

# BEHAVIOR RESEARCH METHODS

## Peekbank: An open, large-scale repository for developmental eye-tracking data of children's word recognition

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Complete List of Authors:	Zettersten, Martin; Princeton University, Psychology Yurovsky, Daniel; Carnegie Mellon University, Department of Psychology Xu, Tian; Indiana University, Department of Psychological and Brain Sciences Uner, Sarp; Vanderbilt University, Data Science Institute Tsui, Angeline; Stanford University, Department of Psychology Schneider, Rose; University of California San Diego, Department of Psychology Saleh, Annissa; The University of Texas at Austin, Department of Psychology Meylan, Stephan; Massachusetts Institute of Technology, Department of Brain and Cognitive Sciences; Duke University, Department of Psychology and Neuroscience Marchman, Virginia; Stanford University, Psychology Mankowitz, Jessica; Stanford University, Department of Psychology MacDonald, Kyle; McD Tech Labs Long, Bria; Stanford University, Department of Psychology Lewis, Molly; Carnegie Mellon University, Department of Psychology Kachergis, George; Stanford University, Department of Psychology Handa, Kunal; Brown University deMayo, Benjamin; Princeton University, Department of Psychology Carstensen, Alexandra; University of California San Diego, Department of Psychology Braginsky, Mika; MIT, Department of Brain and Cognitive Sciences Boyce, Veronica; Stanford University, Department of Psychology Bhatt, Naiti; New York University, Department of Psychology Bergey, Claire; The University of Chicago, Department of Psychology Frank, Michael; Stanford University, Psychology



January 24, 2022

Dear Editorial Board,

We are writing to submit our manuscript titled *Peekbank: An open, large-scale repository for developmental eye-tracking data of children's word recognition* to be considered for publication in *Behavior Research Methods*.

The paper introduces *Peekbank*, a flexible and reproducible interface to developmental eye-tracking datasets focused on children's word recognition (website: <https://langcog.github.io/peekbank-website/>). The goal of the project is to provide a resource for researchers interested in studying children's lexical development, by compiling existing data on children's word recognition (as measured in the looking-while-listening eye-tracking paradigm) into a large-scale, standardized repository. The project provides both an open database of developmental eye-tracking data in an easily accessible, tabular format, as well as processing tools for working with the database. These include an R package for accessing the database (<https://github.com/langcog/peekbankr>) and a Shiny app for visualizing the data (<https://peekbank-shiny.com/>). In the paper, we provide readers with an overview of the database and the functionalities offered by the various Peekbank tools. We believe this paper will be of interest to a broad audience of researchers in developmental psychology, cognitive science, and linguistics.

All of the data and code from the paper has been made publicly available through GitHub (<https://github.com/langcog/peekbank-paper>) and OSF (<https://osf.io/pr6wu/>), along with additional documentation on the Peekbank project website.

We would like to suggest the following reviewers:

Tristan Mahr ([tristan.mahr@wisc.edu](mailto:tristan.mahr@wisc.edu))

Caitlin Fausey ([fausey@uoregon.edu](mailto:fausey@uoregon.edu))

Hugh Rabagliati ([hugh.rabagliati@ed.ac.uk](mailto:hugh.rabagliati@ed.ac.uk))

Arielle Borovsky ([aborovsky@purdue.edu](mailto:aborovsky@purdue.edu))

A preprint of the paper has been made publicly available on *PsyArXiv* (<https://psyarxiv.com/tgnzv>). This work has not been published previously and is not considered for publication elsewhere, and has been contributed to by all authors. For a full author list, along with CRediT-based authorship contributions, see here:

[https://docs.google.com/spreadsheets/d/e/2PACX-1vRD-LJD\\_dTAQaAynyBlwXvGpfAVzP-3Pi6JTDG15m3PYZe0c44Y12U2a\\_hwdmhIstpjyigG2o3na4y/pubhtml](https://docs.google.com/spreadsheets/d/e/2PACX-1vRD-LJD_dTAQaAynyBlwXvGpfAVzP-3Pi6JTDG15m3PYZe0c44Y12U2a_hwdmhIstpjyigG2o3na4y/pubhtml)

Thank you for your consideration,

Martin Zettersten (corresponding author), on behalf of the Peekbank team

Email: [martincz@princeton.edu](mailto:martincz@princeton.edu), Phone: 210-557-9525, Address: Department of Psychology, Princeton University, Princeton, NJ 08544

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<sup>1</sup> Peekbank: An open, large-scale repository for developmental eye-tracking data of children's word recognition

Martin Zettersten<sup>1</sup>, Daniel Yurovsky<sup>2</sup>, Tian Linger Xu<sup>3</sup>, Sarp Uner<sup>4</sup>, Angeline Sin Mei Tsui<sup>5</sup>,  
Rose M. Schneider<sup>6</sup>, Annissa N. Saleh<sup>7</sup>, Stephan Meylan<sup>8,9</sup>, Virginia Marchman<sup>5</sup>, Jessica  
Mankowitz<sup>5</sup>, Kyle MacDonald<sup>10</sup>, Bria Long<sup>5</sup>, Molly Lewis<sup>2</sup>, George Kachergis<sup>5</sup>, Kunal  
Handa<sup>11</sup>, Benjamin deMayo<sup>1</sup>, Alexandra Carstensen<sup>6</sup>, Mika Braginsky<sup>9</sup>, Veronica Boyce<sup>5</sup>,  
Naiti S. Bhatt<sup>12</sup>, Claire Bergey<sup>13</sup>, & Michael C. Frank<sup>5</sup>

<sup>1</sup> Department of Psychology, Princeton University

<sup>2</sup> Department of Psychology, Carnegie Mellon University.

<sup>3</sup> Department of Psychological and Brain Sciences, Indiana University

<sup>4</sup> Data Science Institute, Vanderbilt University

<sup>5</sup> Department of Psychology, Stanford University

<sup>6</sup> Department of Psychology, University of California, San Diego

<sup>7</sup> Department of Psychology, The University of Texas at Austin

<sup>8</sup> Department of Psychology and Neuroscience, Duke University

ment of Brain and Cognitive Sciences, Massachusetts Institute of Technology

<sup>9</sup> Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology

<sup>10</sup> Core Technology, McD Tech Labs

<sup>11</sup> Brown University

<sup>12</sup> Department of Psychology, New York University

<sup>13</sup> Department of Psychology, University of Chicago

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21 Author Note

22       **Acknowledgements.** We would like to thank the labs and researchers that have  
23 made their data publicly available in the database. For further information about  
24 contributions, see <https://langcog.github.io/peekbank-website/docs/contributors/>.

25       **Open Practices Statement.** All code for reproducing the paper is available at  
26 <https://github.com/langcog/peekbank-paper>. Raw and standardized datasets are available  
27 on the Peekbank OSF repository (<https://osf.io/pr6wu/>) and can be accessed using the  
28 peekbankr R package (<https://github.com/langcog/peekbankr>).

29       **CRediT author statement.** Outside of the position of the first and the last author,  
30 authorship position was determined by sorting authors' last names in reverse alphabetical  
31 order. An overview over authorship contributions following the CRediT taxonomy can be  
32 viewed here: [https://docs.google.com/spreadsheets/d/e/2PACX-1vRD-LJD\\_dTAQaAynyBlwXvGpfAVzP-3Pi6JTDG15m3PYZe0c44Y12U2a\\_hwdmhIstpjyigG2o3na4y/pubhtml](https://docs.google.com/spreadsheets/d/e/2PACX-1vRD-LJD_dTAQaAynyBlwXvGpfAVzP-3Pi6JTDG15m3PYZe0c44Y12U2a_hwdmhIstpjyigG2o3na4y/pubhtml).

34       Correspondence concerning this article should be addressed to Martin Zettersten,  
35 Department of Psychology, Princeton University, 218 Peretsman Scully Hall, Princeton, NJ  
36 08540. E-mail: [martincz@princeton.edu](mailto:martincz@princeton.edu)

## Abstract

38 The ability to rapidly recognize words and link them to referents is central to children's  
39 early language development. This ability, often called word recognition in the developmental  
40 literature, is typically studied in the looking-while-listening paradigm, which measures  
41 infants' fixation on a target object (vs. a distractor) after hearing a target label. We present  
42 a large-scale, open database of infant and toddler eye-tracking data from  
43 looking-while-listening tasks. The goal of this effort is to address theoretical and  
44 methodological challenges in measuring vocabulary development. We first present how we  
45 created the database, its features and structure, and associated tools for processing and  
46 accessing infant eye-tracking datasets. Using these tools, we then work through two  
47 illustrative examples to show how researchers can use Peekbank to interrogate theoretical  
48 and methodological questions about children's developing word recognition ability.

