The Alice Datasets: fMRI & EEG Observations of Natural Language Comprehension

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Abstract

The Alice Datasets combine observations from magnetic resonance imaging as well as electrophysiology while human participants listened to the same literary narrative in English. Along with these neural signals and the text of the story, we also provide a variety of word-by-word predictors motivated by research in computational linguistics and cognitive science. These predictors range from prosody to morphology to syntax. These annotated, naturalistic datasets can be used to replicate prior work and test new hypotheses about natural language comprehension in the brain.

Keywords: fMRI, EEG, neurolinguistics, naturalistic, English, cognitive methods, corpus

1. Introduction

While there has been a tradition of using naturalistic language corpora in computational linguistics, this practice has only recently become popular within the cognitive neuroscience of language. In this neighboring field "naturalistic" stimuli are now offering a new way to study language comprehension in the brain, in synergy with natural language processing (NLP) tools (Armeni et al., 2017; Brennan, 2016).

From a neurolinguistic perspective, contextually-situated naturalistic stimuli present an opportunity to investigate multiple linguistic levels, including phonemes, syllables, words, phrases, sentences and discourse, all simultaneously within the same dataset. Such an opportunity creates new avenues for linking hypotheses between various linguistic representations and neurobiological architectures in the brain (Kandylaki and Bornkessel-Schlesewsky, 2019).

This paper introduces a new language resource, the Alice Datasets, which is naturalistic in this sense (Maguire, 2012; Willems, 2015; Hamilton and Huth, 2018). It packages together neuroimaging and electrophysiological measures from many speakers listening to the same text – the first chapter of Lewis Carroll's *Alice's Adventure in Wonderland* (1865). It shares an underlying book with the cross-linguistic project, *Alice in the Language Localizer Wonderland* (Fedorenko, 2016) and an emphasis on naturalistic text with the Narrative Brain Dataset (Lopopolo et al., 2018) (hereafter NBD). However the current project is based on a longer continuous narrative than in either of these projects (12 mins 24 secs vs 6 mins 30 secs on an average for NBD). This larger corpus facilitates the study of linguistic phenomena that may not be attested sufficiently often in smaller samples. The Alice Datasets include both high spatial resolution (fMRI) and high temporal resolution (EEG) neural signals. And since this resource is in English (rather than Dutch, the language of the NBD), it offers the chance to apply a very wide array of speech and natural language technologies. Together, these properties make the Alice Datasets a first-line choice for those seeking to com-

pare AI systems to human neural signals (Beinborn et al., 2019).

2. Dataset Structure

The Alice Datasets include data from two modalities each of which are discussed separately below.

2.1. Magnetic Resonance Dataset

The fMRI dataset consists of raw BOLD signals, pre-processed derivatives, and metadata files. The data files are named and organized according to the Brain Imaging Data Structure (BIDS) Specification, version 1.1.1.

The raw data are organized with a folder corresponding to each subject, with 26 subjects total (numbered from 18-53, see Table 2). For each subject, anatomical and functional MRI data files in NIfTi format are found in *anat/* and *func/* folders, respectively, with one file of each type. The anatomical MRI scans were anonymized by removing facial structure using PyDeface (Poldrack, 2015).

The *derivatives/* folder includes subfolders for all 26 participants where the fMRI data are pre-processed as described in section 4.4. The exact parameters used are also included in the *sub-*_preprocess.mat* files.

Metadata files include participant information, summarized in Table 2. Each subject also has a file *sub-*_task-alice_bold.json* which defines the scanner parameters, and a file *sub-*_task-alice_events.tsv* which defines the onset and duration of the listening task, while the audio file used is found in the *stimuli/* folder, along with the 12-question quiz used to assess comprehension, and a file with linguistic and computational annotations for the story.

