

EEG Many Pipelines - Code Mechanics

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Author Note

Authorship order was randomly determined via the `sample` function in *R*.

SS preprocessed the data and performed time-frequency analysis (research questions 2b, 2c, 3b, 4b). **AS** preprocessed the data and performed ERP analysis (research questions 1, 2a, 3a, 4a). **AM** was responsible for project management, GitHub repository, and reproducibility. **SS**, **AS**, and **AM** wrote the report.

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Abstract

One or two sentences providing a **basic introduction** to the field, comprehensible to a scientist in any discipline.

Two to three sentences of **more detailed background**, comprehensible to scientists in related disciplines.

One sentence clearly stating the **general problem** being addressed by this particular study.

One sentence summarizing the main result (with the words “**here we show**” or their equivalent).

Two or three sentences explaining what the **main result** reveals in direct comparison to what was thought to be the case previously, or how the main result adds to previous knowledge.

One or two sentences to put the results into a more **general context**.

Two or three sentences to provide a **broader perspective**, readily comprehensible to a scientist in any discipline.

Keywords: EEG Many Pipelines, scene categorization, vision, EEG, ERP, time-frequency analysis, Bayesian multilevel linear regression, TFCE

Word count: X

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1 Introduction

Timeline of our contribution to the EEGManyPipelines project:

- we registered for the EEGManyPipelines project on 2021-09-15, and received the confirmation email 2021-09-20.
- instructions for downloading the data and for analysis were sent 2021-10-08. These are saved within the repository at `data_in_repo/original_data/instructions`.
- we received the link to the submission portal on 2022-05-02
- we've submitted the pre-processed data on

2 Methods

2.1 Preprocessing - ERP

For each participant, the continuous EEG data was assigned electrode coordinates and filtered with two consecutive Hamming windowed sinc FIR filters (high-pass 0.1 Hz, low-pass 40 Hz). Bad or noisy channels were detected using several approaches implemented in the PREP pipeline (Bigdely-Shamlo, Mullen, Kothe, Su, & Robbins, 2015), including flat or missing signal, “bad-by-high-frequency-noise” (frequency components above 50 Hz considerably higher than median channel noisiness, as calculated using a robust Z -scoring method and default threshold $z > 5$), “bad-by-correlation” (maximum correlation with another channel below the default $r = .4$; fraction of bad correlation windows above the default threshold of 0.01), “bad-by-deviation” (amplitude deviates from the median channel amplitude, as calculated using a robust Z -scoring method and default threshold $z > 5$), and signal prediction based on signals and spatial locations of other

channels lower than default threshold of $r = .75$ (random sample consensus approach, *RANSAC*; Fischler and Bolles (1987)).¹ Channels identified as noisy were removed from the data and subsequently interpolated via a spherical spline procedure (Perrin, Pernier, Bertrand, & Echallier, 1989).

Afterwards, the EEG data were re-referenced to the average signal across channels. Ocular artifacts were then corrected by means of independent component analysis via the *picard* algorithm (Ablin, Cardoso, & Gramfort, 2018) and the resulting components were correlated with activity recorded from the EOG channels, in order to identify which components best represented horizontal eye movements and blinks. The components that correlated the highest with the EOG channels were then removed from the EEG data before re-conversion into channel space.

The EEG data was subsampled by a factor of four (i.e., from 512 Hz to 128 Hz) and segmented into epochs extending from -200ms to +500ms time-locked to scene onset, and baseline correction was applied using the pre-stimulus interval. The epoched data was then subjected to *Autoreject*, an automated artifact detection algorithm based on machine-learning classifiers and cross-validation to estimate the optimal peak-to-peak threshold (Jas, Engemann, Bekhti, Raimondo, & Gramfort, 2017). This algorithm was implemented to remove artifacts not identified by previous preprocessing steps and, depending on the number of bad sensors for a given trial, either repairs the trial based on spherical spline interpolation or excludes it from further analysis.²

Finally, the clean epoched data were separated into 8 conditions to investigate each research question:

- **RQ1**

1. *manmade*: scenes categorized as **man-made**, presented for the first time or

¹ For more details, see the documentation of `NoisyChannels`.