**49** *Keywords:* word recognition; eye-tracking; vocabulary development;  
**50** looking-while-listening; visual world paradigm; lexical processing

51 Word count: 6605

- 52 Peekbank: An open, large-scale repository for developmental eye-tracking data of children's  
53 word recognition

54 Across their first years of life, children learn words at an accelerating pace (Frank,  
55 Braginsky, Yurovsky, & Marchman, 2021). While many children will only produce their first  
56 word at around one year of age, most children show signs of understanding many common  
57 nouns (e.g., *mommy*) and phrases (e.g., *Let's go bye-bye!*) much earlier in development  
58 (Bergelson & Swingley, 2012, 2013; Tincoff & Jusczyk, 1999). Although early word  
59 understanding is a critical element of first language learning, the processes involved are less  
60 directly apparent in children's behaviors and are less accessible to observation than  
61 developments in speech production (Fernald, Zangl, Portillo, & Marchman, 2008;  
62 Hirsh-Pasek, Cauley, Golinkoff, & Gordon, 1987). To understand a spoken word, children  
63 must process the incoming auditory signal and link that signal to relevant meanings – a  
64 process often referred to as word recognition. One of the primary means of measuring word  
65 recognition in young infants is using eye-tracking techniques that gauge where children look  
66 in response to linguistic stimuli (Fernald, Zangl, Portillo, & Marchman, 2008). The logic of  
67 these methods is that if, upon hearing a word, a child preferentially looks at a target  
68 stimulus rather than a distractor, the child is able to recognize the word and activate its  
69 meaning during real-time language processing. Measuring early word recognition offers  
70 insight into children's early word representations: children's speed of response (i.e., moving  
71 their eyes; turning their heads) to the unfolding speech signal can reveal children's level of  
72 comprehension (Bergelson, 2020; Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998).  
73 Word recognition skills are also thought to build a foundation for children's subsequent  
74 language development. Past research has found that early word recognition efficiency is  
75 predictive of later linguistic and general cognitive outcomes (Bleses, Makransky, Dale, Højen,  
76 & Ari, 2016; Marchman et al., 2018).

77 While word recognition is a central part of children's language development, mapping

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3     78 the trajectory of word recognition skills has remained elusive. Studies investigating children's  
4     79 word recognition are typically limited in scope to experiments in individual labs involving  
5     80 small samples tested on a handful of items. The limitations of single datasets makes it  
6     81 difficult to understand developmental changes in children's word knowledge at a broad scale.  
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13         82 One way to overcome this challenge is to compile existing datasets into a large-scale  
14 database in order to expand the scope of research questions that can be asked about the  
15 development of word recognition abilities. This strategy capitalizes on the fact that the  
16 looking-while-listening paradigm is widely used, and vast amounts of data have been  
17 collected across labs on infants' word recognition over the past 35 years (Golinkoff, Ma, Song,  
18 & Hirsh-Pasek, 2013). Such datasets have largely remained isolated from one another, but  
19 once combined, they have the potential to offer general insights into lexical development.  
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21         89 Similar efforts to collect other measures of language development have borne fruit in recent  
22 years. For example, WordBank aggregated data from the MacArthur-Bates Communicative  
23 Development Inventory, a parent-report measure of child vocabulary, to deliver new insights  
24 into cross-linguistic patterns and variability in vocabulary development (Frank, Braginsky,  
25 Yurovsky, & Marchman, 2017, 2021). In this paper, we introduce *Peekbank*, an open  
26 database of infant and toddler eye-tracking data aimed at facilitating the study of  
27 developmental changes in children's word recognition.  
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### 43     96 Measuring Word Recognition: The Looking-While-Listening Paradigm

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46         97 Word recognition is traditionally studied in the looking-while-listening paradigm  
47 (Fernald, Zangl, Portillo, & Marchman, 2008; alternatively referred to as the intermodal  
48 preferential looking procedure, Hirsh-Pasek, Cauley, Golinkoff, & Gordon, 1987). In these  
49 studies, infants listen to a sentence prompting a specific referent (e.g., *Look at the dog!*)  
50 while viewing two images on the screen (e.g., an image of a dog – the target image – and an  
51 image of a bird – the distractor image). Infants' word recognition is evaluated by how  
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3       103 quickly and accurately they fixate on the target image after hearing its label. Past research  
4       104 has used this basic method to study a wide range of questions in language development. For  
5       105 example, the looking-while-listening paradigm has been used to investigate early noun  
6       106 knowledge, phonological representations of words, prediction during language processing, and  
7       107 individual differences in language development (Bergelson & Swingley, 2012; Golinkoff, Ma,  
8       108 Song, & Hirsh-Pasek, 2013; Lew-Williams & Fernald, 2007; Marchman et al., 2018; Swingley  
9       109 & Aslin, 2002).

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11       110 While this research has been fruitful in advancing understanding of early word  
12       111 knowledge, fundamental questions remain. One central question is how to accurately capture  
13       112 developmental change in the speed and accuracy of word recognition. There is ample  
14       113 evidence demonstrating that infants become faster and more accurate in word recognition  
15       114 over the first few years of life (e.g., Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998).  
16       115 However, precisely measuring developmental increases in the speed and accuracy of word  
17       116 recognition remains challenging due to the difficulty of distinguishing developmental changes  
18       117 in word recognition skill from changes in knowledge of specific words. This problem is  
19       118 particularly thorny in studies with young children, since the number of items that can be  
20       119 tested within a single session is limited and items must be selected in an age-appropriate  
21       120 manner (Peter et al., 2019). More broadly, key differences in the design choices (e.g., how  
22       121 distractor items are selected) and analytic decisions (e.g., how the analysis window is defined)  
23       122 between studies can obscure developmental change if not appropriately taken into account.

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25       123 One approach to addressing these challenges is to conduct meta-analyses aggregating  
26       124 effects across studies while testing for heterogeneity due to researcher choices (Bergmann et  
27       125 al., 2018; Lewis et al., 2016). However, meta-analyses typically lack the granularity to  
28       126 estimate participant-level and item-level variation or to model behavior beyond  
29       127 coarse-grained effect size estimates. An alternative way to approach this challenge is to  
30       128 aggregate trial-level data from smaller studies measuring word recognition with a wide range

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3     129 of items and design choices into a large-scale dataset that can be analyzed using a unified  
4     130 modeling approach. A sufficiently large dataset would allow researchers to estimate  
5     131 developmental change in word recognition speed and accuracy while generalizing across  
6     132 changes related to specific words or the design features of particular studies.

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12     133 A related open theoretical question is understanding changes in children's word  
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14 recognition at the level of individual items. Looking-while-listening studies have been limited  
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16 in their ability to assess the development of specific words. One limitation is that studies  
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18 typically test only a small number of trials for each item, reducing power to precisely measure  
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20 the development of word-specific accuracy (DeBolt, Rhemtulla, & Oakes, 2020). A second  
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22 limitation is that target stimuli are often yoked with a narrow set of distractor stimuli (i.e., a  
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24 child sees a target with only one or two distractor stimuli over the course of an experiment),  
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26 leaving ambiguous whether accurate looking to a particular target word can be attributed to  
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28 children's recognition of the target word or their knowledge about the distractor.

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31     142 Aggregating across many looking-while-listening studies has the potential to meet these  
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33 challenges by increasing the number of observations for specific items at different ages and by  
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35 increasing the size of the inventory of distractor stimuli that co-occur with each target.

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39     145 **Replicability and Reproducibility**

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43     146 A core challenge facing psychology in general, and the study of infant development in  
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45 particular, are threats to the replicability and reproducibility of core empirical results (Frank  
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47 et al., 2017; Nosek et al., 2022). In infant research, many studies are not adequately powered  
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49 to detect the main effects of interest (Bergmann et al., 2018). This issue is compounded by  
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51 low reliability in infant measures, often due to limits on the number of trials that can be  
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53 collected from an individual infant in an experimental session (Byers-Heinlein, Bergmann, &  
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55 Savalei, 2021). One hurdle to improving power in infant research is that it can be difficult to  
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57 develop a priori estimates of effect sizes and how specific design decisions (e.g., the number

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3     154 of test trials) will impact power and reliability. Large-scale databases of infant behavior can  
4     155 aid researchers in their decision-making by allowing them to directly test how different  
5     156 design decisions affect power and reliability. For example, if a researcher is interested in  
6     157 understanding how the number of test trials could impact the power and reliability of their  
7     158 looking-while-listening design, a large-scale infant eye-tracking database would allow them to  
8     159 simulate possible outcomes across a range of test trials, providing the basis for data-driven  
9     160 design decisions.

