Speech intelligibility measurement

A latent variable approach on utterances' transcriptions

Jose Rivera[1], Sven de Maeyer[2], and Steven Gillis[3]

[1] Department of Training and Education Sciences,
University of Antwerp, Antwerp, Belgium
E-mail: JoseManuel.RiveraEspejo@uantwerpen.be

(corresponding author)

[2] Department of Training and Education Sciences,
University of Antwerp, Antwerp, Belgium
E-mail: sven.demaeyer@uantwerpen.be

[3] Computational Linguistics, and Psycholinguistics Research Centre
University of Antwerp, Antwerp, Belgium
E-mail: steven.gillis@uantwerpen.be

July 25, 2022

Abstract

Contents

1. Introduction **4**

2. Materials and Methods **5**
2.1. Children . . . 5
2.2. Stimuli . . . 5
2.3. Experimental setup . . . 5
2.4. Causal framework . . . 6
2.5. Statistical analysis . . . 8

3. Results **9**
3.1. About the variability of the data . . . 9
3.2. About our hypothesis . . . 10
3.3. The speech intelligibility scale . . . 12
3.4. Posterior predictive . . . 13
3.5. Influential observations . . . 13

4. Discussion **15**

5. Acknowledgments **16**

6. Author contributions **16**

7. Financial support **16**

8. Conflicts of interest **16**

9. Research transparency and reproducibility **16**

A. Supplementary **17**
A.1. Children characteristics . . . 17
A.2. Experiment details . . . 18
A.2.1. Transcription task . . . 18
A.2.2. Entropy calculation . . . 18
A.3. About speech intelligibility . . . 19
A.4. Sampling bias . . . 20
A.5. Model details . . . 20
A.5.1. Variability in the beta-proportion distribution . . . 20
A.5.2. Data pre-processing . . . 20
A.5.3. Priors and hyper-priors . . . 21
A.5.4. Estimation procedure . . . 22
A.5.5. Simulation . . . 22
A.5.6. Model selection . . . 23

Bibliography **25**

List of Figures

1. DAG: causal diagram . . . 6
2. Model 10, posterior predictive: variability present in the data . . . 10
3. Model 10, posterior predictive: *true* entropy and *speech intelligibility* scales . . . 13
4. Model 10, posterior predictive: entropy replicates, *true* entropy, and distributions . . . 14
5. Model 10, influential observations . . . 14
6. Variability in a beta-proportional distribution . . . 20
7. Prior distribution implications . . . 21
8. Group contrasts: power on small hearing group differences . . . 22

List of Tables

1. Proposed statistical models . . . 9
2. Selected statistical models: results . . . 11
3. Characteristics of selected children . . . 17
4. Alignment and entropy calculation . . . 18
5. Fit of statistical models: WAIC . . . 24
6. Fit of statistical models: PSIS . . . 24

1. Introduction

Intelligible speech can be defined as the extent to which the elements in an speaker's acoustic signal, e.g. phonemes or words, can be correctly recovered by a listener [47, 72, 69, 36]. Intelligible spoken language carries an important societal value, as its attainment requires all core components of speech perception, cognitive processing, linguistic knowledge, and articulation to be mastered [36]. In that sense, *speech intelligibility* is considered a milestone in children's language development, and more practically, it is qualified as the ultimate checkpoint for the success of speech therapy, and the 'gold standard' for assessing the benefit of cochlear implantation [13].

As the literature suggest, multiple approaches can be taken to quantify *speech intelligibility* [4, 5, 32, 45]. However, among them, *objective rating* methods on spontaneous speech tasks are considered to produce more valid[1] and reliable[2] scores than any other method, and consequently, their outcome is used as an 'objective' measure of intelligibility [5, 27].

Objective rating methods uses listeners to transcribe children's utterances, and later uses such information to construct a score. Finally, the stimuli used in the transcription comes from spontaneous speech tasks[3]. In that sense, in the transcription task, intelligibility can be inferred from the extent a set of transcribers can identify the word contained in an utterance [5].

