Original article

Why do we think we know what we know? A metaknowledge analysis of the salt controversy

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Abstract

Background: Although several public health organizations have recommended population-wide reduction in salt intake, the evidence on the population benefits remains unclear. We conducted a metaknowledge analysis of the literature on salt intake and health outcomes.

Methods: We identified reports—primary studies, systematic reviews, guidelines and comments, letters or reviews—addressing the effect of sodium intake on cerebro-cardiovascular disease or mortality. We classified reports as supportive or contradictory of the hypothesis that salt reduction leads to population benefits, and constructed a network of citations connecting these reports. We tested for citation bias using an exponential random graph model. We also assessed the inclusion of primary studies in systematic reviews on the topic.

Results: We identified 269 reports (25% primary studies, 5% systematic reviews, 4% guidelines and 66% comments, letters, or reviews) from between 1978 and 2014. Of these, 54% were supportive of the hypothesis, 33% were contradictory and 13% were inconclusive. Reports were 1.51 [95% confidence interval (CI) 1.38 to 1.65] times more likely to cite reports that drew a similar conclusion, than to cite reports drawing a different conclusion. In all, 48 primary studies were selected for inclusion across 10 systematic reviews. If any given primary study was selected by a review, the probability that a further review would also have selected it was 27.0% (95% CI 20.3% to 33.7%).

Conclusions: We documented a strong polarization of scientific reports on the link between sodium intake and health outcomes, and a pattern of uncertainty in systematic reviews about what should count as evidence.

Key words: Sodium chloride (dietary), bias (epidemiology), bibliometric analysis, review literature as topic

> **Key Messages**
> - We documented a strong polarization of scientific reports on the link between sodium intake and health outcomes.
> - A majority of the existing papers are supportive of the salt hypothesis but a substantial minority are not.
> - Published reports supporting either side of the hypothesis are less likely to cite contradictory papers.
> - There was very little consistency in the selection of primary studies in systematic reviews on the topic.

Background

Universal salt reduction has been the subject of considerable scientific controversy over several decades.[1,2] Proponents of population-wide reduction in salt consumption note that high sodium intakes increase blood pressure and thus the risk of cerebro-cardiovascular events, and assert that salt reduction policies will produce major public health benefits. The World Health Organization (WHO) recommends reducing sodium intake to < 2 g/day in adults.[3] Opponents of population-based salt reduction argue that the relationship between sodium intake and clinical outcomes is U- or J-shaped and that the harms associated with low sodium intakes may mitigate any potential benefits of blood pressure reductions arising from decreased salt intakes.[4,5] In a recent report, the United States Institute of Medicine of the National Academies of Science concluded that there is a lack of evidence for benefits of reducing sodium intake to the very low levels recommended by the WHO.[6]

In many respects, the divide between the uncertainty in the scientific literature about the potential benefits of salt reduction in populations and the certitude expressed by decision makers involved in developing public health policies in this arena is jarring.[1,7] Whereas several authors involved in the conduct of systematic reviews of the evidence on sodium have argued that the salt hypothesis is a distraction with little empirical grounding,[8] others have asserted that salt reduction in populations should be a central public health priority in the 21st century.[9] Assuming that all parties involved have the best interests of science and public health in mind, this controversy raises questions about the production of knowledge in population health science and how that production influences public health practice.[10]

Toward the end of contributing to population health epidemiology, we examined the patterns of knowledge generation surrounding this controversy. First, we used network analysis to assess the patterns of citations among reports pertaining to the effect of population-level sodium intake on cerebro-cardiovascular disease or all-cause mortality. Second, we assessed the agreement in primary study selection between relevant systematic reviews. By tracking the networks of citations between reports and among researchers co-authoring reports, we aimed to better understand how this controversy has been sustained and to expose beliefs or preferences that shape knowledge production underlying this scientific literature.[11]

Methods

Selection of reports

We systematically reviewed the literature to include all: (i) reports of primary studies; (ii) systematic reviews; (iii) clinical practice guidelines or consensus statements; and (iv) comments, letters or narrative reviews. We considered as eligible all reports that addressed the effect of sodium intake, or interventions targeting sodium intake, on cerebro-cardiovascular disease or all-cause mortality. Eligible primary studies were randomized trials, cohort studies and case-control studies. Simulation modelling efforts, cost-effectiveness studies and ecological analyses were deemed ineligible.