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21     161 In addition to threats to replicability, the field of infant development also faces  
22     162 concerns about analytic reproducibility – the ability for researchers to arrive at the same  
23     163 analytic conclusion reported in the original research article, given the same dataset. A recent  
24     164 estimate based on studies published in a prominent cognitive science journal suggests that  
25     165 analyses can remain difficult to reproduce, even when data are made available to other  
26     166 research teams (Hardwicke et al., 2018). Aggregating data in centralized databases can aid  
27     167 in improving reproducibility in several ways. First, building a large-scale database requires  
28     168 defining a standardized data specification. Recent examples include the **brain imaging**  
29     169 **data structure** (BIDS), an effort to specify a unified data format for neuroimaging  
30     170 experiments (Gorgolewski et al., 2016), and the data formats associated with **ChildProject**,  
31     171 for managing long-form at-home language recordings (Gautheron, Rochat, & Cristia, 2021).  
32     172 Defining a data standard – in this case, for infant eye-tracking experiments – supports  
33     173 reproducibility by guaranteeing that critical information will be available in openly shared  
34     174 data and by making it easier for different research teams to understand the data structure.  
35     175 Second, open databases make it easy for researchers to generate open and reproducible  
36     176 analytic pipelines, both for individual studies and for analyses aggregating across datasets.  
37     177 Creating open analytic pipelines across many datasets also serves a pedagogical purpose,  
38     178 providing teaching examples illustrating how to implement analytic techniques used in  
39     179 influential studies and how to conduct reproducible analyses with infant eye-tracking data.

**180 Peekbank: An open database of developmental eye-tracking studies.**

181 What all of these open challenges share is that they are difficult to address at the scale  
182 of a single research lab or in a single study. To address this challenge, we developed  
183 *Peekbank*, a flexible and reproducible interface to an open database of developmental  
184 eye-tracking studies. The Peekbank project (a) collects a large set of eye-tracking datasets  
185 on children's word recognition, (b) introduces a data format and processing tools for  
186 standardizing eye-tracking data across heterogeneous data sources, and (c) provides an  
187 interface for accessing and analyzing the database. In the current paper, we introduce the  
188 key components of the project and give an overview of the existing database. We then  
189 provide two worked examples of how researchers can use Peekbank. In the first, we examine  
190 a classic result in the word recognition literature, and in the second we aggregate data across  
191 studies to investigate developmental trends in the recognition of individual words.

**192 Design and Technical Approach****193 Database Framework**

194 One of the main challenges in compiling a large-scale eye-tracking database is the lack  
195 of a shared data format: both labs and individual experiments can record their results in a  
196 wide range of formats. For example, different experiments encode trial-level and  
197 participant-level information in many different ways. Therefore, we have developed a  
198 common tabular format to support analyses of all studies simultaneously.

199 As illustrated in Figure 1, the Peekbank framework consists of four main components:

200 (1) a set of tools to *convert* eye-tracking datasets into a unified format, (2) a relational  
201 database populated with data in this unified format, (3) a set of tools to *retrieve* data from  
202 this database, and (4) a web app (using the Shiny framework) for visualizing the data. These

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3 components are supported by three packages. The `peekds` package (for the R language, R  
4 Core Team, 2021) helps researchers convert existing datasets to use the standardized format  
5 of the database. The `peekbank` module (Python) creates a database with the relational  
6 schema and populates it with the standardized datasets produced by `peekds`. The database  
7 is served through MySQL, an industry standard relational database server, which may be  
8 accessed by a variety of programming languages, and can be hosted on one machine and  
9 accessed by many others over the Internet. As is common in relational databases, records of  
10 similar types (e.g., participants, trials, experiments, coded looks at each timepoint) are  
11 grouped into tables, and records of various types are linked through numeric identifiers. The  
12 `peekbankr` package (R) provides an application programming interface, or API, that offers  
13 high-level abstractions for accessing the tabular data stored in Peekbank. Most users will  
14 access data through this final package, in which case the details of data formatting,  
15 processing, and the specifics of connecting to the database are abstracted away from the user.

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**Database Schema**

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35 The Peekbank database contains two major types of data: (1) metadata regarding  
36 experiments, participants, and trials, and (2) time course looking data, detailing where a  
37 child is looking on the screen at a given point in time (Fig. 2).

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42 **Metadata.** Metadata can be separated into four parts: (1) participant-level  
43 information (e.g., demographics), (2) experiment-level information (e.g., the type of eye  
44 tracker used to collect the data), (3) session information (e.g. a participant's age for a  
45 specific experimental session), and (4) trial information (e.g., which images or videos were  
46 presented onscreen, and paired with which audio).

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54 **Participant Information.**

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56 Invariant information about individuals who participate in one or more studies (e.g, a  
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## PEEK BANK REPOSITORY FOR EYE-TRACKING DATA

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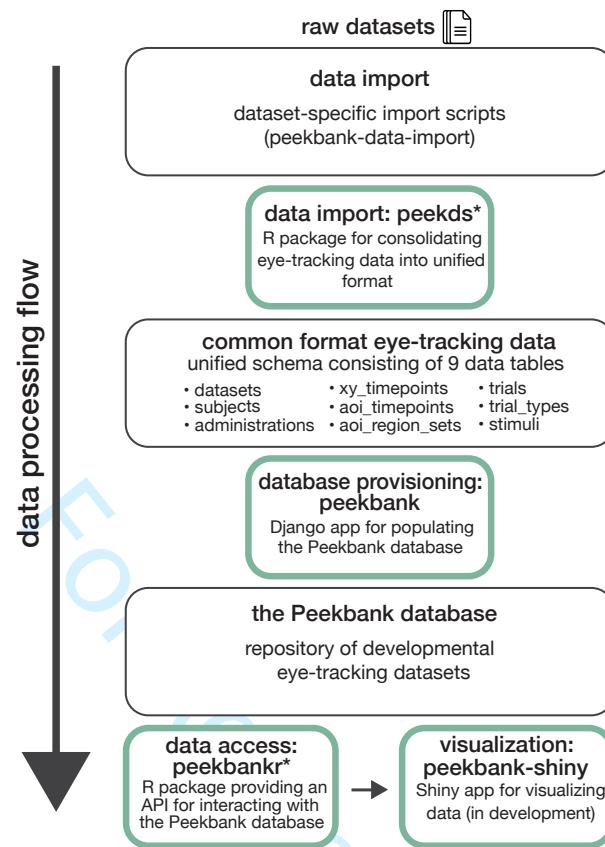


Figure 1. Overview of the Peekbank data ecosystem. Peekbank tools are highlighted in green.  
\* indicates R packages introduced in this work.

227 participant's first language) is recorded in the **subjects** table, while the **administrations**  
 228 table contains information about each individual session in a given study (see Session  
 229 Information, below). This division allows Peekbank to gracefully handle longitudinal designs:  
 230 a single participant can complete multiple sessions and thus be associated with multiple  
 231 administrations.

232 Participant-level data includes all participants who have experiment data. In general,  
 233 we include as many participants as possible in the database and leave it to end-users to  
 234 apply the appropriate exclusion criteria for their analysis.

### 235 ***Experiment Information.***

236 The **datasets** table includes information about the lab conducting the study and the

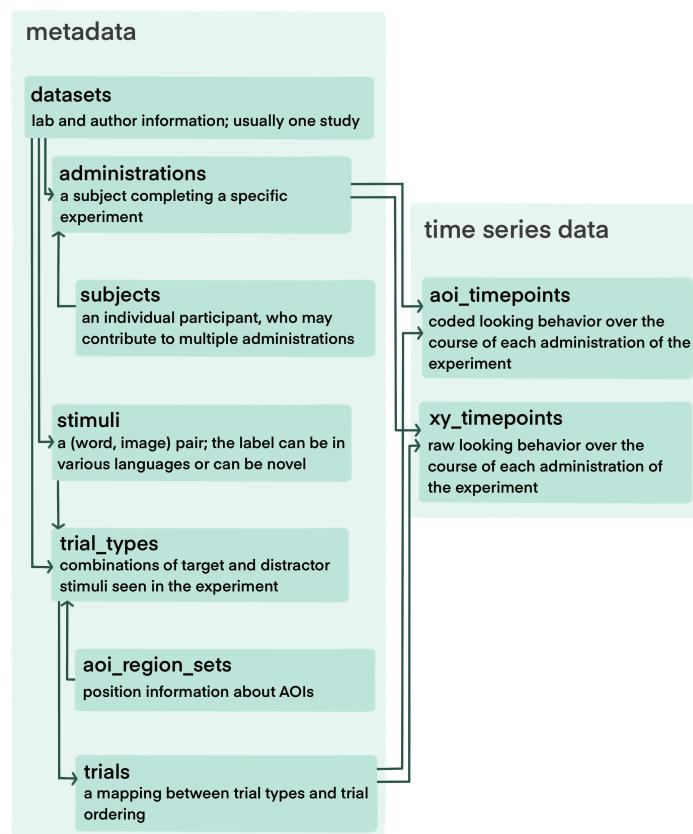


Figure 2. The Peekbank schema. Each darker rectangle represents a table in the relational database.

relevant publications to cite regarding the data. In most cases, a dataset corresponds to a single study.

Information about the experimental design is split across the `trial_types` and `stimuli` tables. The `trial_types` table encodes information about each trial *in the design of the experiment*,<sup>1</sup> including the target stimulus and location (left vs. right), the distractor stimulus and location, and the point of disambiguation for that trial. If a dataset used automatic eye-tracking rather than manual coding, each trial type is additionally linked to a set of area of interest (x, y) coordinates, encoded in the `aoi_region_sets` table. The

<sup>1</sup> We note that the term *trial* is ambiguous and could be used to refer to both a particular combination of stimuli seen by many participants and a participant seeing that particular combination at a particular point in the experiment. We track the former in the `trial_types` table and the latter in the `trials` table.

