

APPLICATION

Facilitating systematic reviews, data extraction and meta-analysis with the METAGEAR package for R

Marc J. Lajeunesse*

Department of Integrative Biology, University of South Florida, 4202 East Fowler Avenue, Tampa, FL 33620, USA

Summary

1. The R package ecosystem is rich in tools for the statistics of meta-analysis. However, there are few resources available to facilitate research synthesis as a whole.
2. Here, I present the METAGEAR package for R. It is a comprehensive, multifunctional toolbox with capabilities aimed to cover much of the research synthesis taxonomy: from applying a systematic review approach to objectively assemble and screen the literature, to extracting data from studies, and to finally summarize and analyse these data with the statistics of meta-analysis.
3. Current functionalities of METAGEAR include the following: an abstract screener GUI to efficiently sieve bibliographic information from large numbers of candidate studies; tools to assign screening effort across multiple collaborators/reviewers and to assess inter-reviewer reliability using kappa statistics; PDF downloader to automate the retrieval of journal articles from online data bases; automated data extractions from scatter-plots, box-plots and bar-plots; PRISMA flow diagrams; simple imputation tools to fill gaps in incomplete or missing study parameters; generation of random-effects sizes for Hedges' d , log response ratio, odds ratio and correlation coefficients for Monte Carlo experiments; covariance equations for modelling dependencies among multiple effect sizes (e.g. with a common control, phylogenetic correlations); and finally, summaries that replicate analyses and outputs from widely used but no longer updated meta-analysis software.
4. Research synthesis practices are vital to many disciplines in the sciences, including ecology and evolutionary biology, and METAGEAR aims to enrich the scope, quality and reproducibility of what can be achieved with the systematic review and meta-analysis of research outcomes.

Key-words: data extraction and retrieval, effect sizes, meta-analysis, MetaWin, quantitative reviews, research synthesis, systematic review

Introduction

Critical goals to research synthesis practices are to generate robust, aggregate views of accumulated research findings (Hunter & Schmidt 2004), and to explore sources of variability in that research (Lajeunesse 2010; Jennions, Lortie & Koricheva 2013a). Ideally, these goals are achieved by pairing systematic review methods with the statistics of meta-analysis to yield high-quality syntheses. For example, a systematic review is first used to carefully plan and implement a strategy to locate studies, assess their eligibility and extract relevant research findings in a repeatable and transparent way (Khan *et al.* 2003; Pullin & Stewart 2006). A meta-analysis is then used to statistically model sources of variability within and between studies with the aim to quantitatively weight and aggregate their findings (Koricheva, Gurevitch & Mengersen 2013). Although this taxonomy of practices is meant to produce scientifically explicit and defensible overviews of research, it is also accompanied by a variety of implementation challenges. For example, the number and complexity of tasks involved in

generating a high-quality synthesis require a diverse combination of software tools – which are numerous and growing due to broad interdisciplinary interests in research synthesis (reviewed by Schmid *et al.* 2013). This diversity of tools can reduce efforts to make synthesis more repeatable and transparent, given that it can yield mixed standards for solving common problems with the screening, extraction and analysis of study outcomes (Bayliss & Beyer 2015).

Here, I introduce METAGEAR, an R package aimed at improving the reproducibility of systematic reviews and meta-analysis. It is a comprehensive toolbox that spans the entire research synthesis taxonomy, and supports a large diversity of functionalities to help screen abstracts, download articles, extract data from figures and model dependencies within and among effect sizes, and various other tools to improve the quality of statistics used in meta-analysis (Table 1). It is also meant to assist with the management of large collaborative projects by offering tools to help distribute work effort and to assess the reliability of that effort (Cohen 1960). Much of METAGEAR's toolbox arose from teaching research synthesis and participating in large projects where tasks are often distributed among multiple individuals with various skill sets, experience, access to

*Correspondence author. E-mail: lajeunesse@usf.edu

Table 1. A sample of the R functions available in METAGEAR grouped by research synthesis taxonomy

Function	Description
Systematic review	
<code>abstract_screener()</code>	A GUI for vetting the titles and abstracts of study references
<code>effort_distribute()</code>	Distributes screening and extraction effort randomly and evenly among the reviewing team
<code>effort_merge()</code>	Combines effort from collaborative screening jobs and calculation of inter-reviewer agreement based on Cohen's kappa
<code>plot_PRISMA()</code>	Generates a flow diagram of the phases of a systematic review
Data retrieval and extraction	
<code>PDFs_collect()</code>	Automatically fetches PDFs using the DOI of multiple journal references
<code>figure_scatterPlot()</code>	Extracts data points from a scatter-plot figure image
<code>figure_boxPlot()</code>	Extracts means and error bars from a box-plot figure image
<code>figure_barPlot()</code>	Extracts means and error bars from a bar-plot figure image
<code>figure_add()</code>	Adds points manually to a figure image
Modelling effect sizes	
<code>impute_SD()</code>	Imputes missing standard deviations (SDs) using coefficient of variation of complete data or based on resampling techniques
<code>covariance_commonControl()</code>	Estimates the VCV matrix for multiple effect sizes with a common control
<code>covariance_multivariate()</code>	Estimates the VCV matrix based on a correlation matrix for multivariate effects
<code>random_d()</code>	Generates random-effect sizes based on Hedges' <i>d</i> or Cohen's <i>g</i>
<code>random_RR()</code>	Generates random log response ratios (RRs)
<code>random_r()</code>	Generates random Pearson product-moment correlation coefficients (<i>rs</i>)
<code>random_OR()</code>	Generates random log odd ratios (ORs)
Meta-analysis	
<code>replicate_MetaWin2.0()</code>	Duplicates the results and output of a meta-analysis performed by METAWIN 2.0 (Rosenberg, Adams & Gurevitch 2000)
<code>replicate_phyloMeta1.3()</code>	Replicates the results and output of traditional and phylogenetic meta-analyses performed by PHYLOMETA (Lajeunesse 2011b)
<code>MA_effectsTable()</code>	Generates an ANOVA-like-effects table first described by Hedges & Olkin (1985)
<code>effects_powerAnalysis()</code>	Computes the statistical power of a pooled effect size or Q-statistic

