

<sup>1</sup> Language Without Borders: A Step-by-Step Guide to Analyzing  
<sup>2</sup> Webcam Eye-Tracking Data for L2 Research

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<sup>8</sup> Abstract

Eye-tracking has become a valuable tool for studying cognitive processes in second language (L2) acquisition and bilingualism (Godfroid et al., 2024). While research-grade infrared eye-trackers are commonly used, there are a number of issues that limit its wide-spread adoption. Recently, consumer-based webcam eye-tracking has emerged as an attractive alternative, requiring only internet access and a personal webcam. However, webcam eye-tracking presents unique design and preprocessing challenges that must be addressed for valid results. To help researchers overcome these challenges, we developed a comprehensive tutorial focused on visual world webcam eye-tracking for L2 language research. Our guide will cover all key steps, from design to data preprocessing and analysis, where we highlight the R package `webgazeR`, which is open source and freely available for download and installation: <https://github.com/jgeller112/webgazeR>. We offer best practices for environmental conditions, participant instructions, and tips for designing visual world experiments with webcam eye-tracking. To demonstrate these steps, we analyze data collected through the Gorilla platform (Anwyl-Irvine et al., 2020) using a single word Spanish visual world paradigm (VWP) and show competition within and between L2/L1. This tutorial aims to empower researchers by providing a step-by-step guide to successfully conduct visual world webcam-based eye-tracking studies. To follow along with this tutorial, please download the entire manuscript and its accompanying code with data from here: [https://github.com/jgeller112/L2\\_VWP\\_Webcam](https://github.com/jgeller112/L2_VWP_Webcam).

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<sup>1</sup> Eye-tracking technology, which has a history spanning over a century, has seen remarkable advancements. In the early days, eye-tracking sometimes required the use of contact lenses fitted with search coils, often requiring anesthesia, or the attachment of suction cups to the sclera of the eyes (Płużyczka, 2018).

4 These methods were not only cumbersome for the researcher, but also uncomfortable and invasive for par-  
5 ticipants. Over time, such approaches have been replaced by non-invasive, lightweight, and user-friendly  
6 systems. Today, modern eye-tracking technology is widely accessible in laboratories worldwide, enabling  
7 researchers to tackle critical questions about cognitive processes . This evolution has had a profound impact  
8 on fields such as psycholinguistics and bilingualism, opening up new possibilities for understanding how  
9 language is processed in real time (Godfroid et al., 2024).

10 Despite its widespread adoption in cognitive and behavioral research, eye-tracking technology faces  
11 several obstacles that can limit its accessibility and integration into research programs. One significant chal-  
12 lenge is the specialized expertise required to operate research-grade eye-trackers. Proper calibration, data  
13 collection, and analysis often demand extensive training, meaning that studies typically need to be con-  
14 ducted in controlled lab environments by trained students or faculty. This reliance on specialized skills can  
15 be a barrier for researchers who lack access to experienced personnel or institutional support.

16 Cost is another major limitation. High-quality eye-tracking equipment can be prohibitively expen-  
17 sive, with prices ranging from a few thousand dollars (e.g., Gazepoint; [www.gazept.com](http://www.gazept.com)) to tens of thousands  
18 of dollars for more advanced systems (e.g., Tobii; [www.tobii.com](http://www.tobii.com), SR Research; [www.sr-research.com](http://www.sr-research.com)).  
19 These costs extend beyond the hardware, as proprietary software, maintenance, and upgrades can further  
20 strain research budgets. Consequently, institutions with limited funding may find it challenging to invest in  
21 or sustain eye-tracking research.

22 Time constraints also pose a significant hurdle. Many labs possess only a limited number of eye-  
23 trackers, restricting the number of participants that can be run simultaneously. This limitation can lead to  
24 prolonged data collection periods, especially for studies requiring large sample sizes or longitudinal designs.  
25 The time-intensive nature of both data collection and the subsequent analysis can deter researchers from  
26 integrating eye-tracking into their projects.

27 In addition to the above, an issue often not discussed is the burden placed on participants. Partici-  
28 pating in eye-tracking studies requires participants to come into the lab. This significantly limits the sample  
29 or population researchers can recruit. Behavioral science research, in general, frequently suffers from a lack  
30 of diversity, relying heavily on participants who are predominantly Western, Educated, Industrialized, Rich,  
31 Democratic, and able-bodied (WEIRD-A) (Henrich et al., 2010). This focus often excludes individuals from

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32 geographically dispersed areas, those from lower socioeconomic backgrounds, and people with disabilities  
33 who may face barriers to accessing research facilities. In language research, this issue is particularly evident,  
34 as it often prioritizes modal listeners and speakers, which are typically characterized as young, monolingual,  
35 and neurotypical (Blasi et al., 2022; Bylund et al., 2024; McMurray et al., 2010)

36 Collectively, these challenges—expertise, cost, time, and space/location—mean that not all re-  
37 searchers have the resources or capacity to incorporate eye-tracking into their research program nor recruit  
38 the sample they want, thereby limiting the broader adoption of this powerful methodology in fields where it  
39 could provide valuable insights.

#### 40 Eye-tracking outside the lab

41 Methods that allow participants to use their own equipment from anywhere in the world offer a  
42 potential solution to the issues outlined above, enabling researchers to recruit more diverse and disadvantaged  
43 samples and explore a broader range of questions (Gosling et al., 2010). The shift toward online behavioral  
44 experiments has been gradually increasing in the behavioral sciences and has become ever more important  
45 since the COVID-19 pandemic forced many to explore options outside the lab (Anderson et al., 2019; Rodd,  
46 2024). The *onlineification* of behavioral research has prompted the development of eye-tracking methods  
47 that do not rely on traditional lab settings.

48 One method, manual eye-tracking (Trueswell, 2008), involves using video recordings of participants,  
49 which can be collected through online teleconferencing platforms such as Zoom ([www.zoom.com](http://www.zoom.com)). Here eye  
50 gaze (direction) is manually analyzed post-hoc frame by frame from these recordings. However, this method  
51 raises ethical and privacy concerns, as not all participants may be comfortable having their videos recorded  
52 and stored for analysis.

53 Another method, which is the focus of this tutorial, is automated eye-tracking or webcam eye-  
54 tracking. Webcam eye-tracking requires three things: 1. A personal computer. 2. An internet connection  
55 and 3. A purchased or pre-installed webcam. Gaze information can be collected via a web browser. One  
56 common method to perform webcam eye-tracking is through an open source, free, and actively maintained  
57 JavaScript library plugin called WebGazer.js (Papoutsaki et al., 2016). This plugin is already incorporated  
58 into several popular experimental platforms (e.g., Gorilla, *jsPsych*, PsychoPy, and PCIbex; (Anwyl-Irvine  
59 et al., 2020; Leeuw, 2015; Peirce et al., 2019; Zehr & Schwarz, 2018). WebGazer.js runs locally through  
60 a person's personal computer via a browser. A benefit of WebGazer.js is that it does not require users to  
61 download any software, and is fully integrated in the browser, making it extremely easy to start webcam  
62 eye-tracking. In addition, videos taken from webcams are not recorded and saved which eliminates some of  
63 the ethical and privacy concerns.

64 WebGazer.js utilizes facial feature detection to estimate gaze positions in real time through a webcam.  
65 At each time point, determined by the sampling rate, x and y coordinates of the gaze are recorded. The  
66 system employs machine learning to analyze the relative movement of the eyes and infer the gaze location  
67 on the screen. To enhance accuracy, calibration and validation procedures are implemented, during which  
68 participants fixate on markers with known positions on the screen.

69 During calibration, users interact with visual stimuli by looking at and clicking on randomly placed  
70 dots or by following a moving dot across the screen. This interaction allows the system to map eye positions  
71 to specific screen coordinates. In the subsequent validation phase, participants repeat a similar procedure,  
72 enabling researchers to assess the accuracy of the gaze predictions. These procedures provide an estimate of  
73 the deviation between the calibrated eye-tracking data (where the system predicts the participant looked) and  
74 the actual known positions of the stimuli, thus allowing for the evaluation and refinement of gaze estimation  
75 accuracy.

76 It is important to note that WebGazer.js is not the only method available. Other methods have been  
77 implemented by companies like Tobii ([www.tobii.com](http://www.tobii.com)) and Labvanced (Kaduk et al., 2024). However,  
78 because these methods are proprietary, they are less accessible and difficult to reproduce.

79 The algorithms underlying webcam-based eye tracking differ significantly from those used in  
80 research-grade eye trackers. Research-grade systems commonly employ video-based recording and rely on  
81 one or more cameras and the pupil-corneal reflection (P-CR) method to track gaze with high precision (Carter  
82 & Luke, 2020). This method utilizes infrared light to illuminate the eyes, capturing reflections (known as  
83 glints) from the cornea and pupil. High-speed cameras simultaneously capture images at rates of hundreds or  
84 thousands of frames per second to measure eye position. By combining data from the corneal reflections and  
85 pupil location, these systems calculate gaze direction and position. To derive real-world information about  
86 where participants looked, a transformation is required, which is usually done mathematically (Hooge et al.,  
87 2024).

88 This leads to an important question: how does consumer-grade webcam eye tracking compare to  
89 research-grade systems? While validation studies are ongoing, webcam-based eye trackers generally exhibit  
90 reduced spatiotemporal accuracy. Studies have reported that these systems achieve spatial accuracy and  
91 precision exceeding  $1^\circ$  of visual angle, with latencies ranging from 200 ms to 1000 ms (Kaduk et al., 2024;  
92 Semmelmann & Weigelt, 2018; Slim et al., 2024; Slim & Hartsuiker, 2023). Furthermore, the sampling rate  
93 of webcam-based systems is much lower, typically capped at 60 Hz, with most studies reporting average or  
94 median rates around 30 Hz (Bramlett & Wiener, 2024; Prystauka et al., 2024). Unlike research-grade systems,  
95 webcam eye trackers do not use infrared light; instead, they rely on ambient light from the participant's  
96 environment. This dependency introduces additional variability in tracking performance.

97 To compare, a study of 15 research-grade eye-trackers by Hooge et al. (2024) found that precision  
98 ranged from  $0.1^\circ$  to  $0.35^\circ$ , while accuracy ranged from  $0.3^\circ$  to  $0.75^\circ$ . Additionally, research-grade eye-  
99 trackers have low latency and can achieve high sampling rates—for example, the SR EyeLink 1000 Plus can  
100 sample at 2,000 Hz. These advanced capabilities make research-grade systems ideal for studies requiring  
101 high temporal and spatial resolution.

## 102 **Bringing the visual world paradigm (VWP) online**

103 Despite the differences between research-grade and consumer grade eye-tracking, a number of stud-  
104 ies have begun to look at if lab-based results replicate online using webcam eye-tracking. Most relevant to  
105 this tutorial are online replications using the VWP (Tanenhaus et al., 1995; cf. Cooper, 1974). For the past

106 25 years, the VWP has been a dominant force in language research, helping researchers tackle a wide range of  
107 topics, including sentence processing (Altmann & Kamide, 1999; Huettig et al., 2011; Kamide et al., 2003),  
108 word recognition (Allopenna et al., 1998; Dahan et al., 2001; Huettig & McQueen, 2007; McMurray et al.,  
109 2002), bilingualism (Hopp, 2013; Ito et al., 2018; Rossi et al., 2019), and the effects of brain damage on  
110 language (Mirman & Graziano, 2012; Yee et al., 2008).

111 What makes the widespread use of the VWP even more remarkable is the simplicity of the task. In a  
112 typical VWP experiment, participants view a display containing several objects (in the form of pictures) and  
113 are asked to select one of them by pointing or clicking. As they listen to a spoken word or phrase that identifies  
114 the target object, their eye movements are recorded in real time. The standard finding using the VWP is that  
115 listeners show eye movements to the picture that represents the spoken word, while demonstrating predictive  
116 processing, such that eye movements to pictures occur before an entire word is available. Remarkably, looks  
117 to each object align very closely—and with precise timing—with the mental activation of the word or concept  
118 it represents. This provides a unique and detailed view of how cognitive processes unfold in real time

119 Most research on visual world eye-tracking has been conducted in laboratory settings using research-  
120 grade eye-trackers. However, several attempts have been made to conduct these experiments online using  
121 webcam-based eye-tracking. Most online VWP replications have focused on sentence-based language pro-  
122 cessing. These studies have looked at effects of set size and determiners (Degen et al., 2021), verb semantic  
123 constraint (Prystauka et al., 2024; Slim & Hartsuiker, 2023), grammatical aspect and event comprehension  
124 (Vos et al., 2022), and lexical interference (Prystauka et al., 2024).

125 More relevant to the current paper are findings from single-word VWP studies conducted online.  
126 To date, only one study has investigated visual world webcam eye-tracking with single words. Slim et al.  
127 (2024) examined a phonemic cohort task. In the cohort task, pictures were displayed randomly in one of four  
128 quadrants, and participants were instructed to fixate on the target based on the auditory cue. On each trial,  
129 one of the pictures was phonemically similar to the target in onset (e.g., *MILK – MITTEN*).

130 They were able to observe significant fixations to the cohort compared to the control condition,  
131 replicating lab-based single word VWP experiments with research grade eye-trackers (e.g., Allopenna et al.,  
132 1998). However, Slim et al. (2024) only observed these competition effects in a later time window compared  
133 to traditional, lab-based eye-tracking.

134 It is important to note, however, that while these studies represent successful replication attempts,  
135 there is an important caveat. Most notably, some studies (e.g., Degen et al., 2021; Slim et al., 2024; Slim  
136 & Hartsuiker, 2023) reported considerable delays in the temporal onset of effects. Several factors likely  
137 contribute to these delays, including reduced spatial precision, computational demands, the size of areas of  
138 interest (AOIs), and the number of calibrations performed (Degen et al., 2021).

139 More recent work has addressed these limitations by utilizing an updated version of WebGazer.js and  
140 using different experimental platforms. For instance, Vos et al. (2022) demonstrated a significant reduction in  
141 delays—approximately 50 ms—when comparing lab-based and online versions of the VWP using an updated  
142 version of WebGazer.js within the jsPsych framework (Leeuw, 2015). Furthermore, studies by Prystauka et  
143 al. (2024) and Bramlett and Wiener (2024), which leveraged the Gorilla platform alongside the improved

<sup>144</sup> WebGazer algorithm, reported effects comparable to those observed in traditional lab-based VWP studies.

<sup>145</sup> These findings underscore the potential of the online version of the VWP, powered by webcam eye-  
<sup>146</sup> tracking, to achieve results similar to those of traditional lab-based methods. Importantly, they demonstrate  
<sup>147</sup> that this approach can effectively be used to study competition effects in single-word speech perception.

<sup>148</sup> **Tutorial**

<sup>149</sup> Taken together, it seems that webcam eye-tracking is a viable alternative to lab-based eye-tracking.  
<sup>150</sup> Given this, we aimed to support researchers in their efforts to conduct high-quality webcam eye-tracking  
<sup>151</sup> studies with the VWP. While a valuable tutorial on webcam eye-tracking in the VWP already exists (Bramlett  
<sup>152</sup> & Wiener, 2024), we believe there is value in having multiple resources available to researchers. To this end,  
<sup>153</sup> we sought to expand on the tutorial by Bramlett and Wiener (2024) by incorporating many of their useful  
<sup>154</sup> recommendations, but also offering an R package to help streamline data pre-processing.