## PEEK BANK REPOSITORY FOR EYE-TRACKING DATA

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4 245 **trial\_types** table links trial types to the **aoi\_region\_sets** table and the **trials** table.  
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6 246 Each trial\_type record links to two records in the **stimuli** table, identified by the  
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8 247 **distractor\_id** and the **target\_id** fields.  
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11 248 Each record in the **stimuli** table is a (word, image) pair. In most experiments, there  
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13 249 is a one-to-one mapping between images and labels (e.g., each time an image of a dog  
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15 appears it is referred to as *dog*). For studies in which there are multiple potential labels per  
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17 image (e.g., *dog* and *chien* are both used to refer to an image of a dog), images can have  
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19 multiple rows in the **stimuli** table with unique labels. This structure is useful for studies on  
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21 synonymy or using multiple languages. It is also possible for an image to be associated with  
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23 a row with no label, if the image appears solely as a distractor (and thus its label is  
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25 ambiguous). For studies in which the same label refers to multiple images (e.g., the word *dog*  
26  
27 refers to an image of a dalmatian and a poodle), the same label can have multiple rows in  
28  
29 the **stimuli** table with unique images.  
30  
31

32  
33 258 ***Session Information.***  
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36  
37 259 The **administrations** table includes information about the participant or experiment  
38  
39 that may change between sessions of the same study, even for the same participant. This  
40  
41 includes the age of the participant, the coding method (eye-tracking vs. hand-coding), and  
42  
43 the properties of the monitor that was used.  
44  
45

46  
47 263 ***Trial Information.***  
48  
49

50  
51 264 The **trials** table includes information about a specific participant completing a  
52  
53 specific instance of a trial type. This table links each record in the time course looking data  
54  
55 (described below) to the trial type and specifies the order of the trials seen by a specific  
56  
57 participant.  
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3       **Time course data.** Raw looking data is a series of looks to areas of interest (AOIs),  
4 such as looks to the left or right of the screen, or to (x, y) coordinates on the experiment  
5 screen, linked to points in time. For data generated by eye-trackers, we typically have (x, y)  
6 coordinates at each time point, which we encode in the `xy_timepoints` table. These looks  
7 are also recoded into AOIs according to the AOI coordinates in the `aoi_region_sets` table  
8 using the `add_aois()` function in `peekds`, and encoded in the `aoi_timepoints` table. For  
9 hand-coded data, we typically have a series of AOIs (i.e., looks to the left vs. right of the  
10 screen), but lack information about exact gaze positions on-screen; in these cases the AOIs  
11 are recoded into the categories in the Peekbank schema (target, distractor, other, and  
12 missing) and encoded in the `aoi_timepoints` table; however, these datasets do not have any  
13 corresponding data in the `xy_timepoints` table.  
14

15  
16       Typically, timepoints in the `xy_timepoints` table and `aoi_timepoints` table need to  
17 be regularized to center each trial's time around the point of disambiguation – such that 0 is  
18 the time of target word onset in the trial (i.e., the beginning of *dog* in *Can you find the*  
19 *dog?*). We re-centered timing information to the onset of the target label to facilitate  
20 comparison of target label processing across all datasets.<sup>2</sup> If time values run throughout the  
21 experiment rather than resetting to zero at the beginning of each trial, `rezero_times()` is  
22 used to reset the time at each trial. After this, each trial's times are centered around the  
23 point of disambiguation using `normalize_times()`. When these steps are complete, the  
24 time course is ready for resampling.  
25

26  
27       To facilitate time course analysis and visualization across datasets, time course data  
28 must be resampled to a uniform sampling rate (i.e., such that every trial in every dataset has  
29 observations at the same time points). All data in the database is resampled to 40 Hz  
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53       <sup>2</sup> While information preceding the onset of the target label in some datasets such as co-articulation cues  
54 (Mahr, McMillan, Saffran, Ellis Weismer, & Edwards, 2015) or adjectives (Fernald, Marchman, & Weisleder,  
55 2013) can in principle disambiguate the target referent, we use a standardized point of disambiguation based  
56 on the onset of the label for the target referent. Onset times for other potentially disambiguating information  
57 (such as adjectives) can typically be recovered from the raw data provided on OSF.  
58  
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(observations every 25 ms), which represents a compromise between retaining fine-grained timing information from datasets with dense sampling rates (maximum sampling rate among current datasets: 500 Hz) while minimizing the possibility of introducing artifacts via resampling for datasets with lower sampling rates (minimum sampling rate for current datasets: 30 Hz). Further, 25 ms is a mathematically convenient interval for ensuring consistent resampling; we found that using 33.333 ms (30 Hz) as our interval simply introduced a large number of technical complexities. The resampling operation is accomplished using the `resample_times()` function. During the resampling process, we interpolate using constant interpolation, selecting for each interpolated timepoint the looking location for the earlier-observed time point in the original data for both `aoi_timepoints` and `xy_timepoints` data. Compared to linear interpolation (see e.g., Wass, Smith, & Johnson, 2013) – which fills segments of missing or unobserved time points by interpolating between the observed locations of timepoints at the beginning and end of the interpolated segment –, constant interpolation has the advantage that it is more conservative, in the sense that it does not introduce new look locations beyond those measured in the original data. One possible application of our new dataset is investigating the consequences of other interpolation functions for data analysis.

## Processing, Validation, and Ingestion

The `peekds` package offers functions to extract the above data. Once the data have been extracted in a tabular form, the package also offers a validation function that checks whether all tables have the required fields and data types expected by the database. In an effort to double check the data quality and to make sure that no errors are made in the importing script, we create a time course plot based on our processed tables to replicate the results in the paper that first presented each dataset as part of the import procedure. Once this plot has been created and checked for consistency and all tables pass our validation

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4     316 functions, the processed dataset is ready for reprocessing into the database using the  
5     317 peekbank library. This library applies additional data checks, and adds the data to the  
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7     318 MySQL database using the Django web framework.  
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11     319 Currently, the import process is carried out by the Peekbank team using data offered  
12     320 by other research teams. In the future, we hope to allow research teams to carry out their  
13  
14     321 own import processes with checks from the Peekbank team before reprocessing. To this end,  
15  
16     322 import script templates are available for both hand-coded datasets and automatic  
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18     323 eye-tracking datasets for research teams to adapt to their data.  
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23     324 **Current Data Sources**  
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Table 1  
*Overview of the datasets in the current database.*

Study Citation	Dataset name	N	Mean age (mos.)	Age range (mos.)	Method	Language
Adams et al., 2018	ft_pt	69	17.1	13–20	manual coding	English
Byers-Heinlein et al., 2017	mix	48	20.1	19–21	eye-tracking	English, French
Casillas et al., 2017	tseltal	23	31.3	9–48	manual coding	Tseltal
Fernald et al., 2013	fmw	80	20.0	17–26	manual coding	English
Frank et al., 2016	tablet	69	35.5	12–60	eye-tracking	English
Garrison et al., 2020	yoursmy	35	14.5	12–18	eye-tracking	English
Hurtado et al., 2007	xsectional	49	23.8	15–37	manual coding	Spanish
Hurtado et al., 2008	input_uptake	76	21.0	17–27	manual coding	Spanish
Mahr et al., 2015	coartic	29	20.8	18–24	eye-tracking	English
Perry et al., 2017	cowpig	45	20.5	19–22	manual coding	English
Pomper & Saffran, 2016	switchingCues	60	44.3	41–47	manual coding	English
Pomper & Saffran, 2019	salientme	44	40.1	38–43	manual coding	English
Potter & Lew-Williams, unpublished	canine	36	23.8	21–27	manual coding	English
Potter et al., 2019	remix	44	22.6	18–29	manual coding	Spanish, English
Ronfard et al., 2021	lsc	40	20.0	18–24	manual coding	English
Swingley & Aslin, 2002	mispron	50	15.1	14–16	manual coding	English
Weisleder & Fernald, 2013	stl	29	21.6	18–27	manual coding	Spanish
Yurovsky & Frank, 2017	attword	288	25.5	13–59	eye-tracking	English
Yurovsky et al., 2013	reflook_socword	435	33.6	12–70	eye-tracking	English
Yurovsky et al., unpublished	reflook_v4	45	34.2	11–60	eye-tracking	English

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49     325 The database currently includes 20 looking-while-listening datasets comprising  $N=1594$   
50  
51     326 total participants (Table 1). The current data represents a convenience sample of datasets  
52  
53     327 that were (a) datasets collected by or available to Peekbank team members, (b) made  
54  
55     328 available to Peekbank after informal inquiry or (c) datasets that were openly available. Most  
56  
57     329 datasets (14 out of 20 total) consist of data from monolingual native English speakers. They  
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3     330 span a wide age spectrum with participants ranging from 9 to 70 months of age, and are  
4     331 balanced in terms of gender (47% female). The datasets vary across a number of  
5     332 design-related dimensions, and include studies using manually coded video recordings and  
6     333 automated eye-tracking methods (e.g., Tobii, EyeLink) to measure gaze behavior. All studies  
7     334 tested familiar items, but the database also includes 5 datasets that tested novel  
8     335 pseudo-words in addition to familiar words. Users interested in a subset of the data (e.g.,  
9     336 only trials testing familiar words) can filter out unwanted trials using columns available in  
10    337 the schema (e.g., using the column `stimulus_novelty` in the `stimuli` table).

