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NeuroElectro: A Window to the World's Neuron Electrophysiology Data

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Neuroinformatics Infrastructure

2 ABSTRACT

The behavior of neural circuits is determined largely by the electrophysiological properties of the neurons they contain. Understanding the relationships of these properties requires the ability to first identify and catalog each property. However, information about such properties is largely locked away in decades of closed-access journal articles with heterogeneous conventions for reporting results, making it difficult to utilize the underlying data. We solve this problem through the NeuroElectro project: a Python library, RESTful API, and web application (at <http://neuroelectro.org>) for the extraction, visualization, and summarization of published data on neurons' electrophysiological properties. Information is organized both by neuron type (using neuron definitions provided by NeuroLex) and by electrophysiological property (using a newly developed ontology). We describe the techniques and challenges associated with the automated extraction of tabular electrophysiological data and methodological metadata from journal articles. We further discuss strategies for how to best combine, normalize and organize data across these heterogeneous sources. NeuroElectro is a valuable resource for experimental physiologists looking to supplement their own data, for computational modelers looking to constrain their model parameters, and for theoreticians searching for undiscovered relationships among neurons and their properties.

Keywords: neuroinformatics, electrophysiology, database, text-mining, metadata, API, machine learning, natural language processing

1 INTRODUCTION

21 Brains achieve efficient function through implementing a division of labor, in which different types of
22 neurons serve distinct functional and computational roles. One striking way in which neuron types differ
23 is in their electrophysiology properties. Though the electrophysiology of many neuron types has been
24 previously characterized and documented across decades of research, these data exist across thousands of
25 journal articles, making cross-study neuron-to-neuron comparisons difficult.

26 Neurophysiology lacks a centralized resource where consensus data on basic physiological
27 measurements from many neuron types and studies are accessible for reference and subsequent meta-
28 analyses. For example, though it is common for neurophysiologists to measure and report neuronal
29 measurements such as resting membrane potential and input resistance, there is not a public database
30 which compiles this information. In other domains of neuroscience such efforts have made more progress.
31 In the domain of neuroanatomical connectivity, information on connectivity between different brain
32 regions is being compiled by experts at the Brain Architecture Management System project (BAMS)
33 across hundreds of publications (**Bota et al.**, 2005). Parallel to this effort is the WhiteText Project,
34 which addresses a complementary goal by algorithmically mining brain region connectivity statements
35 from journal abstracts using biomedical natural language processing (bioNLP) methods (**French et al.**,
36 2009, 2012). Similarly, in the domain of neuroimaging, the NeuroSynth Project has mined fMRI-
37 based brain activation maps from published x,y,z coordinate data tables from thousands of neuroimaging
38 publications (**Yarkoni et al.**, 2011). These literature-based methods can be contrasted with projects such
39 as NeuroMorpho.org (**Parekh and Ascoli**, 2013) and ModelDB (**Migliore et al.**, 2003; **Hines et al.**,
40 2004), which index neuron morphological reconstructions and computational models for simulating
41 neuron activity by obtaining this information directly from investigators.

42 Success among these projects can be defined according to different criteria. Such criteria include
43 completeness and comprehensiveness; for example, what percentage of relevant connectivity studies
44 are indexed within BAMS? How many different neuron types are contained within the NeuroMorpho
45 database? Alternatively, success can be defined in terms of the utility of these databases in driving
46 subsequent research, like the use of BAMS as a resource for discovering relationships between brain
47 region connectivity and gene expression (**French and Pavlidis**, 2011) or the use of NeuroMorpho to
48 discover general scaling relationships among the morphology of neuron types (**Teeter and Stevens**, 2011).
49 Similarly, NeuroSynth is widely used by cognitive scientists as a starting point for designing functional
50 imaging studies. Thus while these projects are not yet comprehensive and likely contain data records of
51 varying quality, these resources may nevertheless be employed to draw novel inferences.

52 These projects are logically divided according to their methods for obtaining the source data: through
53 the use of manual methods like expert curation or user contributions versus automated methods such
54 as text-mining. Notably, these approaches differ in their scale and accuracy; while algorithmic methods
55 can “scale-up” and be applied to arbitrary numbers of publications, they typically have a lower accuracy
56 relative to human-curated content (**French et al.**, 2009). This lower accuracy is often attributed to the
57 rich lexical complexity of biomedical texts which often require considerable context and background
58 knowledge to understand and parse (**Dickman**, 2003; **Ambert and Cohen**, 2012). The competing
59 constraints of scale versus accuracy pose a challenge for large-scale compilation of neuroscientific data.

60 Here, we built a custom infrastructure framework for extracting electrophysiological measurements for
61 specific neuron types from published neurophysiology articles. These measurements included properties
62 such as input resistance and resting membrane potential, as well as associated metadata (i.e., article-
63 specific methodological details). Our methods combine algorithmic literature text-mining, drawing from
64 the approach used by NeuroSynth (**Yarkoni et al.**, 2011) where neurophysiological measurements are
65 primarily extracted from data tables, as well as manual curation, leveraging the background knowledge

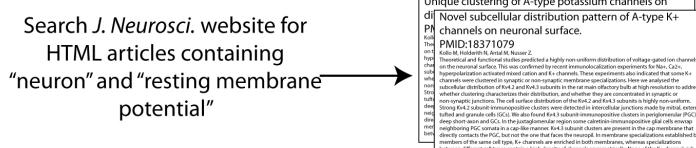
66 of domain experts. The resulting neurophysiology database, named NeuroElectro, can be interactively
 67 viewed and explored through a public web interface at <http://neuroelectro.org>.

2 MATERIALS, METHODS, & RESULTS

2.1 OVERVIEW

68 We describe and validate our semi-automated methodology for obtaining neuronal biophysical
 69 measurements directly from published reports in the literature (summarized in Fig. 1). After obtaining
 70 full article texts from publishers, we then used text-mining algorithms to identify concepts specific to
 71 electrophysiology and neuron types, which we then validated manually.