different computing platforms (e.g. Windows and Mac), and not having a single dedicated source that everyone could freely and remotely use to accomplish tasks. Given that clarity and repeatability are central themes to research synthesis, I hope that by packaging all these functionalities into a single source, I can set the groundwork for large and collaborative synthesis projects, as well as provide a standardized theatre for teaching systematic reviews and meta-analysis. Below, I outline stage-by-stage how METAGEAR facilitates research synthesis projects and promotes repeatability in their practices. As a complement to this outline, I also provide an R vignette with illustrative examples as Appendix S1.

SCREENING ABSTRACTS, DELEGATING TASKS AND RETRIEVING ARTICLES

Identifying candidate studies is one of the first key stages in a systematic review. However, literature searches with bibliographic data bases such as Web of Knowledge or Google Scholar will generate thousands of study references – this is unavoidable given that search terms should aim to yield the most inclusive results (see Curtis *et al.* 2013). The challenge here is that the title and abstract of all of these references need to be screened as a first attempt to sift those that are relevant for the synthesis project. There are already several options to help assist in reference screening and coding (i.e. tagging which to exclude/include). Reference-managing software such as Endnote or Mendeley can be shoehorned for this purpose (see

King *et al.* 2011). There are also dedicated subscription-based screeners such as COVIDENCE (<https://www.covidence.org>) and DISTILLERSR (<http://distillercer.com>), and some even try to automate the screening process using machine learning (ABSTRACTR; Wallace *et al.* 2012). METAGEAR also supports an easy-to-use GUI screener to assist with the screening and coding of references (see Table 1 and Fig. 1). To help avoid potential selection bias based on the author, journal or year of the study (see Jennions *et al.* 2013b), the GUI offers only the title and abstract as the sole appraisal criteria for inclusion/exclusion (Fig. 1).

If screening tasks are to be delegated across a research team, METAGEAR supports collaborative tools (see Table 1) that can randomly divide study references among members evenly or unevenly (i.e. assigning more work to some and less to others) and generate dual-screening designs where two members independently code the same reference subset to evaluate the repeatability or consistency of screening tasks (also known as inter-reviewer agreement). Each member can then work remotely on their reference subset using the abstract screener. Screening tasks can also be redistributed should screening commitments change (or if team members fall behind, and it will happen!), and the teams' progress can finally be combined and summarized (see example of this workflow in the Appendix S1). For example, `effort_summary()` will calculate Cohen's (1960) kappa (*K*) to assess inter-reviewer agreement if a dual-reviewing design was implemented. Here is an example of this summary

based on the efforts from a screening exercise of 479 abstracts completed in my research synthesis course:

```

=== SCREENING EFFORT SUMMARY ===
149 candidate studies identified
141 studies excluded
189 studies with conflicting agreement needing
additional screening
—
479 TOTAL SCREENED
=== DUAL SCREENING DESIGN SUMMARY ===
    
```

Team_A	MAYBE	NO	YES	TOTAL	%	Team_B	MAYBE	NO	YES	TOTAL	%	Cohen's K
Bryan	27	44	27	98	20.46	Neal	11	44	43	98	20.46	0.2899 (fair)
Keith	15	28	56	99	20.67	Nick	10	52	37	99	20.67	0.3371 (fair)
Jake	20	28	51	99	20.67	Ashley	5	38	56	99	20.67	0.452 (moderate)
Neiman	1	57	41	99	20.67	Jeremy	11	53	35	99	20.67	0.5546 (moderate)
Marc	19	23	42	84	17.54	Jason	12	41	31	84	17.54	0.3585 (fair)
TOTAL	82	180	217	479	100.00	TOTAL	49	228	202	479	100.00	