The last search was conducted in September 2014. We searched MEDLINE, the Cochrane Database of Systematic Reviews, the Database of Abstracts of Reviews of Effects, the WHO Institutional Repository for Information Sharing, the US National Guideline Clearinghouse, the National Institute for Health and Care Excellence, the American Heart Association and American Stroke Association statements and guidelines, and the Dietary Guidelines for Americans. We identified primary studies by screening the lists of studies included in the selected systematic reviews. In addition, we screened the reference lists of all reports. For a detailed description of the selection criteria and search strategies, see Web Text 1 (available as Supplementary data at *IJE* online).

Classification of reports

Two authors (L.T., S.G.) classified each report into one of three categories: supportive of the hypothesis that population-wide reduction of sodium intake results in reduction in cerebro-cardiovascular disease or all-cause mortality; contradictory of this hypothesis; or inconclusive. Our

primary assessment was based on the conclusion reported in the abstract of the selected reports. If there was no abstract or summary statement about the effect of sodium intake or of interventions targeting sodium intake on cerebro-cardiovascular disease or all-cause mortality, our assessment was based on a review of statements in the full-text report.

Citation network analysis

First, we constructed the network of citations connecting the reports. We identified the citations between the selected reports by using the Web of Science database and by manually screening all selected articles. We counted multiple citations from an article to another as one citation. We constructed a directed acyclic graph in which each node was a report and edges were directed from a citing report to a cited report. We distinguished multiple publications of the same report (whether there was a clear statement that republishing was intentional or not).

Second, we used an exponential random graph (ERG) model to explain the probability of a citation link between two reports, based on publication year, type of report (i.e. primary study, systematic review, guideline and comment, letter or review), journal impact factor and network structure.[12,13] The model was used to formally test for homophily according to report classification (supportive, contradictory, inconclusive): our hypothesis was that a report would be more likely to cite another report that drew the same conclusion (supportive, contradictory or inconclusive). The interpretation of the results of an ERG model is similar to that of a logistic regression model and we expressed results in terms of odds ratios.

Third, we identified the most influential reports in the citation network by using a random walk approach (see Supplementary data, available at *IJE* online).[14] We assessed the likelihood that a supportive, contradictory or inconclusive report was among the most influential reports.

Co-authorship network analysis

We identified the authors of each report. First, we produced Lorenz curves showing the cumulative fraction of supportive, contradictory and inconclusive reports against the cumulative fraction of authors. In this analysis, we divided up the authorship credit for a report among all authors (e.g. each author on a three-author report was credited with a third of an authorship).

Second, we constructed an undirected network graph in which each node was an author and edges connected two authors who co-signed at least one report. Node size was proportional to the number of reports written by the author and edge width was proportional to the number of reports co-signed by the two authors.

Third, based on the classification of reports, we classified each author into three groups of positions, i.e. as being supportive, contradictory or inconclusive. We assessed the degree to which authors who co-signed at least two reports had similar positions. We estimated an homophily index as the number of co-authorships external to the groups minus the number of co-authorships internal to the groups divided by the total number of co-authorships.[15] The index ranges from −1 (homophily) to +1 (heterophily).

Agreement in primary study selection between systematic reviews

We assessed the agreement between systematic reviews as to which primary studies they included. We assessed which outcomes, which populations and which study designs were used in each study. We estimated the overall probability that, if a primary study was selected in a systematic review, another review would also select it.[16] Finally, we estimated the likelihood that a systematic review included a supportive, contradictory or inconclusive study, respectively. In this analysis, we considered multiple publications of the same report as unique.

Results

Characteristics of reports

We selected 269 distinct reports (Web Figure 1, available as Supplementary data at *IJE* online). Among these, 68 reported the results of 60 primary studies, 14 reported the results of 10 systematic reviews, 11 reported the conclusions of 9 clinical practice guidelines and 176 were comments, letters or narrative reviews (Table 1). A total of 148 (55%) reports were published in 2011 or after. In all: 146 (54%) of the reports were supportive of the hypothesis that population-wide reduction of sodium intake is associated with reduced cerebro-cardiovascular disease or all-cause mortality; 88 (33%) were contradictory of this hypothesis; and 35 (13%) were inconclusive.

