they need to
43 222 conduct analyses that take into account sources of error before, during and after linkage (Table 1,
44 223 steps 1-3). The analyst should report any evaluation of linkage accuracy against a reference standard
45 224 and how they used this information in their analyses in meta-data or research reports (see appendix
46 225 3).
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51 226 The analyst should report use of record-level indicators of linkage uncertainty (e.g. match weights) in
52 227 the analyses, for example, whether varying the match score changed the results of analyses (Table 1,
53 228 step 3, 3a(ii-iii)).(5, 14, 35) An alternative approach is to use match weights for all possible links to
54 229 select the correct value for the variable of interest (known as prior informed imputation).(4, 39) This
55 230 method avoids errors that could be incurred by accepting the wrong record as a link. If the analyst
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3 231 does not have record level indicators of the linkage process, they can adjust for linkage error based
4 232 on comparisons of the linked data with the unlinked source populations or through external
5 233 comparisons with expected rates (Table 1, step 3, 3a(i)).
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9 234 **Step 4. Reporting the results of analyses of linked data**

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11 235 Reports of studies using linked data should, where possible, include information on items in Steps 1
12 236 to 3. Information should be prioritised to enable users of studies (e.g. journal editors, researchers,
13 237 policy makers, data providers and linkers and the public) to understand the extent of linkage error
14 238 and the potential impact on results and reproducibility of analyses.(2, 40) Research reports should
15 239 continue to use the STROBE guidance, supplemented by the 13-item RECORD statement for specific
16 240 items of information for observational studies using administrative data, including the four items
17 241 about data linkage (Appendix 3)(6). When publishing results, statistical disclosure controls may
18 242 prevent publication of potentially disclosive information, such as minimum-maximum ranges and
19 243 small cell sizes, which could provide insights into linkage error. In these circumstances, potentially
20 244 disclosive results may need to be restricted to approved users.(41)
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28 245 **Discussion**

29 246 **Main findings of this study**

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34 247 GUILD aims to improve the quality of data processing, linkage, analyses and research reports by
35 248 raising awareness about detailed information that could be shared at each step of the linkage
36 249 pathway. The guidance also aims to highlight the responsibilities of data providers, linkers and
37 250 analysts, not just report writers, to make this information available.
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42 251 **What is already known?**

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45 252 Linkage error can contribute to selection bias or information bias or both, depending on the study
46 253 design and the way in which linkage is used to generate the variables used in analyses. The STROBE
47 254 and RECORD reporting guidelines make recommendations about information that should be
48 255 included in research reports of observational studies based on electronic health datasets but do not
49 256 provide guidance on potential sources of linkage error.(6, 42)
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53 257 **What this study adds**

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3 258 GUILD highlights the choices and decisions made during data processing that affect linkage error and
4 259 hence the results of analyses. Sharing information along the data linkage pathway could improve the
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6 260 transparency and reproducibility of research, promote the use of improved methods to address
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8 261 linkage error, and improve the interpretation of studies based on linked data.
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11 262 **Limitations of the study**
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13 263 Development of the GUILD guidance involved iterative discussions with UK and international linkage
14 264 experts but did not use formal consensus methods. The scope of GUILD is broad, involving different
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16 265 processes and a variety of agencies, analysts and methods. Further methodological research can
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18 266 inform updates to this guidance and help to prioritise key items of information that should be made
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20 267 available. There is also a need to develop appropriate formats (e.g. meta-data, data sharing
21 268 agreements) for sharing information about sources of linkage error while preserving the privacy of
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23 269 data entities or individuals.
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26 270 Linked administrative data is a powerful resource, which is increasingly used to underpin policy,
27 271 organisation of services, and research. Transparency throughout the linkage pathway is important to
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29 272 ensure that the validity of this resource is fit-for-purpose.
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5
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29 288 Tropical Medicine, London, UK), Rainer Schnell (City University, London, UK).