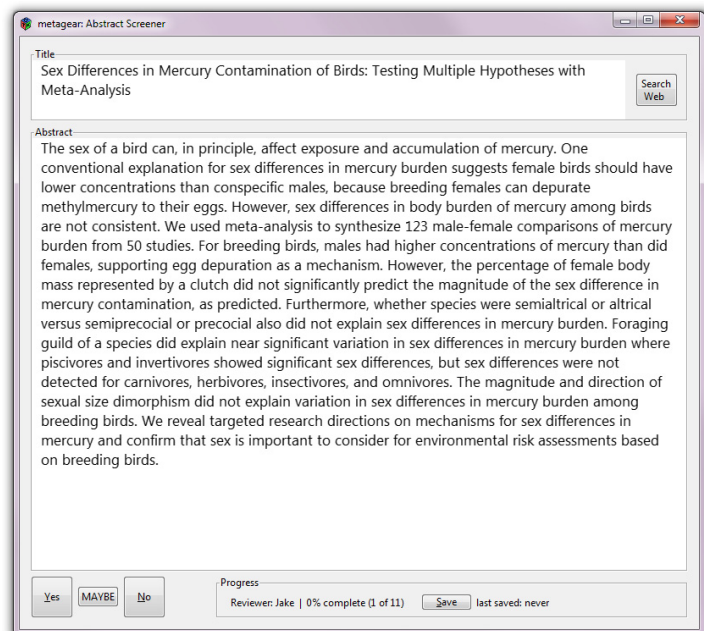
The magnitude of Cohen’s kappa is also scored following Landis & Koch’s (1977) interpretation ‘benchmarks’ ranging from poor (<0.0), slight (0.0–0.2), fair (0.21–0.4), moderate (0.41–0.6), substantial (0.61–0.8), to almost perfect inclusion/exclusion agreement (0.81–1.0). References with disagreements for inclusion/exclusion should be discussed and rescreened by the team. In the example above, one of the reasons for the high disagreement was failure to establish clearly defined inclusion criteria prior to screening efforts. Curtis *et al.* (2013) provide helpful guidelines to avoid this issue by developing an explicit protocol for assessing the inclusion and exclusion of studies.

Once all study references have been screened, the next stage is to retrieve their full texts. This is tedious when there are hundreds or thousands of studies to collect. Here, METAGEAR

can be used to automate the download of these studies (Table 1). Much like the reference-managing software ENDNOTE, METAGEAR’s downloader uses the DOI (digital object identifier) of each bibliographic entry as a starting point to fetch PDFs online. Note that the DOIs of published articles are readily available and are often included when references are exported from bibliographic data bases (e.g. Web of Knowledge). Following the DOI link, the downloader then uses publisher-tailored HTML searches to identify PDFs to download – these *ad hoc* searches are necessary due to the lack

of standardized access to e-journals. It is important to note that the success of these downloads will be conditional on the journal subscription coverage of the host institution running METAGEAR. However, this limitation can be harnessed to assess subscription or availability bias when collating studies from different types of institutions or countries. Another benefit of automating downloads is that it standardizes the file name of each downloaded PDF. The filenames of PDFs from online journals are often uninformative or cryptic, and having a standardized name (such as the unique study ID of each reference) will later help speed up the retrieval of documents for data extractions. Finally, it is also necessary to emphasize that the downloader is only meant to expedite the gathering of PDFs from published journal articles; the downloaded files will be incomplete, and additional (manual) effort will still be needed

Fig. 1. The GUI from the `abstract_screener()` function to help sieve and code the references of candidate studies for systematic reviews and meta-analysis. Sometimes bibliographic data bases such as Web of Knowledge will not have complete bibliographic information for a journal article (e.g. DOI, abstract), and the title-to-browser button is meant to quickly search for this information on Google. The GUI also includes a progression tracker for the number of abstracts screened, as well as a button to save screening progress.