<sup>155</sup> The purpose of this tutorial is to provide an overview of the basic set-up and design features of an  
<sup>156</sup> online VWP task using the Gorilla platform (Anwyl-Irvine et al., 2020) and to highlight the pre-processing  
<sup>157</sup> steps needed to analyze webcam eye-tracking data. Here we use the popular open source programming  
<sup>158</sup> language R and introduce the `webgazeR` package (Geller & Prystauka, 2024) to facilitate pre-processing of  
<sup>159</sup> webcam data. To highlight the steps needed to process webcam eye-tracking data we present data from a  
<sup>160</sup> Spanish spoken word VWP with L2 Spanish speakers. To our knowledge, L2 processing and competitor  
<sup>161</sup> effects have not been looked at in the online version of the VWP.

<sup>162</sup> The structure of the tutorial will be as follows. We first outline the general methods used to conduct  
<sup>163</sup> a visual world webcam eye-tracking experiment. Next, we detail the data preprocessing steps required to  
<sup>164</sup> prepare the data for analysis. Finally, we demonstrate one statistical approach for analyzing our preprocessed  
<sup>165</sup> data, highlighting its application and implications.

<sup>166</sup> To promote transparency and reproducibility, this tutorial was written in R (R Core Team, 2024)  
<sup>167</sup> using Quarto (Allaire et al., 2024), an open-source publishing system that allows for dynamic and static  
<sup>168</sup> documents. This allows figures, tables, and text to be programmatically included directly in the manuscript,  
<sup>169</sup> ensuring that all results are seamlessly integrated into the document. To increase computational reproducibil-  
<sup>170</sup> ity we use the `rix` (Rodrigues & Baumann, 2025) package which harnesses the power of the `nix` (Dolstra &  
<sup>171</sup> contributors, 2023) ecosystem to help with computational reproducibility. Not only does this give us a snap-  
<sup>172</sup> shot of the packages used to create the current manuscript, but it also takes a snapshot of system dependencies  
<sup>173</sup> used at run-time. This way reproducers can easily re-use the exact same environment by installing the `nix`  
<sup>174</sup> package manager and using the included `default.nix` file to set up the right environment. The `README` file  
<sup>175</sup> in the GitHub repository contains detailed information on how to set this up to reproduce the contents of the  
<sup>176</sup> current manuscript. We have also included a video tutorial.

177

## L2 VWP Webcam Eye-tracking

178 To highlight the preprocessing steps required to analyze webcam eye-tracking data, we examined the  
179 competitive dynamics of second-language (L2) learners of Spanish, whose first language is English, during  
180 spoken word recognition. Specifically, we investigated both within-language and cross-language (L2/L1)  
181 competition using webcam-based eye-tracking.

182 It is well established that competition plays a critical role in language processing (Magnuson et al.,  
183 2007). In speech perception, as the auditory signal unfolds over time, competitors (or cohorts)—phonological  
184 neighbors that differ from the target by an initial phoneme—become activated. To successfully recognize the  
185 spoken word, these competitors must be inhibited or suppressed. For example, as the word *wizard* is spoken,  
186 cohorts like *whistle* might also be briefly activated and in order for *wizard* to be recognized, *whistle* must be  
187 suppressed. A key question in the L2 literature is whether competition can occur cross-linguistically, with  
188 interactions between a speaker’s first language (L1) and second language (L2). Recent work by Sarrett et  
189 al. (2022) explored this question using carefully designed stimuli to examine within- and between linguis-  
190 tic (L2/L1) competition in adult L2 Spanish learners using a Spanish VWP. Their study included two key  
191 conditions:

- 192 1. Spanish-Spanish (within) condition: A Spanish competitor was presented alongside the target word.  
193 For example, if the target word spoken was *cielo* (sky), the Spanish competitor was *ciencia* (science).
- 194 2. Spanish-English (cross-linguistic) condition: An English competitor was presented for the Spanish target  
195 word. For example, if the target word spoken was *botas* (boots), the English competitor was *border*.

196 Sarrett et al. (2022) also included a no competition condition where the Spanish-English pairs were  
197 not cross-linguistic competitors (e.g., *frontera* as the target word and *botas - boots* as an unrelated item in  
198 the pair). They observed competition effects in both of the critical conditions: within (e.g., *cielo - ciencia*)  
199 and between (e.g., *botas - border*). For this tutorial, we collected data to conceptually replicate their pattern  
200 of findings.

201 There are two key differences between our dataset and the original study by Sarrett et al. (2022) worth  
202 noting. First, Sarrett et al. (2022) focused on adult L2 Spanish speakers and posed more fine-grained ques-  
203 tions about the time course of competition and resolution and its relationship with L2 language acquisition.  
204 Second, unlike Sarrett et al. (2022), who measured Spanish proficiency objectively using LexTALE-esp  
205 (Izura et al., 2014)), we relied on Prolific’s filters to recruit L2 Spanish speakers.

206 Our primary goal here was to demonstrate the pre-processing steps required to analyze webcam-  
207 based eye-tracking data. A secondary goal was to provide evidence of L2 competition within and between  
208 or cross-linguistically using this methodology. To our knowledge, no papers have looked at spoken word  
209 recognition and competition using online methods. It is our hope that researchers can use this to test more  
210 detailed questions about L2 processing using webcam-based eye-tracking.

211 **Method**

212 All tasks herein can be previewed here (<https://app.gorilla.sc/openmaterials/953693>). The  
213 manuscript, data, and R code can be found on Github ([https://github.com/jgeller112/webcam\\_gazeR\\_VWP](https://github.com/jgeller112/webcam_gazeR_VWP)).

214 **Participants**

215 We recruited participants from Prolific, a participant recruitment platform, who were: (1) between  
216 the ages of 18 and 36 years old, (2) native English speakers, (3) were also fluent in Spanish, and (4) residents of  
217 the US. All participants were taken to the Gorilla hosting and experiment platform ([www.gorilla.sc](http://www.gorilla.sc); (Anwyl-  
218 Irvine et al., 2020). The participant flow is shown in Figure 1. A total of 187 participants consented to  
219 participate in the study. Of these, 121 passed the headphone screener checkpoint and 111 proceeded to  
220 the VWP. Out of the 111 participants that entered the VWP, 91 total made it to the final surveys at the  
221 end. Among those, 32 participants successfully completed the VWP task with at least 100 trials, while 79  
222 participants did not provide adequate data to be included (failed calibration attempts). Table 1 provides  
223 basic demographic information about the participants who completed the full experiment. After applying  
224 additional exclusion criteria (accuracy < 80%) and excessive missing eye-data (> 30%), the final sample  
225 consisted of 28 participants with usable eye-tracking data.

226 **Materials**

227 **VWP..**

228 **Items.** We adapted materials from Sarrett et al. (2022). In their cross-linguistic VWP, participants  
229 were presented with four pictures and a spoken Spanish word and had to select the image that matched the  
230 spoken word by clicking on it. The word stimuli for the experiment were chosen from textbooks used by  
231 students in their first and second year college Spanish courses.

232 The item sets consisted of two types of phonologically-related word pairs: one pair of Spanish-  
233 Spanish words and another of Spanish-English words. The Spanish-Spanish pairs were unrelated to the  
234 Spanish-English pairs. All the word pairs were carefully controlled on a number of dimensions (see Sarrett  
235 et al., 2022).

236 There were three experimental conditions: (1) the Spanish-Spanish (within) condition, where one of  
237 the Spanish words was the target and the other was the competitor; (2) the Spanish-English (cross-linguistic)  
238 condition, where a Spanish word was the target and its English phonological cohort served as the competitor;  
239 and (3) the No Competitor condition, where the Spanish word did not overlap with any other word in the set.  
240 The Spanish-Spanish condition had twice as many trials as the other conditions due to the interchangeable  
241 nature of the target and competitor words in that pair.

242 There were 15 sets of 4 items (half the number of sets used in (Sarrett et al., 2022). Each item within a  
243 set was repeated 4 times as the target word. This yielded 240 trials (15 sets × 4 items per set × 4 repetitions).  
244 Each item set consisted of one Spanish-Spanish cohort pair and one Spanish-English cohort pair. Both

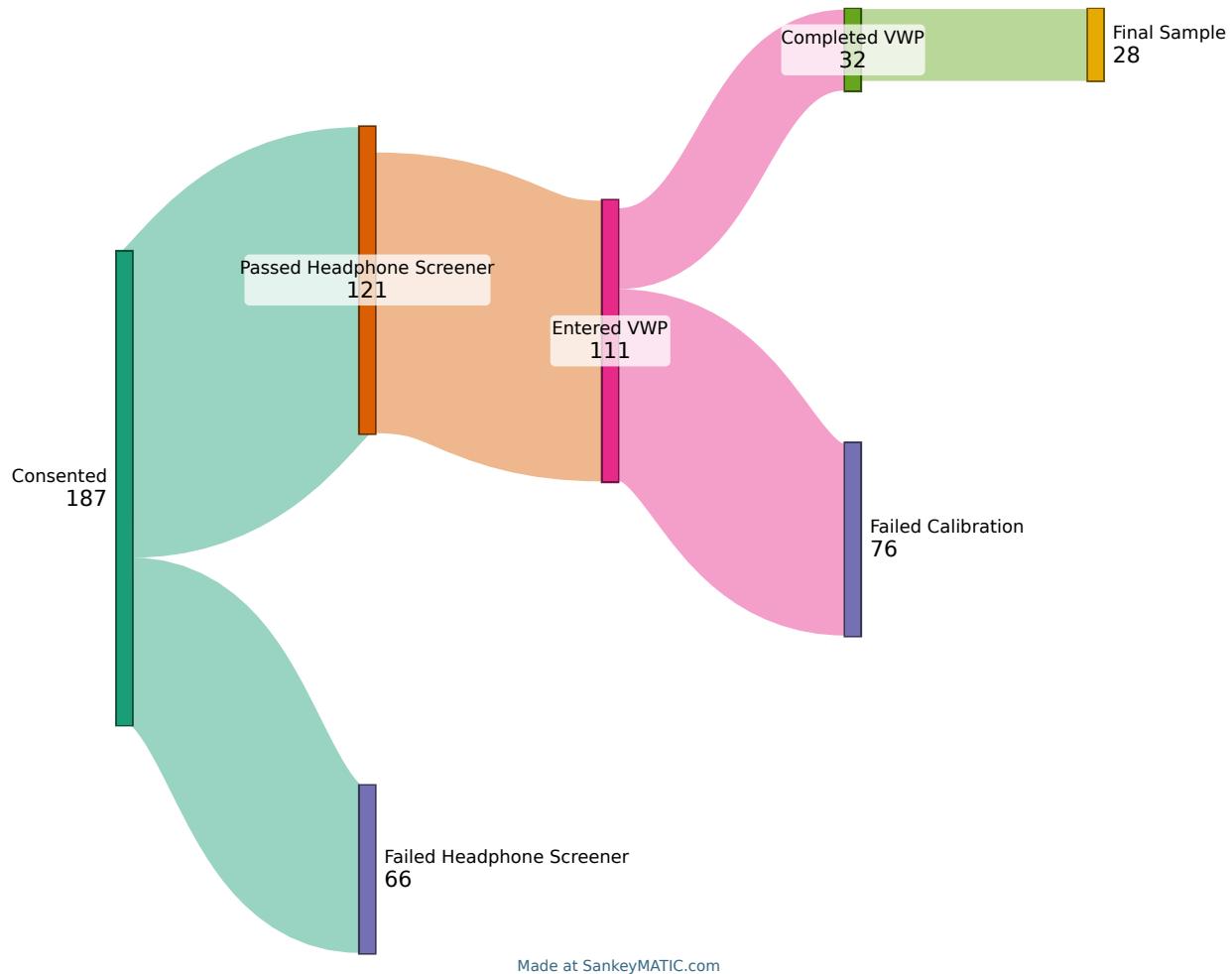
**Table 1***Participant demographic variables*

| <b>Characteristic</b>                        | <b>N = 91<sup>1</sup></b> |
|--|---------------------------|
| <b>Age</b>                                   | (20.0, 35.0), 28.2(4.4)   |
| <b>Gender</b>                                |                           |
| Female                                       | 42 / 91 (46%)             |
| Male   | 49 / 91 (54%)             |
| <b>Spoken dialect</b>                        |                           |
| Do not know                                  | 11 / 91 (12%)             |
| Midwestern                                   | 19 / 91 (21%)             |
| New England                                  | 11 / 91 (12%)             |
| Other (please specify)                       | 7 / 91 (7.7%)             |
| Pacific northwest                            | 7 / 91 (7.7%)             |
| Pacific southwest                            | 7 / 91 (7.7%)             |
| Southern                                     | 21 / 91 (23%)             |
| Southwestern                                 | 8 / 91 (8.8%)             |
| <b>Ethnicity</b>                             |                           |
| Decline to state                             | 1 / 91 (1.1%)             |
| Hispanic or Latino                           | 38 / 91 (42%)             |
| Not Hispanic or Latino                       | 52 / 91 (57%)             |
| <b>Race</b>                                  |                           |
| American Indian/Alaska Native                | 2 / 91 (2.2%)             |
| Asian  | 13 / 91 (14%)             |
| Black or African American                    | 10 / 91 (11%)             |
| Decline to state                             | 7 / 91 (7.7%)             |
| More than one race                           | 4 / 91 (4.4%)             |
| White  | 55 / 91 (60%)             |
| <b>Browser</b>                               |                           |
| Chrome                                       | 77 / 91 (85%)             |
| Edge   | 3 / 91 (3.3%)             |
| Firefox                                      | 7 / 91 (7.7%)             |
| Safari                                       | 4 / 91 (4.4%)             |
| <b>Years Speaking Spanish</b>                | (0, 35), 15(10)           |
| <b>% Experience Using Spanish Daily Life</b> | 25(23)                    |

<sup>1</sup>(Min, Max), Mean(SD); n / N (%); Mean(SD)

**Figure 1**

*Participant flow, from recruitment to final sample*



245 items in a Spanish-Spanish pair had a “reciprocal” competitor relationship (that is, we could test activation  
 246 for *cielo* given *ciencia*, and for *ciencia* given *cielo*). Consequently, there were 120 trials in the Spanish-  
 247 Spanish condition. In contrast, only one item from the Spanish-English pair had the specified competitor  
 248 relationship (we could test activation for *frontera border*, given *botas*, but when hearing *frontera*, there was  
 249 no competitor). Thus, there were only 60 trials for each the Spanish-English competition as well as the No  
 250 Competitor condition. Items occurred in each of the four corners of the screen on an equal numbers of trials.

251 **Stimuli.** In Sarrett et al. (2022) all auditory stimuli were recorded by a female bilingual speaker  
 252 whose native language was Mexican Spanish and also spoke English. Stimuli were recorded in a sound-  
 253 attenuated room sampled at 44.1 kHz. Auditory tokens were edited to reduce noise and remove clicks. The  
 254 auditory tokens were then amplitude normalized to 70 dB SPL. For each target word, there were four separate  
 255 recordings so each instance was unique.