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33 290 iterations of the guidance for review by the wider group of experts. RG further revised the guidance
34
35 291 in response to comments from journal reviewers and from the meeting of international experts. All
36
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38
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For Peer Review

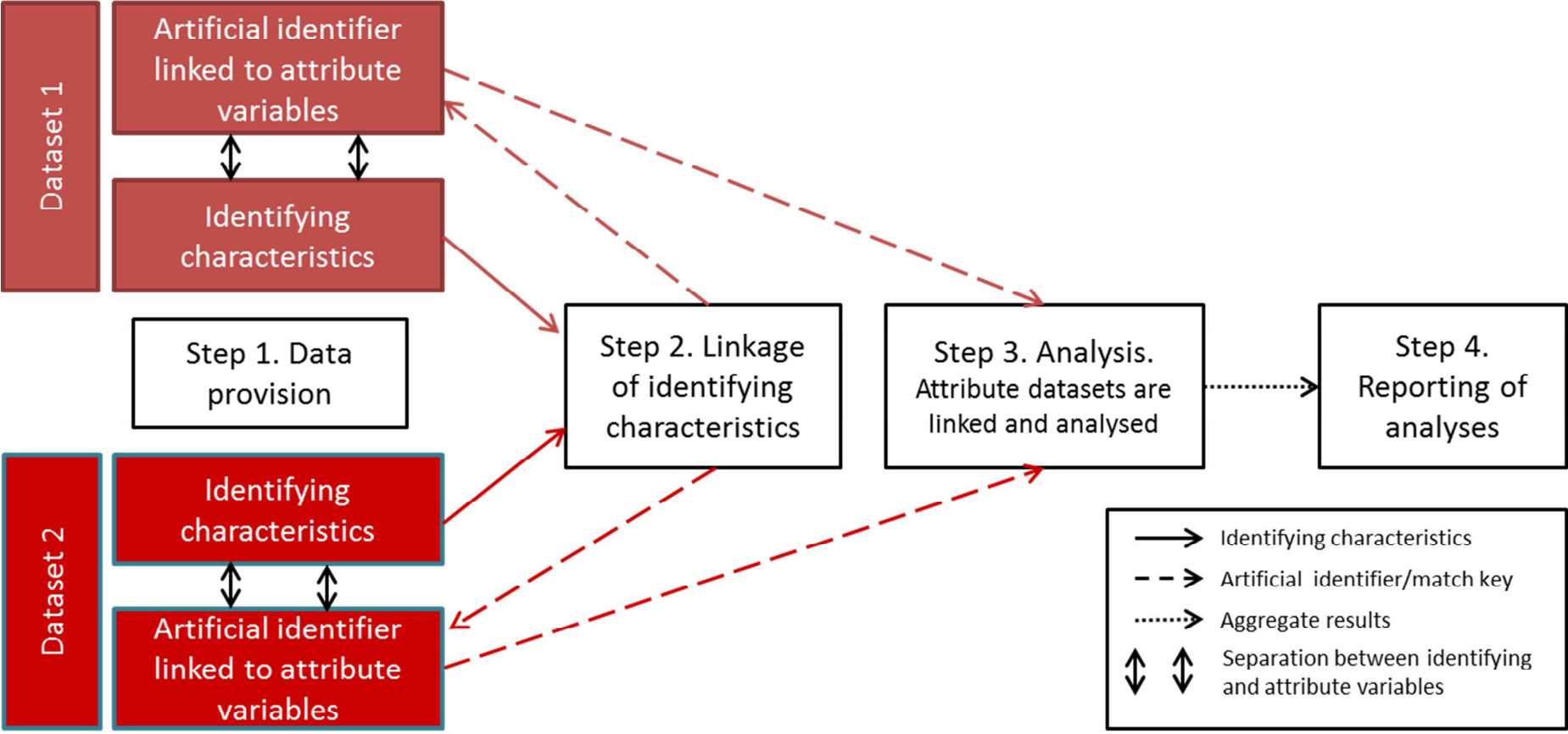
Table 1: GUILD guidance information to be shared before, during and after data linkage