1. Obtain full texts of relevant articles



2. Find articles containing data tables

The diagram shows a search query on the left: "Look for data tables by finding full texts containing html <table> tags". An arrow points from this query to a table of extracted data. The table has three columns: RS Cell and FS Cell, with RMP (mV), AP threshold (mV), and Tau (ms) as rows.

	RS Cell	FS Cell
RMP (mV)	-65 +/- 2	-70 +/- 1
AP threshold (mV)	-45 +/- 1	-50 +/- 1
Tau (ms)	20 +/- 5	45 +/- 9

3. Map concepts and extract values from data table

1. Electrophysiology concept mapping
"RMP (mV)" -> resting membrane potential
(fuzzy-string matching against electrophysiology property synonym lists)
2. Neuron concept mapping
"RS Cell" -> Neocortex pyramidal cell layer
2-3
(usually done manually, new neuron types added when necessary)
3. Data value mapping
"-65+/-2" -> mean: -65
error: 2
4. Manual validation of concept mapping and data extraction
5. Addition of extracted data to Neuro-Electro database

Figure 1. Illustration of workflow for obtaining electrophysiological information from the research literature.

2.2 ARTICLE IDENTIFICATION

72 We obtained electrophysiological data from 10 neuroscience specific journals (Table 1), which include:
 73 *Journal of Neuroscience*, *Journal of Neurophysiology*, and *Journal of Physiology* (among others). We
 74 selected these journals because they often devote a significant fraction of an article's main text, tables,
 75 and figures to detailed characterizations and summaries of intrinsic neuronal biophysical properties.

76 We obtained tens of thousands of potentially relevant full article texts directly from publisher websites.
 77 We first identified potential articles that were likely to contain information relevant to neuron biophysics
 78 using the native search functions provided within the journal websites and only downloaded articles
 79 containing in their full text any of a specific list of terms including "input resistance" and "resting

Table 1. Statistics of journals represented in the NeuroElectro database. Listing of journals and counts of articles downloaded (articles obtained), articles with published data tables containing neurophysiological information which has been manually validated by an expert curator (validated), and articles which likely contain information in a data table which has not yet been manually curated (not validated). Not validated articles are those which have at least 4 algorithmically assigned electrophysiological concepts within data tables.

Journal	Articles obtained	Validated	Not validated
J. Neurosci.	19002	104	560
J. Neurophysiol.	12078	94	555
J. Physiol. (Lond.)	10543	44	235
Neuroscience	3035	14	205
Eur. J. Neurosci.	2495	7	117
Brain Res.	3017	7	146
Neuron	1657	4	43
Epilepsia	463	2	23
Neurosci. Lett.	1468	2	34
Hippocampus	208	2	10

80 membrane potential” (Fig. 1). This pre-selection step allowed us to identify and download only articles
 81 that contained data relevant to our project. Upon identifying candidate articles, we then downloaded the
 82 full text of each potentially-relevant article as HTML; articles downloaded from the publisher Elsevier
 83 (e.g., *Neuron* and *Brain Research*) were downloaded as XML using the provided text-mining API and
 84 subsequently converted to HTML. We chose to work with HTML (as opposed to PDF or XML) because
 85 HTML provides a machine-readable markup of the article’s content, allowing us to easily identify relevant
 86 elements within the article – such as data tables and the methods section – using publicly available
 87 HTML-parsing tools (here we used the Beautiful Soup HTML-processing library implemented in Python:
 88 <http://www.crummy.com/software/BeautifulSoup/bs4/doc/>). Furthermore, because
 89 HTML is a single semi-structured standard used across publishers, we could write relatively generic
 90 HTML-processing algorithms applicable to content published across journals. Our focus on using HTML
 91 limits us to relatively newer articles - typically those published after 1996 - because before this time
 92 most publications are only available as scanned PDF files. However, because the rate of publication
 93 across the field has grown exponentially, this HTML-available subset constitutes the majority of published
 94 neuroscience articles.

95 We stored the HTML-enhanced full text of each article in our database and associated each article
 96 with its corresponding PubMed ID (<http://www.ncbi.nlm.nih.gov>). These 8-digit IDs serve as
 97 publisher-independent unique identifiers for each article, and allow us to use PubMed-specific tools, such
 98 as a powerful API (i.e., PubMed eutils, <http://www.ncbi.nlm.nih.gov/books/NBK25500/>).
 99 For example, this API provides the ability to query each article’s MeSH terms (MEdical Subject Headings)
 100 and returns basic methodological information such as animal species and strain.

2.3 ELECTROPHYSIOLOGICAL PROPERTY IDENTIFICATION

101 **2.3.1 Rationale for focusing on electrophysiological property extraction from data tables.** In order to
 102 algorithmically extract information on neuron electrophysiology from these articles, we needed to first
 103 specify the data types of interest. Our preference was to obtain as much detailed information about neuron
 104 electrophysiological properties as possible: ideally, this would include raw data corresponding to recorded
 105 electrophysiological traces. In mining information from articles, we were presented with multiple options
 106 (illustrated in Fig. 2), including extraction from: 1) the text of the article including figure captions, 2)

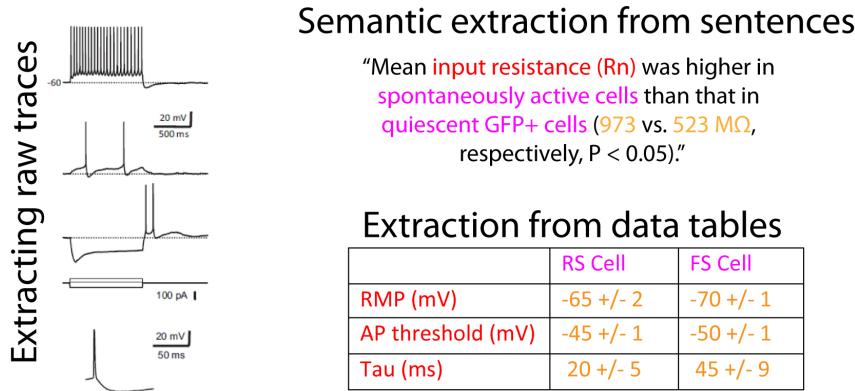


Figure 2. Illustration of the sources within an article containing information relevant to neuron electrophysiological properties. Data on neuronal electrophysiological properties are presented within article figures and raw traces, sentences within the article text, and formatted data tables. The raw traces and references are from van Brederode et al. (2011) and the data table is a constructed example. Colored text indicates electrophysiological concepts (red), neuron concepts (pink), or neurophysiological data (yellow).