256 Visual stimuli were images from a commercial clipart database that were selected by a consensus

257 method involving a small group of students. All .wav files were converted to .mp3 for online data collection.  
258 All stimuli can be found here: <https://osf.io/mgkd2/>.

259       **Headphone screener.** Headphones were required for all participants. To ensure this, we used a six-  
260 trial task taken from Woods et al. (2017). On each trial, three tones of the same frequency and duration were  
261 presented sequentially. One tone had a lower amplitude than the other two tones. Tones were presented in  
262 stereo, but the tones in the left and right channels were 180 out of phase across stereo channels—in free field,  
263 these sounds should cancel out or create distortion, whereas they will be perfectly clear over headphones.  
264 The listener picked which of the three tones was the quietest. Performance is generally at the ceiling when  
265 wearing headphones but poor when listening in the free field (due to phase cancellation).

266       **Participant background and experiment conditions questionnaire.** Participants completed a de-  
267 mographic questionnaire as part of the study. The questions covered basic demographic information, includ-  
268 ing age, gender, spoken dialect, ethnicity, and race.

269       Participants also answered a series of questions related to their personal health and environmental  
270 conditions during the experiment. These questions addressed any history of vision problems (e.g., corrected  
271 vision, eye disease, or drooping eyelids) and whether they were currently taking medications that might impair  
272 judgment. Participants also indicated if they were wearing eyeglasses, contacts, makeup, false eyelashes, or  
273 hats.

274       The questionnaire inquired about their environment, asking if there was natural light in the room, if  
275 they were using a built-in camera or an external one (with an option to specify the brand), and their estimated  
276 distance from the camera. Participants were asked to estimate how many times they looked at their phone or  
277 got up during the experiment and whether their environment was distraction-free.

278       Additional questions assessed the clarity of calibration instructions, allowing participants to suggest  
279 improvements, and asked if they were wearing a mask during the session. These questions aimed to gather  
280 insights into personal and environmental factors that could impact data quality and participant comfort during  
281 the experiment.

282       To gauge L2 experience, we asked participants when they started speaking Spanish, how many years  
283 of Spanish speaking experience they had, and to provide, on a scale between 0-100, how often they use  
284 Spanish in their daily lives.

285       **Procedure**

286       All tasks were completed in a single session, lasting approximately 45 minutes. The tasks were  
287 presented in a fixed order: consent, headphone screener, spoken word VWP, and questionnaire items.

288       The experiment was programmed in the Gorilla Experiment Platform (Anwyl-Irvine et al., 2020),  
289 with personal computers as the only permitted device type. Upon entering the online study, participants  
290 received general information to decide if they wished to participate, after which they provided informed  
291 consent. Participants were then instructed to adjust the volume to a comfortable level while noise played.

292       Next, participants completed a headphone screening test. They had three attempts to pass this test.

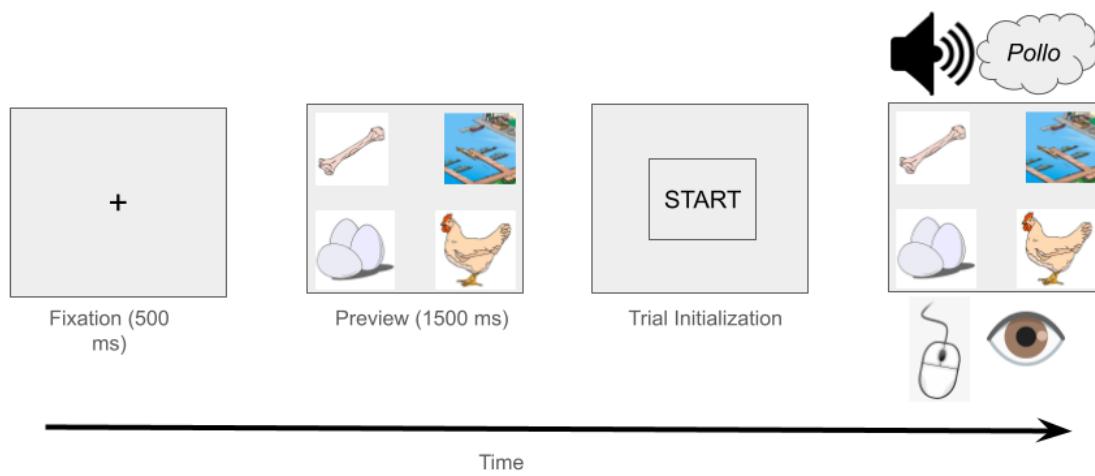
293 If unsuccessful by the third attempt, participants were directed to an early exit screen, followed by the ques-  
294 tionnaire.

295 For those who passed the screening, the next task was the VWP. This began with instructional videos  
296 providing specific guidance on the ideal experiment setup for eye-tracking and calibration procedures. You  
297 can view the videos here: <https://osf.io/mgkd2/>. Participants were then required to enter full-screen mode  
298 before calibration. A 9-point calibration procedure was used. Calibration occurred every 60 trials for a  
299 total of 3 calibrations. Participants had three attempts to successfully complete each calibration phase. If  
300 calibration was unsuccessful, participants were directed to an early exit screen, followed by the questionnaire.

301 In the main VWP task, each trial began with a 500 ms fixation cross at the center of the screen. This  
302 was followed by a preview screen displaying four images, each positioned in a corner of the screen. After  
303 1500 ms, a start button appeared in the center. Participants clicked the button to confirm they were focused  
304 on the center before the audio played. Once clicked, the audio was played, and the images remained visible.  
305 Participants were instructed to click the image that best matched the spoken target word, while their eye  
306 movements were recorded. Eye movements were only recorded on that screen. Figure 2 displays the VWP  
307 trial sequence.

**Figure 2**

*VWP trial schematic*



308 After completing the main VWP task, participants proceeded to the final questionnaire, which in-  
309 cluded questions about the eye-tracking task and basic demographic information. Participants were then  
310 thanked for their participation.

311 **Preprocessing data**

312 After the data is collected you can begin preprocessing your data. Below we highlight the steps  
313 needed to preprocess your webcam eye-tracking data and get it ready for analysis. For some of this prepro-  
314 cessing we will use the newly created `webgazeR` pacckage (v. 0.1.0) which is an extension of the `gazeR`  
315 package (Geller et al., 2020) which was created to analyze VWP data from lab-based studies.

316 For preprocessing visual world webcam eye data, we follow six general steps:

- 317 1. Reading in data  
318 2. Data exclusion  
319 3. Combining trial- and eye-level data  
320 4. Assigning areas of interest (AOIs)  
321 5. Time binning  
322 6. Aggregating (optional)

323 For each of these steps, we will display R code chunks demonstrating how to perform each step with  
324 helper functions (if applicable) from the `webgazeR` (Geller & Prystauka, 2024) package in R.

325 **Load packages**

326 **Package Installation and Setup.** Before turning to the preprocessing code below, we will need to  
327 make sure all the necessary packages are installed. The code will not run if the packages are not installed  
328 properly. If you have already installed the packages mentioned below, then you can skip ahead and ignore this  
329 section. To install the necessary packages, simply run the following code - it may take some time (between  
330 1 and 5 minutes to install all of the libraries so you do not need to worry if it takes some time).

331 **webgazeR installation.** The `webgazeR` package is installed from the Github repository using the  
332 `remotes` (Csárdi et al., 2024) package.

```
library(remotes) # install github repo  
  
remotes::install_github("jgeller112/webgazeR")
```

333 Once this is installed, `webgazeR` can be loaded along with additional useful packages. The following  
334 code will load the required packages or install them if you do not have them on your system.

```
# List of required packages
required_packages <- c(
  "tidyverse",      # data wrangling
  "here",           # relative paths instead of absolute aids in reproducibility
  "tinytable",       # nice tables
  "janitor",        # functions for cleaning up your column names
  "webgazeR",        # has webcam functions
  "readxl",          # read in Excel files
  "ggokabeito",      # color-blind friendly palettes
  "flextable",        # Word tables
  "permuco",         # permutation analysis
  "foreach",          # permutation analysis
  "geomtextpath",      # for plotting labels on lines of ggplot figures
  "cowplot"          # combine ggplot figures
)
```

335        Once `webgazeR` and other helper packages have been installed and loaded the user is ready to start  
 336        cleaning your data.

337        ***Reading in data***

338        **Behavioral, trial-level, data.** To process eye-tracking data you will need to make sure you have both  
 339        the behavioral data and the eye-tracking data files. We have all the data needed in the repository by navigating  
 340        to the L2 subfolder from the main project directory (`~/data/L2`). For the behavioral data, Gorilla produces a  
 341        `.csv` file that includes trial-level information (here contained in the object `L2_data`). The files needed are  
 342        called `data_exp_196386-v5_task-scf6.csv` and `data_exp_196386-v6_task-scf6.csv`. We have  
 343        two files because we ran a modified version of the experiment.

344        The `.csv` files contain meta-data for each each trial, such as what picture were presented on each  
 345        trial, which object was the target, reaction times, audio presentation times, what object was clicked on, etc.  
 346        To load our data files into our R environment, we use the `here` (Müller, 2020) package to set a relative  
 347        rather than an absolute path to our files. We read in the data files from the repository for both versions of  
 348        the task and merge the files together. `L2_data` merges both `data_exp_196386-v5_task-scf6.csv` and  
 349        `data_exp_196386-v6_task-scf6.csv` into one object.

```
# load in trial level data
# combine data from version 5 and 6 of the task
L2_1 <- read_csv(here("data", "L2", "data_exp_196386-v5_task-scf6.csv"))
L2_2 <- read_csv(here("data", "L2", "data_exp_196386-v6_task-scf6.csv"))
```

```
L2_data <- rbind(L2_1, L2_2) # bind the two objects together
```

350         **Eye-tracking data.** Gorilla currently saves each participant's eye-tracking data on a per-trial ba-  
 351         sis. The raw subfolder in the project repository contains the eye-tracking files by participant for each trial  
 352         individually (~/data/L2/raw). Contained in those files, we have information pertaining to each trial such as  
 353         participant id, time since trial started, x and y coordinates of looks, convergence (the model's confidence  
 354         in finding a face (and accurately predicting eye movements), face confidence (represents the support vector  
 355         machine (SVM) classifier score for the face model fit), and information pertaining to the the AOI screen  
 356         coordinates (standardized and user-specific). The vwp\_files\_L2 object below contains a list of all the files  
 357         contained in the folder. Because vwp\_files\_L2 contains trial data as well as calibration data, we remove  
 358         the calibration trials and save the non-calibration to to vwp\_paths\_filtered\_L2.

```
# Get the list of all files in the folder
vwp_files_L2 <- list.files(here::here("data", "L2", "raw"), pattern =
  "\\.xlsx$", full.names = TRUE)
# Exclude files that contain "calibration" in their filename
vwp_paths_filtered_L2 <- vwp_files_L2[!grepl("calibration", vwp_files_L2)]
```

359         When data is generated from Gorilla, each trial in your experiment is saved as an individual  
 360         file. Because of this, we need some way to take all the individual files and merge them together. The  
 361         merge\_webcam\_files() function from webgazeR merges trial-level data from each participant into a sin-  
 362         gle tibble or data frame. Before running the merge\_webcam\_files() function, ensure that your working  
 363         directory is set to where the files are stored. The merge\_webcam\_files() function reads in all the .xlsx  
 364         files from the raw subfolder, binds them together into one dataframe, and cleans up the column names. The  
 365         function then filters the data to include only rows where the type is “prediction” and the screen\_index  
 366         matches the specified value (in our case, screen 4 is where we collected eye-tracking data). If you recorded  
 367         across multiple screens the screen\_index argument can take multiple values (e.g., screen\_index= c(1,  
 368         4, 5) will take eye-tacking information from screens, 1, 4, and 5)). merge\_webcam\_files() also renames  
 369         the spreadsheet\_row column to trial and sets both trial and subject as factors for further analysis in  
 370         our pipeline. As a general note, all steps should be followed in order due to the renaming of column names.  
 371         If you encounter an error it might be because column names have not been changed.

```
setwd(here::here("data", "L2", "raw")) # set working directory to raw data folder
edat_L2 <- merge_webcam_files(vwp_paths_filtered_L2, screen_index=4) # eye
  tracking occurred on screen index 4
```

**372    *Subject and trial level data removal***

**373**       To ensure high-quality data, it is essential to filter out unreliable data based on both behavioral and  
**374** eye-tracking criteria before merging datasets. In our dataset, participants will be excluded if they meet any  
**375** of the following conditions: failure to successfully calibrate throughout the experiment (less than 100 trials),  
**376** low accuracy ( $< 80\%$ ), low sampling rates ( $< 5$ ), and a high proportion of gaze data outside the screen  
**377** coordinates ( $> 30\%$ ). Successful calibration is crucial for capturing accurate eye-tracking measurements,  
**378** so participants who could not maintain proper calibration may have inaccurate gaze data. Similarly, low  
**379** accuracy may indicate poor engagement or task difficulty, which can reduce the reliability of the behavioral  
**380** data and suggest that eye-tracking data may be less precise. In addition to this, we remove incorrect trials  
**381** from remaining participants so we only look at correct trials.

**382**       First, we will create a cleaned up version of our behavioral, trial-level data L2\_data by creating an  
**383** object named eye\_behav\_L2 that selects useful columns from that file and renames stimuli to make them  
**384** more intuitive. Because most of this will be user-specific, no function is called here. Below we describe  
**385** the preprocessing done on the behavioral data file. The below code processes and transforms the L2\_data  
**386** dataset into a cleaned and structured format for further analysis. First, the code renames several columns for  
**387** easier access using janitor::clean\_names() (Firke, 2023) function. We then select only the columns we  
**388** need and filter the dataset to include only rows where zone\_type is “response\_button\_image”, representing  
**389** the picture selected for that trial. Afterward, the function renames additional columns (tlpic to TL, trpic  
**390** to TR, etc.). We also renamed participant\_private\_id to subject, spreadsheet\_row to trial, and  
**391** reaction\_time to RT. This makes our columns consistent with the edat\_L2 above for merging later on.  
**392** Lastly, reaction\_time (RT) is converted to a numeric format for further numerical analysis.