Item	Concept	Guidance
Step 1	Data provision	
1a	Population included in the dataset	Data providers should give details of the population included in the dataset (e.g. everyone registered with a GP), the geographic coverage of the data (e.g. England and Wales), the number of records in each source dataset and how any 'opt-outs' were dealt with
1b	Linkability of the dataset	Details should be shared about how the data were generated (e.g. face-to-face), processed (e.g. a self-entered form or entered by an administrator) and quality controlled (e.g. manually checked), including how identifying characteristics were:
1b(i)		- collected and allocated
1b(ii)		- updated as further personal data were collected, and dates of most recent updates
1b(iii)		- checked and cleaned, including any validation rules
1b(iv)		- replaced with artificial identifiers to reduce disclosure before being released for linkage
Step 2	Data linkage	
2a	Descriptions of linkage processes	Data linkers should provide descriptions of how the linkage was done including:
2a(i)		- a clear description of the data sources and identifying characteristics used for linkage, details of how identifiers were cleaned and validated before linkage, patterns of missingness, the expected range of values after cleaning, and how any de-duplication was performed.
2a(ii)		- details of any transformation or replacement with artificial identifiers before linkage

2a(iii)		<ul style="list-style-type: none"> - a detailed description of the method (or algorithm) used for linkage, whether it was rule-based (e. deterministic) or score based (e.g.. probabilistic linkage), and how multiple linkages were handled.
2a(iv)		<ul style="list-style-type: none"> - a detailed description of any new derived variables that were introduced during the linkage process (e.g. confidence level or probability of linkage or link score)
2a(v)		<ul style="list-style-type: none"> - details of any blocking or grouping methods used for score-based linkage and how match scores were derived
2b	Record-level indicators of the linkage process	Data linkers should provide analysts with record-level indicators of the data linkage process to enable adjustments for linkage error in the analyses. Indicators could include the pass-ID (the step in a rule-based linkage process when a pair of records linked), or match scores (e.g. match weights used in probabilistic linkage).
2c	Aggregate linkage results	Data linkers should make available descriptions, tables and flow diagrams depicting linkage accuracy for each linkage undertaken. These should include:
2c(i)		<ul style="list-style-type: none"> - a description of the number of records that were linked and unlinked in each of the source files
2c(ii)		<ul style="list-style-type: none"> - a table comparing the aggregate characteristics of individuals in the linked and unlinked records for each source dataset (defined by the analyst in agreement with the data linker)
2c(iii)		<ul style="list-style-type: none"> - a description of the “representativeness” of the linked dataset to each source dataset, for example, including weights that can be applied to allow grossing up the linked dataset to better represent the source datasets
2c(iv)		<ul style="list-style-type: none"> - a flow diagram to represent the steps in linkage and numbers involved at each step
2d	Generic reports of linkage accuracy	The data linker should report generic information about the quality of linkage carried out. This should include:
2d(i)		<ul style="list-style-type: none"> - estimates of linkage error rates based on regular

		quality monitoring of linkage accuracy. For example, measures of the sensitivity and specificity for the algorithm used.
2d(ii)		- details of how error rates were estimated, for example, by comparing linked records with a reference dataset.
2e	Descriptions of disclosure controls	Data linkers should describe any statistical disclosure controls used to reduce identifiability of linked data prior to release to data analysts.
2f	Overview of data linkage	Data linkers should establish systems to improve the quality of linkage studies, for example, by publishing a database detailing the data linkages undertaken with links to publications. The advisory and approvals structure for data linkage should include experts who can scrutinize the impact of linkage processes on results of analyses.
Step 3	Data analyses	Data analysts should assess and report on the quality of the linked data used for analyses.
3a	Account for linkage error	Analysts should report how analyses took into account linkage error, including:
3a(i)		- how record-level indicators of the linkage process or aggregate measures reflecting linkage quality were used for adjustments, including underlying assumptions and methods used
3a(ii)		- Uncertainty analyses of the effects of linkage errors
3a(iii)		- Sensitivity analyses to determine the impact of assumptions used in the analyses.
Step 4	Reporting study findings	Reports of linkage studies should, where possible, include items in Steps 1-3, building on the RECORD statement for research reports (appendix 3).(6)