Citation network analysis

Figure 1 shows the complex citation network corresponding to 2156 citations between the 269 reports, with 821.1 million citation paths supporting it. Half of the reports were cited 2 times or less whereas 10% of the reports were cited 25 times or more. Primary studies on average received 22 citations, systematic reviews 19 citations, guidelines 14 citations, and comments, letters, or reviews 4 citations.
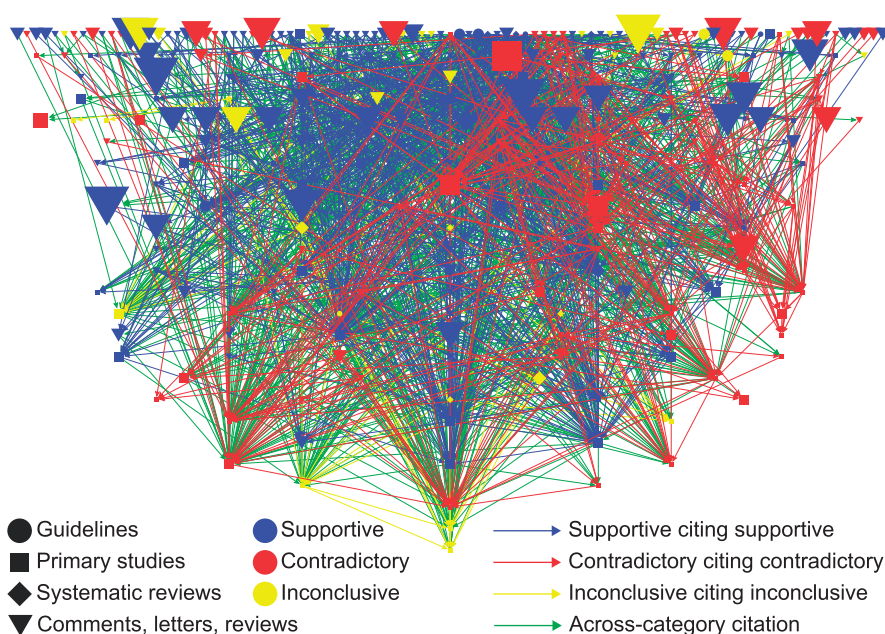
Figure 1. Citation network graph with 269 reports and 2165 citations. Each node is a report, and edges are directed from the citing report down to the cited report. Node shape indicates the type of report and node colour corresponds to the report classification (supportive, contradictory, inconclusive). Node size is proportional to journal impact factors. Any given report cannot cite a later report but only an earlier or concurrent report, thus there are no loops from a node back to itself. We organized the network into a depth partition of 25 hierarchical levels reflecting the emergent appearance of reports in citation paths. The top level corresponds to most recent reports that have not been cited yet. The deeper levels correspond to older reports. Sink nodes correspond to seed papers (i.e. the first to address the link between sodium intake and health outcomes). An exponential random graph model analysis showed that reports were 1.51 (95% CI 1.38 to 1.65, $P < 10^{-4}$) times more likely to cite a report that drew a similar conclusion (supportive, contradictory, or inconclusive).

Table 1. Characteristics of 269 reports

	All articles ($n = 269$)	Supportive[a] ($n = 146$)	Contradictory[a] ($n = 88$)	Inconclusive[a] ($n = 35$)
Type of article				
Primary study	68	27	34	7
Systematic review	14	5	3	6
Guideline	11	8	0	3
Comment, letter, review	176	106	51	19
Publication year[b]	2011 [1978–2014]	2011 [1992–2014]	2010 [1985–2014]	2012 [1978–2014]
Number of citations received[a]	2 [0–83]	2 [0–79]	1 [0–83]	2 [0–76]

[a]We classified reports as being supportive of the hypothesis that (population-wide) reduction of sodium intake was beneficial regarding all-cause mortality or cerebro-cardiovascular diseases, or contradictory of this hypothesis, or inconclusive.

[†]Median [min-max].

The distribution of citations received was similar between the three categories of reports (supportive, contradictory or inconclusive) (Web Figure 2, available as Supplementary data at *IJE* online). However, according to a multivariate exponential random graph model, reports were 1.51 (95% CI 1.38 to 1.65, $P < 10^{-4}$) times more likely to cite a report that drew a similar conclusion (supportive, contradictory or inconclusive), all other variables held constant (Table 2). Lastly, we identified 12 influential reports (Web Figure 3, available as Supplementary data at *IJE* online). Ten reported the results of primary studies and two of systematic reviews. There was not sufficient

evidence for an association between report conclusions and the likelihood of being influential (3%, 7% and 6% in supportive, contradictory and inconclusive reports, respectively, exact P-value = 0.23).