**393**       It is important to note here that what the behavioral spreadsheet denotes as trial is not in fact the trial  
**394** number used in the eye-tracking files. Thus it is imperative you use spreadsheet\_row as trial number to  
**395** merge the two files successfully.

```
eye_behav_L2 <- L2_data %>%
  janitor::clean_names() %>%
  # Select specific columns to keep in the dataset
  dplyr::select(participant_private_id, correct, tlpic, trpic, blpic, brpic,
  ~ condition,
    eng_targetword, targetword, typetl, typetr, typebl, typebr,
  ~ zone_name,
    zone_type, reaction_time, spreadsheet_row, response) %>%
  # Filter the rows where 'Zone.Type' equals "response_button_image"
  dplyr::filter(zone_type == "response_button_image") %>%
```

```

# Rename columns for easier use and readability
dplyr::rename(
  TL = tlpic,          # Rename 'tlpic' to 'TL'
  TR = trpic,          # Rename 'trpic' to 'TR'
  BL = blpic,          # Rename 'blpic' to 'BL'
  BR = brpic,          # Rename 'brpic' to 'BR'
  targ_loc = zone_name, # Rename 'zone_name' to 'targ_loc'
  subject = participant_private_id, # Rename 'participant_private_id' to
  ~ 'subject'
  trial = spreadsheet_row, # Rename 'spreadsheet_row' to 'trial'
  acc = correct,         # Rename 'correct' to 'acc' (accuracy)
  RT = reaction_time    # Rename 'reaction_time' to 'RT'
) %>%
  # Convert the 'RT' (Reaction Time) column to numeric type
dplyr::mutate(RT = as.numeric(RT),
  subject = as.factor(subject),
  trial = as.factor(trial))

```

396       **Audio onset.** Because we are playing audio on each trial and running this experiment from the  
 397 browser, audio onset is never going to be consistent across participants. In Gorilla there is an option to  
 398 collect advanced audio features (you must make sure you select this when designing the study) such as when  
 399 the audio play was requested, played, and ended. To do so you must click on advanced settings and select  
 400 1 (see Figure 3). We will want to incorporate this timing information into our analysis pipeline. Gorilla  
 401 records the onset of the audio which varies by participant. We are extracting that in the `audio_rt_L2` object  
 402 by filtering `zone_type` to `content_web_audio` and a response equal to “AUDIO PLAY EVENT FIRED”.  
 403 This will tell us when the audio was triggered in the experiment. We are creating a column called `(RT_audio)`  
 404 which we will use later on to correct for audio delays. Please note that on some trials the audio may not play.  
 405 This is a function of the browser a participant is using and the experimenter has no control over this (see <https://support.gorilla.sc/support/troubleshooting-and-technical/technical-checklist#autoplayingsoundandvideo>).

```

audio_rt_L2 <- L2_data %>%
  janitor::clean_names() %>%
  select(participant_private_id, zone_type, spreadsheet_row, reaction_time,
  ~ response) %>%

```

**Figure 3***Advanced audio settings in Gorilla*

Web Audio ?

If  0 allow participant to start media manually. Choose 1 (start manually) or 0. Default: 1

Media can be played up to  times. Default: 1

If  (setting) advance when media is finished. Choose 1 (advance when finished) or 0. Default: 0

**Advanced Settings** + Show

If  1 , provide additional metrics on audio events Choose 1 for on or 0/unset for off. Default: 0/unset.

Audio format:  mp3 . When playing audio files specified by embedded data, manually specify the format (usually wav or mp3) here. Default: mp3

Show Stop Button:  (setting) . When playing audio, show a stop button allowing the audio file to be stopped. Choose 1 for on (show stop button), or 0/unset for off. Default: 0/unset

Show full audio controls:  (setting) . Show a full set of controls for the audio file, allowing participants to play, pause, rewind etc. Choose 1 for on (show full controls), or 0/unset for off. Default: 0/unset

**Localisation Settings** ? Docs + Show

```

filter(zone_type=="content_web_audio", response=="AUDIO PLAY EVENT FIRED")%>%
  distinct() %>%
dplyr::rename("subject" = "participant_private_id",
  "trial" ="spreadsheet_row",
  "RT_audio" = "reaction_time",
  "Fired" = "response") %>%
select(-zone_type) %>%
mutate(RT_audio=as.numeric(RT_audio))

```

407 We then merge this information with eye\_behav\_L2.

```

# merge the audio Rt data to the trial level object
trial_data_rt_L2 <- merge(eye_behav_L2, audio_rt_L2, by=c("subject", "trial"))

```

408 **Trial removal.** As stated above, participants who did not successfully calibrate 3 times or less were  
 409 rejected from the experiment. Deciding to remove trials is ultimately up to the researcher. In our case, we  
 410 removed participants with less than 100 trials. Let's take a look at how many participants meet this criterion  
 411 by probing the trial\_data\_rt\_L2 object. In Table 2 we can see several participants failed some of the cal-  
 412 ibration attempts and do not have an adequate number of trials. Again we make no strong recommendations  
 413 here. If you decide to use a criterion such as this, we recommend pre-registering your choice.

```

# find out how many trials each participant had
edatntrials_L2 <- trial_data_rt_L2 %>%
  dplyr::group_by(subject)%>%
  dplyr::summarise(ntrials=length(unique(trial)))

```

414 Let's remove them participants with less than 100 trials from the analysis using the below code.

```

trial_data_rt_L2 <- trial_data_rt_L2 %>%
  filter(subject %in% edatntrials_bad_L2$subject)

```

415 **Low accuracy.** In our experiment, we want to make sure accuracy is high (> 80%). Again, we want  
 416 participants that are fully attentive in the experiment. In the below code, we keep participants with accuracy  
 417 equal to or above 80% and only include correct trials and assign it to trial\_data\_acc\_clean\_L2.

```

# Step 1: Calculate mean accuracy per subject and filter out subjects with mean
  ↳ accuracy < 0.8
subject_mean_acc_L2 <- trial_data_rt_L2 %>%

```

**Table 2**

*Participants with less than 100 trials*

| subject  | ntrials |
|----------|---------|
| 12102265 | 2       |
| 12110638 | 55      |
| 12110829 | 59      |
| 12110878 | 59      |
| 12110897 | 60      |
| 12111234 | 57      |
| 12111244 | 58      |
| 12111363 | 58      |
| 12111663 | 57      |
| 12111703 | 58      |
| 12111869 | 60      |
| 12111960 | 46      |
| 12112152 | 59      |
| 12212113 | 56      |
| 12213826 | 99      |
| 12213965 | 59      |

```

group_by(subject) %>%
  dplyr::summarise(mean_acc = mean(acc, na.rm = TRUE)) %>%
  filter(mean_acc > 0.8)

# Step 2: Join the mean accuracy back to the main dataset and exclude trials with
# accuracy < 0.8
trial_data_acc_clean_L2 <- trial_data_rt_L2 %>%
  inner_join(subject_mean_acc_L2, by = "subject") %>%
  filter(acc==1) # only use accurate responses for fixation analysis

```

418       **RTs.** There is much debate on how to handle reaction time (RT) data (see Miller, 2023). Because  
 419 of this, we leave it up to the reader and researcher to decide what to do with RTs. In this tutorial we leave  
 420 RTs untouched.

421       **Sampling rate.** While most commercial eye-trackers sample at a constant rate, data captured by  
 422       webcams are widely inconsistent. Below is some code to calculate the sampling rate of each participant.  
 423       Ideally, you should not have a sampling rate less than 5 Hz. It has been recommended you drop those values  
 424       (Bramlett & Wiener, 2024) The below function `analyze_sample_rate()` calculates the sampling rate for  
 425       each subject and each trial in our eye-tracking dataset (`edat_L2`). The `analyze_sample_rate()` function  
 426       provides overall statistics, including the option to report mean or median (Bramlett & Wiener, 2024) sampling  
 427       rate and standard deviation of sampling rates in your experiment. The function also generates a histogram  
 428       of sampling rates by subject. Looking at Figure 4, the sampling rate ranges from 5 to 35 Hz with a median  
 429       sampling rate of 21.56. This corresponds to previous webcam eye-tracking work [e.g., Bramlett and Wiener  
 430       (2024); Prystauka et al. (2024)]

```
samp_rate_L2 <- analyze_sampling_rate(edat_L2, summary_stat="median")
```

```
431 Overall median Sampling Rate (Hz): 21.56171771
432 Overall Standard Deviation of Sampling Rate (Hz): 7.399937723
433
434 Sampling Rate by Trial:
435 # A tibble: 10,665 x 5
436   subject trial max_time n_times     SR
437   <fct>    <fct>    <dbl>    <int>  <dbl>
438   1 12102265 8        4895     108  22.1
439   2 12102265 11       4920.    112  22.8
440   3 12102265 15       4911.    79   16.1
441   4 12102265 17       4916.    113  23.0
442   5 12102265 20       4903.    112  22.8
443   6 12102265 21       1826.    40   21.9
444   7 12102265 28       4917.    114  23.2
445   8 12102265 31       4913.    79   16.1
446   9 12102265 34       4948.    88   17.8
447  10 12102265 35      4901.    93   19.0
448 # i 10,655 more rows
449
450 median Sampling Rate by Subject:
451 # A tibble: 60 x 2
452   subject summary_SR
453   <fct>      <dbl>
454   1 12102265  21.9
455   2 12102286  30.6
456   3 12102530  19.9
457   4 12110559  29.3
```

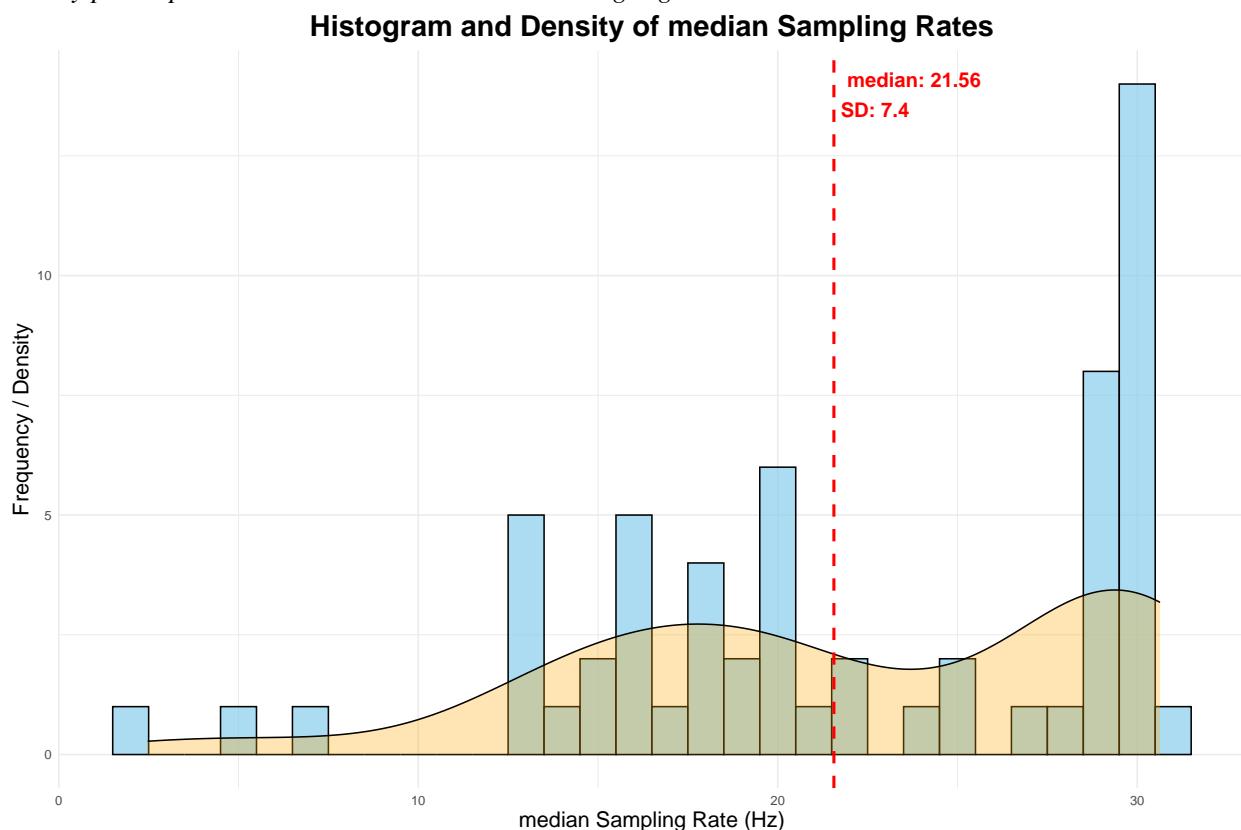
```

458 5 12110579      13.3
459 6 12110585      30.1
460 7 12110586      14.8
461 8 12110600      2.47
462 9 12110638      29.0
463 10 12110685     19.5
464 # i 50 more rows

```

**Figure 4**

*Participant sampling-rate for L2 experiment. A histogram and overlayed density plot shows median sampling rate by participant. The overall median and SD is highlighted in red.*



```

465 When using the above function, separate data frames are produced by-participant and by-trial. These
466 can be added to the behavioral data frame using the below code.

```

```

# Extract by-subject and by-trial sampling rates from the result
subject_sampling_rate <- samp_rate_L2$summary_SR_by_subject # Sampling rate by
#> subject
trial_sampling_rate <- samp_rate_L2$SR_by_trial # Sampling rate by trial

```



**Table 3**

*Out of bounds gaze statistics*

| subject  | totalpoints | outsidecount | totalmissing% | xoutsidecount | youtsidecount | xoutside% | youtside% |
|----------|-------------|--------------|---------------|---------------|---------------|-----------|-----------|
| 12102265 | 6,197.00    | 1,132.00     | 18.27         | 202.00        | 947.00        | 3.26      | 15.28     |
| 12102286 | 11,765.00   | 354.00       | 3.01          | 267.00        | 181.00        | 2.27      | 1.54      |
| 12102530 | 9,025.00    | 385.00       | 4.27          | 244.00        | 147.00        | 2.70      | 1.63      |
| 12110559 | 11,890.00   | 416.00       | 3.50          | 194.00        | 222.00        | 1.63      | 1.87      |
| 12110579 | 5,822.00    | 1,063.00     | 18.26         | 697.00        | 436.00        | 11.97     | 7.49      |
| 12110585 | 13,974.00   | 776.00       | 5.55          | 83.00         | 694.00        | 0.59      | 4.97      |

476       **Out-of-bounds (outside of screen).** It is important that we do not include points that fall outside  
 477 the standardized coordinates (0,1). The `gaze_oob()` function calculates how many of the data points fall  
 478 outside the standardized range. Here we need our eye-tracking data (`edat_L2`). Running the `gaze_oob()`  
 479 function returns a table listing how many data points fall outside this range (total, X and Y), and also provides  
 480 percentages (see Table 3). This information would be useful to include in the final

```
oob_data_L2 <- gaze_oob(edat_L2)
```

481       We can also add add by-participant and by-trial out of bounds data to our behavioral, trial-level, data  
 482 (`filter_edat_L2`) and finally exclude participants and trials with more than 30% missing data. The value  
 483 of 30 is just a suggestion and should not be used as a rule of thumb for all studies nor are we endorsing this  
 484 value.

```
remove_missing <- oob_data_L2 %>%
  # Start with the `oob_data`  

  # dataset and assign the result to `remove_missing`  

  select(subject, total_missing_percentage) %>%
  # Select only the `subject`  

  # and `total_missing_percentage` columns from `oob_data`  

  left_join(filter_edat_L2, by = "subject") %>%
  # Perform a left join with  

  # `filter_edat` on the `subject` column, keeping all rows from `oob_data`  

  filter(total_missing_percentage < 30) %>%
  # Filter the data to keep  

  # only rows where `total_missing_percentage` is less than 30 %>%
  na.omit()
```

485 *Eye-tracking data*

486       **Convergence and confidence.** In the eye-tracking data we need to remove rows with poor convergence  
 487       and confidence scores in our eye-tracking data. The convergence column refers to WebGazer.js  
 488       confidence in finding a face (and accurately predicting eye movements). Confidence values vary from 0 to 1,  
 489       and numbers less than 0.5 suggest that the model has probably converged. face\_conf represents the support  
 490       vector machine (SVM) classifier score for the face model fit. This score indicates how strongly the image  
 491       under the model resembles a face. Values vary from 0 to 1, and here numbers greater than 0.5 are indicative  
 492       of a good model fit. In our edat\_L2 object we filter out convergence less than 0.5 and face confidence greater  
 493       than 0.5 and save it to edat\_1\_L2

```
edat_1_L2 <- edat_L2 %>%
  dplyr::filter(convergence <= .5, face_conf >= .5) # remove poor convergnce and
  ↪ face confidence
```

494       **Combining eye and trial-level data.** Next, we will combine the eye-tracking data and behavioral  
 495       data. In this case, we'll use right\_join to add the behavioral data to the eye-tracking data. This en-  
 496       sures that all rows from the eye-tracking data are preserved, even if there isn't a matching entry in the be-  
 497       havioral data (missing values will be filled with NA). The resulting object is called dat\_L2. We use the  
 498       distinct() function afterward to remove any duplicate rows that may arise during the join

```
dat_L2 <- right_join(edat_1_L2,remove_missing, by = c("subject","trial"))

dat_L2 <- dat_L2 %>%
  distinct() # make sure to remove duplicate rows
```

499 **Areas of Interest**500 *Zone coordinates*

501       In the lab, we can control many aspects of the experiment that cannot be controlled online. Participants  
 502       will be completing the experiment under a variety of conditions including, different computers, with  
 503       very different screen dimensions. To control for this, Gorilla outputs standardized zone coordinates (labeled  
 504       as x\_pred\_normalised and y\_pred\_normalised in the eye-tracking file) . As discussed in the Gorilla  
 505       documentation, the Gorilla lays everything out in a 4:3 frame and makes that frame as big as possible. The  
 506       normalized coordinates are then expressed relative to this frame; for example, the coordinate 0.5, 0.5 will  
 507       always be the center of the screen, regardless of the size of the participant's screen. We used the normalized  
 508       coordinates in our analysis (in general, you should always use normalized coordinates). However, there are  
 509       a few different ways to specify the four coordinates of the screen, which are worth highlighting here.