² For more details, see the documentation of `autoreject`.

previously (`new` and `old`), subsequently remembered or forgotten (`subsequent_remembered` and `subsequent_forgotten`), excluding NA in behavioral responses (although scene category is independent from response, NA may reflect drops in attention and, consequently, incomplete stimulus perception)

2. *natural*: scenes categorized as `natural`, `new` and `old`, `subsequent_remembered` and `subsequent_forgotten`, excluding NA in behavior

- **RQ2**

3. *new*: `man-made` and `natural` scenes, presented for the first time (`new`), `subsequent_remembered` and `subsequent_forgotten`, excluding NA in behavior
4. *old*: `man-made` and `natural` scenes, presented previously (`old`), `subsequent_remembered` and `subsequent_forgotten`, excluding NA in behavior

- **RQ3**

5. *old-hit*: `man-made` and `natural` scenes, presented previously (`old`), successfully recognized as such (`hit`), can include NA in memory (the image has been successfully categorized as `old`, regardless of whether it is recognized as such in subsequent presentations)
6. *old-miss*: `man-made` and `natural` scenes, presented previously (`old`), not recognized as such (`miss`), can include NA in memory

- **RQ4**

7. *remembered*: `man-made` and `natural` scenes, `new` and `old`, `subsequent_remembered`, include all behavior
8. *forgotten*: `man-made` and `natural` scenes, `new` and `old`, `subsequent_forgotten`, include all behavior

2.2 Preprocessing - TFR

Signal preprocessing for time-frequency analysis followed a similar procedure, with the following exceptions: (i) high-pass filter cut-off 1 Hz; (ii) continuous data segmented into 800 ms epochs (-300ms to +500ms time-locked to scene onset) and baseline corrected using the pre-stimulus interval.

The preprocessed data were then submitted to a Morlet wavelet analysis to transform the data into the time-frequency domain with 18 log-scaled frequency bins ranging from 4 to 40 Hz, to increase sensitivity at lower frequency ranges such as the theta band. To optimize both spectral and temporal resolution, the number of cycles to include in the sliding time window were defined by dividing each individual frequency by two. After transforming the data to the time-frequency domain, the data were decimated by a factor of two (sampling every second time point) to increase computational efficiency.

3 Analysis

3.1 RQ1

We were asked to test the following:

RQ1. There is an effect of scene category (i.e., a difference between images showing man-made vs. natural environments) on the amplitude of the N1 component, i.e. the first major negative EEG voltage deflection.

To address this question, we identified the N1 ERP component by visually inspecting topographies and waveforms of the grand-average signal (i.e., collapsed across all participants and both *man-made* and *natural* conditions). This unbiased *collapsed localizer* approach (Luck & Gaspelin, 2017, p. 150) revealed a negative deflection at electrodes *PO7*, *PO3*, *O1*, *PO4*, *PO8*, *O2* (region of interest, *ROI*), and a time window between 130 - 180

ms after stimulus onset. Participant- and condition-specific N1 amplitude was extracted by averaging values recorded at this ROI and time window.

Subsequently, we fit a Bayesian multilevel linear model on N1 amplitude values, with *condition* (2 levels: *man-made*, *natural*) as *constant* (a.k.a. fixed) effect and participant and trial as *varying* (a.k.a. random) effects. We allowed intercepts and slopes to vary as a function of participant and trials, to model general and condition-specific inter-individual differences. As a likelihood function, we chose a Gaussian distribution.