Although the literature conceptualize *speech intelligibility* as in the previous paragraph [5], and further suggest multiple perspectives and approaches to measure it [4, 5, 45], to authors knowledge no paper tries to estimate the individuals' intelligibility score. Moreover, no paper test their research hypothesis directly on an intelligibility outcome, but rather on surrogate measures of it. For instance, Flipsen [32] uses

This is exacerbated

We believe this paper make three specific contributions to the understanding of the factors that drive the intelligibility of spoken language. First, we develop a novel analysis using a latent variable approach [26]. More specifically, we model *speech intelligibility* as a latent variable that can be inferred from the entropy replicates. This method offers three specific benefits. On the one hand, the method 'constructs' an intelligibility score, which in turn, allow us to test different hypothesis and even make individual comparisons at the appropriate level. On the other hand, it allow us to control for different sources of variation. This is particularly important as, by failing to account for the appropriate hierarchies in the data, we could be 'manufacturing' false confidence in the parameter estimates, leading us to incorrect inferences [53]. Finally, the method also provides a 'criterion' on how reliable are the entropy replicates to measure speech intelligibility.

Second, we use Directed Acyclic Graph (DAG) [59, 17] to depict all the relevant variables though to influence speech intelligibility. We describe in detail our causal and non-causal hypothesis, and supplement our description with a causal diagram. The benefit of the method lies, not only, in that it makes the assumptions of our hypothesis more transparent, but also allow us to derive statistical procedures from the aforementioned causal assumptions [53, 78, 62].

Accompanying the intelligibility assessment methods, the literature supply a myriad of factors that are thought also contribute to the (under)development of intelligible spoken language [57, 6, 40, 28]. Among these are audiology related factors, such chronological age, age at implantation, the duration of device use, *hearing age*, bilateral or contralateral cochlear implantation, and the children's preoperative and postoperative hearing levels. On the other hand, there are also child related factors, such as the cause of the hearing impairment (genetic, infections), additional disabilities (mental retardation, speech motor problems), and gender. Finally, there are also environmental factors, such as communication modality.

Third and final, we wrap the analysis procedure under the Bayesian framework, providing the assumptions, and the steps required to reproduce the computational implementation of the models.

Considering all of the above, this paper seeks to investigates the speech intelligibility levels of normal hearing (NH) versus hearing-impaired children with cochlear implants (HI/CI). For that purpose, ten utterances recordings, from thirty two NH and HI/CI children, were selected from a large corpus of *spontaneously spoken speech* collected by the CLiPS research center. Additionally, we set up an experiment, where one hundred language students transcribed each stimuli to the Qualtrics environment [76]. Finally,

[1] The extent to which scores are appropriate for their intended interpretation and use [50, 67].

[2] The extend to which a measure would give us the same result over and over again [67], i.e. measure something, free from error, in a consistent way.

[3] Task with the highest level of ecological validity, followed by contextualized utterances and reading at loud tasks [32, 25].

the transcriptions were transformed into an entropy measure per utterance, which served as our outcome variable.

Bibliography

[1] Anderson, D. [2008]. *Model Based Inference in the Life Sciences: A Primer on Evidence*, Springer.

[2] Baudonck, N., Buekers, R., Gillebert, S. and Van Lierde, K. [2008]. Speech intelligibility of flemish children as judged by their parents, *Folia Phoniatrica et Logopaedica* **61**(5): 288–295.
doi: https://doi.org/10.1159/000235994.

[3] Betancourt, M. and Girolami, M. [2012]. Hamiltonian monte carlo for hierarchical models.
url: https://arxiv.org/abs/1312.0906v1.

[4] Boonen, N., Kloots, H. and Gillis, S. [2020]. Rating the overall speech quality of hearing-impaired children by means of comparative judgements, *Journal of Communication Disorders* **83**: 1675–1687.
doi: https://doi.org/10.1016/j.jcomdis.2019.105969.