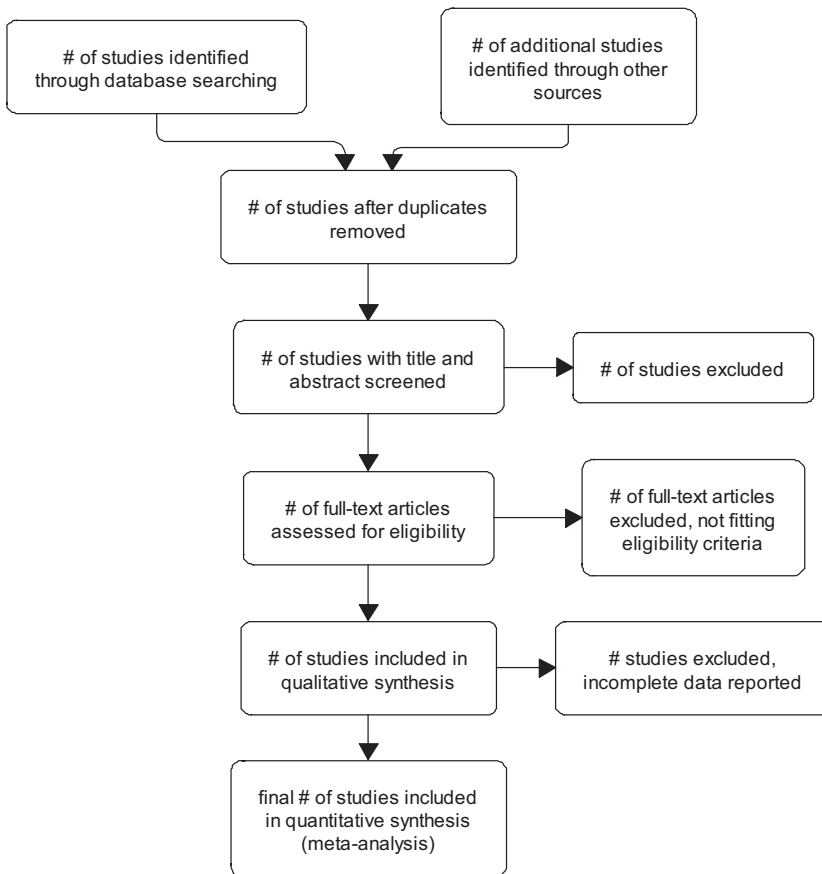


Fig. 2. An example of a PRISMA flow diagram generated by the `plot_PRISMA()` function.

to acquire all the full texts (e.g. articles that could not be downloaded, book chapters, dissertations). However, any download failure will get coded and summarized to further help locate these missing texts (see Appendix S1).

Finally, it is often useful to record and present each phase of the screening process and number of studies included and excluded in the final meta-analysis with a PRISMA diagram (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; see Moher *et al.* 2009). The `plot_PRISMA()` function can be used to quickly generate and update flow diagrams as each phase or stage gets completed. For example, below is the R script to generate the plot presented in Fig. 2:

```

phases c("START_PHASE: # of studies identified
through database searching",
"START_PHASE: # of additional studies identified
through other sources",
"# of studies after duplicates removed",
"# of studies with title and abstract screened",
"EXCLUDE_PHASE: # of studies excluded",
"# of full-text articles assessed for eligibility",
"EXCLUDE_PHASE: # of full-text articles excluded,
not fitting eligibility criteria",
"# of studies included in qualitative synthesis",
"EXCLUDE_PHASE: # studies excluded, incomplete data
reported",
"final # of studies included in quantitative
synthesis (meta-analysis)")
plot_PRISMA(phases)

```

EXTRACTING AND IMPUTING DATA

Extracting data from studies to calculate effect sizes (a common currency that quantitatively summarizes the magnitude and sign of study outcomes) is by far the most difficult and time-consuming stage of the entire research synthesis process. It is a manual activity where researchers must read and interpret the text/tables/figures of each study with the goals of unearthing all the quantitative data needed to calculate effect sizes (such as sample sizes, means; Hedges 1981; Lajeunesse & Forbes 2003), and all the qualitative/quantitative information needed to establish moderator groups and annotations useful for hypothesis testing and quality control (see Koricheva, Gurevitch & Mengersen 2013). This activity is never straightforward, and there are many challenges that can make studies nearly impenetrable for data extractions.

A particularly challenging task is extracting or reverse engineering the plotted data from published figures. Although there are many options to help extract data available only in graphical form, such as general image manipulation software (i.e. MS POWERPOINT, MS PAINT), image software with specialized plug-ins (IMAGEJ; Abramoff, Magelhaes & Ram 2004), or dedicated data extraction software such as DATATHIEF (Tummers 2006) or GRAPHCLICK (In Neuchatel 2008), these tools are often not cross-platform and can be poorly documented. Further, none of these are tailored with research synthesis in mind. METAGEAR offers manual and automated tools to help extract numerical data

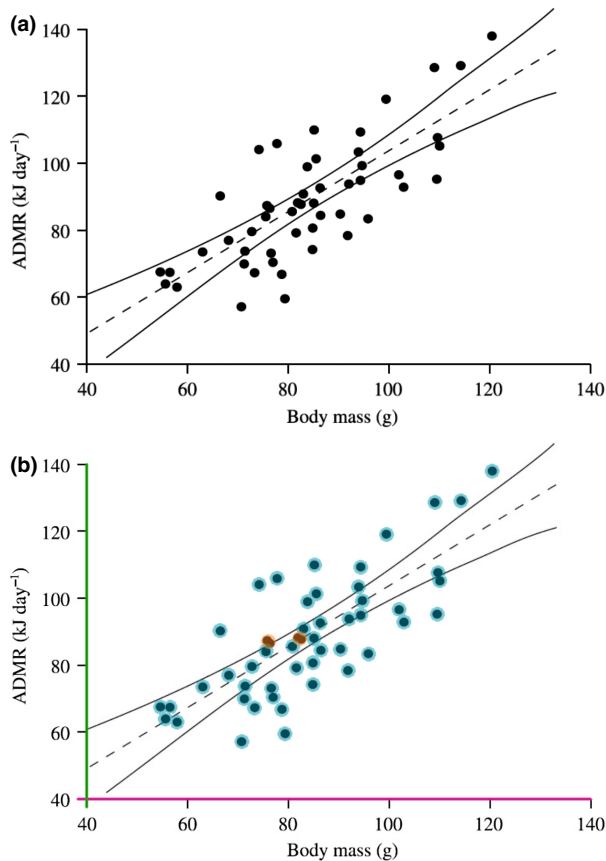


Fig. 3. An example of automated data extractions using METAGEAR from a figure image using `figure_scatterPlot()`. The top panel (a) is the original figure reported by Kam *et al.* (2003; Fig. 2). The bottom panel (b) contains the detected objects on that figure: blue circles are the detected points, orange circles are clusters of points that could not be separated, green vertical line is the detected Y-axis, and the pink horizontal line is the detected X-axis. These detected objects are used to estimate the regression line and correlation coefficient of the points depicted in the image.