## 19 20 21     338 Versioning and Reproducibility

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25     339 The content of Peekbank will change as we add additional datasets and revise previous  
26     340 ones. To facilitate reproducibility of analyses, we use a versioning system by which  
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28     341 successive releases are assigned a name reflecting the year and version, e.g., 2022.1. By  
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30     342 default, users will interact with the most recent version of the database available, though the  
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32     343 `peekbankr` API allows researchers to run analyses against any previous version of the  
33  
34     344 database. For users with intensive use-cases, each version of the database may be  
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36     345 downloaded as a compressed .sql file and installed on a local MySQL server.

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40     346 Peekbank allows for fully reproducible analyses using our source data, but the goal is  
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42     347 not to reproduce precisely the analyses – or even the datasets – in the publications whose  
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44     348 data we archive. Because of our emphasis on a standardized data importing and formatting  
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46     349 pipeline, there may be minor discrepancies in the time course data that we archive compared  
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48     350 with those reported in original publications. Further, we archive all of the data that are  
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50     351 provided to us – including participants that might have been excluded in the original studies,  
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52     352 if these data are available – rather than attempting to reproduce specific exclusion criteria.  
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54     353 We hope that Peekbank can be used as a basis for comparing different exclusion and filtering  
55  
56     354 criteria – as such, an inclusive policy regarding importing all available data helps us provide

<sup>355</sup> a broad base of data for investigating these decisions.

## Interfacing with Peekbank

357 Peekbankr

The `peekbankr` API offers a way for users to access data from the database and flexibly analyze it in R. The majority of API calls simply allow users to download tables (or subsets of tables) from the database. In particular, the package offers the following functions:

- `connect_to_peekbank()` opens a connection with the Peekbank database to allow tables to be downloaded with the following functions
  - `get_datasets()` gives each dataset name and its citation information
  - `get_subjects()` gives information about persistent participant identifiers (e.g., native languages, sex)
  - `get_administrations()` gives information about specific experimental administrations (e.g., participant age, monitor size, gaze coding method)
  - `get_stimuli()` gives information about word–image pairings that appeared in experiments
  - `get_trial_types()` gives information about pairings of stimuli that appeared in the experiment (e.g., point of disambiguation, target and distractor stimuli, condition, language)
  - `get_trials()` gives the trial orderings for each administration, linking trial types to the trial IDs used in time course data
  - `get_aoi_region_sets()` gives coordinate regions for each area of interest (AOI) linked to trial type IDs
  - `get_xy_timepoints()` gives time course data for each participant’s looking behavior in each trial, as (x, y) coordinates on the experiment monitor

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4     • `get_aoi_timepoints()` gives time course data for each participant's looking behavior  
5                 in each trial, coded into areas of interest  
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9     Once users have downloaded tables, they can be merged using `join` commands via their  
10       linked IDs. A set of standard merges are shown below in the "Peekbank in Action" section;  
11       these allow the common use-case of examining time course data and metadata jointly.  
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16     Because of the size of the XY and AOI data tables, downloading data across multiple  
17       studies can be time-consuming. Many of the most common analyses of the Peekbank data  
18       require downloading the `aoi_timepoints` table, thus we have put substantial work into  
19       optimizing transfer times. In particular, `connect_to_peekbank` offers a data compression  
20       option, and `get_aoi_timepoints` by default downloads time courses via a compressed  
21       (run-length encoded) representation, which is then uncompressed on the client side. More  
22       information about these options (including how to modify them) can be found in the  
23       package documentation.  
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34     **Shiny App**  
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38     One goal of the Peekbank project is to allow a wide range of users to easily explore and  
39       learn from the database. We therefore have created an interactive web application –  
40       `peekbank-shiny` – that allows users to quickly and easily create informative visualizations  
41       of individual datasets and aggregated data (<https://peekbank-shiny.com/>).  
42  
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45     `peekbank-shiny` is built using Shiny, a software package for creating web apps for data  
46       exploration with R, as well as the `peekbankr` package. All code for the Shiny app is publicly  
47       available (<https://github.com/langcog/peekbank-shiny>). The Shiny app allows users to  
48       create commonly used visualizations of looking-while-listening data, based on data from the  
49       Peekbank database. Specifically, users can visualize:  
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57     1. the *time course of looking data* in a profile plot depicting infant target looking across  
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3       403      trial time  
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5       404      2. *overall accuracy*, defined as the proportion target looking within a specified analysis  
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7       405      window  
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9       406      3. *reaction times* in response to a target label, defined as how quickly participants shift  
10      407      fixation to the target image on trials in which they were fixating on the distractor  
11      408      image at onset of the target label  
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16      409      4. an *onset-contingent plot*, which shows the time course of participant looking as a  
17      410      function of their look location at the onset of the target label

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21      411      Users are given various customization options for each of these visualizations, e.g.,  
22  
23      412      choosing which datasets to include in the plots, controlling the age range of participants,  
24  
25      413      splitting the visualizations by age bins, and controlling the analysis window for time course  
26  
27      414      analyses. Plots are then updated in real time to reflect users' customization choices. A  
28  
29      415      screenshot of the app is shown in Figure 3. The Shiny app thus allows users to quickly  
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31      416      inspect basic properties of Peekbanks datasets and create reproducible visualizations without  
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33      417      incurring any of the technical overhead required to access the database through R.

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37      418      **OSF site**  
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419      In addition to the Peekbank database proper, all data is openly available on the  
420      Peekbank OSF webpage (<https://osf.io/pr6wu/>). The OSF site also includes the original raw  
421      data (both time series data and metadata, such as trial lists and participant logs) that was  
422      obtained for each study and subsequently processed into the standardized Peekbank format.  
423      Users who are interested in inspecting or reproducing the processing pipeline for a given  
424      dataset can use the respective import script (openly available on GitHub,  
425      <https://github.com/langcog/peekbank-data-import>) to download and process the raw data  
426      from OSF into its final standardized format. Where available, the OSF page also includes  
427      additional information about the stimuli used in each dataset, including in some instances

## PEEK BANK REPOSITORY FOR EYE-TRACKING DATA

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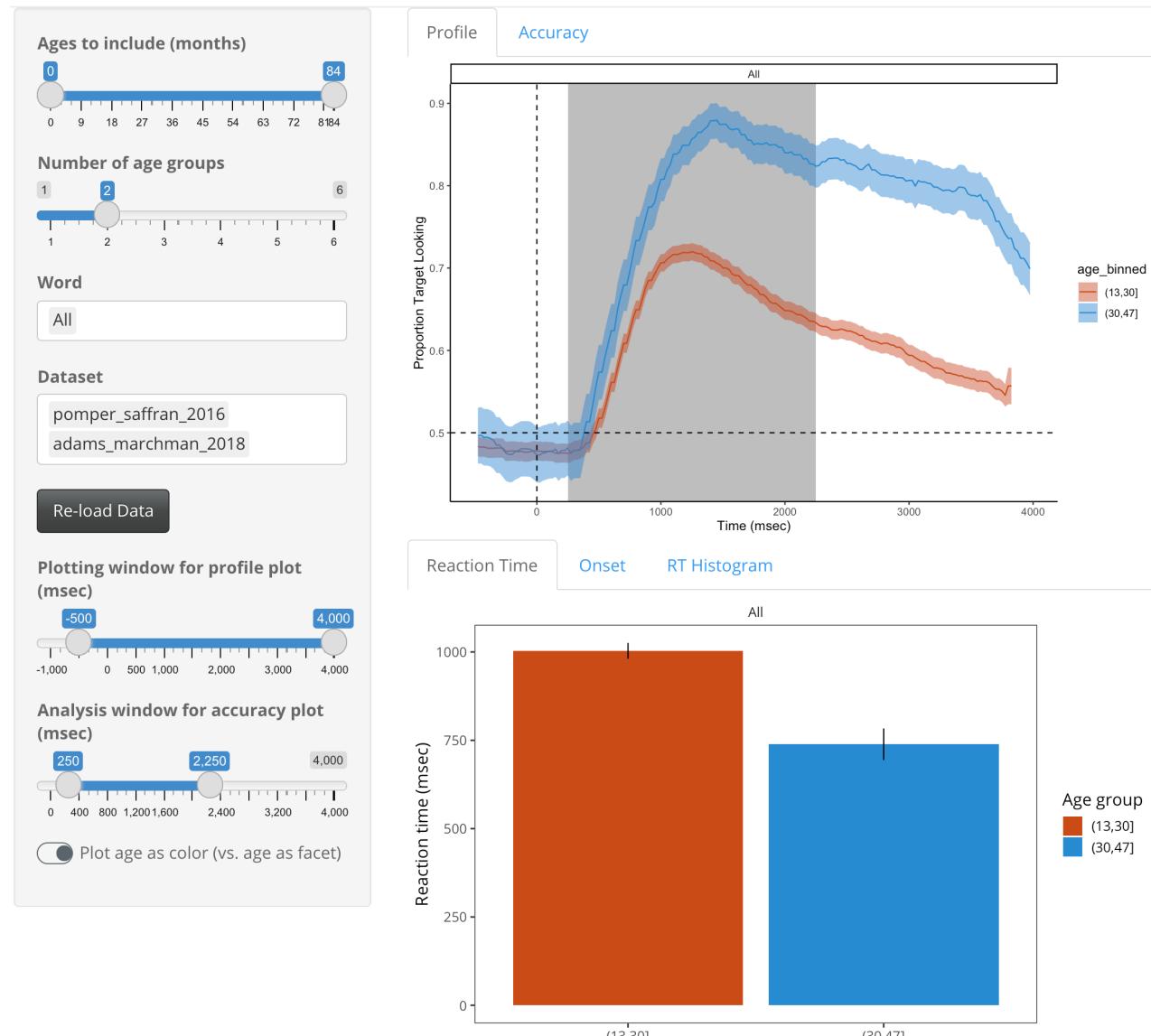