[5] Boonen, N., Kloots, H., Nurzia, P. and Gillis, S. [2021]. Spontaneous speech intelligibility: early cochlear implanted children versus their normally hearing peers at seven years of age, *Journal of Child Language* pp. 1–26.
doi: https://doi.org/10.1017/S0305000921000714.

[6] Boons, T., Brokx, J., Dhooge, I., Frijns, J., Peeraer, L., Vermeulen, A., Wouters, J. and van Wieringen, A. [2012]. Predictors of spoken language development following pediatric cochlear implantation, *Ear and Hearing* **33**(5): 617–639.
doi: https://doi.org/10.1097/AUD.0b013e3182503e47.

[7] Boons, T., De Raeve, T., Langereis, M., Peeraer, L., Wouters, L. and van Wieringen, A. [2013]. Expressive vocabulary, morphology, syntax and narrative skills in profoundly deaf children after early cochlear implantation, *Research in Developmental Disabilities* **34**(6): 2008–2022.
doi: https://doi.org/10.1016/j.ridd.2013.03.003.
url: https://www.sciencedirect.com/science/article/pii/S0891422213001078.

[8] Bowen, C. [2011]. Table1: Intelligibility.
url: http://www.speech-language-therapy.com.

[9] Bruijnzeel, H., Ziylan, F., Stegeman, I., V., T. and Grolman, W. [2016]. A systematic review to define the speech and language benefit of early (<12 months) pediatric cochlear implantation, *Audiol Neurotol* **21**: 113–126.
doi: https://doi.org/10.1159/000443363.

[10] Carroll, J. [2006]. *Measurement error in nonlinear models: a modern perspective*, Chapman and Hall/CRC.
doi: https://doi.org/10.1201/9781420010138.

[11] Castellanos, I., Kronenberger, W., Beer, J., Henning, S., Colson, B. and Pisoni, D. [2014]. Preschool speech intelligibility and vocabulary skills predict long-term speech and language outcomes following cochlear implantation in early childhood, *Cochlear Implants International* **15**(4): 200–210.
doi: https://doi.org/10.1179/1754762813Y.0000000043.

[12] Chamberlain, T. [1965]. The method of multiple working hypotheses, *Science* **148**(3671): 754–759.
url: https://www.jstor.org/stable/1716334.

[13] Chin, S., Bergeson, T. and Phan, J. [2012]. Speech intelligibility and prosody production in children with cochlear implants, *Journal of Communication Disorders* **45**: 355–366.
doi: https://doi.org/10.1016/j.jcomdis.2012.05.003.

[14] Chin, S. and Kuhns, M. [2014]. Proximate factors associated with speech intelligibility in children with cochlear implants: A preliminary study, *Clinical Linguistics & Phonetics* **28**(7-8): 532–542.
doi: https://doi.org/10.3109/02699206.2014.926997.

[15] Chin, S. and Tsai, P. [2001]. Speech intelligibility of children with cochlear implants and children with normal hearing: A preliminary report. Progress report. Indiana University, Bloomington, Indiana.

[16] Chin, S., Tsai, P. and Gao, S. [2003]. Connected speech intelligibility of children with cochlear implants and children with normal hearing, *American journal of speech-language pathology* **12**(4): 440–451.
doi: https://doi.org/10.1044/1058-0360(2003/090).
url: https://pubs.asha.org/doi/10.1044/1058-0360

[17] Cinelli, C., Forney, A. and Pearl, J. [2022]. A crash course in good and bad controls, *SSRN* .
doi: http://dx.doi.org/10.2139/ssrn.3689437.
url: https://ssrn.com/abstract=3689437.

[18] Cohen, J. [1988]. *Statistical power analysis for the behavioral sciences*, Routledge.

[19] De Raeve, L. [2016]. Cochlear implants in belgium: Prevalence in paediatric and adult cochlear implantation, *European Annals of Otorhinolaryngology, Head and Neck Diseases* **133**: S57–S60. 12th European Symposium on Pediatric Cochlear Implant (ESPCI 2015).
doi: https://doi.org/10.1016/j.anorl.2016.04.018.
url: https://www.sciencedirect.com/science/article/pii/S1879729616300813.