107 the figures of the article, or 3) data tables presented within the article. In addition to these, authors often
108 submit supplemental materials and figures which also contain neurophysiological data.

109 Given the challenges in mining raw electrophysiological traces from figure images, we instead focused
110 on obtaining information about basic neuronal electrophysiological properties, such as input resistances
111 and resting membrane potentials. Though this information is often presented within the text of the article,
112 it is usually presented in complex sentence structures that are difficult to accurately parse algorithmically.
113 Published data tables, on the other hand, present a unique opportunity for electrophysiological data
114 extraction, since common techniques exist for extracting information from structured tables (Yarkoni
115 et al., 2011). Moreover, because tables succinctly summarize multiple attributes of a collected dataset, the
116 effort of an expert curator can be put to best use when validating tables relative to validating content mined
117 from article sentences or figure panels. While we estimate that only 5-10% of electrophysiology articles
118 contain data tables, there is sufficient redundancy within the field (i.e., multiple investigators often publish
119 articles on the same neuron type) that focusing on data tables nevertheless yields substantial coverage of
120 electrophysiological properties across many major neuron types.

121 **2.3.2 Extracting information on electrophysiological properties.** In extracting electrophysiological
122 data, we took advantage of the fact that certain measurements are commonly made during intracellular
123 recordings. For example, such recordings are commonly used to: 1) measure a neuron's resting
124 membrane potential, 2) to apply hyperpolarizing current injections for measurement of input resistance
125 and membrane time constant, and 3) to apply depolarizing current steps to evoke action potentials (spikes)
126 and enable measurement of characteristics such as spike threshold, width, and amplitude.

127 We developed an electrophysiological lexicon comprising 28 measurements that we found to be
128 commonly reported in the literature, largely based on previously published definitions (Toledo-Rodriguez
129 et al., 2004; Ascoli et al., 2008). To account for subtle differences in terminology that authors use to refer
130 to the same electrophysiological concept (e.g., resting membrane potential is often referred to as "rmp")

131 and “ V_{rest} ”), we also identified a common list of synonyms to map to each concept. Together, these
132 electrophysiological concepts and their synonyms define a preliminary ontology for electrophysiological
133 concepts (included in Supplemental Materials). Moreover, this physiological measurement ontology can
134 serve as a scaffolding for a more in-depth ontology of electrophysiological investigations (e.g., Ontology
135 for Experimental Neurophysiology, **Bruha et al.** (2013)). The terms in our preliminary ontology are also
136 indexed and defined within NeuroLex (<http://neurolex.org>, **Larson and Martone**, 2013)).

137 To identify data corresponding to electrophysiological properties reported within a data table,
138 we developed algorithms to search data table header elements and assess whether these elements
139 corresponded to any of the electrophysiological concept synonyms in our ontology. We first identified
140 table header elements by searching for table elements composed primarily of non-numeric characters.
141 For each putative header element, we then used fuzzy string matching algorithms (implemented using
142 the fuzzywuzzy library in Python: <https://github.com/seatgeek/fuzzywuzzy>), to assess
143 the textual match between the header element and each of the electrophysiological synonyms. These
144 fuzzy matching algorithms combine a number of string match metrics into a single “match value”,
145 including whether a pair of strings completely match, contain matching substrings, or contain matching
146 but misordered substrings. If the table header and electrophysiological synonym match value exceeded
147 a specified threshold, the table header and corresponding row or column of numeric values were
148 automatically mapped to the electrophysiological concept. Similarly, we mapped whole rows or columns
149 to specific neuron types recorded during normotypic or “wild-type” conditions.

150 We then manually corrected cases where these algorithms misassigned an electrophysiological concept.
151 For example, a common algorithmic mis-assignment was the case when an author used the string “EPSP
152 amplitude” to refer to the electrophysiological concept excitatory post-synaptic potential amplitude. In
153 these cases, our algorithms incorrectly mapped this string to “spike amplitude” because the former concept
154 is not in our current ontology. In a test sample of 279 articles that were manually curated, we found that
155 78% of concept-matchings (901/1152) were identified correctly with no supervision, with the remainder
156 manually corrected.

157 2.3.3 *Accounting for differences in electrophysiological definitions across investigators.* By focusing
158 on textually matching the electrophysiological terms in each table to a list of electrophysiological
159 concepts, we are implicitly assuming that electrophysiological properties are measured in the same way
160 by investigators across different articles. For example, the most common method that electrophysiologists
161 use to measure a neuron’s spike properties is to record from the neuron in current-clamp mode and apply
162 peri-threshold depolarizing currents to evoke 1-2 spikes over several hundred milliseconds or more. The
163 neuron’s spike amplitude is then commonly measured by calculating the difference between the neuron’s
164 voltage at spike threshold and spike peak for the first evoked spike (e.g. (**Connors et al.**, 1982; **Toledo-**
165 **Rodriguez et al.**, 2004)). However, experimental differences exist between how investigators measure and
166 compute these properties; we divide these differences into roughly 3 categories: *protocol*, *calculation*, and
167 *condition* differences. For example, investigators can use different experimental protocols to measure the
168 spike amplitude, like evoking spikes using current steps much greater than rheobase current required to
169 elicit a single spike (*protocol differences*). Additionally, the spike amplitude itself can be calculated in
170 different ways, such as using the neuron’s resting membrane potential as the baseline instead of the spike
171 threshold (*calculation differences*). Furthermore, the value of spike amplitude that an investigator reports
172 will also be affected by specific experimental conditions such as the animal species or age and recording
173 solution temperature or contents (*condition differences*).