Figure 3. Screenshot of the Peekbank Shiny app, which shows a variety of standard analysis plots as a function of user-selected datasets, words, age ranges, and analysis windows. Shown here are mean reaction time and proportion target looking over time by age group for two selected datasets.

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4 428 the original stimulus sets (e.g., image and audio files).  
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## Peekbank in Action

19 430 In the following section, we provide examples of how users can access and analyze the  
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21 data in Peekbank. First, we provide an overview of some general properties of the datasets  
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23 in the database. We then demonstrate two potential use-cases for Peekbank data. In each  
24  
25 case, we provide sample code to demonstrate the ease of doing simple analyses using the  
26  
27 database. Our first example shows how we can investigate the findings of a classic study.  
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30 435 This type of investigation can be a very useful exercise for teaching students about best  
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32 practices for data analysis (e.g., Hardwicke et al., 2018) and also provides an easy way to  
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34 explore looking-while-listening time course data in a standardized format. Our second  
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36 example shows an exploration of developmental changes in the recognition of particular  
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38 words. Besides its theoretical interest (which we will explore more fully in subsequent work),  
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40 this type of analysis could in principle be used for optimizing the stimuli for new  
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42 experiments, especially as the Peekbank dataset grows and gains coverage over a greater  
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44 number of items. All analyses are conducted using R [Version 4.1.1; R Core Team (2021)]<sup>3</sup>

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49 3 We, furthermore, used the R-packages *dplyr* [Version 1.0.7; Wickham, François, Henry, and Müller (2021)],  
50 *forcats* [Version 0.5.1; Wickham (2021a)], *ggplot2* [Version 3.3.5; Wickham (2016)], *ggthemes* [Version 4.2.4;  
51 Arnold (2021)], *here* [Version 1.0.1; Müller (2020)], *papaja* [Version 0.1.0.9997; Aust and Barth (2020)],  
52 *peekbankr* [Version 0.1.1.9002; Braginsky, MacDonald, and Frank (2021)], *purrr* [Version 0.3.4; Henry and  
53 Wickham (2020)], *readr* [Version 2.0.1; Wickham and Hester (2021)], *stringr* [Version 1.4.0; Wickham (2019)],  
54 *tibble* [Version 3.1.4; Müller and Wickham (2021)], *tidyR* [Version 1.1.3; Wickham (2021b)], *tidyverse* [Version  
55 1.3.1; Wickham et al. (2019)], *viridis* [Version 0.6.1; Garnier et al. (2021a); Garnier et al. (2021b)],  
56 *viridisLite* [Version 0.4.0; Garnier et al. (2021b)], and *xtable* [Version 1.8.4; Dahl, Scott, Roosen, Magnusson,  
57 and Swinton (2019)].  
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4 443 General Descriptives  
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Study Citation	Unique Items	Prop. Target	95% CI
Adams et al., 2018	8	0.65	[0.63, 0.67]
Byers-Heinlein et al., 2017	6	0.55	[0.52, 0.58]
Casillas et al., 2017	30	0.59	[0.54, 0.63]
Fernald et al., 2013	12	0.65	[0.63, 0.67]
Frank et al., 2016	24	0.64	[0.6, 0.68]
Garrison et al., 2020	87	0.60	[0.56, 0.64]
Hurtado et al., 2007	8	0.59	[0.55, 0.63]
Hurtado et al., 2008	12	0.61	[0.59, 0.63]
Mahr et al., 2015	10	0.71	[0.68, 0.74]
Perry et al., 2017	12	0.61	[0.58, 0.63]
Pomper & Saffran, 2016	40	0.77	[0.75, 0.8]
Pomper & Saffran, 2019	16	0.74	[0.72, 0.75]
Potter & Lew-Williams, unpub.	16	0.65	[0.61, 0.68]
Potter et al., 2019	8	0.63	[0.58, 0.67]
Ronfard et al., 2021	8	0.69	[0.65, 0.73]
Swingley & Aslin, 2002	22	0.57	[0.55, 0.59]
Weisleder & Fernald, 2013	12	0.63	[0.6, 0.66]
Yurovsky & Frank, 2017	6	0.63	[0.62, 0.65]
Yurovsky et al., 2013	6	0.61	[0.6, 0.63]
Yurovsky et al., unpub.	10	0.61	[0.57, 0.65]

25 Table 2  
26 Average proportion target looking in each dataset.  
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444 One of the values of the uniform data format we use in Peekbank is the ease of  
 445 providing cross-dataset descriptions that can give an overview of some of the general  
 446 patterns found in our data. A first broad question is about the degree of accuracy in word  
 447 recognition found across studies. In general, participants demonstrated robust, above-chance  
 448 word recognition in each dataset (chance=0.5). Table 2 shows the average proportion of  
 449 target looking within a standard critical window of 367-2000ms after the onset of the label  
 450 for each dataset (Swingley & Aslin, 2002). Proportion target looking was generally higher for  
 451 familiar words ( $M = 0.66$ , 95% CI = [0.65, 0.67],  $n = 1543$ ) than for novel words learned  
 452 during the experiment ( $M = 0.59$ , 95% CI = [0.58, 0.61],  $n = 822$ ).

453 A second question of interest is about the variability across items (i.e., target labels)  
 454 within specific studies. Some studies use a smaller set of items (e.g., 8 nouns, Adams et al.,  
 455 2018) while others use dozens of different items (e.g., Garrison, Baudet, Breitfeld, Aberman,  
 456 & Bergelson, 2020). Figure 4 gives an overview of the variability in proportion looking to the

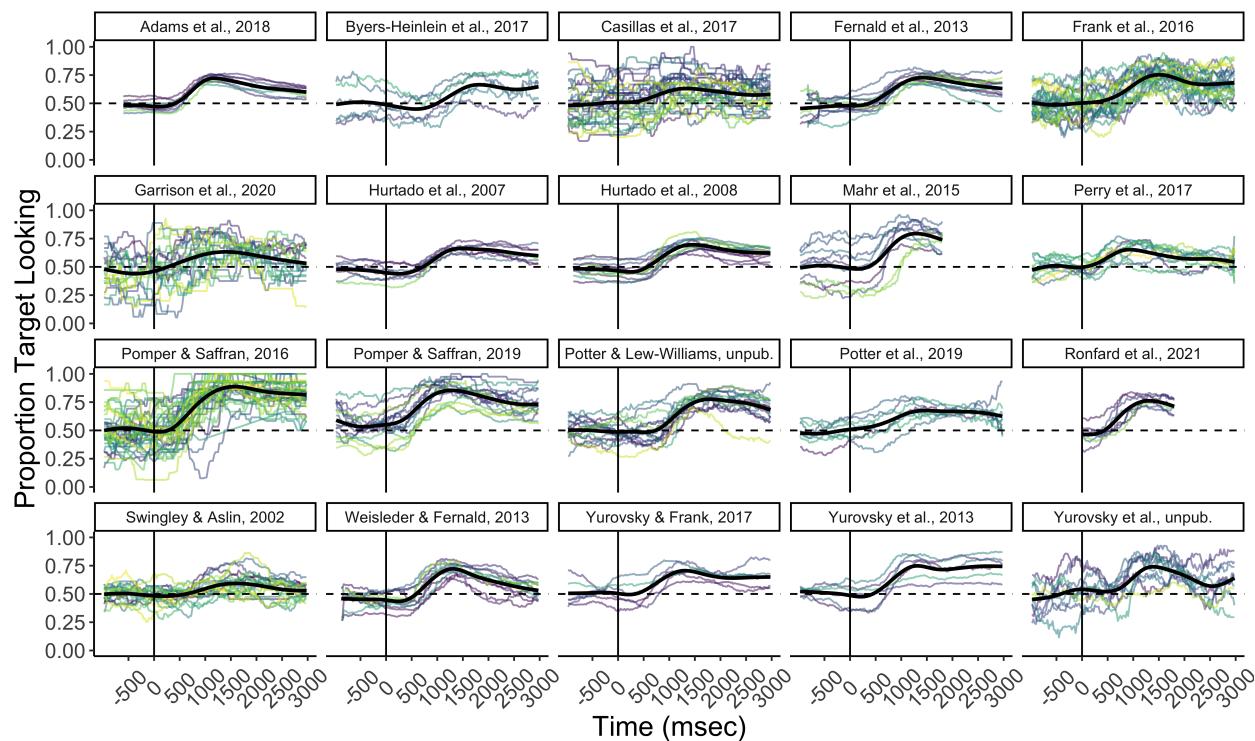


Figure 4. Item-level variability in proportion target looking within each dataset (chance=0.5). Time is centered on the onset of the target label (vertical line). Colored lines represent specific target labels. Black lines represent smoothed average fits based on a general additive model using cubic splines.

target item for individual words in each dataset. Although all datasets show a gradual rise in average proportion target looking over chance performance, the number of unique target labels and their associated accuracy vary widely across datasets.