[20] Deffner, D., Rohrer, J. and McElreath, R. [2022]. A causal framework for cross-cultural generalizability, *Advances in Methods and Practices in Psychological Science* . (in press).

[21] Dettman, S., Dowell, R., Choo, D., Arnott, W., Abrahams, Y., Davis, A., Dornan, D., Leigh, J., Constantinescu, G., Cowan, R. and Briggs, R. [2016]. Long-term communication outcomes for children receiving cochlear implants younger than 12 months, *Otology & Neurotology* **37**(2): e82–e95.
doi: https://doi.org/10.1097/MAO.0000000000000915.

[22] Drennan, W. and Rubinstein, J. [2008]. Music perception in cochlear implant users and its relationship with psychophysical capabilities, *Journal of Rehabilitation Research and Development* **45**: 779–790.
doi: https://doi.org/10.1682/JRRD.2007.08.0118.

[23] Duane, S., Kennedy, A., Pendleton, B. and Roweth, D. [1987]. Hybrid monte carlo, *Physics Letters B* **195**(2): 216–222.
doi: https://doi.org/10.1016/0370-2693(87)91197-X.
url: https://www.sciencedirect.com/science/article/pii/037026938791197X.

[24] Duchesne, L. and Marschark, M. [2019]. Effects of age at cochlear implantation on vocabulary and grammar: A review of the evidence, *American Journal of Speech-Language Pathology* **28**(4): 1673–1691.
doi: 10.1044/2019_AJSLP-18-0161.
url: https://pubs.asha.org/doi/abs/10.1044/2019$_{A}JSLP-18-0161$.

[25] Ertmer, D. [2011]. Assessing speech intelligibility in children with hearing loss: Toward revitalizing a valuable clinical tool, *Language, Speech, and Hearing Services in Schools* **42**(1): 52–58.
doi: https://doi.org/10.1044/0161-1461(2010/09-0081).

[26] Everitt, B. [1984]. *An Introduction to Latent Variable Models*, Monographs on Statistics and Applied Probability, Springer Dordrecht.
doi: https://doi.org/10.1007/978-94-009-5564-6.

[27] Faes, J., De Maeyer, S. and Gillis, S. [2021]. Speech intelligibility of children with an auditory brainstem implant: a triple-case study, pp. 1–50. (submitted).

[28] Fagan, M., Eisenberg, L. and Johnson, K. [2020]. Investigating early pre-implant predictors of language and cognitive development in children with cochlear implants, *in* M. Marschark and H. Knoors (eds), *Oxford handbook of deaf studies in learning and cognition*, Oxford University Press, pp. 46–95.
doi: https://doi.org/10.1093/oxfordhb/9780190054045.013.3.

[29] Farrar, D. and Glauber, R. [1967]. Multicollinearity in regression analysis: The problem revisited, *Review of Economics and Statistics* **49**(1): 92–107.
doi: https://doi.org/10.2307/1937887.
url: https://www.jstor.org/stable/1937887.

[30] Figueroa-Zúñiga, J., Arellano-Valle, R. and Ferrari, S. [2013]. Mixed beta regression, *Computational Statistics Data Analysis* **61**: 137–147.
doi: https://doi.org/10.1016/j.csda.2012.12.002.

[31] Flexer, C. [2011]. Cochlear implants and neuroplasticity: linking auditory exposure and practice, *Cochlear Implants International* **12**(sup1): S19–S21.
doi: https://doi.org/10.1179/146701011X13001035752255.

[32] Flipsen, P. [2006]. Measuring the intelligibility of conversational speech in children, *Clinical Linguistics & Phonetics* **20**(4): 303–312.
doi: https://doi.org/10.1080/02699200400024863.