from scatter-plot, box-plot and bar-plot figures. Below is a worked example where I use METAGEAR to extract the plotted points from Fig. 2 of Kam *et al.*'s (2003) study on predictors of metabolic rates in mice (this figure is reprinted here as Fig. 3a). Kam *et al.*'s (2003) study also reports the regression coefficients and R^2 of this plot. I will compare these reported values with those estimated by METAGEAR (the original published results were as follows: $Y = 12.03 + 0.907 * X$ with an $R^2 = 0.59$ and a sample size of $N = 51$).

I first obtained an image of the figure directly from the article's PDF with a screenshot, then cropped it to include only the figure itself and its axes and finally saved it as a JPG (file name: "Kam_et_al_2003_Fig 2.jpg"; see Fig. 3a). Obtaining an image directly from a PDF is often preferred over images provided by online HTML articles as they tend to be higher quality and can be resized without quality loss. High image quality will improve the success of automated data extractions as it increases the detection and separation of points and axes (Pau *et al.* 2010). The function `figure_scatterPlot()` can then be used to extract the data from the image as follows:

```
> figure_scatterPlot("Kam_et_al_2003_Fig2.jpg")
```

The default use of this function will plot a raster image of all the detected axes and scatter-plot points (see Fig. 3b), return an R data frame of the estimated X and Y data from this plot (which can be analysed, plotted, saved or rescaled) and print to console the following regression summary and estimated effect size and variance (here the effect size is Pearson's r correlation coefficient):

```
regression fit: Y = 11.92586 + 0.9077 * X, R-squared = 0.59498
Pearsons r = 0.7713478, var(r) = 0.0034903, N = 49
```

The extracted regression parameters are very similar to what was reported by Kam *et al.* (2003).

However, note that `figure_scatterPlot()` was unable to separate two clusters of points on the reported figure. These clusters are emphasized in orange (see Fig. 3b), and although not shown, they were also coded along with the X and Y data frame of the extracted data. This is also why the sample size of the extracted regression was $N = 49$ and not 51 as reported by Kam *et al.* (2003). I could not find any established guidelines on how to treat clusters of points that cannot be separated within a figure, but given that this issue will be common for scatter-plots with high N and data densities, METAGEAR supports two options. First, it will automatically treat a cluster as a single point based on the centroid of that cluster. This is perhaps analogous to imputing the missing points with a single estimate based on the average X and Y within that cluster. In the example above, this imputation of clusters yielded a very similar regression outcome as those reported in the original study. Secondly, METAGEAR also offers a way to manually interpolate individual points within a plot with the `figure_addPoints()` function. Here, the user essentially points and clicks on the figure to add points not detected by the extraction algorithm. As a final point, the defaults of `figure_scatterPlot()` are optimized for images of size ca. 650 by 650 pixels; tweaking the default parameters such as axis-bar thickness and point size will be necessary for successful extractions from images outside this size range (see examples in Appendix S1).

Another common challenge when extracting data from studies is when crucial information for computing effect sizes is neither found nor reported in the study – such as the variances, standard deviations (SDs) or standard errors (SEs). This is a widespread barrier for calculating effect sizes (Lajeunesse & Forbes 2003), but one common workaround is to use conversions or alternative formulations of effect sizes to compute effects (reviewed by Lipsey & Wilson 2001; Lajeunesse 2013a). A large diversity of conversions are available (i.e. converting t - or F -tests to Hedges' d), and many are offered by the `COMPUTE.E.S.R` package (Del Re 2012) and Lipsey & Wilson's (2001) companion website: http://www.campbellcollaboration.org/resources/effect_size_input.php. When conversions are not possible, METAGEAR supports a few simple imputation

approaches that can be used to fill gaps in missing SDs (see Table 1). These imputation tools were outlined by Lajeunesse (2013a) and either involve estimating the coefficient of variation from the (complete) observed data or rely on resampling approaches to fill gaps. Therefore, as a caveat to their use and success, these imputation tools should only be applied when data extractions from all studies have been completed. These SD imputation tools include Bracken's (1992) method for filling missing information using the coefficient of variation from all studies with complete information. METAGEAR also provides two variations on Rubin & Schenker's (1991) 'hot deck' imputation approach. The first is a strictly random hot deck imputation where SDs are imputed using all the observed SDs, while the other imputes only SDs that are nearest neighbours relative to their means (i.e. impute SDs from data with means of similar scale).