#### Investigating prior findings: Swingley and Aslin (2002)

Swingley and Aslin (2002) investigated the specificity of 14-16-month-olds' word representations using the looking-while-listening paradigm, asking whether recognition would be slower and less accurate for mispronunciations, e.g. *opal* (mispronunciation) instead of *apple* (correct pronunciation).<sup>4</sup> In this short vignette, we show how easily the data in

<sup>4</sup> The original paper investigated both close (e.g., *opple*, /apl/) and distant (e.g., *opal*, /opl/) mispronunciations. For simplicity, here we combine both mispronunciation conditions since the close vs. distant mispronunciation manipulation showed no effect in the original paper.

## PEEK BANK REPOSITORY FOR EYE-TRACKING DATA

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465 Peekbank can be used to visualize this result. Our goal here is not to provide a precise  
 466 analytical reproduction of the analyses reported in the original paper, but rather to  
 467 demonstrate the use of the Peekbank framework to analyze datasets of this type. In  
 468 particular, because Peekbank uses a uniform data import standard, it is likely that there will  
 469 be minor numerical discrepancies between analyses on Peekbank data and analyses that use  
 470 another processing pipeline.

```
16 library(peekbankr)
17 aoi_timepoints <- get_aoi_timepoints(dataset_name = "swingley_aslin_2002")
18 administrations <- get_administrations(dataset_name = "swingley_aslin_2002")
19 trial_types <- get_trial_types(dataset_name = "swingley_aslin_2002")
20 trials <- get_trials(dataset_name = "swingley_aslin_2002")
```

25 We begin by retrieving the relevant tables from the database, `aoi_timepoints`,  
 26 `administrations`, `trial_types`, and `trials`. As discussed above, each of these can be  
 27 downloaded using a simple API call through `peekbankr`, which returns dataframes that  
 28 include ID fields. These ID fields allow for easy joining of the data into a single dataframe  
 29 containing all of the information necessary for the analysis.

```
36 swingley_data <- aoi_timepoints |>
37   left_join(administrations) |>
38   left_join(trials) |>
39   left_join(trial_types) |>
40   filter(condition != "filler") |>
41   mutate(condition = if_else(condition == "cp", "Correct", "Mispronounced"))
```

45 As the code above shows, once the data are joined, condition information for each  
 46 timepoint is present and so we can easily filter out filler trials and set up the conditions for  
 47 further analysis.

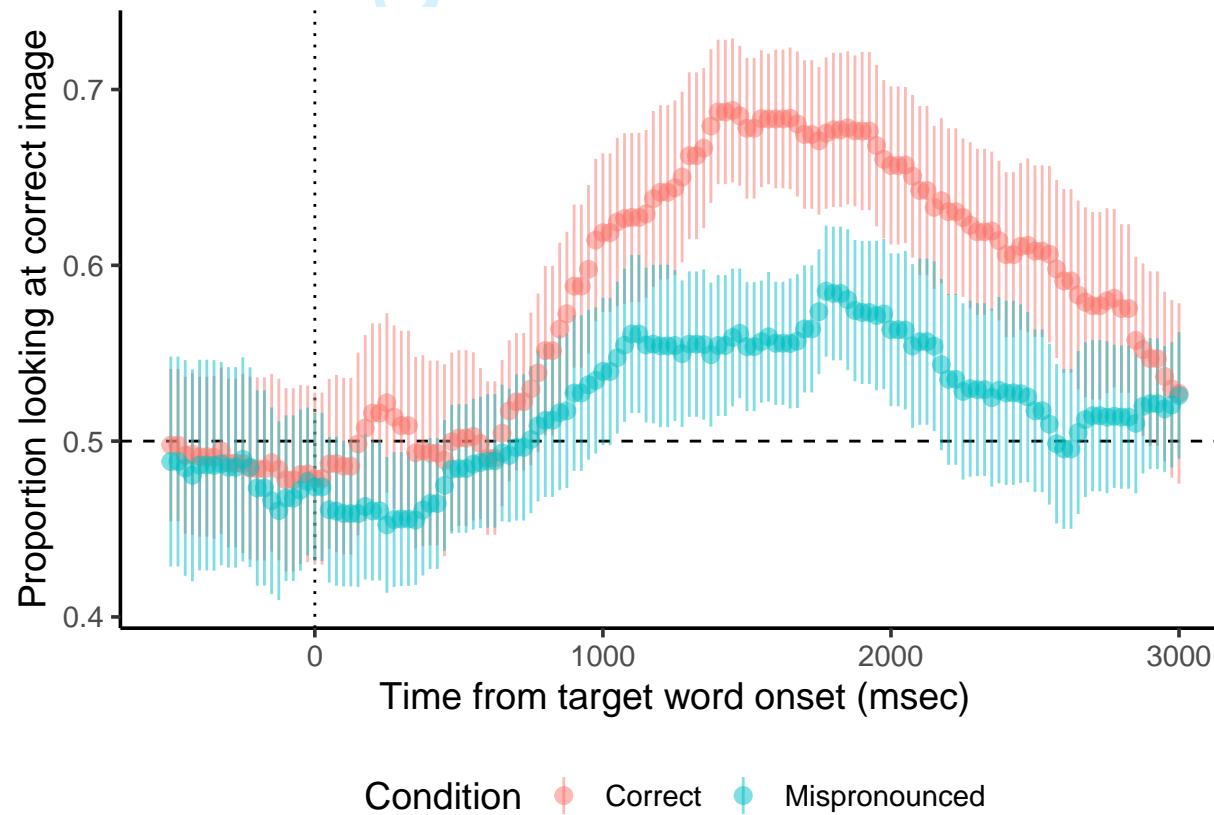
```
52 accuracies <- swingley_data |>
53   group_by(condition, t_norm, administration_id) |>
54   summarize(correct = sum(aoi == "target") /
55             sum(aoi %in% c("target", "distractor"))) |>
```

```

1
2
3
4     group_by(condition, t_norm) |>
5     summarize(mean_correct = mean(correct),
6                 ci = 1.96 * sd(correct) / sqrt(n())))
7
8
9

```

479 The final step in our analysis is to create a summary dataframe using `dplyr`  
 480 commands. We first group the data by timestep, participant, and condition and compute the  
 481 proportion looking at the correct image. We then summarize again, averaging across  
 482 participants, computing both means and 95% confidence intervals (via the approximation of  
 483 1.96 times the standard error of the mean). The resulting dataframe can be used for  
 484 visualization of the time course of looking.



485 *Figure 5.* Proportion looking at the correct referent by time from the point of disambiguation  
 486 (the onset of the target noun) in Swingley & Aslin (2002). Colors show the two pronunciation  
 487 conditions; points give means and ranges show 95% confidence intervals. The dotted line  
 488 shows the point of disambiguation and the dashed line shows chance performance.