174 When manually curating the text-mined content for the most commonly reported electrophysiological
175 properties (resting membrane potential, input resistance, membrane time constant, spike half-width,
176 spike amplitude, and spike threshold), we took care to account for where the investigator had calculated
177 an electrophysiological measurement using an inconsistent methodology (e.g., protocol or calculation
178 differences) by normalizing such measurements to a common reference definition or removing such data
179 when normalization was not possible. However we note that we could not identify all of these cases (in
180 particular: spike amplitude, input resistance, and membrane time constant), in part because investigators

A

Table 1.
Comparison of electrophysiological properties in adult +/+ and stg/stg in deep layer cortical neurons

	+/+	stg/stg	P
V_{rest} , mV	-74.4 ± 1.5 (25)	-73.7 ± 1.7 (27)	ns
R_{in} , MΩ	170 ± 25 (20)	170 ± 13 (22)	ns
Time constant, ms	26.9 ± 2.6 (14)	32.1 ± 3.1 (22)	ns
AP overshoot, mV	37.0 ± 3.7	34.1 ± 3.14 [11–58] (23)	ns

B

Table 1.
Comparison of electrophysiological properties in adult +/+ and stg/stg in deep layer cortical neurons

	+/ Concept: Neocortex pyramidal cell layer 5-6	stg/stg	P
V_{rest} , mV Concept: resting membrane potential	-74.4 ± 1.5 (25)	-73.7 ± 1.7 (27)	ns
R_{in} , MΩ Concept: input resistance	170 ± 25 (20)	170 ± 13 (22)	ns
Time constant, ms Concept: membrane time constant	26.9 ± 2.6 (14)	32.1 ± 3.1 (22)	ns
AP overshoot, mV Concept: spike overshoot	37.0 ± 3.7	34.1 ± 3.14 [11–58] (23)	ns

Figure 3. Example data table illustrating mark-up and annotation of entities. A. Example published data table containing neurophysiological information. Data table from **Pasquale et al.** (1997). B. Same as A, but semantically marked up with algorithmic and manually curated annotations. Markups in red and pink indicate electrophysiological and neuron type concepts and yellow indicates extracted data measurements. Note that here the textual string “+/+” and “stg/stg” refers to the normotypic and manipulated condition, respectively.

181 did not always explicitly define how these measurements were calculated within their article. We note that
 182 in cases where we pool measurements which are measured using inconsistent protocols or calculations,
 183 this will tend to add unexplained variance to our data set. Given these measurement inconsistencies, we
 184 provide our recommendations for how these electrophysiological properties should be reported in future
 185 investigations via our electrophysiology ontology (see Supplemental Materials).

2.4 NEURON TYPE IDENTIFICATION

186 **2.4.1 Using neuron types defined by NeuroLex.** To extract physiological information specific to
 187 individual neuron types, we had to identify which neuron types were reported in each article. However, in
 188 many cases uniquely identifying the neuron type(s) reported in any given study and mapping these to a
 189 canonical “neuron type” is difficult. This difficulty arises in part because investigators use different criteria
 190 for classifying neurons, including electrophysiological, morphological, or molecular characteristics
 191 (**Ascoli et al.**, 2008; **Huang and Zeng**, 2013; **Fishell and Heintz**, 2013).

192 To define canonical neuron types, we chose to use an existing list of approximately 250 neuron types
 193 and definitions provided by NeuroLex, a community-sourced, expert-defined collection of neuron types
 194 (<http://neurolex.org>; **Shepherd** (2003); **Hamilton et al.** (2012); **Larson and Martone** (2013)).
 195 Moreover, we chose to use NeuroLex to keep our database consistent with existing resources and to enable
 196 future researchers to combine these resources seamlessly. NeuroLex also provides synonyms for each
 197 neuron type, which we utilized to identify the neuron type(s) in each article. In cases where a neuron type
 198 was investigated in the literature across multiple articles but not indexed within NeuroLex (e.g. cerebellar
 199 nucleus neurons), we manually added this neuron type to our database’s listing and provided this neuron
 200 type to the NeuroLex neuron curators for incorporation (Gordon Shepherd, personal communication).
 201 Our specific criteria for identifying each of the neuron types reflected in the database are given in the
 202 Supplemental Materials.

203 2.4.2 *Identifying specific neuron types within an article.* Because of the complexity in unambiguously
204 identifying neuron types, we used a mixed text-mining and manual approach to map the neuron types
205 studied in each article to canonical NeuroLex neuron types. First, we used text-mining algorithms to
206 provide an initial “best guess” of the most likely neuron type. Specifically, we used a bag-of-words
207 approach (Aldous, 1985) on the full article text. This approach ignores the serial structure of the words
208 in the document and utilizes only the frequency of occurrence of each word within the document. We
209 next compared the article’s word-frequency histogram to the listing of neuron synonyms provided by
210 NeuroLex, ranking all neuron types by their likelihood of being actually studied within that article.
211 In comparison to articles that we manually curated, we found that this automated approach accurately
212 identified the neurons studied in each article with an accuracy of 30% (120 of 399 total) and up to 55%
213 when defining success as the studied neuron appearing as one of the top three neuron types suggested
214 by the bag-of-words method. Because of the relatively low accuracy of an automated-only approach,
215 we added a manual curation step where a curator identified the recorded neuron type using HTML drop
216 down menus enriched by the bag-of-words search (e.g., Fig. 4). As previously described, we mapped
217 individual data table elements and corresponding rows or columns to specific neuron types recorded
218 under normotypic conditions. We note that currently we only identify data from normotypic or “control”
219 neurons represented in tables, but plan to identify data from additional conditions in future work (e.g.
220 from pharmacologically manipulated or genetically modified animals).

2.5 EXTRACTION OF ELECTROPHYSIOLOGICAL DATA VALUES

221 After identifying specific electrophysiological properties and neuron types reported in a data table
222 (corresponding to row or column table headers), we then algorithmically extracted the data corresponding
223 to the table intersection of these (Fig. 3). We developed custom string regular expressions (Thompson,
224 1968) to parse the string corresponding to the numeric data. Specifically, we found that data strings were
225 often of the form: “XX ± YY (ZZ)”, where XX, YY, and ZZ refer to the mean, error term, and sample
226 size (i.e. the “n”), respectively. Often the number of replicates or error measurement were not reported
227 or were reported in alternative ways within the table. Presently, the error term is not resolved as either a
228 standard deviation or standard error measurement in the current version of NeuroElectro, but could easily
229 be resolved in future iterations.