2.2. Electrophysiological Dataset

The EEG data consists of raw data, pre-processed derivatives, and auxiliary files containing stimulus and participant details. The raw data themselves are MATLAB files (MATLAB, 2015) organized with one file for each of the 49 subjects (e.g. *S47.mat*). Each file contains anonymized data-structures generated by the open-source FieldTrip Toolbox
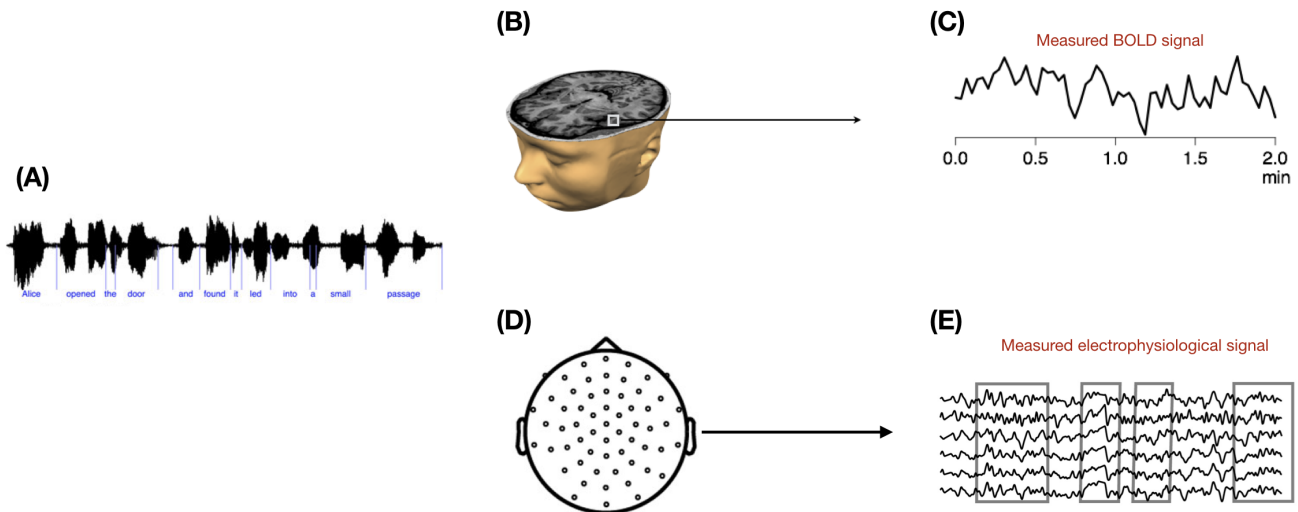
Figure 1: Overview of the Alice Datasets acquisition while participants listen to an audiobook. (A): Sample excerpt from the audiobook stimulus. (B): Representation of brain during fMRI recording where the signal from each voxel is measured independently. (C): Sample blood oxygen level dependant (BOLD) signal at a specific voxel collected using fMRI. (D): Schematic diagram of a scalp with EEG electrodes (E): Sample electrophysiological signal in the brain collected using EEG.

(Oostenveld et al., 2011). A separate file, *proc.zip*, contains contains the pre-processing parameters that were derived during data analysis for 42 of the datasets (seven datasets were not fully pre-processed due to excessive artifacts.) Auxilliary files include the questionnaire used to assess comprehension, and the behavioral responses recorded from each participant along with notes about the datasets that were not pre-processed due to artifacts and the datasets from participants that did not meet behavioral criteria. A *README.txt* file describes all of the contents of the dataset in detail.

3.   Linguistic Stimuli

The EEG and fMRI recordings in the Alice Dataset are based on the same chapter of *Alice's Adventure in Wonderland*. The version used was Kristen McQuillan's reading of the first chapter of *Alice's Adventure in Wonderland* from LibriVox (2015). The chapter used does not include significant word-play, such as the famous Jabberwocky poem that appears elsewhere in the story.

The stimulus chapter comprises 2,129 words in 84 sentences which are on average 25.8 words long (SD = 24.2). As part of our analysis these sentences are parsed using the Stanford Parser (Klein and Manning, 2003). The resulting tree-structures indicate that the stimuli have a reasonable syntactic diversity: The stimuli average 2.31 clauses each and attest, for example, 153 different types of VP rules.

The audio was slowed by 20% using the pitch-preserving PSOLA algorithm, implemented in Praat (Boersma and Weenink, 2016), to improve comprehensibility and was normalized to 70 dB SPL. An independent rater judged the digitally altered stimulus to sound natural and to be easier to understand than the raw audio recording. The stimulus lasted 12.4 minutes. The stimulus is available as Supplementary Material.

4.   Magnetic Resonance Dataset

4.1.   Participants

29 participants were scanned and 1 participant was excluded due to excessive head movement and 2 were excluded due to poor behavioral performance (as described below). All exclusions were assessed prior to running the statistical analyses. Participants included were twenty-six volunteers (15 women and 11 men, 18–24 years old) with no history of psychiatric, neurological, or other medical illness or history of drug or alcohol abuse that might compromise cognitive functions. All strictly qualified as right-handed on the Edinburgh handedness inventory (Oldfield, 1971) and self-identified as native English speakers. They gave their written informed consent prior to participation, in accordance with Cornell University IRB (#1310004157) guidelines and were compensated for their participation. Their demographic data along with quiz scores are provided in the metadata file and in the Appendix.