An important aspect of Bayesian analysis is the choice of priors (e.g., Natarajan & Kass, 2000). Given the susceptibility of the electrophysiological signal to inter-individual differences (e.g., skull thickness, skin conductance, or hair), we decided to base our priors on the current data by visually inspecting the *collapsed localizer* (see above). For the main analysis, we placed **informative priors** on the *intercept* – a normal distribution with mean $\mu = 4$ and standard deviation $\sigma = 2$: $Normal(4, 2)$ – and β coefficient, $Normal(0, 1)$. To assess whether our chosen informative prior would bias parameter estimates (and, consequently, the interpretation of the results; Depaoli and van de Schoot (2017)), we ran the same multilevel linear model with **weakly informative** priors (*intercept*: $Normal(4, 4)$; β : $Normal(0, 4)$) and **uninformative** priors (*intercept*: $Normal(4, 10)$; β : $Normal(0, 10)$). We anticipated that the choice of prior would have negligible effects on the posterior distributions, because the influence of the prior washes out with a large amount of data (Edwards, Lindman, & Savage, 1963).

Since we had no prior knowledge regarding the standard deviation of participant and trials, we placed a **weakly informative prior** on these varying effects: a *t*-distribution with degrees of freedom $\nu = 3$, location $\mu = 0$, and scale $\sigma = 2$, $Student(3, 0, 2)$.

Models were fitted in *R* using the **brms** package (Bürkner, 2018), which employs the probabilistic programming language *Stan* (Carpenter et al., 2017) to implement a Markov chain Monte Carlo (MCMC) algorithm (i.e., No-U-Turn sampler; Homan and Gelman (2014)) to estimate posterior distributions of the parameters of interest. Four MCMC

chains with 4000 iterations (2000 warm-up) and no thinning were run to estimate parameters in each of the fitted models. Model convergence was assessed as follows: (i) visual inspection of trace plots, rank plots, and graphical posterior predictive checks (Gabry, Simpson, Vehtari, Betancourt, & Gelman, 2019); (ii) Gelman-Rubin \hat{R} statistic (Gelman et al., 2013) – comparing the between-chains variability to the within-chain variability – between 1 and 1.05 (see also Nalborczyk, Batailler, Loevenbruck, Vilain, & Bürkner, 2019).

Posterior distributions of the model parameters were summarized using the mean and 95% credible interval (CI). Differences between conditions were calculated by computing the difference between posterior distributions of the respective conditions.

Statistical inference was performed using the **HDI + ROPE** decision rule (Kruschke, 2018): values were accepted or rejected against a null hypothesis considering a small effect as practically equivalent to zero (Region of Practical Equivalence; *ROPE*). To mitigate the inevitable subjectivity intrinsic in arbitrarily choosing the range of negligible values, we explored a range of plausible ROPEs, from $\pm 0.05 \mu V$ to $\pm 0.5 \mu V$ in steps of $0.01 \mu V$. If the percentage of the posterior differences within the full ROPE was smaller than 5%, the null hypothesis was rejected.

3.2 RQ2a

We were asked to test the following:

RQ2a. There are effects of image novelty (i.e., between images shown for the first time/new vs. repeated/old images) within the time-range from 300–500 ms on EEG voltage at fronto-central channels.

To address this question, for each participant and *new/old* condition (see section 2.1) we averaged activity in the time window between 300 - 500 ms after stimulus onset and

electrodes *FC1*, *FC2*, *FCz*, i.e., electrodes strictly classified as fronto-central according to the international 10/10 electrode system (Chatrian, Lettich, & Nelson, 1985).

We fit Bayesian multilevel linear models following the procedure described in section 3.1, with the following differences in priors: (i) **informative priors**: $Normal(-8, 2)$ on intercept, $Normal(0, 1)$ on β ; (ii) **weakly informative priors**: $Normal(-8, 4)$ on intercept, $Normal(0, 4)$ on β ; (iii) **uninformative priors**: $Normal(-8, 10)$ on intercept, $Normal(0, 10)$ on β .

Summaries of the posterior distributions of model parameters and statistical inference were performed as described in section 3.1.

3.3 RQ2b and RQ2c

We were asked to test the following:

RQ2b. There are effects of image novelty (i.e., between images shown for the first time/new vs. repeated/old images) within the time-range from 300–500 ms on theta power at fronto-central channels.