230 When designing our processing algorithms, we parsed data strings from right to left: first searching for
231 data entities contained within parentheses, then for entities contained to the right of the ± term, and finally
232 the remaining term which we assumed to refer to the mean term. We found that occasionally data were
233 reported as “XX (LL - HH)” – where LL and HH indicate the lower and upper limits of a data range – and
234 accounted for these cases similarly. We used regular expressions to identify entities such as digits, decimal
235 signs, parentheses, and ± signs. We then converted the individual data elements which were encoded as
236 textual strings of digits to double precision decimal entities before storing these into our database. Our
237 focus here was primarily on parsing the mean value from a data record (i.e., summarizing the properties
238 of a number of recorded neurons), but also extracted and stored the error term and sample size where
239 possible. Using these methods, we were able to extract 2176 electrophysiological values for 93 distinct
240 neuron types within 279 articles.

2.6 MANUAL VALIDATION OF AUTOMATED DATA EXTRACTION

241 Following these automated concept identification and data extraction steps, we manually validated
242 associated concepts and fixed incorrect concept mappings as necessary. We developed custom-HTML
243 and javascript code to allow human curators to graphically interact with downloaded HTML data tables
244 and “mark-up” entities within the table (Fig. 4). This code allows for textual based elements of the HTML
245 table to be semantically annotated using drop down menus and text fields. Moreover, because annotation
246 is implemented via user interfaces composed of interactive web pages and drop down menus, these user
247 interfaces are simple enough to be utilized by other expert curators with little formal instruction.

Table 2. A partial listing of metadata attributes and extraction methodology. Metadata attributes are extracted through combining PubMed Medical Subject Heading terms (MeSH Terms) and custom regular expressions (Regex). Regular expression column (or MeSH Term column) indicates specific regular expressions (or MeSH terms) used for identifying metadata concept entities.

Metadata Concept	Values	Extraction method	Regular Expression	MeSH Term
Species	Rats Mice	MeSH Term only		Rats Mice
Electrode Type	Guinea Pigs Patch-clamp sharp	MeSH Term + Regex	"whole cell" or "patch clamp" "sharp electrode"	Guinea Pigs Patch-Clamp Techniques
Animal Strain	Fischer 344 Long-Evans Sprague-Dawley Wistar C57BL BALB C	MeSH Term only		Rats, Inbred F344 Rats, Long-Evans Rats, Sprague-Dawley Rats, Wistar Mice, Inbred C57BL Mice, Inbred BALB C
Prep Type	in vitro in vivo cell culture model	MeSH Term+Regex	"slice" or "in vitro" "in vivo" "culture" "model"	Cell Culture Techniques Computer Simulation
Jxn Potential	Not Corrected Corrected	Regex	"not junction potential" "junction potential"	
Rec Temperature	Continuous value Room temperature	Regex	"record ... C" or "experiment C" "record room temperature"	
Animal Age	Continuous value	Regex	Find digits near: "P#-#" or "P#-P#"	

2.7 METADATA IDENTIFICATION

248 Given the strong relationships between experimental conditions, such as animal species or recording
 249 temperature, and electrophysiological measurements (e.g., input resistances are known to decrease when
 250 measured in neurons from older animals (Zhu, 2000; Okaty et al., 2009; Kinnischtzke et al., 2012)),
 251 we also identified information on article-specific experimental conditions by extracting this information
 252 primarily from each article's methods section. For each article, we found the methods section by
 253 developing custom HTML tag filters for each journal (e.g., common publisher-defined HTML tags for
 254 methods sections are "Methods" or "Experimental procedures"). For each metadata entity that we focused
 255 on (species, animal strain, electrode type, preparation type, liquid junction potential correction, animal
 256 age, recording temperature), we devised custom automated text searching methods to identify these
 257 based on combining regular expressions (Thompson, 1968) with PubMed MeSH terms (Table 2). In
 258 other words, rather than taking a machine-learning based approach and training classifiers (Mccallum,
 259 2002), we took a rule-based approach and developed custom rules for identifying metadata entities. For
 260 example, to identify whether the recording electrode's liquid junction potential was corrected for in the
 261 study (Neher, 1992), we searched for whether the character string "junction potential" was mentioned
 262 within the methods section and, if so, whether the sentence or phrase containing the term was explicitly
 263 negated (indicating that the junction potential was not corrected for). Here, we identified and parsed

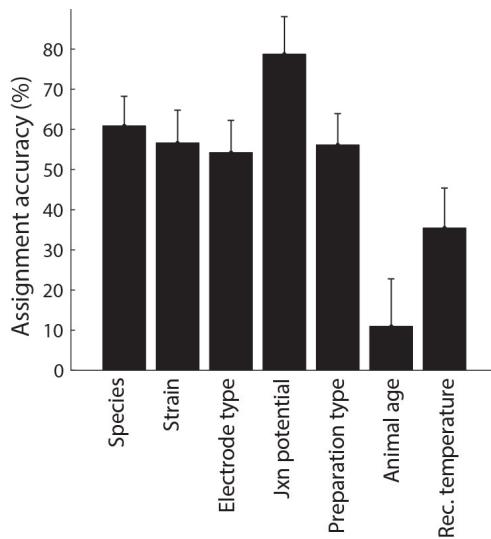
Table 1.