**Table 4**

*Quadrant coordinates in standardized space*

| loc | x_normalized | y_normalized | width_normalized | height_normalized | xmin | ymin | xmax | ymax |
|-----|--------------|--------------|------------------|-------------------|------|------|------|------|
| TL  | 0.00         | 0.50         | 0.50             | 0.50              | 0.00 | 0.50 | 0.50 | 1.00 |
| TR  | 0.50         | 0.50         | 0.50             | 0.50              | 0.50 | 0.50 | 1.00 | 1.00 |
| BL  | 0.00         | 0.00         | 0.50             | 0.50              | 0.00 | 0.00 | 0.50 | 0.50 |
| BR  | 0.50         | 0.00         | 0.50             | 0.50              | 0.50 | 0.00 | 1.00 | 0.50 |

510       **Quadrant approach.** One way is to make the AOIs as big as possible, dividing the screen into four

511 quadrants. This approach has been used in several studies [e.g., (Bramlett & Wiener, 2024; Prystauka et al.,

512 2024). Table 4 lists coordinates for the quadrant approach and Figure 5 shows how each quadrant looks in

513 standardized space.

514       We plot all the fixations in each of the quadrants highlighted in different colors (Figure 5), removing

515 points outside the standardized screen space.

516       We plot all the fixations in each of the quadrants highlighted in different colors (Figure 5), removing

517 points outside the standardized screen space. As a note, we have decided to use an outer edge approach

518 here (eliminating eye fixations that extend beyond the screen coordinates). Bramlett and Wiener (2024) have

519 suggested an inner-edge approach and we may add this functionality once more testing is done. For now, we

520 believe that the outer edge approach leads to the least amount of bias in the eye-tracking pipeline.

521       **Matching conditions with screen locations.** The goal of the below code is to assign condition codes

522 (e.g., Target, Unrelated, Unrelated2, and Cohort) to each image in the dataset based on the screen location

523 where the image is displayed (e.g., TL, TR, BL, BR).

524       For each trial, the images are dynamically placed at different screen locations, and the code maps

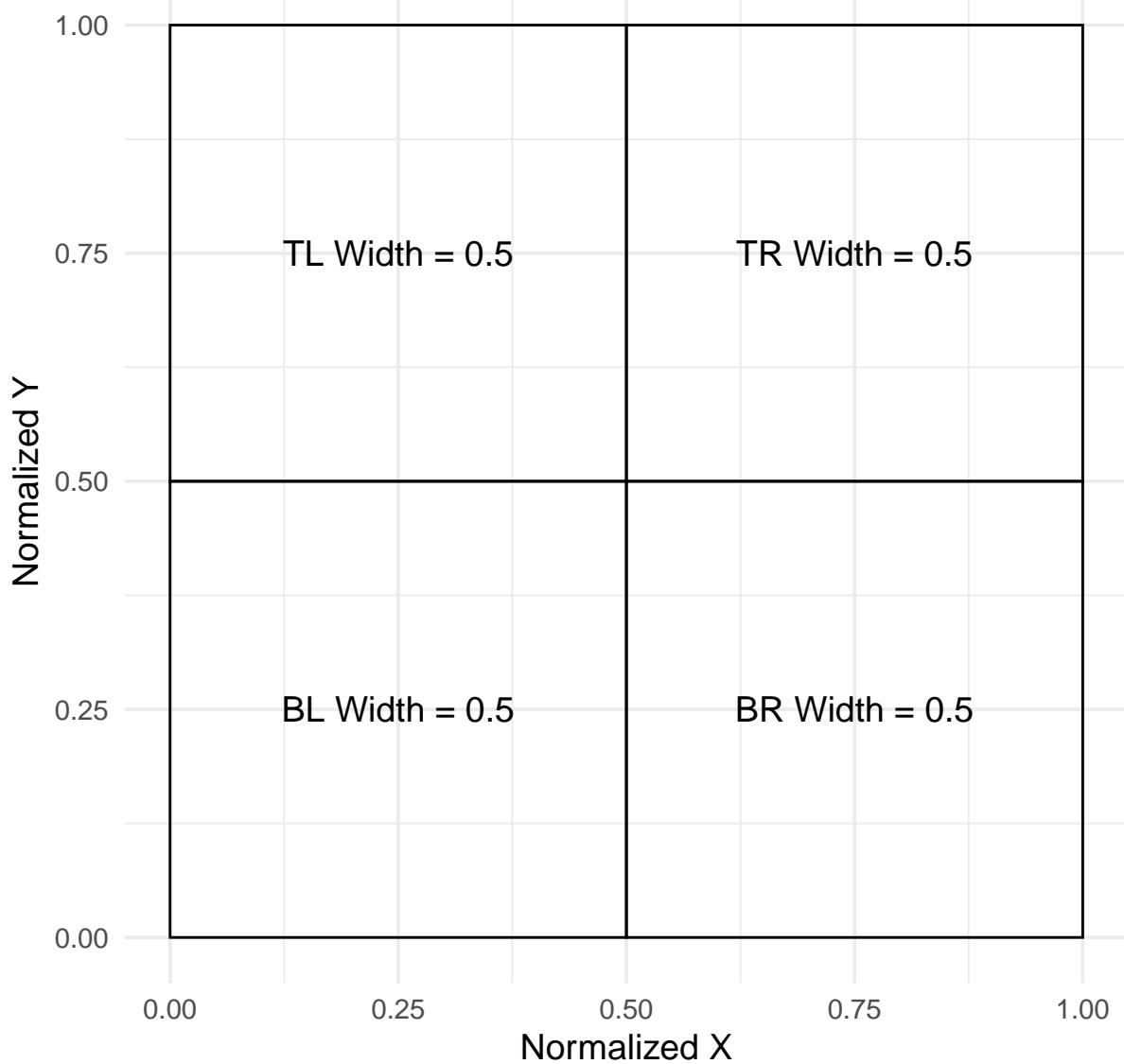
525 each image to its corresponding condition based on these locations.

```
# Assuming your data is in a data frame called dat_L2
dat_L2 <- dat_L2 %>%
  mutate(
    Target = case_when(
      typetl == "target" ~ TL,
      typetr == "target" ~ TR,
      typebl == "target" ~ BL,
      typebr == "target" ~ BR,
      TRUE ~ NA_character_ # Default to NA if no match
    ),
  )
```

**Figure 5**

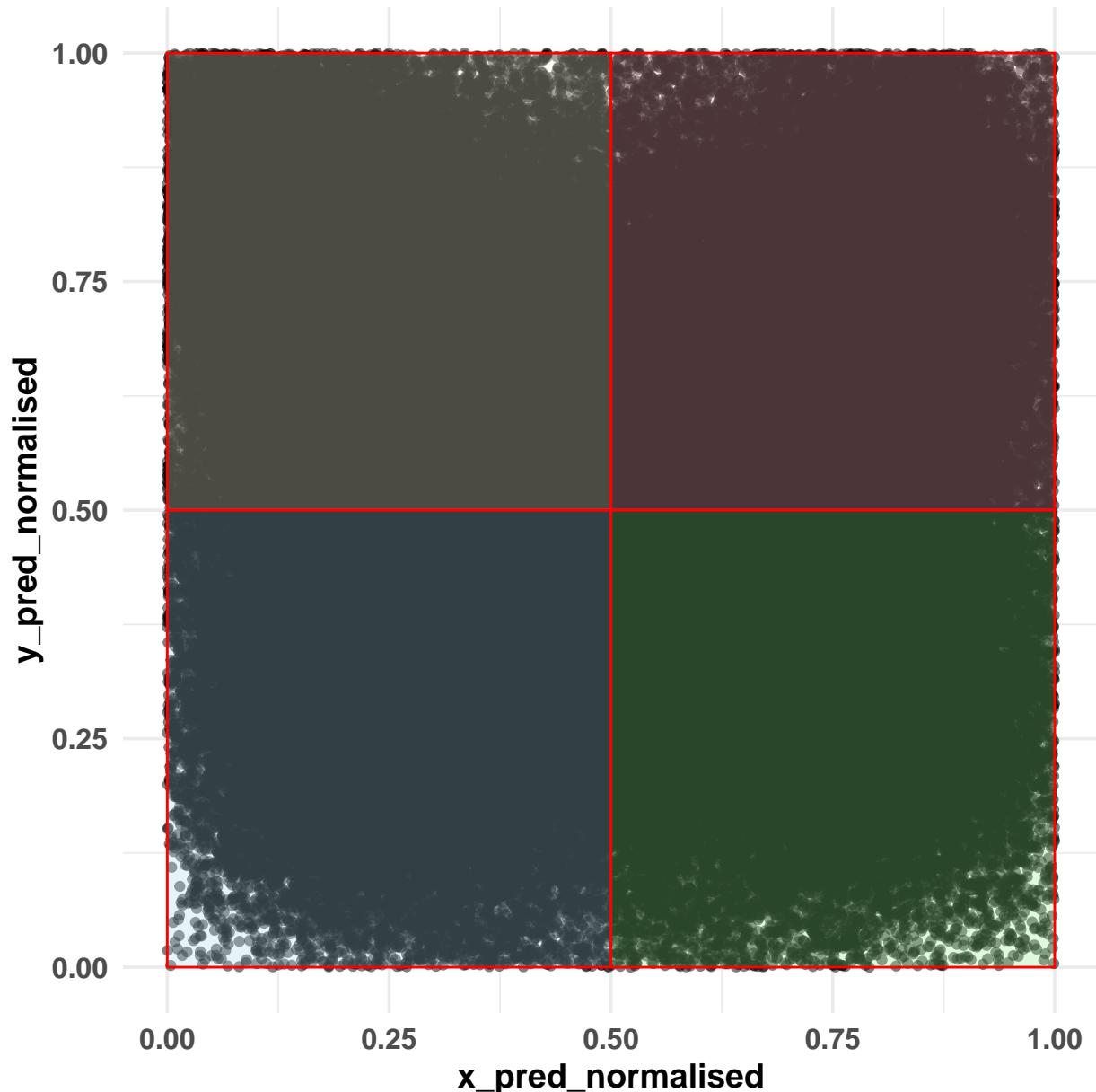
*AOI coordinates in standardized space using the quadrant approach*

### Quadrants with Width Annotations



**Figure 6**

*Looks to each quadrant of the screen*



```

Unrelated = case_when(
  typetl == "unrelated1" ~ TL,
  typetr == "unrelated1" ~ TR,
  typebl == "unrelated1" ~ BL,
  typebr == "unrelated1" ~ BR,
  TRUE ~ NA_character_
),
Unrelated2 = case_when(
  typetl == "unrelated2" ~ TL,
  typetr == "unrelated2" ~ TR,
  typebl == "unrelated2" ~ BL,
  typebr == "unrelated2" ~ BR,
  TRUE ~ NA_character_
),
Cohort = case_when(
  typetl == "cohort" ~ TL,
  typetr == "cohort" ~ TR,
  typebl == "cohort" ~ BL,
  typebr == "cohort" ~ BR,
  TRUE ~ NA_character_
)
)
)

```

526        In addition to tracking the condition of each image during randomized trials, a custom function,  
 527 `find_location()`, determines the specific screen location of each image by comparing it against the list  
 528 of possible locations. This function ensures that the appropriate location is identified or returns NA if no  
 529 match exists. Specifically, `find_location()` first checks if the image is NA (missing). If the image is NA,  
 530 the function returns NA, meaning that there's no location to find for this image. If the image is not NA, the  
 531 function creates a vector called `loc_names` that lists the names of the possible locations. It then attempts to  
 532 match the given image with the locations. If a match is found, it returns the name of the location (e.g., TL,  
 533 TR, BL, or BR) of the image.

```

# Apply the function to each of the targ, cohort, rhyme, and unrelated columns
dat_colnames_L2 <- dat_L2 %>%
  rowwise() %>%
  mutate(
    targ_loc = find_location(c(TL, TR, BL, BR), Target),
    cohort_loc = find_location(c(TL, TR, BL, BR), Cohort),
    unrelated_loc = find_location(c(TL, TR, BL, BR), Unrelated),
  )
)

```

```

unrealted2_loc= find_location(c(TL, TR, BL, BR), Unrelated2),
) %>%
ungroup()

```

534       Once we do this we can use the `assign_aoi()` function to loop through our object called  
 535 `dat_colnames_L2` and assign locations (i.e., TR, TL, BL, BR) to where participants looked at on the screen.  
 536 This requires the x and y coordinates and the location of our aois `aoi_loc`. Here we are using the quadrant  
 537 approach. This function will label non-looks and off screen coordinates with NA. To make it easier to read  
 538 we change the numerals assigned by the function to actual screen locations (e.g., TL, TR, BL, BR).

```

assign_L2 <- webgazeR::assign_aoi(dat_colnames_L2,X="x_pred_normalised",
← Y="y_pred_normalised",aoi_loc = aoi_loc)

AOI_L2 <- assign_L2 %>%

mutate(loc1 = case_when(
  AOI==1 ~ "TL",
  AOI==2 ~ "TR",
  AOI==3 ~ "BL",
  AOI==4 ~ "BR"
))