[33] Flipsen, P. [2008]. Intelligibility of spontaneous conversational speech produced by children with cochlear implants: A review, *International Journal of Pediatric Otorhinolaryngology* **72**(5): 559–564.
doi: https://doi.org/10.1016/j.ijporl.2008.01.026.
url: https://www.sciencedirect.com/science/article/pii/S0165587608000645.

[34] Flipsen, P. and Colvard, L. [2006]. Intelligibility of conversational speech produced by children with cochlear implants, *Journal of Communication Disorders* **39**(2): 93–108.
doi: https://doi.org/10.1016/j.jcomdis.2005.11.001.
url: https://www.sciencedirect.com/science/article/pii/S0021992405000614.

[35] Fogarty, L., Madeleine, A., Holding, T., Powell, A. and Kandler, A. [2022]. Ten simple rules for principled simulation modelling, *PLOS Computational Biology* **18**(3): 1–8.
doi: https://doi.org/10.1371/journal.pcbi.1009917.

[36] Freeman, V., Pisoni, D., Kronenberger, W. and Castellanos, I. [2017]. Speech intelligibility and psychosocial functioning in deaf children and teens with cochlear implants, *Journal of Deaf Studies and Deaf Education* **22**(3): 278–289.
doi: https://doi.org/10.1093/deafed/enx001.

[37] Geers, A. and Nicholas, J. [2013]. Enduring advantages of early cochlear implantation for spoken language development, *Journal of speech, language, and hearing research* **56**(2): 643–655.
doi: https://doi.org/10.1044/1092-4388(2012/11-0347.

[38] Geers, A., Nicholas, J., Tobey, E. and Davidson, L. [2016]. Persistent language delay versus late language emergence in children with early cochlear implantation, *Journal of Speech, Language, and Hearing Research* **59**(1): 155–170.
doi: 10.1044/2015_JSLHR-H-14-0173.
url: https://pubs.asha.org/doi/abs/10.1044/2015$_JSLHR - H - 14 - 0173$.

[39] Gelman, A., Carlin, J., Stern, H., Dunson, D., Vehtari, A. and Rubin, D. [2014]. *Bayesian Data Analysis*, Texts in Statistical Science, third edn, Chapman and Hall/CRC.

[40] Gillis, S. [2018]. Speech and language in congenitally deaf children with a cochlear implant, *in* E. Dattner and D. Ravid (eds), *Handbook of Communication Disorders: Theoretical, Empirical, and Applied Linguistic Perspectives*, De Gruyter Mouton, chapter 37, pp. 765–792.
doi: https://doi.org/10.1515/9781614514909-038.

[41] Grandon, B., Martinez, M., Samson, A. and Vilain, A. [2020]. Long-term effects of cochlear implantation on the intelligibility of speech in french-speaking children, *Journal of Child Language* **47**(4): 881892.
doi: https://doi.org/10.1017/S0305000919000837.

[42] Habib, M., Waltzman, S., Tajudeen, B. and Svirsky, M. [2010]. Speech production intelligibility of early implanted pediatric cochlear implant users, *International Journal of Pediatric Otorhinolaryngology* **74**(8): 855–859.
doi: https://doi.org/10.1016/j.ijporl.2010.04.009.
url: https://www.sciencedirect.com/science/article/pii/S0165587610002004.

[43] Hoffman, M. and Gelman, A. [2014]. The no-u-turn sampler: Adaptively setting path lengths in hamiltonian monte carlo, *Journal of Machine Learning Research* **15**: 1593–1623.
url: https://www.jmlr.org/papers/volume15/hoffman14a/hoffman14a.pdf.

[44] Hoyle, R. e. [2014]. *Handbook of Structural Equation Modeling*, Guilford Press.

[45] Hustad, K., Mahr, T., Natzke, P. and Rathouz, P. [2020]. Development of speech intelligibility between 30 and 47 months in typically developing children: A cross-sectional study of growth, *Journal of Speech, Language, and Hearing Research* **63**(6): 1675–1687.
doi: https://doi.org/10.1044/2020$_JSLHR - 20 - 00008$.
url :$https://pubs.asha.org/doi/abs/$10.1044/2020$_JSLHR - 20 - 00008$.