Comparison of electrophysiological properties in adult +/+ and stg/stg in deep layer cortical neurons

	+/ Concept: Neocortex pyramidal cell layer 5-6	stg/stg
V _r , mV Concept: resting membrane potential	-74.4 ± 1.5 (25)	-73.7 ± 1.7 (27)
R _{in} , MΩ Concept: input resistance		
•Ephys Prop Neuron		
'input resistance' <input type="button" value="Submit"/>	170 ± 25 (20)	170 ± 13 (22)
'None selected' 'cell capacitance'		
'input resistance'	26.9 ± 2.6 (14)	32.1 ± 3.1 (22)
'resting membrane potential'		
'membrane time constant'		
'spike amplitude'		
'spike half-width'		
'spike threshold'		
'rheobase'		
'firing frequency'		
'AHP duration'		
'cell diameter'		
	[12–67] (14)	
zation, mV	6.9 ± 1.1 (14)	1.5 ± 0.7 (12)

Figure 4. Example of human validation of algorithmically assigned content. All textual elements of a table are enhanced using HTML and javascript to allow for assignment of neuron or electrophysiological concepts using drop down menus. Example data table from Pasquale et al. (1997).

264 distinct sentences within the methods section using tools provided within the Natural Language Tool Kit
 265 in Python (Bird et al., 2009).

**Figure 5.** Accuracy of metadata assignment using automated methods alone. Error indicate 95% binomial confidence intervals.

266 Following automated identification of article metadata, we then manually checked each article to
 267 ascertain that algorithmically-tagged metadata was identified correctly and, as before, we corrected
 268 misidentified content as necessary through the use of custom HTML forms. We found that the mean
 269 accuracy of algorithmic metadata assignment was approximately 50% (Fig. 5) and was typically lower
 270 for identifying continuous-valued metadata (e.g. animal age or recording temperature) relative to nominal
 271 metadata such as species and electrode type.

2.8 OBJECT MODELS AND RELATIONAL DATABASE

272 We stored extracted data and metadata using a relational database implemented in MySQL (<http://dev.mysql.com/doc/refman/5.6/en/>) built from a Python Django object model (<https://www.djangoproject.com/>). The object model contains classes for a number of fields, such as full
273 article texts, electrophysiological properties, neuron types, synonyms, electrophysiological data values,
274 and experimental metadata (Fig. S1). A useful feature of the relational nature of the database is that it
275 enables linking between classes (e.g., linking between neuron types and electrophysiological properties
276 reported by a single investigator across multiple articles). This linking feature facilitates efficient and
277 arbitrary querying of data; for example, querying for known electrophysiological data on olfactory bulb
278 mitral cells recorded *in vitro* and published between the dates 2000 and 2004. For example, such a feature
279 could be used to assess whether measurements of olfactory bulb mitral cells have changed as a function
280 of time or are dependent upon whether the data are collected *in vitro* or *in vivo*.
281

2.9 WEB APPLICATION

283 The primary results of NeuroElectro are viewable at <http://www.neuroelectro.org> where the
284 data can be interactively explored.

285 **2.9.1 Human interface** The web interface is organized around neuron types and electrophysiological
286 properties. For example, each neuron type has its own webpage where extracted data corresponding
287 to specific electrophysiological properties is graphically and interactively displayed (graphical plot
288 interactivity implemented using the jqPlot javascript toolbox, <http://www.jqplot.com/>). Users
289 can thus visualize the mean and variability of electrophysiological values across papers, view references
290 plus experimental metadata, and easily navigate to primary data from specific papers. Furthermore, users
291 can view electrophysiological data across all of the neuron types in the database - putting phenotypic
292 properties of a given neuron type into the larger context of other neuron types located throughout the
293 nervous system.

294 The web application also contains preliminary features to allow website visitors to contribute to the
295 NeuroElectro resource. For example, users can suggest articles which contain electrophysiological data
296 which are not already in the database. We also invite visitors to become “expert curators” for neurons
297 of interest. In the future, we plan to build functionality that will allow investigators to upload raw and
298 summary data, such as recorded voltage and current traces. In addition, we plan to continue mining the
299 literature and adding neurophysiological measurements as they are published.

300 **2.9.2 API** An initial API (application programmer interface) providing public access to the
301 electrophysiological data is described at <http://neuroelectro.org/api/docs/>. This RESTful
302 API allows contents of the NeuroElectro database to be dynamically retrieved in JSON or XML format to
303 utilize this data within external applications. For example, using the current API, a developer could build
304 an application which dynamically queries NeuroElectro for all data corresponding to layer 2/3 neocortical
305 pyramidal cells and then uses this data to constrain parameters for a Hodgkin-Huxley type neuron model
306 (**Hodgkin and Huxley**, 1952). Example use cases of the current API (version 1) include:

- 307 • <http://neuroelectro.org/api/1/n/> : Returns a list of all neurons with electrophysiological
308 data indexed in NeuroElectro.
- 309 • <http://neuroelectro.org/api/1/nedm/?nlex=sao830368389> : Returns a list of all
310 indexed data on CA1 pyramidal cells (queried using the NeuroLex identifier for CA1 pyramidal cells,
311 *sao830368389*).
- 312 • http://neuroelectro.org/api/1/nes/?e_name=Input%20Resistance&n_name=Cerebellum%20Purkinje%20Cell : Returns a data record composed of the mean, standard

314 deviation, and sample size n, summarizing input resistance measurements from cerebellar Purkinje
315 cells based on all indexed articles in NeuroElectro database. Here the database query is performed
316 using the textual strings for the electrophysiological and neuron type concepts.

317 Our future plans are to work with domain ontologists to further develop the existing API into a formal
318 relational data format (RDF) specification, allowing further querying and extending of NeuroElectro into
319 additional resources. All code used in the project and the website is available at http://bitbucket.org/rgerkin/neuroelectro_org.

3 DISCUSSION

321 We have developed, applied, and validated a methodology and pipeline for extracting – from existing
322 literature on cellular neurophysiology – measurements of basic biophysical properties from diverse neuron
323 types throughout the nervous system. Currently, the NeuroElectro database contains 2344 manually
324 curated electrophysiological measurements from 98 neuron types from 335 publications. Of these
325 electrophysiological measurements, 2176 (93%) were obtained from 279 (83%) publications using the
326 semi-automated approach described here. In addition, we machine-extracted and manually validated 1667
327 methodological conditions (metadata) from these publications. This represents the single largest collection
328 of neurophysiological data ever compiled and represents a potentially valuable tool for scientific discovery.