Co-authorship network analysis

We identified 643 distinct authors with a median of 3 authors per report. The production of reports was unbalanced: 25% and 28% of authors produced 75% of contradictory and supportive reports but 41% of authors produced 75% of inconclusive reports (Figure 2). We
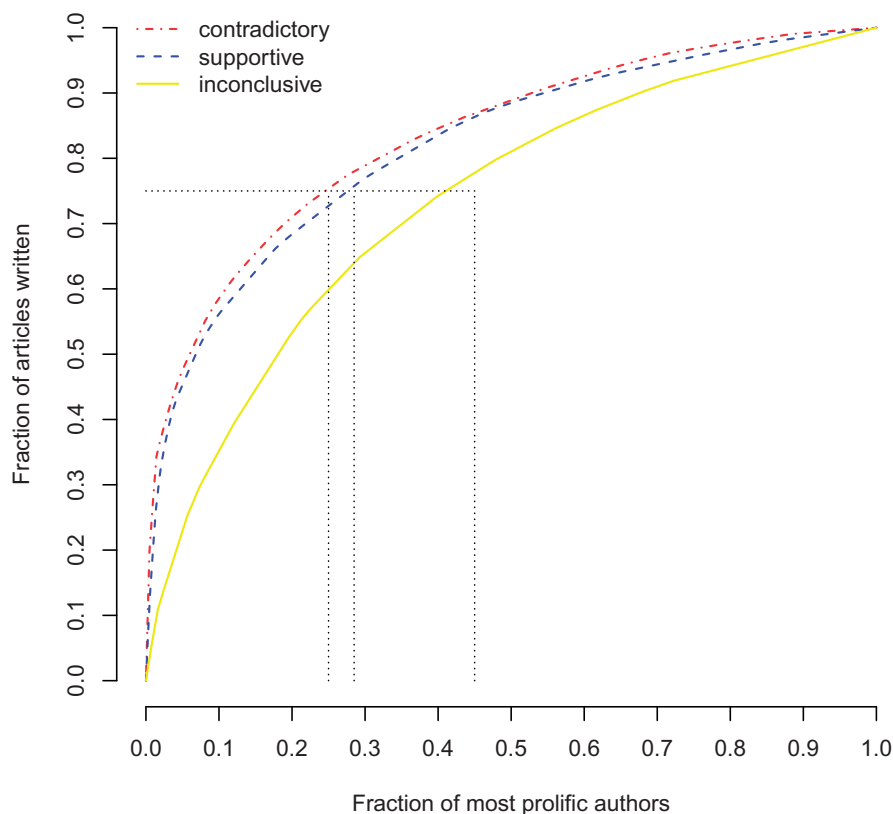
Figure 2. Fraction of reports written by the most prolific authors. The Lorenz curves show the cumulative fractions of supportive, contradictory and inconclusive reports against the cumulative fractions of authors. Credit for multi-author reports was divided among co-authors (e.g. each author on a three-author report was credited with a third of an authorship). The production of reports was unbalanced: 25% and 28% of authors produced 75% of contradictory and supportive reports but 41% of authors produced 75% of inconclusive reports, suggesting that few authors making strong arguments either supportive or contradictory of the salt hypothesis dominate the field, whereas authors whose findings are inconclusive appear more heterogeneous.

Table 2. Multivariate model explaining 2156 citation links among 269 reports

Terms[a]	Odds ratio (95% confidence interval)	P-value
Structural homophily (within-category citation)	1.51 (1.38–1.65)	$<10^{-4}$
Type of cited report		
Comment, letter, review	1	
Primary study	9.73 (8.71–10.86)	$<10^{-4}$
Systematic review	6.39 (5.39–11.53)	$<10^{-4}$
Guideline	3.65 (2.93–4.55)	$<10^{-4}$
Difference in publication year between citing and cited reports[b]	0.83 (0.80–0.86)	$<10^{-4}$
Difference in journal impact factor between citing and cited reports[c]	0.93 (0.89–0.97)	$<10^{-2}$

Results are expressed in terms of odds ratios. Reports were 1.5 times more likely to cite a report within the same category (i.e. supportive of the hypothesis that sodium intake reduction is beneficial, contradictory of this hypothesis or inconclusive), all other variables held constant. Systematic reviews were 6.4 times more likely to be cited than comments, letters, or reviews.