RQ2c. There are effects of image novelty (i.e., between images shown for the first time/new vs. repeated/old images) within the time-range from 300–500 ms on alpha power at posterior channels.

To address these questions, we conducted a multilevel analysis contrasting the EEG data from trials with *old* images against trials with *new* images (see section 2.1). At the first level (i.e., the participant level), we computed the averaged time-frequency maps for each of the two conditions. We then tested the resulting averaged maps at the second level for significant group effects using a paired-sample *t*-test. We used cluster-based permutation testing, due to its stringent control of familywise error rates (Maris & Oostenveld, 2007). Specifically, for every sample across the three channels, we quantified

the experimental effect by a t -value. Selection of samples for inclusion in a cluster was implemented using threshold-free cluster enhancement (*TFCE*) (Smith & Nichols, 2009). *TFCE* eliminates the free parameter initial threshold value that determines which points are included in clustering by approximating a continuous integration across possible threshold values with a standard Riemann sum. We subsequently clustered selected samples in connected sets based on temporal and spectral adjacency and computed cluster-level statistics by taking the sum of the t -values within every cluster. Subsequently, we performed permutation testing using the Monte Carlo method (1000 permutations) to compute the significance probability of our observed effect (Maris & Oostenveld, 2007) ($\alpha = 0.05$). This analysis results in a cluster of adjacent data points across time, frequencies, and channels, which significantly differs in activity between old and new images.

To test for differences in **theta** (θ) power at fronto-central channels, we focused on the frequency range from 4 - 8 Hz and all frontocentral channels (FC1, FCz, FC2).

To test for differences in **alpha** (α) power at posterior channels, we focused on the frequency range from 8 - 13 Hz and all posterior channels (P7, P5, P3, P1, P2, P4, P6).

3.4 RQ3a

We were asked to test the following:

RQ3a. There are effects of successful recognition of old images (i.e., a difference between old images correctly recognized as old [hits] vs. old images incorrectly judged as new [misses]) on EEG voltage at any channels, at any time.

We followed the same analysis approach described in section 3.3 but on time-series data, comparing *old-hit/old-miss* conditions (see section 2.1) and including all timepoints and channels.

3.5 RQ3b

We were asked to test the following:

RQ3b. There are effects of successful recognition of old images (i.e., a difference between old images correctly recognized as old [hits] vs. old images incorrectly judged as new [misses]) on spectral power, at any frequencies, at any channels, at any time.

We followed the same analysis approach described in section 3.3, this time on *old-hit/old-miss* conditions (see section 2.1) and including all frequencies, timepoints, and channels.

3.6 RQ4a

We were asked to test the following:

RQ4a. There are effects of subsequent memory (i.e., a difference between images that will be successfully remembered vs. forgotten on a subsequent repetition) on EEG voltage at any channels, at any time.

We followed the same analysis approach described in section 3.4, comparing *remembered/forgotten* conditions (see section 2.1) and including all timepoints and channels.

3.7 RQ4b

We were asked to test the following:

RQ4b. There are effects of subsequent memory (i.e., a difference between images that will be successfully remembered vs. forgotten on a subsequent repetition) on spectral power, at any frequencies, at any channels, at any time.

We followed the same analysis approach described in section 3.5, this time on *remembered/forgotten* conditions (see section 2.1) and including all frequencies, timepoints, and channels.