[46] Jaynes, E. [2003]. *Probability Theory: The Logic of Science*, Cambridge University Press.

[47] Kent, R., Weismer, G., Kent, J. and Rosenbek, J. [1989]. Toward phonetic intelligibility testing in dysarthria, *Journal of Speech and Hearing Disorders* **54**(4): 482–499.
doi: https://doi.org/10.1044/jshd.5404.482.

[48] Kruschke, D. [2015]. *Doing Bayesian Data Analysis: A Tutorial with R, JAGS, and Stan*, Elsevier.
url: https://www.sciencedirect.com/book/9780124058880/doing-bayesian-data-analysis.

[49] Kullback, S. and Leibler, R. [1951]. On information and sufficiency, *The Annals of Mathematical Statistics* **22**(1): 79–86.
url: http://www.jstor.org/stable/2236703.

[50] Lesterhuis, M. [2018]. *The validity of comparative judgement for assessing text quality: An assessors perspective*, PhD thesis, University of Antwerp.

[51] MacWhinney, B. [2020]. *The CHILDES Project: Tools for Analyzing Talk*, Lawrence Erlbaum Associates. 3rd Edition.
doi: https://doi.org/10.21415/3mhn-0z89.

[52] Mayer, M. [1969]. *Frog, where are You?*, Boy, a Dog, and a Frog, Dial Books for Young Readers.
url: https://books.google.be/books?id=Asi5KQAACAAJ.

[53] McElreath, R. [2020]. *Statistical Rethinking: A Bayesian Course with Examples in R and STAN*, Chapman and Hall/CRC.

[54] Montag, J., AuBuchon, A., Pisoni, D. and Kronenberger, W. [2014]. Speech intelligibility in deaf children after long-term cochlear implant use, *Journal of Speech, Language, and Hearing Research* **57**(6): 2332–2343.
doi: https://doi.org/10.1044/2014_JSLHR-H-14-0190.
url: https://pubs.asha.org/doi/abs/10.1044/2014$_JSLHR - H - 14 - 0190$.

[55] Neal, R. [2012]. Mcmc using hamiltonian dynamics, *in* S. Brooks, A. Gelman, G. Jones and X. Meng (eds), *Handbook of Markov Chain Monte Carlo*, Chapman Hall/CRC Press, chapter 5, pp. 113–162.
url: https://arxiv.org/abs/1206.1901.

[56] Nicholas, J. and Geers, A. [2007]. Will they catch up? the role of age at cochlear implantation in the spoken language development of children with severe to profound hearing loss, *Journal of speech, language, and hearing research* **50**(4): 1048–1062.
doi: https://doi.org/10.1044/1092-4388(2007/073).

[57] Niparko, J., Tobey, E., Thal, D., Eisenberg, L., Wang, N., Quittner, A. and Fink, N. [2010]. Spoken Language Development in Children Following Cochlear Implantation, *JAMA* **303**(15): 1498–1506.
doi: https://doi.org/10.1001/jama.2010.451.

[58] Nittrouer, S., Caldwell-Tarr, A., Moberly, A. and Lowenstein, J. [2014]. Perceptual weighting strategies of children with cochlear implants and normal hearing, *Journal of Communication Disorders* **52**: 111–133.
doi: https://doi.org/10.1016/j.jcomdis.2014.09.003.
url: https://www.sciencedirect.com/science/article/pii/S0021992414000768.

[59] Pearl, J. [2009]. *Causality: Models, Reasoning and Inference*, Cambrige University Press.

[60] Peng, S., Spencer, L. and Tomblin, J. [2004]. Speech intelligibility of pediatric cochlear implant recipients with 7 years of device experience, *Journal of speech, language, and hearing research* **47**(6): 1227–1236.
doi: https://doi.org/10.1044/1092-4388(2004/092).

[61] R Core Team [2015]. *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria.
url: http://www.R-project.org/.