Model fit: AIC 12037 and BIC 12098 (smaller is better).

[a]The model included an edges term, which measures the structural density of citations. The estimated log-odds of any citation occurring was $=-1.74$ [standard error (SE) 0.10]. Thus, the probability of a citation was $1/[1 + \exp(1.74)] = 15.0\%$ (95% CI 12.7%–17.5%).

[b]Odds ratio associated with a difference of 5 years in publication year.

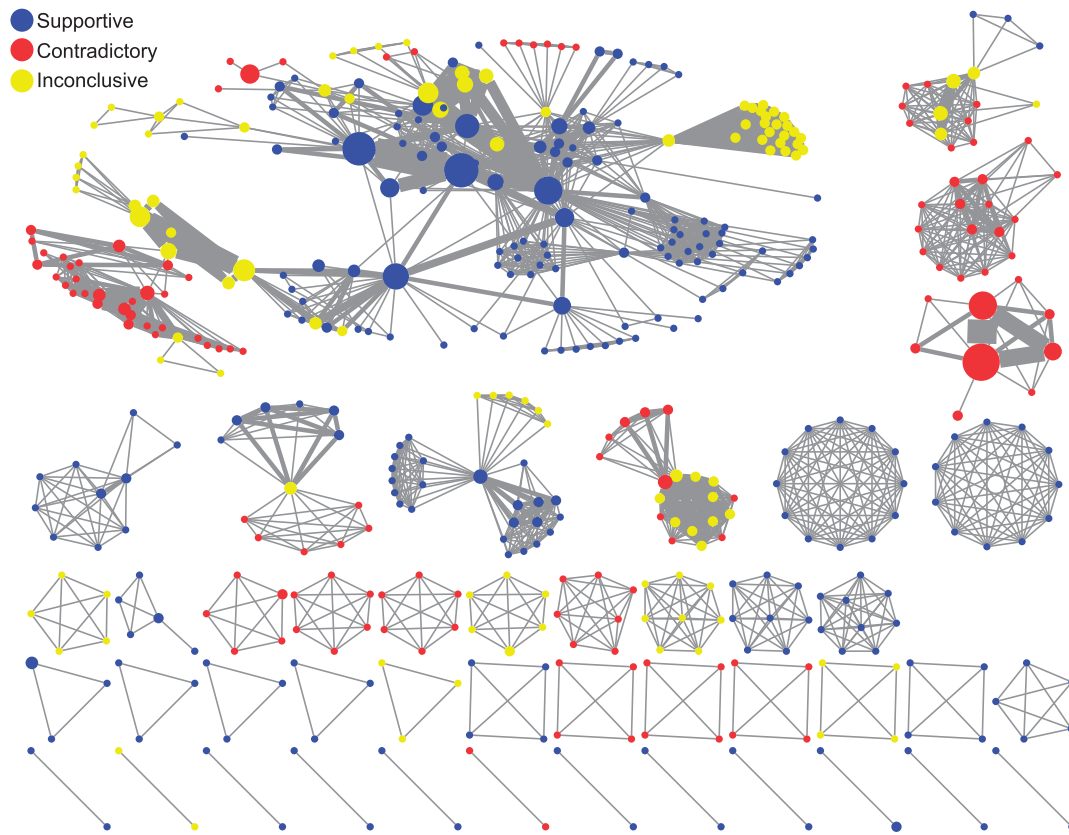[c]Odds ratio associated with a difference of 10 in journal impact factor.

Figure 3. Co-authorship network graph with 643 authors. Each node is an author and two nodes are connected when the corresponding authors co-signed at least one manuscript. Node colour indicates author classification (supportive, contradictory, inconclusive). Node size is proportional to the number of reports the corresponding author signed. Edge width is proportional to the number of reports the corresponding authors co-signed. Networks were drawn using the Harel-Koren Fast Multiscale algorithm. Disconnected network diagrams correspond to authors that never collaborated on manuscripts; in particular, diagrams at the bottom correspond to authors co-authoring a single report. However, the overall pattern showed a strong clustering of co-authorship, with few collaborations between authors holding different positions.

classified 337 authors as being supportive, 178 as being contradictory and 128 as being inconclusive. The network of co-authorship showed a strong clustering, with few collaborations between authors holding different positions (homophily index –0.67) (Figure 3).