4 Results

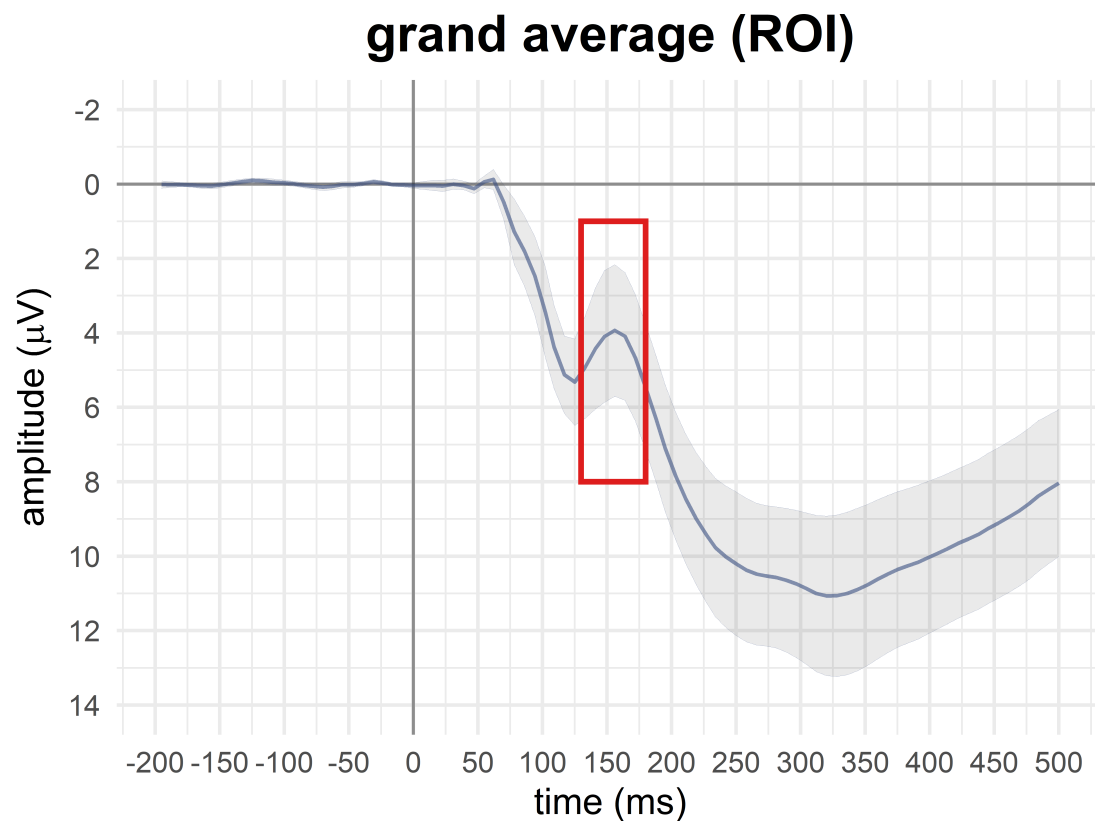


Figure 1. My caption.

4.1 RQ2b, RQ2c, RQ3a, RQ3b, RQ4a, RQ4b

No statistically significant clusters were identified for any of these research questions.

5 Software

EEG preprocessing was carried out using *MNE-Python v0.24.1* (Gramfort, 2013) in *Python v3.9.7* (Van Rossum & Drake, 2009) and *Spyder IDE v5.1.5* (Raybaut, 2009). Analysis, visualization, and report generation were carried out in *R v4.1.3* (R Core Team, 2022) and *RStudio IDE v2022.02.1+461* (RStudio Team, 2020). We used the following *R* packages:

- **data wrangling and analysis:** *here v1.0.1* (Müller, 2020), *Rmisc v1.5* (Hope, 2022), *tidyverse v1.3.1* (Wickham et al., 2019) – in particular *tibble v3.1.6* (Müller & Wickham, 2022), *tidyr v1.2.0* (Wickham & Girlich, 2022), *readr v2.1.2* (Wickham, Hester, & Bryan, 2022), *dplyr v1.0.9* (Wickham, François, Henry, & Müller, 2022) –, *brms v2.17.0* (Bürkner, 2018), *eegUtils v0.7.0* (Craddock, 2022), *emmeans v1.7.3* (Lenth, 2022), *bayestestR v0.11.5.1* (Makowski, Ben-Shachar, & Lüdtke, 2019)
- **visualization:** *ggplot2 v3.3.6* (Wickham, 2016), *eegUtils v0.7.0* (Craddock, 2022), *bayesplot v1.9.0* (Gabry & Mahr, 2022), *viridis v0.6.2* (Garnier et al., 2021-04-11, 2021-04), *tidybayes v3.0.2* (Kay, 2022), *patchwork v1.1.1* (Pedersen, 2020)
- **report generation:** *knitr v1.39* (Xie, 2022), *rmarkdown v2.14* (Allaire et al., 2022), *papaja v0.1.0.9999* (Aust & Barth, 2022)