3.1 SPECIFIC BENEFITS PROVIDED BY THE SEMI-AUTOMATED APPROACH

329 One of the key advantages of the approach described here is that the automated pipeline identifies
330 publications which are likely to contain content relevant to our domain area (i.e., measurements of
331 neuronal biophysics). Thus a human needs only to manually curate the content first identified by the
332 algorithms as being likely relevant, instead of having to identify the relevant content *de novo*. Moreover,
333 the automated identification of neuron types in articles allows us to target manual curation efforts
334 to publications likely to contain data from specific neuron types, such as neurons that are currently
335 underrepresented in the database.

336 Given our laboratory's focus on olfactory circuits, we conducted a natural experiment to compare
337 the efficacy of biophysical property extraction using these semi-automated methods versus traditional
338 methods which do not make use of algorithmic text-mining as a pre-processing step. In a seven-hour
339 curation session (evoking the classic American parable of John Henry versus the steam-powered hammer),
340 a senior graduate student in our laboratory identified 91 electrophysiological measurements (focusing on
341 resting membrane potential, input resistance, membrane time constant, spike amplitude, spike width, and
342 spike threshold) from 35 articles for 7 olfactory bulb neuron types using only prior knowledge of which
343 articles and investigators were likely to have reported such electrophysiological data. In a comparable
344 seven-hour curation session using our semi-automated methods, a single curator (with similar expertise
345 to the first curator) identified 551 electrophysiological measurements from 70 articles across 40 neuron
346 types throughout the nervous system. Moreover, this comparison would likely tilt even more in favor of
347 the semi-automated methods had the curators been less familiar with the primary literature.

3.2 SCALABILITY OF CURRENT APPROACH

348 We note that multiple steps in our approach require manual intervention by an expert curator in order for
349 electrophysiological measurements to be extracted with an acceptably low error rate. Namely, an expert
350 curator needs to confirm which of the machine-identified candidate neuron types are recorded from in each
351 article and where data from the normotypic or “control” states of these neurons are textually referenced
352 within a data table. Moreover, given the current accuracy of the unsupervised algorithmic assignment of
353 electrophysiological concepts and experimental metadata (78% and 50%, respectively), these also need

354 to be manually validated and corrected and normalized as required by an expert. Given the necessity of
355 these manual steps, the scalability of our current approach is limited by our ability to manually curate this
356 information or by our ability to improve the error rate of the automated methods. Despite this limitation,
357 our current pipeline is still much faster than a purely manual one. The methodology could be further
358 improved by addressing falsely matching entities (such as EPSP amplitude in section 2.3.2) by either
359 auto-suggesting alternative matches returned by string-similarity algorithms or by simply adding these
360 concepts to the electrophysiological ontology. Moreover, these improvements would facilitate formally
361 computing the sensitivity and specificity of these entity recognition methods.

3.3 PRELIMINARY USE OF NEUROELECTRO IN SCIENTIFIC WORK

362 The NeuroElectro project is intended to facilitate scientific investigation by providing easy access to large
363 quantities of data about neurons. Because the data is machine-readable, we have already begun to conduct
364 several analyses that would not be possible without this resource. First, we have begun an investigation
365 of the relationships between neurons as defined by the similarity of their electrophysiological properties.
366 This information can be used to make predictions about as yet unmeasured properties. Second, we have
367 begun to explore the relationship between patterns of gene expression (using both the Allen Brain Atlas
368 (**Lein et al.**, 2007) and single cell qPCR approaches) and electrophysiological properties of neurons.
369 Third, we have begun automated testing of quantitative neuron models in concert with SciUnit (**Omar**
370 **et al.**, 2014), under the reasonable assumption that these models should be constrained by the available
371 experimental data. These projects are described in manuscripts currently in preparation.

3.4 EXTENSIONS AND IMPROVEMENTS TO THE CURRENT SEMI-AUTOMATED ALGORITHMS

372 Currently, neuron type identification is a critical bottleneck in our approach. One potential improvement
373 would be to replace the nonspecific bag-of-words approach we are currently using in favor of a
374 bioNLP classifier-based approach (**Mccallum**, 2002). Specifically, we propose adapting the named entity
375 recognition methodology used by the WhiteText project for tagging brain regions mentioned in literature
376 (**French et al.**, 2009; **French and Pavlidis**, 2012) and first identifying spans of text likely to pertain to a
377 neuron type before mapping these textual spans to a individual neuron type within the neuron ontology.

378 The approach described here is highly effective for extracting biophysical measurements presented
379 within machine-readable data tables published within journal articles. However, the current requirement
380 that these data tables exist in a machine parseable format, such as HTML or XML, limits this approach
381 from being directly applied to older manuscripts, which are only available as scanned images. Existing
382 approaches, such as optical character recognition technology (OCR; e.g. (**Ramakrishnan et al.**, 2012))
383 may be applied toward this problem in the future.

384 Given the relatively low accuracy of the automated approach to identifying neuron types, there may
385 be several avenues through which this process can be improved. For example, we note the automated
386 approach was particularly ineffective when the neuron type investigated within an article was not already
387 described in NeuroLex or when the neuron had an insufficient list of synonyms associated with it.
388 The current implementation of NeuroElectro also does not consider common neuron type acronyms
389 (e.g., that olfactory bulb mitral cells are commonly referred to as “MCs”). Adding acronym and
390 abbreviation identification to future iterations will thus likely improve the automated approach (**Okazaki**
391 **and Ananiadou**, 2006; **French and Pavlidis**, 2012). Moreover, our current implementation of the bag-
392 of-words algorithm would likely be enhanced via minor improvements, such as only identifying neurons
393 using the text of the abstract or results and discarding text from the introduction or discussion. As neuron
394 identification forms the major bottleneck in the scalability of NeuroElectro due to the requirement for
395 manual curation, we plan to address this bottleneck in future revisions.