[62] Rohrer, J., Schmukle, S. and McElreath, R. [2021]. The only thing that can stop bad causal inference is good causal inference, *PsyArXiv* .
doi: https://doi.org/10.31234/osf.io/mz5jx.

[63] Sawilowsky, S. [2009]. New effect size rules of thumb, *Journal of Modern Applied Statistical Methods* **8**(2).
doi: https://doi.org/10.22237/jmasm/1257035100.
url: http://digitalcommons.wayne.edu/jmasm/vol8/iss2/26.

[64] Shannon, C. [1948]. A mathematical theory of communication, *The Bell System Technical Journal* **27**(3): 379–423.
doi: https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.

[65] Stan Development Team [2020]. RStan: the R interface to Stan. R package version 2.21.2.
url: http://mc-stan.org/.

[66] Stan Development Team. [2021]. *Stan Modeling Language Users Guide and Reference Manual, version 2.26*, Vienna, Austria.
url: https://mc-stan.org.

[67] Trochim, W. [2022]. The research methods knowledge base.
url: https://conjointly.com/kb/.

[68] van Daal, T. [2020]. *Making a choice is not easy?!: Unravelling the task difficulty of comparative judgement to assess student work*, PhD thesis, University of Antwerp.

[69] van Heuven, V. [2008]. Making sense of strange sounds: (mutual) intelligibility of related language varieties. a review, *International Journal of Humanities and Arts Computing* **2**(1-2): 39–62.
doi: https://doi.org/10.3366/E1753854809000305.

[70] Vehtari, A., Simpson, D., Gelman, A., Yao, Y. and Gabry, J. [2021]. Pareto smoothed importance sampling.
url: https://arxiv.org/abs/1507.02646.

[71] Watanabe, S. [2013]. A widely applicable bayesian information criterion, *Journal of Machine Learning Research 14* **14**: 867–897.
url: https://dl.acm.org/doi/10.5555/2567709.2502609.

[72] Whitehill, T. and Chau, C. [2004]. Single-word intelligibility in speakers with repaired cleft palate, *Clinical Linguistics and Phonetics* **18**: 341–355.
doi: https://doi.org/10.1080/02699200410001663344.

[73] Wie, O. B. [2010]. Language development in children after receiving bilateral cochlear implants between 5 and 18 months, *International Journal of Pediatric Otorhinolaryngology* **74**(11): 1258–1266.
doi: https://doi.org/10.1016/j.ijporl.2010.07.026.
url: https://www.sciencedirect.com/science/article/pii/S0165587610003708.

[74] Wie, O., Torkildsen, J., Schauber, S., Busch, T. and Litovsky, R. [2020]. Long-term language development in children with early simultaneous bilateral cochlear implants, *Ear and Hearing* **41**(5): 1294–1305.
doi: https://doi.org/10.1097/AUD.0000000000000851.

[75] Winkler, R. [1967]. The assessment of prior distributions in bayesian analysis, *Journal of the American Statistical Association* **62**(319): 776–800.
doi: https://doi.org/10.1080/01621459.1967.10500894.
url: ttps://www.tandfonline.com/doi/abs/10.1080/01621459.1967.10500894.

[76] Wright, B. [2005]. Qualtrics. (Version December 2018).
url: www.qualtrics.com.

[77] Yanbay, E., Hickson, L., Scarinci, N., Constantinescu, G. and Dettman, S. [2014]. Language outcomes for children with cochlear implants enrolled in different communication programs, *Cochlear Implants International* **15**(3): 121–135.
doi: https://doi.org/10.1179/1754762813Y.0000000062.

[78] Yarkoni, T. [2020]. The generalizability crisis, *The Behavioral and brain sciences* **45**(e1).
doi: https://doi.org/10.1017/S0140525X20001685.

[79] Young, G. and Killen, D. [2002]. Receptive and expressive language skills of children with five years of experience using a cochlear implant, *Annals of Otology, Rhinology & Laryngology* **111**(9): 802–810.
doi: https://doi.org/10.1177/000348940211100908.