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7 References

- Ablin, P., Cardoso, J.-F., & Gramfort, A. (2018). Faster independent component analysis by preconditioning with hessian approximations. *IEEE Transactions on Signal Processing*, 66(15), 4040–4049. <https://doi.org/10.1109/tsp.2018.2844203>
- Allaire, J., Xie, Y., McPherson, J., Luraschi, J., Ushey, K., Atkins, A., ... Iannone, R. (2022). *Rmarkdown: Dynamic documents for R*.
- Aust, F., & Barth, M. (2022). *Papaja: Prepare reproducible APA journal articles with R Markdown*.
- Bigdely-Shamlo, N., Mullen, T., Kothe, C., Su, K.-M., & Robbins, K. A. (2015). The PREP pipeline: Standardized preprocessing for large-scale EEG analysis. *Frontiers in Neuroinformatics*, 9. <https://doi.org/10.3389/fninf.2015.00016>
- Bürkner, P.-C. (2018). Advanced bayesian multilevel modeling with the R package brms. *The R Journal*, 10(1), 395. <https://doi.org/10.32614/rj-2018-017>
- Carpenter, B., Gelman, A., Hoffman, M. D., Lee, D., Goodrich, B., Betancourt, M., ... Riddell, A. (2017). *Stan: A probabilistic programming language*. *Journal of Statistical Software*, 76(1). <https://doi.org/10.18637/jss.v076.i01>
- Chatrian, G. E., Lettich, E., & Nelson, P. L. (1985). Ten Percent Electrode System for Topographic Studies of Spontaneous and Evoked EEG Activities. *American Journal of EEG Technology*, 25(2), 83–92. <https://doi.org/10.1080/00029238.1985.11080163>
- Craddock, M. (2022). *eegUtils: Utilities for electroencephalographic (EEG) analysis*.
- Depaoli, S., & van de Schoot, R. (2017). Improving transparency and replication in bayesian statistics: The WAMBS-Checklist. *Psychological Methods*, 22(2), 240–261. <https://doi.org/10.1037/met0000065>
- Edwards, W., Lindman, H., & Savage, L. J. (1963). Bayesian statistical inference for psychological research. *Psychological Review*, 70(3), 193–242. <https://doi.org/10.1037/h0044139>
- Fischler, M. A., & Bolles, R. C. (1987). *Random sample consensus: A paradigm for model*

- fitting with applications to image analysis and automated cartography*. Elsevier.
<https://doi.org/10.1016/b978-0-08-051581-6.50070-2>
- Gabry, J., & Mahr, T. (2022). *Bayesplot: Plotting for bayesian models*.
- Gabry, J., Simpson, D., Vehtari, A., Betancourt, M., & Gelman, A. (2019). Visualization in bayesian workflow. *Journal of the Royal Statistical Society: Series A (Statistics in Society)*, 182(2), 389–402. <https://doi.org/10.1111/rssa.12378>
- Garnier, S., Ross, N., BoB Rudis, Filipovic-Pierucci, A., Galili, T., Timelyportfolio, ... JJ Chen. (2021-04-11, 2021-04). *Sjmgarnier/viridis: Viridis 0.6.0 (pre-CRAN release)*. Zenodo. <https://doi.org/10.5281/ZENODO.4679424>
- Gelman, A., Carlin, J. B., Stern, H. S., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2013). *Bayesian data analysis*. Chapman and Hall/CRC. <https://doi.org/10.1201/b16018>
- Gramfort, A. (2013). MEG and EEG data analysis with MNE-Python. *Frontiers in Neuroscience*, 7. <https://doi.org/10.3389/fnins.2013.00267>
- Homan, M. D., & Gelman, A. (2014). The no-U-turn sampler: Adaptively setting path lengths in hamiltonian monte carlo. *The Journal of Machine Learning Research*, 15(1), 1593–1623.
- Hope, R. M. (2022). *Rmisc: Ryan miscellaneous*.
- Jas, M., Engemann, D. A., Bekhti, Y., Raimondo, F., & Gramfort, A. (2017). Autoreject: Automated artifact rejection for MEG and EEG data. *NeuroImage*, 159, 417–429.
<https://doi.org/10.1016/j.neuroimage.2017.06.030>
- Kay, M. (2022). *Tidybayes: Tidy data and geoms for bayesian models*.
<https://doi.org/10.5281/zenodo.1308151>
- Kruschke, J. K. (2018). Rejecting or accepting parameter values in bayesian estimation. *Advances in Methods and Practices in Psychological Science*, 1(2), 270–280.
<https://doi.org/10.1177/2515245918771304>
- Lenth, R. V. (2022). *Emmeans: Estimated marginal means, aka least-squares means*.
- Luck, S. J., & Gaspelin, N. (2017). How to get statistically significant effects in any ERP