Participants completed a twelve-question multiple choice questionnaire concerning the contents of the story at the end of the experimental session. Each question had four possible answers. Under the binomial distribution, correctly answering at least 7 questions is required to exceed chance at $\alpha = 0.05$. We excluded data from all participants who did not meet this behavioral threshold.

4.2.   Procedure

After being briefed on the study procedure and giving their informed consent, participants were familiarized with the MRI facility and assumed a supine position on the scanner gurney. The presentation script was written in PsychoPy (Peirce, 2007). Auditory stimuli were delivered through MRI-safe, high-fidelity headphones (Confon HP-VS01, MR Confon, Magdeburg, Germany) inside the head coil. The headphones were secured against the plastic

	Size of Dataset	Spatial Resolution	Temporal Resolution	Length of Stimulus	No. of Timepoints	No. of Words
fMRI Dataset	26 participants	3mm^3	2,000 ms	744 s	372	2,129
EEG Dataset	49 participants	61 electrodes	2ms (500 Hz)		372,000	

Table 1: Summary information about the Alice Datasets.

frame of the coil using foam blocks. Using a spoken recitation of the US Constitution, an experimenter increased the volume stepwise until participants reported that they could hear clearly. Participants then listened passively to the audio storybook. Upon emerging from the scanner, participants completed a twelve-question multiple-choice questionnaire concerning events and situations described in the story. The entire session lasted less than an hour.

4.3. Data Collection

Imaging was performed using a 3T MRI scanner (Discovery MR750, GE Healthcare, Milwaukee, WI) with a 32-channel head coil at the Cornell MRI Facility.

Blood Oxygen Level Dependent (BOLD) signals were collected from twenty nine participants. Thirteen participants were scanned using a T2*-weighted echo planar imaging (EPI) sequence with: a repetition time of 2000 ms, echo time of 27 ms, flip angle of 77°, image acceleration of 2X, field of view of 216 x 216 mm, and a matrix size of 72 x 72. Under these parameters we obtained 44 oblique slices with 3 mm isotropic voxels. Sixteen participants were scanned with a three-echo EPI sequence where the field of view was 240 x 240 mm resulting in 33 slices with an in-plane resolution of 3.75 mm^2 and thickness 3.8mm. This multi-echo sequence was used for reasons that are not related to the present study. For our purposes, analyses of this second group were based exclusively on images from the second EPI echo, where the echo time was 27.5 ms. All other parameters were exactly the same. This selection of the second-echo images renders the two sets of functional images as comparable as possible. Anatomical images were collected with a high resolution T1-weighted (1 x 1 x 1 mm^3 voxel) with a Magnetization-Prepared RApid Gradient-Echo (MP-RAGE) pulse sequence.

4.4. Preprocessing

Preprocessing was done with SPM8 (Friston et al., 2007). Data were spatially realigned based on 6-parameter rigid body transformation using the 2nd degree B-spline method. Functional (EPI) and structural (MP-RAGE) images were co-registered via mutual information and functional images were smoothed with a 3 mm isotropic Gaussian filter. We used the ICBM template provided with SPM8 to put our data into MNI stereotaxic coordinates. The data were high pass filtered at 1/128 Hz and we discarded the first 10 functional volumes. Data from one participant was excluded at this stage due to head movement that exceeded an absolute threshold of 1 mm.

5. Electrophysiological Dataset

5.1. Participants

52 volunteers participated in the study. All participants were adult native speakers of English with normal hearing and no neurological disorders, by self-report. Data from

19 participants was excluded in the published analysis, and these notes are included in the released dataset. Three participants were excluded due to an experimenter error; these are not included in the released dataset. Of the remaining 49 datasets (14 male, age-range 18–29), seven were not fully pre-processed due to excessively noisy data. Additionally, 10 participants (one whose data had excessive noise) did not score above chance on the eight-question comprehension questionnaire given at the end of the recording session.

Participant data for the EEG data are given in Table 3 in the Appendix. All participants gave their written informed consent prior to participation, in accordance to University of Michigan HSBS IRB (#HUM00081060) guidelines and were compensated for their participation.