```

539       In `AOI_L2` we label looks to Targets, Unrelated, and Cohort items with 1 (looked) and 0 (no look)  
 540 using the `case_when` function from the `tidyverse` (Wickham, 2017)

```

AOI_L2 <- AOI_L2 %>%
  mutate(
    target = case_when(loc1 == targ_loc ~ 1, TRUE ~ 0),
    unrelated = case_when(loc1 == unrelated_loc ~ 1, TRUE ~ 0),
    unrealted2 = case_when(loc1 == unrealted2_loc ~ 1, TRUE ~ 0),
    cohort = case_when(loc1 == cohort_loc ~ 1, TRUE ~ 0)
  )

```

541       The locations of looks need to be pivoted into long format—that is, converted from separate columns  
 542      into a single column. This transformation makes the data easier to visualize and analyze. We use the  
 543      pivot\_longer() function from the tidyverse to combine the columns (Target, Unrelated, Unrelated2,  
 544      and Cohort) into a single column called condition1. Additionally, we create another column called Looks,  
 545      which contains the values from the original columns (e.g., 0 or 1 for whether the area was looked at).

```
dat_long_aoi_me_L2 <- AOI_L2 %>%
  select(subject, trial, condition, target, cohort, unrelated, unrelated2, time,
  ~ x_pred_normalised, y_pred_normalised, RT_audio) %>%
  pivot_longer(
    cols = c(target, unrelated, unrelated2, cohort),
    names_to = "condition1",
    values_to = "Looks"
  )
```

546       We further clean up the object by first cleaning up the condition codes. They have a numeral ap-  
 547      pended to them and that should be removed. We then adjust the timing in the gaze\_sub\_L2\_comp object by  
 548      aligning time to the actual audio onset. To achieve this, we subtract RT\_audio from time for each trial. In  
 549      addition, we subtract 300 ms from this to account for the 100 ms of silence at the beginning of each audio  
 550      clip and 200 ms to account for the oculomotor delay when planning an eye movement (Viviani, 1990). Ad-  
 551      ditionally, we set our interest period between 0 ms (audio onset) and 2000 ms. This was chosen based on the  
 552      time course figures in Sarrett et al. (2022) . It is important that you choose your interest area carefully and  
 553      preferably you preregister it. The interest period you choose can bias your findings (Peelle & Van Engen,  
 554      2021). We also filter out gaze coordinates that fall outside the standardized window, ensuring only valid data  
 555      points are retained. The resulting object gaze\_sub\_long\_L2 provides the corrected time column spanning  
 556      from -200 ms to 2000 ms relative to stimulus onset with looks outside the screen removed.

```
# repalce the numbers appended to conditions that somehow got added
dat_long_aoi_me_comp <- dat_long_aoi_me_L2 %>%
  mutate(condition = str_replace(condition, "TCUU-SPENG\\d*", "TCUU-SPENG")) %>%
  mutate(condition = str_replace(condition, "TCUU-SPSP\\d*", "TCUU-SPSP"))%>%
  na.omit()
```

```
# dat_long_aoi_me_comp has condition corrected

gaze_sub_L2_long <-dat_long_aoi_me_comp%>%
  group_by(subject, trial, condition) %>%
  mutate(time = (time-RT_audio)-300) %>% # subtract audio rt onset and account
  ~ for occ motor planning and silence in audio
```

```
filter(time >= -200, time < 2000) %>%
  dplyr::filter(x_pred_normalised > 0,
                x_pred_normalised < 1,
                y_pred_normalised > 0,
                y_pred_normalised < 1)
```

557 **Samples to bins**

558 ***Downsampling***

559       Downsampling into smaller time bins is a common practice in gaze data analysis, as it helps create a  
 560 more manageable dataset and reduces noise. When using research grade eye-trackers, downsampling is often  
 561 not needed. However, with consumer-based webcam eye-tracking it is recommended you downsample your  
 562 data so participants have consistent bin sizes (e.g., (Slim & Hartsuiker, 2023)). In webgazeR we included the  
 563 `downsample_gaze()` function to assist with this process. We apply this function to the `gaze_sub_L2_long`  
 564 object, and set the `bin.length` argument to 100, which groups the data into 100-millisecond intervals. This  
 565 adjustment means that each bin now represents a 100 ms passage of time. We specify `time` as the variable  
 566 to base these bins on, allowing us to focus on broader patterns over time rather than individual millisecond  
 567 fluctuations. There is no agreed upon downsampling value, but with webcam data larger bins are preferred  
 568 (Slim & Hartsuiker, 2023).

569       In addition, the `downsample_gaze()` allows you to aggregate across other variables, such as  
 570 `condition`, `condition1`, and use the newly created `time_bins` variable, which represents the time  
 571 intervals over which we aggregate data. The resulting downsampled dataset, output as Table 5, provides a  
 572 simplified and more concise view of gaze patterns, making it easier to analyze and interpret broader trends.

```
gaze_sub_L2 <- webgazeR::downsample_gaze(gaze_sub_L2_long, bin.length=100,
                                         ← timevar="time", aggvars=c("condition", "condition1", "time_bin"))
```

573       To simplify the analysis, we combine the two unrelated conditions and average them (this is for the  
 574 proportional plots).

```
# Average Fix for unrelated and unrelated2, then combine with the rest
gaze_sub_L2_avg <- gaze_sub_L2 %>%
  group_by(condition, time_bin) %>%
  summarise(
    Fix = mean(Fix[condition1 %in% c("unrelated", "unrelated2")], na.rm =
      ← TRUE),
    condition1 = "unrelated", # Assign the combined label
```

**Table 5**

*Aggregated proportion looks for each condition in each 100 ms time bin*

| condition  | condition1 | time_bin | Fix  |
|------------|------------|----------|------|
| TCUU-ENGSP | cohort     | -200.00  | 0.26 |
| TCUU-ENGSP | cohort     | -100.00  | 0.26 |
| TCUU-ENGSP | cohort     | 0.00     | 0.25 |
| TCUU-ENGSP | cohort     | 100.00   | 0.26 |
| TCUU-ENGSP | cohort     | 200.00   | 0.23 |
| TCUU-ENGSP | cohort     | 300.00   | 0.22 |

```

    .groups = "drop"
) %>%
# Combine with rows that do not include unrelated or unrelated2
bind_rows(gaze_sub_L2 %>% filter(!condition1 %in% c("unrelated",
  "unrelated2")))

```

575       The above will not include the subject variable. If you want to keep participant-level data we need  
 576 to add `subject` to the `aggvars` argument.

```

# add subject-level data
gaze_sub_L2_id <- webgazeR::downsample_gaze(gaze_sub_L2_long, bin.length=100,
  timevar="time", aggvars=c("subject", "condition", "condition1", "time_bin"))

```

## 577 Aggregation

578       Aggregation is an optional step. If you do not plan to analyze proportion data, and instead what time  
 579 binned data with binary outcomes preserved please set the `aggvars` argument to “none.” This will return a  
 580 time binned column, but will not aggregate over other variables.

```

# get back trial level data with no aggregation
gaze_sub_id <- downsample_gaze(gaze_sub_L2_long, bin.length=100, timevar="time",
  aggvars="none")

```

581       We need to make sure we only have one unrelated value.

```
# make only one unrelated condition
gaze_sub_id <- gaze_sub_id %>%
  mutate(condition1 = ifelse(condition1=="unrelated2", "unrelated", condition1))
```

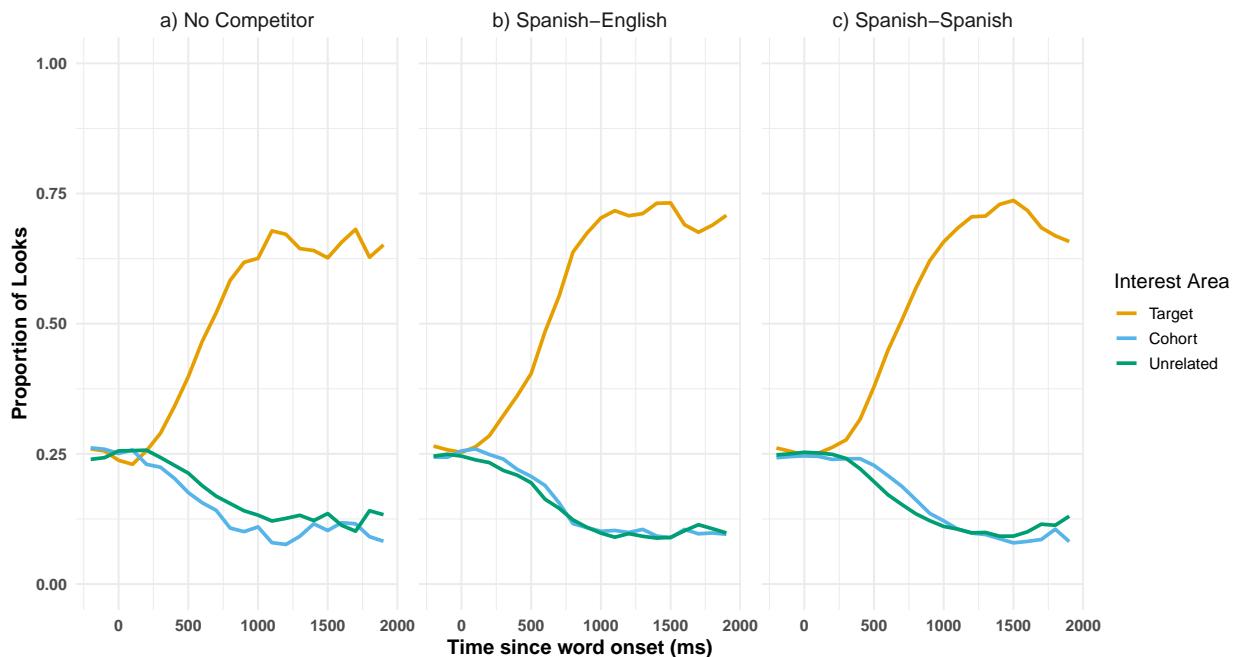
582 **Visualizing time course data**

583 To simplify plotting your time-course data, we have created the `plot_IA_proportions()` function.  
 584 This function takes several arguments. The `ia_column` argument specifies the column containing  
 585 your AOI labels. The `time_column` argument requires the name of your time bin column, and the  
 586 `proportion_column` argument specifies the column containing fixation or look proportions. Additional  
 587 arguments allow you to specify custom names for each IA in the `ia_mapping` argument, enabling you to  
 588 label them as desired. In order to use this function, you must use the `downsample_gaze()` function.

589 Below, we have plotted the time-course data for each condition in Figure 7. By default, the graphs  
 590 utilize a color-blind-friendly palette from the `ggokabeito` package (Barrett, 2021). However, you can set  
 591 the argument `use_color = FALSE` to generate a non-colored version of the figure, where different line types  
 592 and shapes differentiate conditions. Additionally, since these are `ggplot` objects, you can further customize  
 593 them as needed to suit your analysis or presentation preferences.

**Figure 7**

*Comparison of L2 competition effect in the No Competitor (a), Spanish–English (b), the Spanish–Spanish (c) conditions*



**Table 6**

*Gorilla provided standarized gaze coordinates*

| loc | x_normalized | y_normalized | width_normalized | height_normalized | xmin | ymin | xmax | ymax |
|-----|--------------|--------------|------------------|-------------------|------|------|------|------|
| BL  | 0.03         | 0.04         | 0.26             | 0.25              | 0.03 | 0.04 | 0.29 | 0.29 |
| TL  | 0.02         | 0.74         | 0.26             | 0.25              | 0.02 | 0.74 | 0.28 | 0.99 |
| TR  | 0.73         | 0.75         | 0.24             | 0.24              | 0.73 | 0.75 | 0.97 | 0.99 |
| BR  | 0.73         | 0.06         | 0.23             | 0.25              | 0.73 | 0.06 | 0.96 | 0.31 |

#### 594 Gorilla provided coordinates

595 Thus far, we have used the coordinates representing the four quadrants of the screen. However,  
 596 Gorilla provides their own quadrants representing image location on the screen. To the authors' knowledge,  
 597 these quadrants have not been looked at in any studies reporting eye-tracking results. Let's examine how  
 598 reasonable our results are with the Gorilla provided coordinates.

599 We will use the function `extract_aois()` to get the standardized coordinates for each quadrant on  
 600 screen. You can use the `zone_names` argument to get the zones you want to use. In our example, we want the  
 601 TL, BR, BL TR coordinates. We input the object from above `vwp_paths_filtered_L2` that contains all our  
 602 eye-tracking files and extract the coordinates we want. These are labeled in Table 6. In Figure 8 we can see  
 603 that the AOIs are a bit smaller than then when using the quadrant approach. We can take these coordinates  
 604 and use them in our analysis.

605 We are not going to highlight the steps here as they are the same as above. we are just replacing the  
 606 coordinates.

```
# apply the extract_aois fucntion
aois_L2 <- extract_aois(vwp_paths_filtered_L2, zone_names = c("TL", "BR", "TR",
  ↵ "BL"))
```

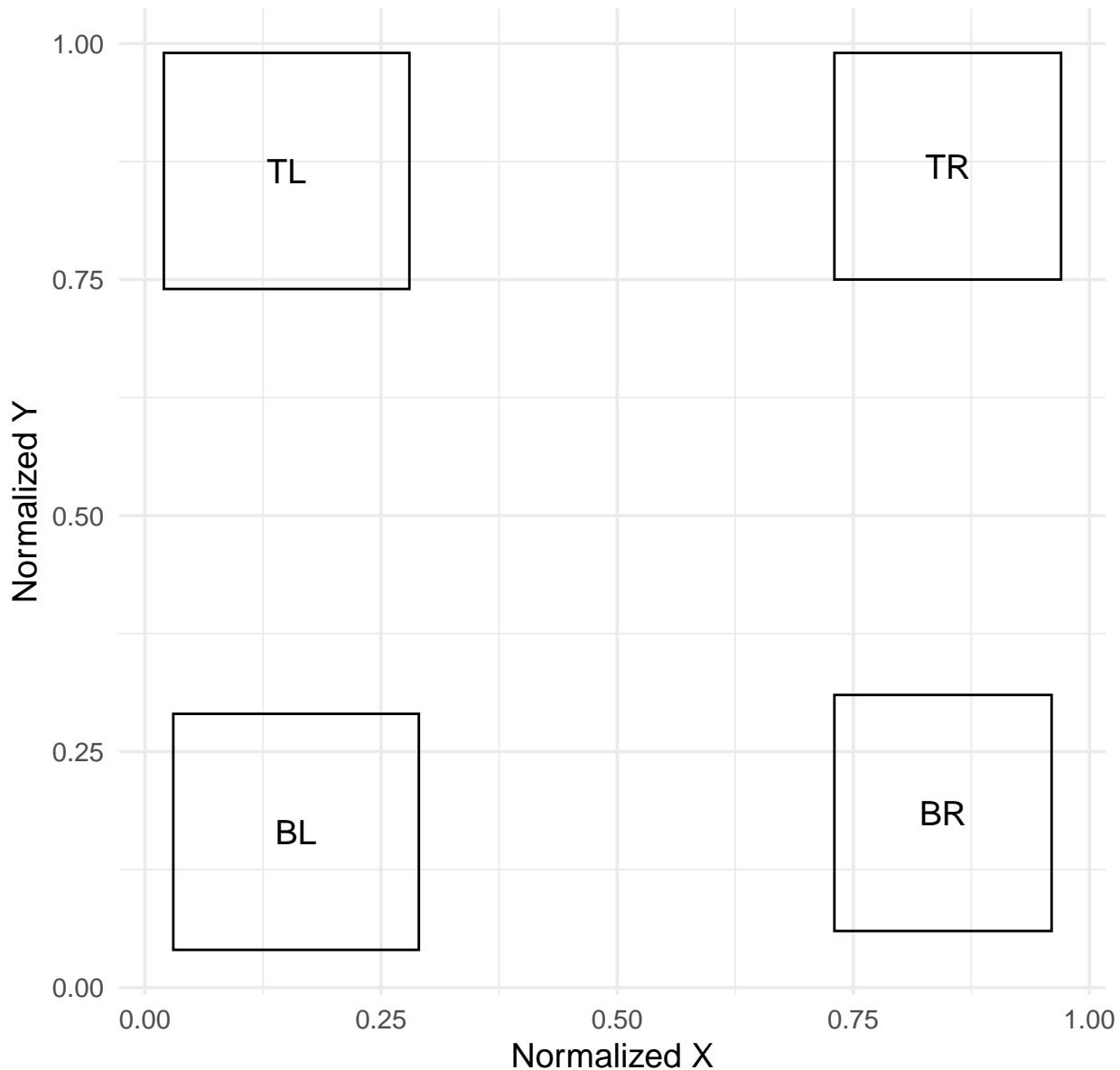
```
assign_L2_gor <- webgazeR::assign_aoi(dat_colnames_L2, X="x_pred_normalised",
  ↵ Y="y_pred_normalised", aoi_loc = aois_L2)
```

#### 607 Visualizing time course data with Gorilla coordinates

608 The Gorilla provided coordinates show a similar pattern to the quadrant approach. However, the  
 609 time course looks a bit nosier given the smaller AOIs.