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Appendix 1. Glossary

Glossary	Description
Administrative data.	Data that has been collected (e.g. by a government department) to enable the provision, monitoring and evaluation of services.
Algorithm.	A sequence of steps or rules to follow in order to process data or perform calculations, normally used by computers.
Anonymisation.	Anonymisation is the process by which the relationship between an individual and the data about them is broken, so that the individual cannot be identified.(43) Alternative terms include de-identification or pseudo-anonymisations.
Artificial identifier	Replacement of real-world identifiers that could be traced to an individual (e.g. NHS number or passport number) with a unique number or code that cannot be used to an individual (or other entity).
Attribute data.	The characteristics of interest about the entity, such as earnings or healthcare. Attribute data are recorded as well-defined variables (e.g. column in a database). Attribute data that are non-identifying and not informative for linkage are kept separate from identifying characteristics under the separation principle.
Blocking.	A method for reducing the number of data comparisons that need to be made. Records are compared only if they already have a degree of similarity defined by the data linker (e.g. blocking by hospital or date of birth). Only records that belong to the same block can possibly be linked.
Block identifier or Blocking key value.	A combination of numbers or letters that identifies the block that each record belongs to.
Blocking key.	Defines how blocks are to be formed (e.g. first two letters of surname connected with year of birth).(4)
Data error.	A broad term referring to misspelt or incorrectly recorded identifying characteristics, false information or missing information.
Data linkage.	The process of linking <i>records</i> from two or more databases that refer to the same

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3 *entity*. These pairs or groups of records are known as *matches* and can relate to a
4 person, place, business and/or organisation.(4) The process of comparing records
5 *records* from two or more databases with the objective to identify pairs or groups
6 of records that refer to the same *entity* is known as data matching.
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10 Deterministic linkage. Two records are designated as matches based on their attributes being the same
11 (e.g. exact match on sex, date of birth and postcode), or highly similar (e.g. match
12 on partial date of birth, exact match on sex and postcode). These matches are
13 determined by a set of rules (an algorithm) created by the data linker.
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18 False match. A record pair that is classified as a match where, however, the two records in the
19 pair refer to two different entities.(4)
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22 Identifying Quasi-identifiable variables that directly identify an individual (e.g. name) or that
23 characteristics. can indirectly be used in combination with others to uniquely identify an individual
24 (e.g. date of birth, sex and postcode).
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28 Linkage error. A generic term referring both to false and missed matches.
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31 Linked data. The product of record linkage, data that has been produced by the record linkage
32 of two or more datasets.
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35 M and U probabilities. Numerical values that represents the probability that two records agree on a
36 variable given they are a true match (m value) and the probability that two records
37 agree on a variable given they are true non-matches (u value).(44)
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40 Match scores. A numerical value that represents the likelihood of two records being a match.(44)
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43 Match rates. The number of linked records out of the total eligible for linkage in one of the
44 source files.
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47 Match weights. A numerical value that is assigned to a certain attribute where the attribute values
48 are the same or similar to each other.(44) This is also known as an agreement
49 weight. Match weights are calculated as the likelihood that two attribute values
50 are in agreement assuming that both records in a candidate record pair
51 correspond to the same entity, divided by the likelihood that two attribute values
52 are in agreement assuming that the two records in a candidate record pair
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3 correspond to different entities.
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8 Missed match. A record pair that is classified as a non-match where, however, both records in the
9 pair correspond to the same entity, otherwise known as a false non-match.
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11 Negative predictive The proportion of record pairs classified by the algorithm as non-links that are true
12 value (NPV). non-matches.
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16 Pass-ID. A combination of numbers or letters that identifies the stage in the linkage method
17 that the match was made. For example, a pass-id could relate to a specific step in a
18 rule-based linkage algorithm.
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22 Personal data. Personal data is defined as data which can be used to identify an individual,
23 including when that data is combined with other information. In some countries,
24 personal data has a specific legal definition.
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28 Positive predictive value The proportion of record pairs classified by the algorithm as links that are true
29 (PPV). matches. This is also known as precision.
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32 Precision. See positive predictive value.
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34 Probabilistic record Records are matched based on the degree of similarity between the linkage
35 linkage. variables, expressed explicitly in terms of the relevant probabilities. This is often
36 known as score-based matching. The approach published by Fellegi and Sunter
37 calculates match weights and non-match weights based on error probabilities and
38 frequency distributions of attribute values in the input databases. Candidate
39 record pairs are classified based on their weight vectors into either matches, non-
40 matches, or potential matches, using a threshold-based and pair-wise classification
41 approach.(44)
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48 Pseudonymised. Data in which identifying fields (e.g. names, dates of births and addresses) have
49 been replaced by one or more artificial identifiers to reduce the risk of
50 identification of individuals.(43)
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54 Recall. See sensitivity.
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57 Sensitivity. The proportion of true matches that are correctly classified as links. This is also
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known as recall.