Agreement in primary study selection between systematic reviews

Overall, the 10 systematic reviews included a total of 48 different primary studies (Figure 4). We identified six potentially eligible studies that were included in none of the systematic reviews and seven additional primary studies that were published after the date of last search of the most recent systematic review. There was poor agreement in primary study selection between the 10 systematic reviews (Web Figure 4A, available as Supplementary data at *IJE* online). The estimated probability that, if a study was selected by a review, a further review would also have selected it was 27.0% (95% CI 20.3% to 33.7%). The 48 selected studies had a wide range of study designs: 52%

were cohort studies and 27% were randomized trials. Of note, the estimated probability that, if a randomized trial was selected by a review, a further review would also have selected it was 15.0% (95% CI 7.2% to 22.9%). The studies included different populations: 35% were conducted in general population and 17% in heart failure population (Web Figure 4B, C). Across the 54 potentially eligible studies, the impact of sodium intake on all-cause mortality was reported in 33 (61%) studies, on cardiovascular mortality in 15 (28%), on cardiovascular diseases in 25 (46%) and on stroke in 21 (39%) (Web Figure 4D). In all, the average likelihood that a systematic review included a primary study was lower for primary studies that reached a contradictory rather than a supportive conclusion (22.6%, 30.7% and 25.5% for contradictory, supportive and inconclusive reports, respectively, $P = 0.18$) (Figure 4). Among the 10 systematic reviews, 4 reached a supportive conclusion, 3 reached a contradictory conclusion and 3 were inconclusive. On average, supportive systematic reviews were more likely to select supportive primary studies than other reviews (43.7% vs 23.0%, $P < 0.001$),
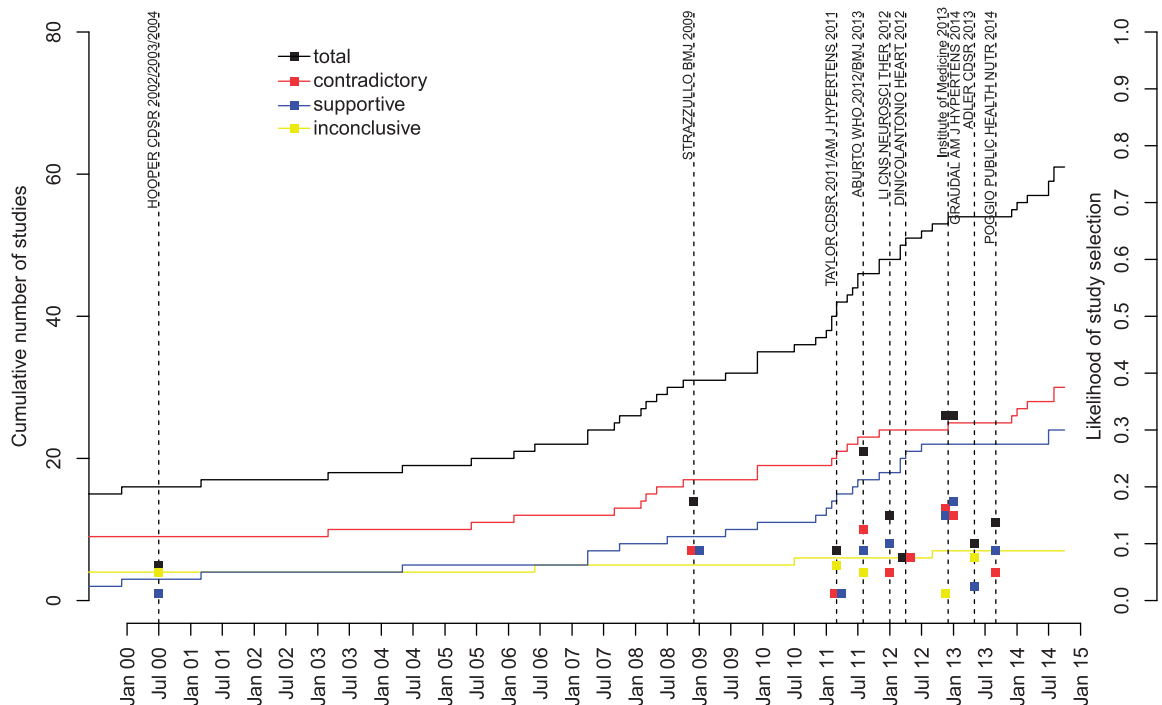
Figure 4. Patterns of primary study selection in 10 systematic reviews. The stair step graphs show the cumulative numbers of primary studies (randomized trials, cohort studies and case-control studies), according to their publication dates. The dotted vertical lines show the systematic reviews, according to the date of last search for primary studies. The squares show the numbers of primary studies selected in each review. For instance, Hooper *et al.* performed the last search in July 2000 and selected 5 primary studies out of 16 potentially eligible. Across the period, the evidence covered by systematic reviews was consistently incomplete: the systematic reviews included from 12% to 48% of primary studies eligible for inclusion. When stratifying by report classification (supportive, contradictory, inconclusive), the average likelihood that a systematic review included a primary study was lower for primary studies that reached a contradictory rather than a supportive conclusion (23%, 31% and 26% for contradictory, supportive and inconclusive reports, respectively, $P = 0.18$).