MODELLING EFFECT SIZES AND DEPENDENCIES

There is considerable interest in modelling dependencies within and among effect sizes for meta-analysis (Gleser & Olkin 1994; Curtis & Queenborough 2012). Dependent effect sizes violate some of the most basic assumptions of statistics, and the goal is to minimize inferential errors when hypothesis testing with meta-analysis (Lajeunesse 2009; Mengersen, Jennions & Schmid 2013). Dependencies can range from using shared information to calculate multiple effect sizes, to modelling effect sizes in a phylogenetic context. METAGEAR supports a broad diversity of tools to calculate covariances and variance-covariance matrices for dependent effect sizes (Table 1). One pervasive form is when multiple effect sizes share data from a common control group (see example in Lajeunesse 2011a). METAGEAR offers the covariance equations needed to model this common-control problem for all the major effect size metrics (e.g. Hedges' d , log response ratio, odds ratio, correlation coefficient) and will also generate the variance-covariance matrices needed to integrate these covariances into meta-analysis using the METAFOR R package (Viechtbauer 2010). An example of this application is found in the Appendix S1. Similarly, phylogenetic dependencies assuming simple Brownian motion models of phenotypic evolution can be modelled in METAGEAR similar to analyses

produced by console program PHYLOMETA (Lajeunesse 2011b; Chamberlain *et al.* 2012; Lajeunesse, Rosenberg & Jennions 2013). Finally for Monte Carlo modelling, METAGEAR has random number generators for several of the major effect size metrics used in meta-analysis (Table 1). These generators create random-effect sizes by sampling their known probability distribution when possible (e.g. non-central t -distribution for Hedges' d) or generate random study parameters (i.e. means, SD and N) that can be used to compute random-effect sizes.

META-ANALYSIS AND THE REPRODUCIBILITY OF SYNTHESSES

The most basic goals of meta-analysis software are to provide weighted regression tools for combining and comparing effect sizes (i.e. with the inverse variance of each effect size as weights; Hedges & Olkin 1985), and to model sources of statistical heterogeneity among effect sizes that exist beyond sampling error, such as the between-study variance (τ^2) component of random-effects models (Higgins & Thompson 2002). Ecologists and evolutionary biologists have historically relied heavily on METAWIN (Rosenberg, Adams & Gurevitch 2000) to meet these statistical goals. With more than 950 published applications to date (Google Scholar: 7/08/15), and with nearly 25% of these from the last 2 years alone (2013–2015), there is also little evidence that this software is losing traction among users. This popularity is also remarkable considering the availability of more sophisticated meta-analysis software, such as COMPREHENSIVE META-ANALYSIS (reviewed by Schmid *et al.* 2013) and the free OPENMEE (Wallace *et al.* 2015), as well as the METAFOR R package which now dominates the statistical analyses of many disciplines (Viechtbauer 2010). There is a lot that could be said about creating easy-to-use, GUI-driven, discipline-tailored software such as METAWIN.

Unfortunately, METAWIN is no longer maintained (last updated in 2007), and it is important that analyses from this software can be reproduced for historical compatibilities as new statistical developments and practices emerge. Further, duplicating the analyses of METAWIN may not be straightforward in R given that some of its statistical approaches were

```

theData <- read.csv(file = "effect.dta", header = TRUE)
replicate_MetaWin2.0(Effect ~ 1, weights = Var, data = theData)

=== START of Rosenberg et al. (2002) metaWin 2.0 output ===

Estimate of pooled variance: 0.243866

SUMMARY RESULTS
-----
Heterogeneity      df      Prob(Chi-Square)
-----
Qtotall 28.729215  29      0.47923

Mean Effect Size      95% CI      Bootstrap CI      Bias CI
-----
E++ 0.916966      0.621266 to 1.212667  0.622620 to 1.196920  0.606058 to 1.187931

Sqrt Pooled Variance = 0.493828
Mean Study Variance = 0.5015 Ratio = 0.984702
-----

=== END of Rosenberg et al. (2002) MetaWin 2.0 output ===

```

never fully documented. For example, it uses a *t*-distribution to estimate 95% confidence intervals and sums of squares of regression models as Q-tests (following Hedges & Olkin 1985) applies a DerSimonian & Laird (1986) approach to estimating τ^2 , and when a moderator variable is included in a random-effects analysis, it recycles the τ^2 from that model to estimate an overall (grand mean) pooled effect size. The function `replicate_MetaWin2.0()` aims to duplicate these statistical approaches and the way they were reported. Below, using one of the original data sets ‘effect.dta’ packaged with METAWIN 2.0, is the output from a random-effects meta-analysis based on this R function:

Conclusions and prospectus

Looking to the future, there is still room to grow in terms of developing tools for research synthesis – such as automating PDF annotations, text-mining tools to enhance data retrieval and extraction, methods to estimate statistical power (Lajeunesse 2013b), multiple-imputation tools (Lajeunesse 2013a; Ellington *et al.* 2015) and better approaches to assess publication bias. There is also a continuing need to improve how synthesis results and meta-analytic outcomes are presented and reported in research articles (Lortie *et al.* 2015). Transparency and clarity are also crucial to strengthen the repeatability of synthesis findings, but are also necessary to improve the second-order analysis of these synthesis-level outcomes (Hunter & Schmidt 2004). Finally, given the often overwhelming interdisciplinary nature of research synthesis methods, I hope that by offering a single dedicated source for all these tools, I can facilitate the training, education and adoption of these diverse methodologies and elevate the standards and practices of what can be achieved by ecologists and evolution biologists with these tools.