3.5 FUTURE METHODS FOR DATA EXTRACTION

396 A more pressing issue with the current approach is its focus on extraction from data tables. We estimate
397 that only 5-10% of published electrophysiological data is contained within tables, while the remaining
398 90-95% is presented within article text or figure images. Given our preference to obtain data in their
399 most raw form, we initially considered extraction of data from figures, e.g. voltage traces of neuronal
400 activity. However, digitizing article figures (presented by publishers as images) into a form that can
401 be further analyzed presents multiple challenges. Though techniques and tools exist to digitize figures,
402 substantial amounts of manual effort are required to employ them correctly, making this figure-based
403 approach difficult to scale to increasing numbers of articles without also employing a large team of
404 human curators. While automatically extracting measurements from figure images will likely prove
405 challenging, our methods can likely be adapted to operate on article text, perhaps by making use of
406 bioNLP methodologies currently used for relationship extraction in the identification of connected brain
407 regions (**French et al.**, 2012) or interacting pairs of proteins (**Kim and Wilbur**, 2011).

408 Future developments in machine extraction of data from the scientific literature will be of great benefit.
409 These should include better semantic understanding of context, ranging from relatively unambiguous
410 notations such as units, to syntax-parsing of free-form prose that relates objects of study to their reported
411 properties. Much progress has been made by computer scientists in some of these areas, and more future
412 engagement with their research should enable vastly more data to be extracted from the literature.

413 We believe that, if successful, the use of NeuroElectro will influence the practices of scientists writing
414 papers and reporting results. Specifically, we recommend the usage of common standards and definitions
415 for basic physiological measurements (**Toledo-Rodriguez et al.**, 2004) and neuron types (**Ascoli et al.**,
416 2008; **Larson and Martone**, 2013). Moreover, we advocate that, where possible, scientists report
417 more basic physiological data overall and report such data using machine-parsable data tables. These
418 recommendations could be made informally by journals (in particular, requested by reviewers during
419 manuscript review) as well as by funding agencies. This change would make it easier for scientists to find
420 and make use of data collected by others. Such a culture shift has the potential to make science function
421 more effectively and efficiently to facilitate discovery.

DISCLOSURE/CONFLICT-OF-INTEREST STATEMENT

422 The authors declare that the research was conducted in the absence of any commercial or financial
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SUPPLEMENTAL DATA

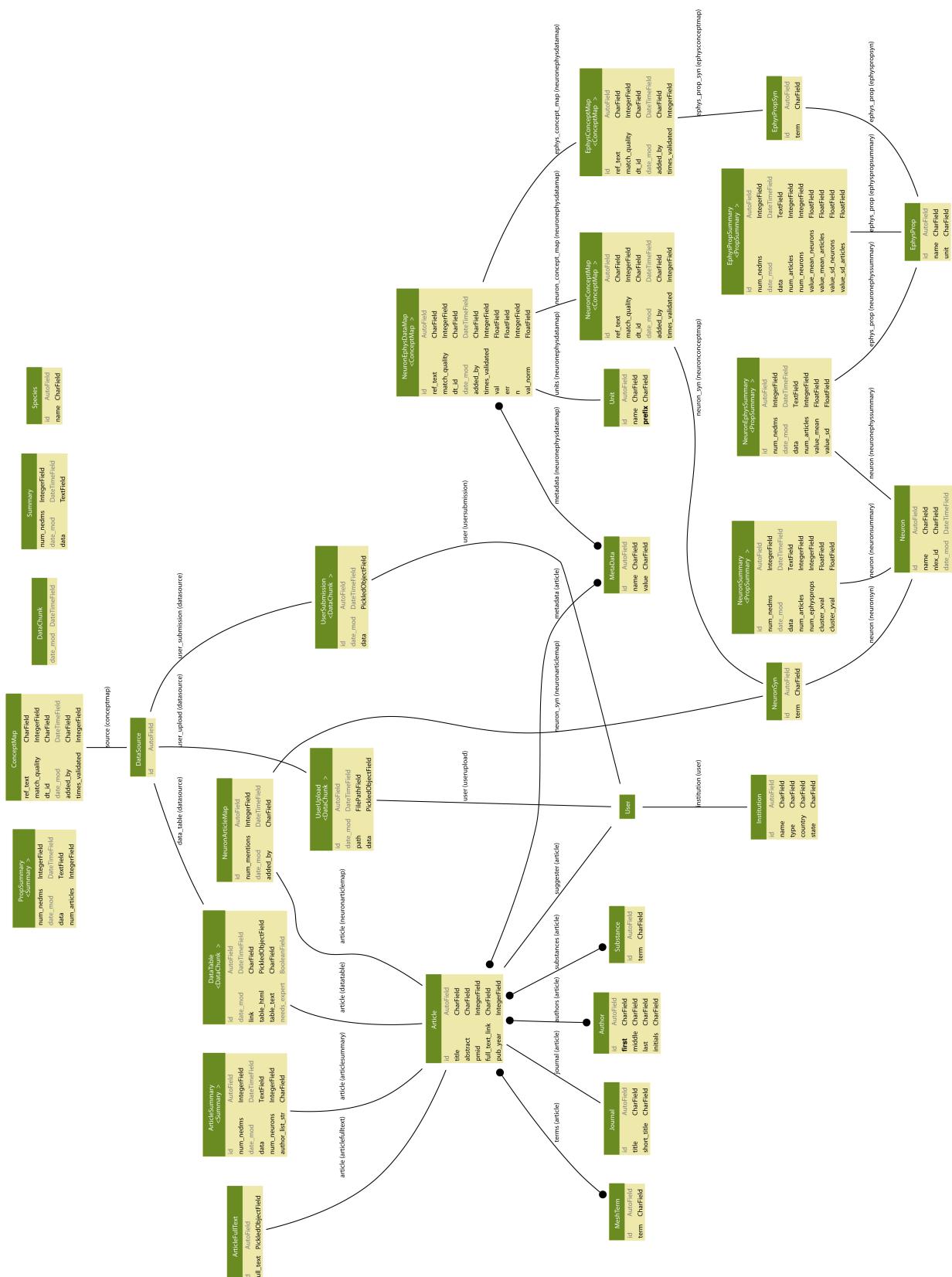


Fig. S1: Illustration of NeuroElectro relational database schema