Specificity. The proportion of true negative matches that are correctly classified as non-links.

Statistical disclosure control (SDC). Methods to measure and reduce the risk of disclosing information on individual entities (e.g.: individuals, households or organisations).(18) SDC can involve changing record level data before analyses (Figure 1, step 3) or aggregate data before reporting of analyses (Figure 1, step 4). SDC before analyses usually involves removal of unique identifiers (e.g. NHS number) and quasi identifying characteristics (e.g. date of birth, postcode). It can also involve changing attribute data to reduce the risk of unique combinations of characteristics that could be used to identify individuals. In this way, SDC can degrade the quality and utility of the data before analysis. SDC is also applied to aggregate data in reports, for example by modifying aggregate results, such as cell sizes containing fewer than 5 individuals (Figure 1, step 4).

True match. A record pair that is classified as a match, where both records in the pair correspond to the same entity. This is also known as a true positive.

True non-match. A record pair that is classified as a non-match, where the two records in the pair correspond to two different entities. This is also known as a true negative.

Trusted third party. An organisation that undertakes record linkage using data provided by other organisations.

Appendix 2. Quantitative measures of linkage accuracy(4)(5)

		True match status	
		Match (record pair is from the same individual)	Non-Match (record pair is from different individuals)
Status after linkage	Link	A: True positive matches	B: False-matches
	Non-link	C: Missed matches	D: True negative matches

Examples of quantitative measures of linkage accuracy are given below.

1. The positive predictive value (PPV) - the proportion of record pairs classified by the algorithm as links that are true matches. Also known as precision.

$$PPV = A/(A+B)$$

2. The negative predictive value (NPV) - the proportion of record pairs classified by the algorithm as non-links that are true non-matches.

$$NPV = D/(D+C)$$

3. The specificity – the proportion of true negative matches that are correctly classified as non-links.

$$\text{Specificity} = D/(B+D)$$

4. The sensitivity – the proportion of true matches that are correctly classified as links. Also known as recall.

$$\text{Sensitivity} = A/(A+C)$$

5. The F-measure – The harmonic mean between positive predictive value and sensitivity. Often used to compare the overall efficiency of a method.

$$\text{F-measure} = 2*(PPV*sensitivity)/(PPV+sensitivity)$$

Appendix 3. Items in the RECORD statement relevant to data linkage(6) Benchimol)**Title and abstract**

RECORD 1.3: If linkage between databases was conducted for the study, this should be clearly stated in the title or abstract. Introduction

Methods: Participants

RECORD 6.3: If the study involved linkage of databases, consider use of a flow diagram or other graphical display to demonstrate the data linkage process, including the number of individuals with linked data at each stage.

Methods: Statistical Methods

RECORD ITEM 12.2: Authors should provide information on the data cleaning methods used in the study.

RECORD ITEM 12.3: State whether the study included person-level, institutional-level, or other data linkage across two or more databases. Linkage techniques and methods used to evaluate linkage quality should be provided.

Results: Participants

RECORD ITEM 13.1: Describe in detail the selection of the persons included in the study (i.e., study population selection), including filtering based on data quality, data availability and linkage. The selection of included persons can be described in the text and/or by means of the study flow diagram.

Discussion: Limitations

Discussion RECORD ITEM 19.1: Discuss the implications of using data that were not created or collected to answer the specific research question(s). Include discussion of misclassification bias, unmeasured confounding, missing data, and changing eligibility over time, as they pertain to the study being reported.