Acknowledgements

I thank J. Richardson, J. Zydek, N. Ogburn, B. MacNeill, J. Zloty and three anonymous reviewers for comments and suggestions. I also thank my colleagues in the OPENMEE software team, J. Gurevitch and B. Wallace, for persuading me to develop tools in R. Funding was supported by NSF grants DBI-1262545 and DEB-1451031.

Documentation and availability

The website and updated vignettes (Appendix S1) for METAGEAR can be found at <https://lajeunesse.myweb.usf.edu>. Documentation and source code are freely available on CRAN (<http://cran.r-project.org/web/packages/metagear>) and GITHUB (<https://github.com/cran/metagear>).

References

- Abramoff, M.D., Magelhaes, P.J. & Ram, S.J. (2004) Image processing with ImageJ. *Biophotonics International*, **11**, 36–42.
- Bayliss, H.R. & Beyer, F.R. (2015) Information retrieval for ecological syntheses. *Research Synthesis Methods*, **6**, 136–148.
- Bracken, M.B. (1992) Statistical methods for analysis of effects of treatment in overviews of randomized trials. *Effective Care of the Newborn Infant* (eds J.C. Sinclair & M.B. Bracken), pp. 13–20. Oxford University Press, Oxford.
- Chamberlain, S.A., Hovick, S.M., Dibble, C.J., Rasmussen, N.L., Van Allen, B.G., Maitner, B.S. *et al.* (2012) Does phylogeny matter? Assessing the impact

- of phylogenetic information in ecological meta-analysis. *Ecology Letters*, **15**, 627–636.
- Cohen, J. (1960) A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*, **20**, 37–46.
- Curtis, P.S. & Queenborough, S.A. (2012) Raising the standards for ecological meta-analysis. *New Phytologist*, **195**, 279–281.
- Curtis, P.S., Mengersen, K., Lajeunesse, M.J., Rothstein, H.R. & Stewart, G.B. (2013) Extraction and critical appraisal of data. *Handbook of Meta-Analysis in Ecology and Evolution* (eds J. Koricheva, J. Gurevitch & K. Mengersen), pp. 52–60. Princeton University Press, Princeton.
- Del Re, A.C. (2012) R package “compute.es”. Available at: <http://cran.rproject.org/package=compute.es> [accessed 30 December 2014].
- DerSimonian, R. & Laird, N. (1986) Meta-analysis in clinical trials. *Controlled Clinical Trials*, **7**, 177–188.
- Ellington, E.H., Bastille-Rousseau, G., Austin, C., Landolt, K.N., Pond, B.A., Rees, E.E., Robar, N. & Murray, D.L. (2015) Using multiple imputation to estimate missing data in meta-regression. *Methods in Ecology and Evolution*, **6**, 153–163.
- Gleser, L.J. & Olkin, I. (1994) Stochastically dependent effect sizes. *The Handbook of Research Synthesis* (eds H.M. Cooper & L.V. Hedges), pp. 339–355. Russell Sage Foundation, New York.
- Hedges, L.V. (1981) Distribution theory for Glass’s estimator of effect size and related estimators. *Journal of Educational Statistics*, **6**, 107–128.
- Hedges, L.V. & Olkin, I. (1985) *Statistical Methods for Meta-Analysis*. Academic Press, New York, NY, USA.
- Higgins, J.P.T. & Thompson, S.G. (2002) Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*, **21**, 1539–1558.
- Hunter, J.E. & Schmidt, F.L. (2004) *Methods of Meta-Analysis: Correcting for Error and Bias in Research Findings*. Sage, Newbury Park.
- In Neuchatel, C.H. (2008). *GraphClick* (Version 3.0). Arizona-Software. Available at: <http://www.arizona-software.ch> [accessed 30 December 2014].
- Jennions, M.D., Lortie, C.J. & Koricheva, J. (2013a) Using meta-analysis to test ecological and evolutionary theory. *Handbook of Meta-Analysis in Ecology and Evolution* (eds J. Koricheva, J. Gurevitch & K. Mengersen), pp. 381–403. Princeton University Press, Princeton.
- Jennions, M.D., Lortie, C.J., Rosenberg, M.S. & Rothstein, H.R. (2013b) Publication and related biases. *Handbook of Meta-Analysis in Ecology and Evolution* (eds J. Koricheva, J. Gurevitch & K. Mengersen), pp. 207–236. Princeton University Press, Princeton.
- Kam, M., Cohen-Gross, S., Khokhlova, I.S., Degen, A.A. & Geffen, E. (2003) Average daily metabolic rate, reproduction and energy allocation during lactation in the Sundeval jird *Meriones crassus*. *Functional Ecology*, **17**, 496–503.
- Khan, K.S., Kunz, R., Kleijnen, J. & Antes, G. (2003) Five steps to conducting a systematic review. *Journal of the Royal Society of Medicine*, **96**, 118–121.
- King, R., Hooper, B. & Wood, W. (2011) Using bibliographic software to appraise and code data in educational systematic review research. *Medical Teacher*, **33**, 719–723.
- Koricheva, J., Gurevitch, J. & Mengersen, K. (2013) *Handbook of Meta-Analysis in Ecology and Evolution*. Princeton University Press, Princeton.
- Lajeunesse, M.J. (2009) Meta-analysis and the comparative phylogenetic method. *American Naturalist*, **174**, 369–381.
- Lajeunesse, M.J. (2010) Achieving synthesis with meta-analysis by combining and comparing all available studies. *Ecology*, **91**, 2561–2564.
- Lajeunesse, M.J. (2011a) On the meta-analysis of response ratios for studies with correlated and multi-group designs. *Ecology*, **92**, 2049–2055.
- Lajeunesse, M.J. (2011b) phyloMeta: a program for phylogenetic comparative analyses with meta-analysis. *Bioinformatics*, **27**, 2603–2604.
- Lajeunesse, M.J. (2013a) Recovering missing or partial data from studies: a survey of conversions and imputations for meta-analysis. *Handbook of Meta-Analysis in Ecology and Evolution* (eds J. Koricheva, J. Gurevitch & K. Mengersen), pp. 195–206. Princeton University Press, Princeton.
- Lajeunesse, M.J. (2013b) Power statistics for meta-analysis: test for mean effects and homogeneity. *Handbook of Meta-Analysis in Ecology and Evolution* (eds J. Koricheva, J. Gurevitch & K. Mengersen), pp. 348–363. Princeton University Press, Princeton.
- Lajeunesse, M.J. & Forbes, M.R. (2003) Variable reporting and quantitative reviews: a comparison of three meta-analytical techniques. *Ecology Letters*, **6**, 448–454.
- Lajeunesse, M.J., Rosenberg, M.R. & Jennions, M.D. (2013) Phylogenetic nonindependence and meta-analysis. *Handbook of Meta-Analysis in Ecology and Evolution* (eds J. Koricheva, J. Gurevitch & K. Mengersen), pp. 284–299. Princeton University Press, Princeton.
- Landis, J.R. & Koch, G.G. (1977) The measurement of observer agreement for categorical data. *Biometrics*, **33**, 159–174.