contradictory systematic reviews were more likely to select contradictory primary studies (41.5% vs 14.4%, $P < 0.001$) and inconclusive systematic reviews were more likely to select inconclusive primary studies (89.7% vs 5.3%, $P < 0.001$).

Discussion

Based on a systematic review of the literature, we documented a strong polarization of scientific reports on the link between sodium intake and clinical outcomes in populations, and a pattern of uncertainty in published systematic reviews. We found, first, that a majority of existing reports were supportive of the hypothesis but that a substantial minority were not. Second, we found substantial citation bias, where published reports preferentially cited previous reports that reached a similar conclusion. Third, the literature in the field was dominated by a few reports and by a few prolific authors, who each hold and repeat particular positions. Fourth, there was very little consistency in the selection of primary studies in systematic reviews, further compounding the challenges the field faces in achieving resolution.

Uncertainty is an important motivator of scientific work. However, it also tends to stifle action, particularly in fields such as public health where practitioners frequently are confronted by problems for which there is little relevant research evidence. The mandates of public health require decision makers to act in the absence of certitude in many, if not most, cases. Given the prominence of population-wide salt reduction as a cornerstone of global health policies to curb cardiovascular disease mortality, the case of salt reduction represents a particularly important example for examining how evidence and uncertainty inform, or do not inform, public health practice. Several modelling studies have concluded that the effects of reducing dietary salt intake on cardiovascular disease mortality, as mediated through blood pressure, would be considerable.[17–19] However, we found that the published literature bears little imprint of an ongoing controversy, but rather contains two almost distinct and disparate lines of scholarship, one supporting and one contradicting the hypothesis that salt reduction in populations will improve clinical outcomes.

We first mapped the salt controversy by connecting reports, through a citation network, in a dialogue of

supportive, contradictory and inconclusive statements. We found evidence of homophily on citation patterns, where authors who had a pro or con point of view were 50% more likely to cite papers with their point of view than the other point of view. We also mapped the controversy by re-attaching the statements to their authors and found marked clustering in existing networks of scientists. We interpret these finding as reflecting the sustained divide between opposing groups of scientists who differ in their interpretation of the data about whether population-wide salt reduction will improve population health. Part of the observed pattern may be explained by direct as well as co-author and collaborative self-citations.[24] The data are consistent with a picture where a few authors and a few key papers dominate the literature. These authors and publications make strong arguments either supportive or contradictory of the salt hypothesis. Those scientific voices whose findings are inconclusive appear more heterogeneous and are situated mainly on the outskirts of the dispute.

Previous studies have shown how citation practices can be biased towards positive, statistically significant findings or distorted by the amplification or avoidance of evidence.[20–23,25–27] Several authors have also discussed the selective citation of studies that support a given hypothesis or idea (viewpoint citation or unbalanced citation).[10,28–30] To our knowledge, our analytical approach is novel as it allows an empirical quantification of such polarization. Our application around the debate about reducing salt intake echoes other scientific controversies, such as the dispute around electronic cigarettes. It could be applicable to different areas of scientific controversy, and our analysis is intended to encourage such empirical investigations; it would be interesting to compare patterns of polarization for other controversial or, conversely, strongly consensual topics.