- experiment (and why you shouldn't). *Psychophysiology*, 54(1), 146–157.
<https://doi.org/10.1111/psyp.12639>
- Makowski, D., Ben-Shachar, M. S., & Lüdtke, D. (2019). *bayestestR: Describing effects and their uncertainty, existence and significance within the bayesian framework*. 4, 1541. <https://doi.org/10.21105/joss.01541>
- Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, 164(1), 177–190.
<https://doi.org/10.1016/j.jneumeth.2007.03.024>
- Müller, K. (2020). *Here: A simpler way to find your files*.
- Müller, K., & Wickham, H. (2022). *Tibble: Simple data frames*.
- Nalborczyk, L., Batailler, C., Loevenbruck, H., Vilain, A., & Bürkner, P.-C. (2019). An introduction to bayesian multilevel models using brms: A case study of gender effects on vowel variability in standard indonesian. *Journal of Speech, Language, and Hearing Research*, 62(5), 1225–1242. https://doi.org/10.1044/2018_jslhr-s-18-0006
- Natarajan, R., & Kass, R. E. (2000). Reference bayesian methods for generalized linear mixed models. *Journal of the American Statistical Association*, 95(449), 227–237.
<https://doi.org/10.1080/01621459.2000.10473916>
- Pedersen, T. L. (2020). *Patchwork: The composer of plots*.
- Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, 72(2), 184–187. [https://doi.org/10.1016/0013-4694\(89\)90180-6](https://doi.org/10.1016/0013-4694(89)90180-6)
- R Core Team. (2022). *R: A language and environment for statistical computing* [Manual]. Vienna, Austria.
- Raybaut, P. (2009). Spyder-documentation. *Available Online at: Pythonhosted. Org*.
- RStudio Team. (2020). *RStudio: Integrated development environment for R* [Manual]. Boston, MA.
- Smith, S., & Nichols, T. (2009). Threshold-free cluster enhancement: Addressing problems

- of smoothing, threshold dependence and localisation in cluster inference. *NeuroImage*, 44(1), 83–98. <https://doi.org/10.1016/j.neuroimage.2008.03.061>
- Van Rossum, G., & Drake, F. L. (2009). *Python 3 reference manual*. Scotts Valley, CA: CreateSpace.
- Wickham, H. (2016). *Ggplot2: Elegant graphics for data analysis*.
- Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., . . . Yutani, H. (2019). *Welcome to the tidyverse*. 4, 1686. <https://doi.org/10.21105/joss.01686>
- Wickham, H., François, R., Henry, L., & Müller, K. (2022). *Dplyr: A grammar of data manipulation*.
- Wickham, H., & Girlich, M. (2022). *Tidyr: Tidy messy data*.
- Wickham, H., Hester, J., & Bryan, J. (2022). *Readr: Read rectangular text data*.
- Xie, Y. (2022). *Knitr: A general-purpose package for dynamic report generation in R*.