485 Figure 5 shows the average time course of looking for the two conditions, as produced  
 486 by the code above. Looks after the correctly pronounced noun appeared both faster

1  
2  
3     487 (deviating from chance earlier) and more accurate (showing a higher asymptote). Overall,  
4     5     488 this example demonstrates the ability to produce this visualization in just a few lines of code.  
6  
7  
8  
9  
10

11     489 **Item analyses**  
12  
13  
14

15     490 A second use-case for Peekbank is to examine item-level variation in word recognition.  
16  
17     491 Individual datasets rarely have enough statistical power to show reliable developmental  
18     492 differences within items. To illustrate the power of aggregating data across multiple datasets,  
19  
20     493 we select the four words with the most data available across studies and ages (apple, book,  
21  
22     494 dog, and frog) and show average recognition trajectories.  
23  
24  
25

26     495 Our first step is to collect and join the data from the relevant tables including  
27  
28     496 timepoint data, trial and stimulus data, and administration data (for participant ages). We  
29  
30     497 join these into a single dataframe for easy manipulation; this dataframe is a common  
31  
32     498 starting point for analyses of item-level data.  
33

```
34 all_aoi_timepoints <- get_aoi_timepoints()
35
36 all_stimuli <- get_stimuli()
37
38 all_administrations <- get_administrations()
39
40 all_trial_types <- get_trial_types()
41
42 all_trials <- get_trials()
43
44
45
46 aoi_data_joined <- all_aoi_timepoints |>
47   right_join(all_administrations) |>
48   right_join(all_trials) |>
49   right_join(all_trial_types) |>
50   mutate(stimulus_id = target_id) |>
51   right_join(all_stimuli) |>
```

```
1
2
3
4     select(administration_id, english_stimulus_label, age, t_norm, aoi)
5
6
7
8
```

499 Next we select a set of four target words (chosen based on having more than 100

500 children contributing data for each word across several one-year age groups). We create age  
501 groups, aggregate, and compute timepoint-by-timepoint confidence intervals using the  $z$   
502 approximation.

```
16
17 target_words <- c("book", "dog", "frog", "apple")
18
19
20 target_word_data <- aoi_data_joined |>
21
22   filter(english_stimulus_label %in% target_words) |>
23
24   mutate(age_group = cut(age, breaks = seq(12, 48, 12))) |>
25
26   filter(!is.na(age_group)) |>
27
28   group_by(t_norm, administration_id, age_group, english_stimulus_label) |>
29
30   summarise(correct = sum(aoi == "target") /
31
32           sum(aoi %in% c("target", "distractor"))) |>
33
34   group_by(t_norm, age_group, english_stimulus_label) |>
35
36   summarise(ci = 1.96 * sd(correct, na.rm=TRUE) / sqrt(length(correct)),
37
38           correct = mean(correct, na.rm=TRUE),
39
40           n = n())
41
42
43
44
```

503 Finally, we plot the data as time courses split by age. Our plotting code is shown

45 below (with styling commands removed for clarity). Figure 6 shows the resulting plot, with  
46 time courses for each of three (rather coarse) age bins. Although some baseline effects are  
47 visible across items, we still see clear and consistent increases in looking to the target, with  
48 the increase appearing earlier and in many cases asymptoting at a higher level for older  
49 children. On the other hand, this simple averaging approach ignores study-to-study variation  
50 (perhaps responsible for the baseline effects we see in the *apple* and *frog* items especially). In  
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4        future work, we hope to introduce model-based analytic methods that use mixed effects  
5        regression to factor out study-level and individual-level variance in order to recover  
6        developmental effects more appropriately (see e.g., Zettersten et al., 2021 for a prototype of  
7        such an analysis).

```
12 ggplot(target_word_data,
13
14     aes(x = t_norm, y = correct, col = age_group)) +
15
16     geom_line() +
17
18     geom_linerange(aes(ymin = correct - ci, ymax = correct + ci),
19
20         alpha = .2) +
21
22     facet_wrap(~english_stimulus_label)
```

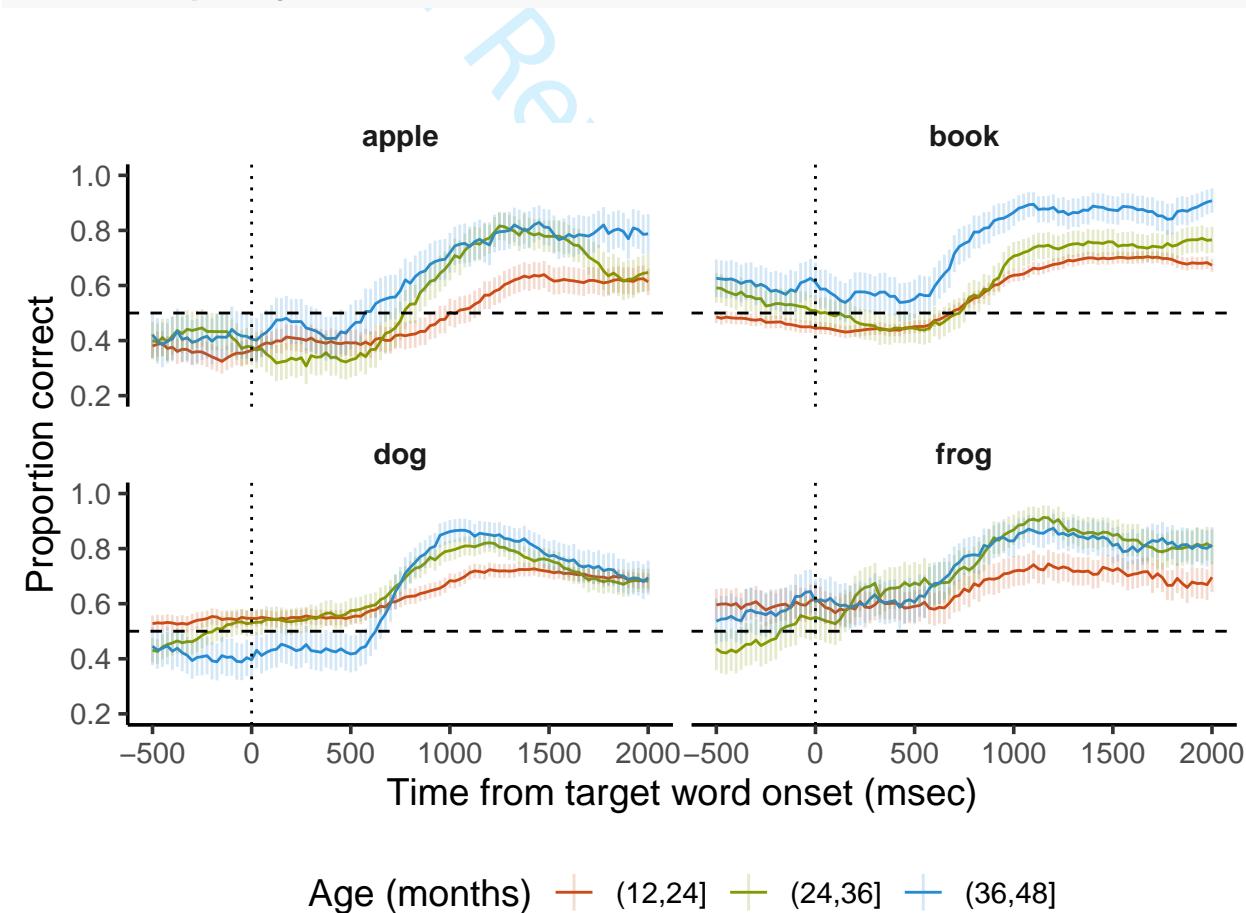


Figure 6. Time course plot for four well-represented target items in the Peekbank dataset, split by three age groups. Each line represents children's average looking to the target image after the onset of the target label (dashed vertical line). Error bars represent 95% CIs.

## Discussion

Theoretical progress in understanding child development requires rich datasets, but collecting child data is expensive, difficult, and time-intensive. Recent years have seen a growing effort to build open source tools and pool research efforts to meet the challenge of building a cumulative developmental science (Bergmann et al., 2018; Frank, Braginsky, Yurovsky, & Marchman, 2017; Sanchez et al., 2019; The ManyBabies Consortium, 2020). The Peekbank project expands on these efforts by building an infrastructure for aggregating eye-tracking data across studies, with a specific focus on the looking-while-listening paradigm. This paper presents an overview of the structure of the database, shows how users can access the database, and demonstrates how it can be used both to investigate prior experiments and to synthesize data across studies.

The current database has a number of limitations, particularly in its number and diversity of datasets. With 20 datasets currently available in the database, idiosyncrasies of particular designs and condition manipulations still have substantial influence on modeling results. Expanding the set of distinct datasets will allow us to increase the number of observations per item across datasets, leading to more robust generalizations across item-level variability. The current database is also limited by the relatively homogeneous background of its participants, both with respect to language (almost entirely monolingual native English speakers) and cultural background (Henrich, Heine, & Norenzayan, 2010; Muthukrishna et al., 2020). Increasing the diversity of participant backgrounds and languages will expand the scope of the generalizations we can form about child word recognition.

Finally, while the current database is focused on studies of word recognition, the tools and infrastructure developed in the project can in principle be used to accommodate any eye-tracking paradigm, opening up new avenues for insights into cognitive development. Gaze behavior has been at the core of many key advances in our understanding of infant

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3       <sup>539</sup> cognition (Aslin, 2007; Baillargeon, Spelke, & Wasserman, 1985; Bergelson & Swingley, 2012;  
4       <sup>540</sup> Fantz, 1963; Liu, Ullman, Tenenbaum, & Spelke, 2017; Quinn, Eimas, & Rosenkrantz, 1993).  
5  
6       <sup>541</sup> Aggregating large datasets of infant looking behavior in a single, openly-accessible format  
7  
8       <sup>542</sup> promises to bring a fuller picture of infant cognitive development into view.  
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For Review Only

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## PEEK BANK REPOSITORY FOR EYE-TRACKING DATA

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