The citation bias we found was paralleled by considerable variation in the inclusion of primary evidence in systematic reviews addressing the effect of sodium intake on cardiovascular outcomes. We found that if a primary study was selected by a review, the chance that another review would also have selected it was less than a third; this probability was lower for randomized trials. This is a level of disagreement that goes beyond differences in selection criteria across reviews. This finding reflects ongoing uncertainty and disagreement about what should count as evidence. Some have previously questioned the role of randomized trials as the source of definitive evidence, and a recent review of the methodological quality of observational studies relating sodium to cardiovascular outcomes found that methodological defects, considered to have the potential to alter the direction of association, affected all 26 observational studies (except for one which showed a

null association).[31] Systematic reviews have the potential to provide the highest level of evidence. However, meta-analysts must cast a dispassionate eye over the literature. In our analysis, we found that the variation in the inclusion of primary evidence directly influenced the conclusions of systematic reviews and that the inclusion or exclusion of specific studies shaped the secondary evidence. This variation threatens the validity of the syntheses and reinforces existing uncertainty about the science that sustains the dispute. These findings have implications for the translation of conflicting, uncertain evidence into public health policy.[7,32,33] Both the misuse of uncertainty and the exaggeration of certainty can shape the outcomes of public health decision-making processes.

Although science has been acutely alert to potential financial conflicts of interest in recent decades[2,34–36] much less attention has been paid to other potential conflicts—particularly biases that are embedded in long-held beliefs that resist re-examination when new data become available.[37] It has previously been suggested that these conflicts of interest may be more powerful than financial consideration.[30,38] Our findings support a strong bias towards the status quo and the absence of a genuine scientific conversation where each side engages the other. The citation patterns underlying this particular debate suggest that the scientific community is not engaged in a collaborative effort to arrive at a data-informed consensus on the matter and instead appears to be divided into two silos. This pattern is worrisome when one considers how such a division may be perpetuated as future generations of researchers are brought up in one or another 'tradition', rendering the gap between the two 'sides' of the argument ever more difficult to bridge. In recognition of this problem, at least in the abstract, Osborne *et al.* proposed to give a central place to collaborative argumentation in the scientific educational process, to help students learn to argue based on available evidence and develop insight into how and why we know what we know.[39] Such an approach might contribute to greater clarity around difficult problems such as salt consumption and public health if a commitment to collaborative argumentation in science can be made.

Our analyses have limitations. First, we may have been missed some relevant reports, despite our search of a range of databases. In particular, we searched comments, letters and narrative reviews in MEDLINE only. We did not consider material from conferences, although some conference proceedings appeared in abstracts that we selected. In fact, we manually screened the reference lists of all reports. Consequently, it is unlikely that a relevant report, if cited, was left out of our claim-specific citation network. Second, our classification of reports as supportive, contradictory or inconclusive was based on conclusions that others may

interpret differently. However, we used explicit criteria for classification that was performed in duplicate by independent reviewers. As a consequence, the classification process was burdensome; natural language processing methods, especially supervised machine learning classification, may be used to reduce the amount of human review required to assess each article, so that the analysis method could be applied to a wider array of topics.[40,41] Third, citation does not mean endorsement and we did not assess if the cited reports were qualified either positively or negatively by the citing reports. The claim-specific citation network may be affected by other biases. For example, reports may have cited previous content in order to criticize its validity or reframe its meaning to divert its implications.[42] Last but not least, we do not here intend to 'take sides' in the salt debate: we neither endorse nor oppose the central hypothesis at hand. Our intention in this article was not to be part of the debate, and our findings should not be used to fuel it. Instead we aimed to better understand the production of scholarship underlying the controversy and, on the basis of a systematic review and quantitative analyses, to try to lay bare and begin to unravel the challenges underlying the dispute.

Supplementary Data

Supplementary data are available at *IJE* online.

Authors' contributions

L.T. and S.G. contributed to the conception and design, to the acquisition of data, and to the analysis and interpretation of data. D.M.J. contributed to the analysis and interpretation of data. L.T. and S.G. drafted the article and D.M.J. revised it critically for important intellectual content. All authors approved the version to be published.

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