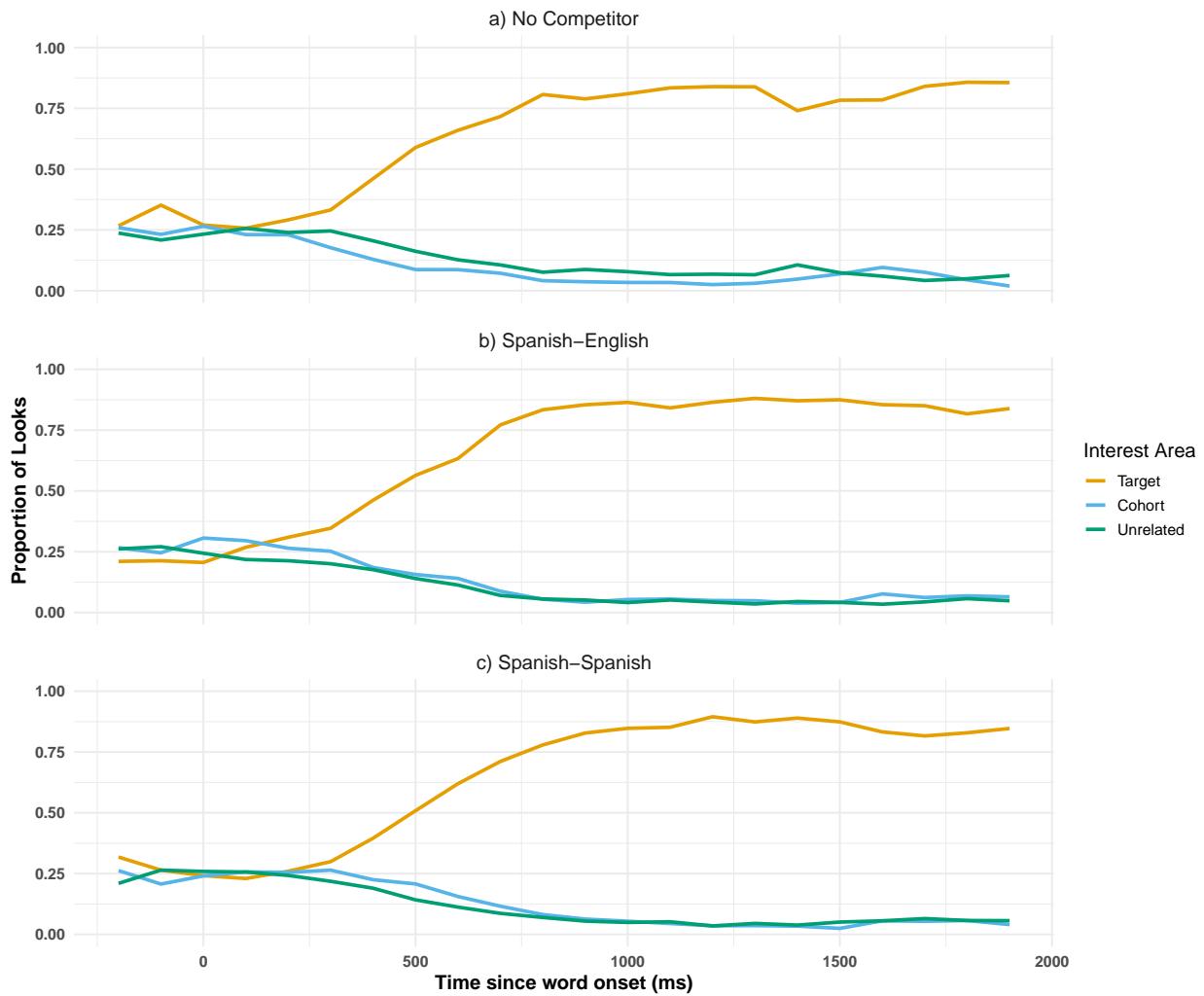
**Figure 8**

*Gorilla provided standardized coordinates for the four quadrants on the screen*



**Figure 9**

*Comparison of competition effects with Gorilla standardized coordinates*



## 610 Modeling data

When analyzing VWP data there are many analytic approaches to choose from (e.g., growth curve analysis (GCA), cluster permutation tests (CPT), generalized additive mixed models (GAMMS), logistic multilevel models, divergent point analysis, etc.), and a lot has already been written describing these methods and applying them to visual world fixation data from the lab (see Ito & Knoeferle, 2023; McMurray & Kutlu, n.d.; Stone et al., 2021) and online (Bramlett & Wiener, 2024). This tutorial's goal, however, is to not evaluate different analytic approaches and tell readers what they should use. All methods have their strengths and weaknesses (see Ito & Knoeferle, 2023). Nevertheless, statistical modeling should be guided by the questions researchers have and thus serious thought needs to be given to the proper analysis. In the VWP, there are two general questions one might be interested in: (1) Are there any overall difference in fixations between conditions and (2) Are there any time course differences in fixations between conditions

621 (and/or groups).

622 With our data, one question we might want to answer is if there are any fixation differences between  
623 the cohort and unrelated conditions across the time course. One statistical approach we chose to highlight  
624 to answer this question is a cluster permutation analysis (CPA). The CPA is suitable for testing differences  
625 between two conditions or groups over an interest period while controlling for multiple comparisons and  
626 autocorrelation.

627 **CPA**

628 CPA is a technique that has become increasingly popular, particularly in the field of cognitive neu-  
629 ropsychology, for analyzing MEG and EEG data (Maris & Oostenveld, 2007). While its adoption in VWP  
630 studies has been relatively slow, it is now beginning to appear more frequently (see Huang & Snedeker, 2020;  
631 Ito & Knoeferle, 2023). Notably, its use is growing in online eye-tracking studies (see Slim et al., 2024; Slim  
632 & Hartsuiker, 2023; Vos et al., 2022).

633 Before I show you how to apply this method to the current dataset, I want to briefly explain what  
634 CPA is. The CPA is a data-driven approach that increases statistical power while controlling for Type I errors  
635 across multiple comparisons—exactly what we need when analyzing fixations across the time course.

636 The clustering procedure involves three main steps:

637 1. Cluster Formation: With our data, a multilevel logistic model is conducted for every data point (con-  
638 dition by time). Please note that any statistical test can be run here. Adjacent data points that surpass  
639 the mass univariate significance threshold (e.g.,  $p < .05$ ) are combined into clusters. The cluster-  
640 level statistic, typically the sum of the t-values (or F-values) within the cluster, is computed labeled  
641 as SumStatistic is output below). By clustering adjacent significant data points, this step accounts for  
642 autocorrelation by considering temporal dependencies rather than treating each data point as indepen-  
643 dent.

644 2. Null Distribution Creation: Next, the same analysis is run as in step 1. However, the analysis is based  
645 on randomly permuting or shuffling the conditions within subjects. This principle of exchangeability is  
646 important here, as it suggests that the condition labels can be exchanged without altering the underlying  
647 data structure. This randomization is repeated n times (e.g., 1000 shuffles), and for each permutation,  
648 the cluster-level statistic is computed. This step addresses the issue of multiple comparisons by con-  
649 structing a distribution of cluster-level statistics under the null hypothesis, providing a baseline against  
650 which observed cluster statistics can be compared. By doing so, the method controls the family-wise  
651 error rate and ensures that significant findings are not simply due to chance.

652 3. Significance Testing: The cluster-level statistics from the observed (real) comparison is compared to  
653 the null distribution we created above. Clusters with statistics falling in the highest or lowest 2.5% of  
654 the null distribution are considered significant (e.g.,  $*p* < 0.05$ ).

655 To perform CPA, we will load in the `permutes` (Voeten, 2023), `permuco` (Frossard & Renaud,  
 656 `foreach` (& Weston, 2022), and `Parallel` (Corporation & Weston, 2022) packages in R. Loading  
 657 these packages allow us to use the `cluster.glmer()` function to run a cluster permutation (10,000 rimes)  
 658 across multiple system cores to speed up the process. We run a CPA on the `gaze_sub_id` object where each  
 659 row in `Looks` denotes whether the AOI was fixated, with values of zero (not fixated) or one (fixated).

660 Below you find sample code to perform multilevel CPA in R (please see the Github repository for  
 661 elaborated code needed to perform CPA).

```
library(permutes) # cpa
library(permuco) # cpa
library(foreach) # for par processing
library(doParallel)

# Step 1: Set up parallel backend
num_cores <- detectCores() - 1 # Use all available cores minus one for system
#<-- stability
cl <- makeCluster(num_cores)
registerDoParallel(cl)

# Step 2: Define the total number of permutations
total_perms <- 1000

# Step 3: Split the permutations across available cores
perms_per_core <- total_perms / num_cores

# Step 4: Use foreach to run the function in parallel
cpa.lme <- foreach(i = 1:num_cores, .combine = 'rbind', .packages = 'permutes')
#<-- %dopar% {
  permutes::clusterperm.glmer(Looks~ condition1_code + (1|subject) + (1|trial),
#<-- data=gaze_sub_L2_cp1, series.var=~time_bin, nperm = perms_per_core)
#}
# Step 5: Stop the parallel backend
stopCluster(cl)
```

662 In the analysis for the Spanish-Spanish condition, one significant cluster was observed between  
 663 500 and 1,100 ms, as indicated in the summary statistics from Table 7. The positive SumStatistic value  
 664 associated with this cluster suggests that competition was greater during this time window. This result im-  
 665 plies that cohorts in the Spanish-Spanish condition exhibited stronger effects or competition compared to  
 666 unrelated items. In Figure 10 significant clusters are highlighted for both the Spanish-Spanish and Spanish-

**Table 7**

*Clustermass statistics for the Spanish-Spanish condition*

| cluster | cluster_mass | p.cluster_mass | bin_start | bin_end | t  | sign | time_start | time_end |       |
|---------|--------------|----------------|-----------|---------|----|------|------------|----------|-------|
| 1       | 210.03       |                | 0         | 7       | 13 | 5.14 | 1          | 500      | 1,100 |

667 English conditions. Both conditions show one significant cluster. Overall, the analysis suggests that both  
 668 the Spanish-Spanish and Spanish-English conditions demonstrate significant competitor effects.

## 669 Discussion

670 Webcam eye-tracking is a relatively nascent technology, and as such, there is limited guidance avail-  
 671 able for researchers. To ameliorate this, we created a tutorial to assist new users of visual world webcam  
 672 eye-tracking, using some of the best practices available (e.g., Bramlett & Wiener, 2024). To further facil-  
 673 itate this process, we created the `webgazeR` package, which contains several helper functions designed to  
 674 streamline data preprocessing, analysis, and visualization.

675 In this tutorial, we covered the basic steps of running a visual world webcam-based eye-tracking  
 676 experiment. We highlighted these steps by using data from a cross-linguistic VWP looking at competitive  
 677 processes in L2 speakers of Spanish. Specifically, we attempted to replicate the experiment by Sarrett et al.  
 678 (2022) where they observed within- and between L2/L1 competition using carefully crafted materials.

679 While the main purpose of this tutorial was to highlight the steps needed to analyze webcam eye-  
 680 tracking data, replicating Sarrett et al. (2022) allowed us to not only assess whether within and between L2/L1  
 681 competition can be found in a spoken word recognition VWP experiment online (one of the first studies to  
 682 do so), but also provide insight in how to run VWP studies online and the issues associated with it.