5.2. Procedure

After being briefed on the study procedure and giving their informed consent, participants were fitted with an elastic cap with 61 actively-amplified electrodes and one ground electrode (actiCap, Brain Products GmbH). Electrodes were distributed equidistantly across the scalp according to the Easycap M10 layout. Conductive gel was inserted into each electrode to reduce impedances to 25 kOhms or below.

Participants listened to the stimulus with insert earphones (EA-2, Etymotic Inc.) in an isolated booth. Prior to hearing the audiobook, a hearing threshold was determined per participant and per ear using 1 kHz tones (300 ms, 10ms fade in/out). The audiobook story was played at 45 dB above this threshold. Following the story, participants completed an eight-question multiple-choice questionnaire asking about events in the story. The entire experimental session lasted 1–1.5 hours.

5.3. Data Collection

Data were recorded at 500 Hz from 61 active electrodes (impedances $< 25k\Omega$) between 0.1 and 200 Hz referenced to an electrode placed on the right mastoid (actiCHamp, Brain Products GmbH).

5.4. Preprocessing

Data processing was conducted using the Fieldtrip toolbox (Oostenveld et al., 2011) in MATLAB (2015). Processing steps included: (i) re-referencing the data to the left and right mastoid electrodes, (ii) high-pass filtering at 0.1 Hz, (iii) epoching the data around each word, (iv) removing ocular artifacts with Independent Component Analysis (ICA), (v) removing remaining artifactual epochs and channels with visual inspection, and (vi) reconstructing missing channels using surface spline interpolation. The processing parameters necessary to recreate these derived data are included along-side the raw data. These parameters include the epoch definitions (2,129; 919 content words and 1,210

function words), the ICA loadings to remove ocular artifacts, and indexes for artifactual epochs and channels.

6. Annotation

6.1. Linguistic Annotation

For both the datasets, the timestamps (onsets and offsets) of every word in the auditory stimulus is included in the annotations, along with a categorical predictor representing whether the word is a content word or function word and the log-transformed lexical frequency of each word, based on the HAL corpus via the English Lexicon Project (Balota et al., 2007).

In the Alice fMRI dataset, the POS tags for each word in the story are provided, as given by the Collin's parser (Collins, 1999). The annotations also include the prosodic break strength of each word. This is a perceptual judgment of break index strength made in light of ToBI annotation guidelines (Beckman et al., 2004). This predictor was used to control for correlations between acoustic variance and syntactic structure.

In the Alice EEG dataset, the following control predictors are also included in the annotations: sentence order, word order (within each sentence), word frequency of the preceding, and following word, and sound power (MATLAB, 2015) at word onset.

6.2. Computational Annotation

Various computational predictors have been tested on both the fMRI and EEG datasets and they are included with the dataset as annotations.

The Alice fMRI dataset's computational annotations consist of word-by-word predictors based on nine different models incorporating two different complexity metrics: surprisal (Hale, 2001) and structural node count (Frazier, 1985; Hawkins, 1994; Miller and Chomsky, 1963) across different levels of syntactic details. These include bigram lexical surprisal, trigram lexical surprisal, bigram POS surprisal, trigram POS surprisal, CFG surprisal, CFG bottom-up node count, CFG top-down node count, MG bottom-up node count, and MG top-down node count. For more details about these predictors and how they were calculated, please see Brennan et al. (2016).

The Alice EEG dataset's computational annotations include word-by-word syntactic surprisal values based on three probabilistic language models: two which condition probabilities solely on solely based on linear sequence information, and one which conditions probabilities based on the hierarchical structure assigned to a particular sequence of words. For further details about these predictors and how they were calculated, please see Brennan and Hale (2019).

7. Data Availability

These parallel datasets are publicly available. The Alice fMRI dataset and supplementary materials is available through OpenNeuro at `doi: 10.18112/openneuro.ds002322.v1.0.3` and shared under a Creative Commons "CC0 1.0 Universal Public Domain Dedication" license ⓒⓞ. The Alice EEG dataset along with its corresponding supplementary materials is available at `doi: 10.7302/Z29C6VNH` and shared under a Creative Commons "Attribution 4.0 International" license ⓒⓘ.

8. Published Analyses of Current Dataset

This naturalistic dataset has been analyzed in various studies to investigate different aspect of language comprehension within ecologically valid settings.