- Lipsey, M.W. & Wilson, D.B. (2001) *Practical Meta-Analysis*. Sage Publications, Thousand Oaks.
- Lortie, C.J., Stewart, G., Rothstein, H. & Lau, J. (2015) How to critically read ecological meta-analyses. *Research Synthesis Methods*, **6**, 124–133.
- Mengersen, K., Jennions, M.D. & Schmid, M.D. (2013) Statistical models for the meta-analysis of nonindependent data. *Handbook of Meta-Analysis in Ecology and Evolution* (eds J. Koricheva, J. Gurevitch & K. Mengersen), pp. 255–283. Princeton University Press, Princeton.
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G. & PRISMA Group. (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *BMJ*, **339**, b2535.
- Pau, G., Fuchs, F., Sklyar, O., Boutros, M. & Huber, W. (2010) EBImage—an R package for image processing with applications to cellular phenotypes. *Bioinformatics*, **26**, 979–981.
- Pullin, A.S. & Stewart, G.S. (2006) Guidelines for systematic review in conservation and environmental management. *Conservation Biology*, **20**, 1647–1656.
- Rosenberg, M.S., Adams, D.C. & Gurevitch, J. (2000) *MetaWin: Statistical Software for Meta-Analysis*. Sinauer Associates, Sunderland.
- Rubin, D.B. & Schenker, N. (1991) Multiple imputation in health-care databases: an overview and some applications. *Statistics in Medicine*, **10**, 585–598.
- Schmid, C.H., Stewart, G.B., Rothstein, H.R., Lajeunesse, M.J. & Gurevitch, J. (2013) Software for statistical meta-analysis. *Handbook of Meta-Analysis in Ecology and Evolution* (eds J. Koricheva, J. Gurevitch & K. Mengersen), pp. 174–194. Princeton University Press, Princeton.
- Tummers, B. (2006) *DataThief III*. Available at: <http://datathief.org> [accessed 30 December 2014].
- Viechtbauer, W. (2010) Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, **36**, 1–48.
- Wallace, B.C., Small, K., Brodley, C.E., Lau, J. & Trikalinos, T.A. (2012) Deploying an interactive machine learning system in an evidence-based practice center: abstractkr. *Proceedings of the 2nd ACM SIGHT International Health Informatics Symposium, Miami, Florida, USA*. New York: ACM, 819–824.
- Wallace, B.C., Dietz, G., Lajeunesse, M.J., Dahabreh, I.J., Trikalinos, T.A., Schmid, C.H. & Gurevitch, J. (2015) OpenMEE: Intuitive, open-source software for meta-analysis in ecology and evolutionary biology. Available at: <http://www.cebm.brown.edu/openmee> [accessed 15 June 2015].

Received 22 May 2015; accepted 27 August 2015

Handling Editor: Richard Fitzjohn

Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Basic examples of screening studies, extracting data, and meta-analysis with the metagear package for R.