Using the EEG data, Brennan and Hale (2019) illustrated that abstract hierarchical structures guide listeners' linguistic predictions, rather than the sequential information. Hale et al. (2018) used Recurrent Neural Net Grammars to interpret a P600-like pattern as syntactic processing work.

Based on the fMRI dataset, Li and Hale (2019) looked into a specific formalization of memory decay along grammatical dependency links, localizing BOLD signals corresponding to this predictors in the left posterior temporal lobe. Brennan et al. (2016) found support for linguistically-rich grammars in temporal but not frontal regions. Li et al. (2016) examined a predictor based the Distributional Hypothesis, confirming a meaning-related role for the anterior temporal lobes. Hale et al. (2015) used metrics like POS ngrams, surprisal, node counts to illustrate that finer-grained predictors make a contribution over and above coarser predictors like ngrams.

9. Conclusion

Our goal in sharing these datasets is to encourage researchers to test theories on common data and to promote more efficient research through reuse. As these naturalistic datasets are not constrained by a specific task or experimental paradigm, they are open to the possibility of multiple researchers testing out different research questions across different levels of linguistic representation. Furthermore, these combined naturalistic datasets makes it relatively easy to run analyses without collecting new data and compare electrophysiological findings with the fMRI results.

10. Acknowledgements

Appendix

This appendix consists of information about the participants and is also available as the metadata with the datasets. Table 2 contains the fMRI participant's gender and age information (as provided by them), their quiz scores, and the final decibel level the audio stimulus was played at.

Table 3 contains the EEG participant's self-reported gender and age, their quiz scores, and notes concerning data that were excluded from the published analysis.

SUBJECT NO.	AGE	GENDER	QUIZ SCORE	FINAL dB
18	22	M	11/12	5
22	22	M	11/12	13
23	19	F	11/12	5.5
24	21	F	7/12	8
26	21	M	9/12	6
28	18	M	10/12	7
30	19	F	10/12	5
31	20	F	10/12	6
35	19	M	11/12	8.5
36	21	M	11/12	10
37	20	M	11/12	11
38	19	F	10/12	11
39	19	M	12/12	10
41	19	M	10/12	10
42	21	M	11/12	10
43	21	F	9/12	10
44	22	F	9/12	11.5
45	19	M	10/12	9.5
46	21	F	6/12	10
47	19	F	10/12	10
48	20	F	10/12	10
49	21	F	8/12	10
50	20	F	11/12	10
51	18	F	11/12	10
52	20	M	5/12	10
53	26	F	11/12	11

Table 2: Participant data for fMRI study

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SUBJECT NO.	AGE	GENDER	QUIZ SCORE	NOTES
S01	20	F	6/8	
S02	19	F	6/8	noise
S03	18	M	6/8	
S04	21	F	7/8	
S05	20	F	7/8	
S06	20	F	5/8	
S07	18	F	4/8	low score
S08	25	M	6/8	
S09	19	F	2/8	low score
S10	19	F	5/8	
S11	22	F	6/8	
S12	19	F	6/8	
S13	19	F	8/8	
S14	18	F	4/4	
S15	25	F	4/4	
S16	18	F	6/8	
S17	19	F	6/8	
S18	19	F	7/8	
S19	18	F	8/8	
S20	24	F	5/8	
S21	24	F	NA[1]	
S22	21	F	6/8	
S23	20	M	3/8	low score
S24	22	F	4/8	low score
S25	22	M	5/8	
S26	21	F	6/8	
S27	21	F	4/8	low score
S28	18	F	7/8	noise
S29	23	M	6/8	noise
S30	29	M	4/8	low score
S31	22	F	3/4	noise, score
S32	19	F	4/8	low score
S33	23	M	8/8	noise
S34	21	M	5/8	
S35	20	F	5/8	
S36	22	M	6/8	
S37	19	M	8/8	
S38	22	M	8/8	
S39	18	F	3/8	low score[2]
S40	19	M	6/8	
S41	19	M	7/8	
S42	21	F	7/8	
S43	21	M	2/8	low score
S44	21	F	7/8	
S45	18	F	5/8	
S46	18	F	3/8	noise, score
S47	18	F	4/8	noise, score
S48	18	F	7/8	
S49	19	F	6/8	noise

Table 3: Participant data for EEG study. Note: [1]Quiz data from one participant is not available. [2]This participant's data was included in the published analysis.

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