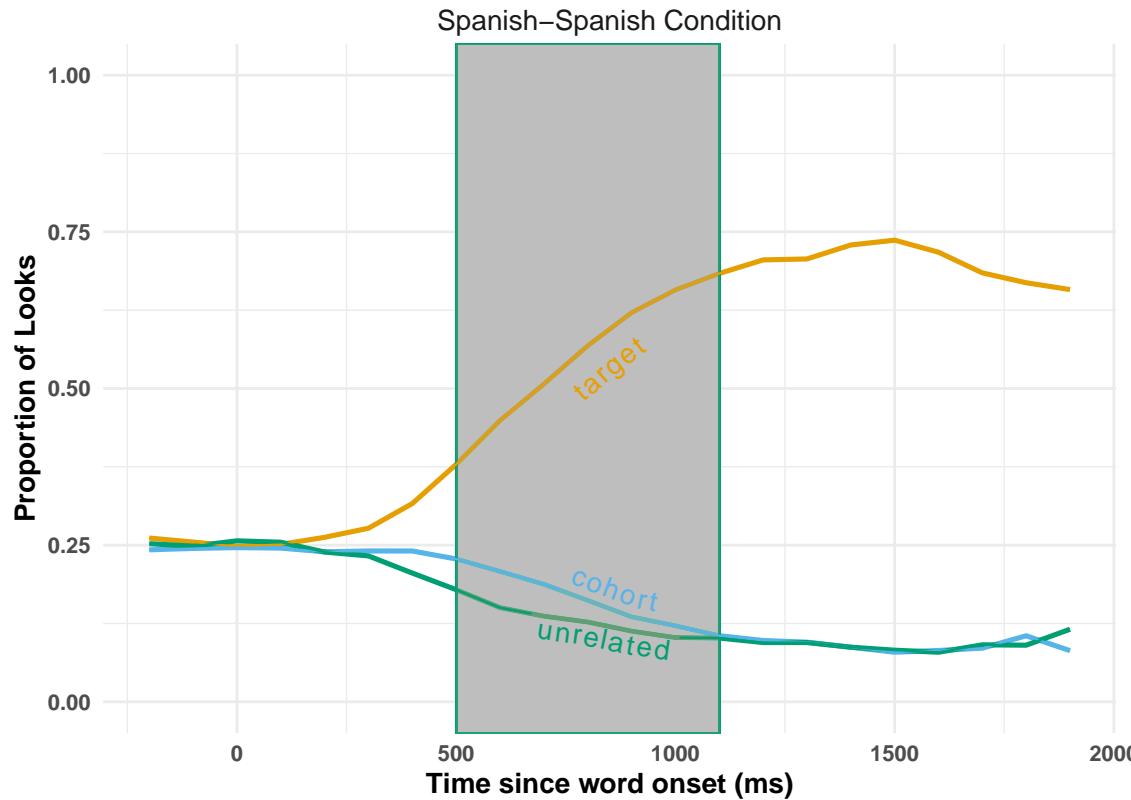
683 Our conceptual replication findings are highly encouraging, demonstrating competition effects both  
 684 within (the Spanish-Spanish condition) and across languages (the Spanish-English condition), closely paral-  
 685 leling the results reported by Sarrett et al. However, several important methodological and sample differences  
 686 war

687 A key methodological difference between our study and Sarrett et al. lies in the approach used to  
 688 analyze the time course of competition. While they employed a non-linear curve-fitting method (see McMurr-  
 689 ray et al., 2010), we used CPA. This methodological distinction limits our ability to address similar temporal  
 690 questions. Nonetheless, the overall temporal patterns are strikingly similar. For instance, our CPA revealed  
 691 a significant cluster starting at 500 ms, whereas Sarrett et al. (2022) identified competition effects emerging  
 692 at approximately 400 ms. This indicates a delay of about 100 ms in competition onset between lab-based  
 693 and online eye-tracking data. This delay, while notable, reflects a significant improvement over previous  
 694 webcam-based studies (e.g., Semmelmann & Weigelt, 2018; Slim et al., 2024). It is important to emphasize,  
 695 however, that CPA clusters cannot reliably be used to make temporal inferences about the onset/offset of

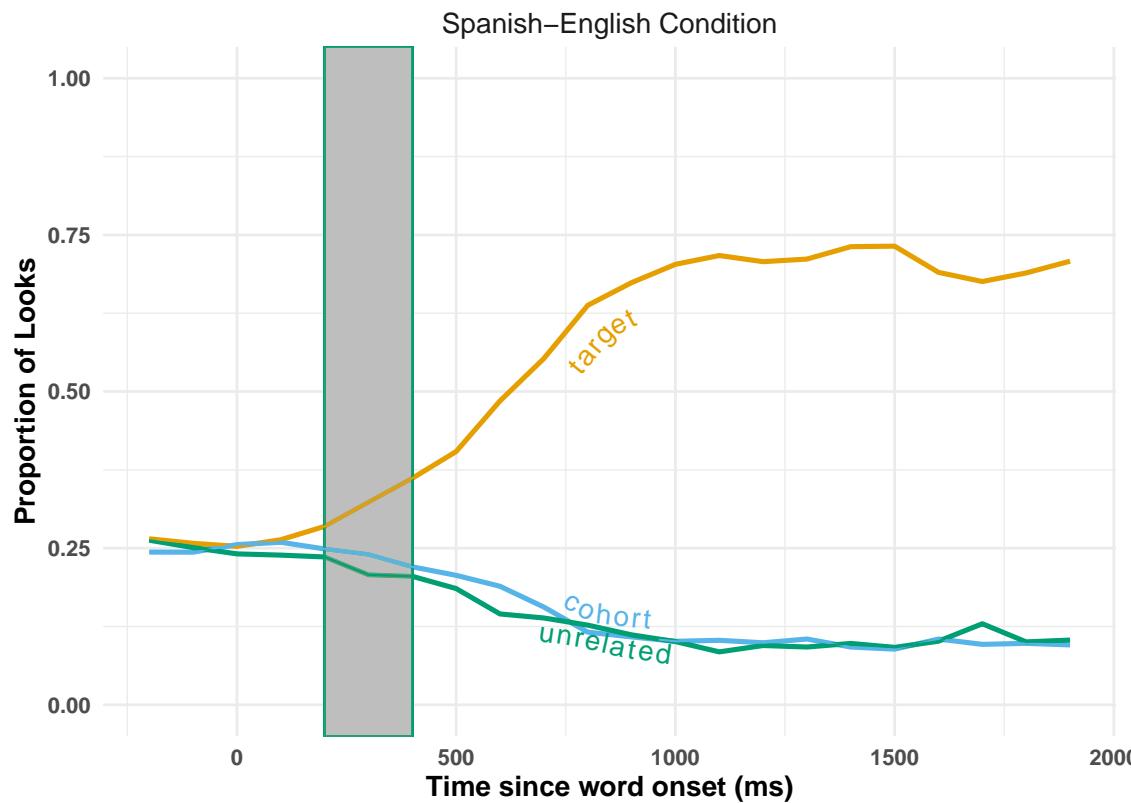
**Figure 10**

Average looks in the cross-linguistic VWP task over time for the Spanish-Spanish condition (a) and the Spanish-English condition (b). The shaded rectangles indicate when cohort looks were greater than chance based on the CPA.

A



B



696 effects (Fields & Kuperberg, 2019; Ito & Knoeferle, 2023).

697 Our study also employed a truncated stimulus set, with only 250 trials compared to the 450 trials in  
698 the original study.<sup>1</sup> Despite this reduction, the number of trials in our study remains larger than most existing  
699 webcam-based studies. Even with the smaller set, we observed a similar pattern of competition effects in  
700 both the Spanish-Spanish and Spanish-English conditions, demonstrating the robustness of our findings.

701 Another notable difference is the recruitment strategy and participant screening. Sarrett et al. re-  
702 cruted participants from a Spanish college course and used the LexTALE-Spanish assessment (Izura et al.,  
703 2014) to evaluate Spanish proficiency. In contrast, our data were collected via Prolific with limited filters,  
704 which only allowed us to screen for native language and experience with another language. This constraint  
705 limited our ability to refine participant selection further and likely contributed to differences in participant  
706 profiles. While Sarrett et al. focused on adult L2 learners with known language proficiency levels, our sample  
707 included a broader range of L2 speakers with limited checks on their language abilities (see Table 1 for range  
708 of Spanish speakers in our study). This may help explain why we did not observe a cohort competition effect  
709 that persisted across the time course as observed by Sarrett et al.

710 Overall, while the methodological and sample differences between the two studies are notable, the  
711 similarities in the competition effects observed within and across languages reinforce the robustness of these  
712 findings across different research settings. While we do not wish to downplay our findings, a more systematic  
713 study is needed to ensure generalizability.

## 714 Limitations

715 While the above suggests that webcam eye-tracking is a promising avenue for language research,  
716 there are some issues that we ran into that need to be addressed. One issue is data loss due to poor calibration.  
717 In our study, we had to throw out ~40% of our data due to poor calibration. Other studies have shown numbers  
718 much higher (e.g., 73%) (Slim & Hartsuiker, 2023) and lower (e.g., 20%) (Prystauka et al., 2024). Given this,  
719 it is still an open question as to what contributes to better vs. poor data quality in webcam eye-tracking. To  
720 this end, we included an assessment after the VWP that included questions on the participants' experimental  
721 set-ups and overall experiences with the eye-tracking experiment. All questions are included Table 8.

## 722 Poor vs. good calibrators

723 In our experimental design, participants were branched based on whether they successfully com-  
724 pleted the experiment or failed calibration at any point. Table 9 highlights the comparisons between good  
725 and poor calibrators. For the sake of brevity, we do not include responses to all questions. You can look  
726 at all the responses at our repo. However, two key differences emerge that may provide insight into factors  
727 influencing successful calibration.

728 One notable difference is the type of webcam used. Participants who failed calibration predomi-

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<sup>1</sup>The curve fitting approach employed by Sarrett et al. (2022) necessitates more trials. If we were to apply that approach the number of trials needed might not be sufficient.

729 nantly reported using built-in webcams, whereas those who successfully calibrated reported using a variety  
730 of external webcams. This suggests that built-in webcams may not provide adequate resolution for effec-  
731 tive calibration in the experiment. In fact, Slim and Hartsuiker (2023) examined the relationship between  
732 calibration scores and frame rate, finding that higher frame rates were associated with improved calibration  
733 performance. Participants using higher-quality webcams may have an easier time calibrating thereby leading  
734 to more reliable gaze data.

735 Another difference lies in the participants' environmental setup. Individuals who failed calibration  
736 were more likely to be in environments with natural light. Since natural light is known to interfere with  
737 eye-tracking, it may have contributed to their inability to calibrate successfully.

738 We did not notice any other differences between those that successfully calibrated vs. those who  
739 did not. For researchers wanting to use webcam eye-tracking, they should try to make sure participants  
740 are in rooms without natural light, and use good web cameras. While we tried to emphasize this in our  
741 instructional videos, more explicit instruction may be needed. An avenue for research would be to compare  
742 lab based webcam eye-tracking to online based webcam eye tracking to see if control of the environment can  
743 produce better results.

744 It is important to note here that Gorilla uses WebGazer.js (Papoutsaki et al., 2016) to perform it's  
745 eye tracking. It is unclear if poor calibration results from the noise introduced by participants' environ-  
746 ments/equipment or if it is a function of the method itself, or both. We have listed some equipment and  
747 environmental factors that may contribute to the poor performance; however it could be the algorithm itself  
748 that is poor. There are other experimental platforms out there that use different eye-tracking ML algorithms  
749 to perform webcam eye-tracking. Labvanced (Kaduk et al., 2024), for example, offers additional eye-tracking  
750 functionality including a virtual chinrest to ensure head movement is restricted to an acceptable range and  
751 warns users if they deviate from this range. Together this might make for a better eye-tracking experience  
752 with less data thrown out. This should be investigated further.

### 753 ***Generalizability to other platforms***

754 We demonstrated how to analyze webcam eye-tracking data from a Gorilla experiment using We-  
755 bGazer.js. While we were unable to validate this pipeline on other experimental platforms using WebGazer.js,  
756 such as PCIbex (Zehr & Schwarz, 2018) or jsPsych (Leeuw, 2015), we believe that this basic pipeline will  
757 generalize to those platforms, as WebGazer.js underlies them all and provides consistent output. We encour-  
758 age researchers to test this pipeline in their own studies and report any issues on our GitHub repository. We  
759 are committed to continuing improvements to `webgazeR`, ensuring that users can effectively analyze webcam  
760 eye-tracking data with our package.

### 761 ***Power***

762 While we successfully demonstrated competition effects similar to Garrett's study, we did not conduct  
763 an a priori power analysis nor was it our intention. With webcam eye-tracking, it has been recommended

**Table 8***Eye-tracking questionnaire items*

| Question   |
|--|
| 1. Do you have a history of vision problems (e.g., corrected vision, eye disease, or drooping eyelids)?            |
| 2. Are you on any medications currently that can impair your judgement?  |
| If yes, please list below:   |
| 4. Does your room currently have natural light?  |
| 5. Are you using the built in camera?  |
| If no, what brand of camera are you using?   |
| 6. Please estimate how far you think you were sitting from the camera during the experiment (an arm's length etc.) |
| 7. Approximately how many times did you look at your phone during the experiment?                                  |
| 8. Approximately how many times did you get up during the experiment?  |
| 9. Was the environment you took the experiment in distraction free?  |
| 10. When you had to calibrate, were the instructions clear?  |
| 11. What additional information would you add to help make things easier to understand?                            |
| 12. Are you wearing a mask?  |

<sup>764</sup> running twice the number of participants from the original sample, or powering the study to detect an effect  
<sup>765</sup> size half as large as the original (Slim & Hartsuiker, 2023; also see Simonsohn, 2015). We did attempt  
<sup>766</sup> to increase our sample size 2x, but were unable to recruit enough participants through Prolific. However,  
<sup>767</sup> our sample size is similar to the lab based studies. Regardless, researchers should be aware of this and plan  
<sup>768</sup> accordingly.

<sup>769</sup> We strongly urge researchers to perform power analyses and justify their sample sizes (Lakens, 2022).  
<sup>770</sup> While tools like G\*Power (Faul et al., 2007) are available for this purpose, we recommend power simulations  
<sup>771</sup> using Monte Carlo or resampling methods on pilot or sample data (see Prystauka et al., 2024; Slim & Hart-  
<sup>772</sup> suiker, 2023). Several excellent R packages, such as `mixedpower` (Kumle et al., 2021) and `SIMR` (Green &  
<sup>773</sup> MacLeod, 2016) make such simulations straightforward and accessible.

<sup>774</sup> **Recommendations**

<sup>775</sup> Based on our findings and limitations, we propose the following recommendations for researchers  
<sup>776</sup> conducting visual world webcam eye-tracking experiments.

<sup>777</sup> **1. Prioritize external webcams**

**Table 9**

*Responses to eye-tracking questions for participants who successfully calibrated vs. participants who had trouble calibrating*

| Question   | Response | Good   | Bad   |
|--|----------|--------|-------|
| 1.Do you have a history of vision problems (e.g., corrected vision, eye disease, or drooping eyelids)? | No       | 65.71  | 64.29 |
| 1.Do you have a history of vision problems (e.g., corrected vision, eye disease, or drooping eyelids)? | Yes      | 34.29  | 35.71 |
| 2.Are you on any medications currently that can impair your judgement?                                 | No       | 100.00 | 98.21 |
| 2.Are you on any medications currently that can impair your judgement?                                 | Yes      | 0.00   | 1.79  |
| 4.Does your room currently have natural light?   | No       | 40.00  | 26.79 |
| 4.Does your room currently have natural light?   | Yes      | 60.00  | 73.21 |
| 5.Are you using the built in camera?   | No       | 14.29  | 8.93  |
| 5.Are you using the built in camera?   | Yes      | 85.71  | 91.07 |
| 9.Was the environment you took the experiment in distraction free?                                     | No       | 11.43  | 3.57  |
| 9.Was the environment you took the experiment in distraction free?                                     | Yes      | 88.57  | 96.43 |

778 Our questionnaire suggested that participants using external webcams had significantly better calibration  
779 success compared to those relying on built-in webcams. External webcams generally provide  
780 higher resolution and frame rates, which are critical for accurate eye-tracking. Researchers should  
781 encourage participants to use external webcams whenever possible.

## 782 2. Optimize environmental conditions

783 Natural light was a common factor in environments where calibration failed. Researchers should advise  
784 participants to conduct experiments in rooms with controlled lighting—ideally, artificial lighting with  
785 minimal glare or shadows—to reduce interference with eye-tracking accuracy.

## 786 3. Conduct a priori power analysis

787 To ensure adequate statistical power, researchers should conduct a priori power analyses either via GUI  
788 like GPower or perform Monte Carlo simulations/resampling on pilot data. This step is particularly  
789 important for online studies, where sample variability can be higher than in controlled lab environments.  
790 To this point, you will have to over-enroll your study due to high attrition rate to reach your  
791 target goal, so please plan accordingly.

## 792 4. Collect detailed post-experiment feedback

793 Including post-experiment questionnaires about participants' setups (e.g., webcam type, browser, light-  
794 ing conditions) can provide valuable insights into calibration success factors. These data can help refine  
795 participant instructions and inclusion criteria for future studies.

796 By adhering to these recommendations, researchers can enhance the reliability and generalizability  
797 of their webcam eye-tracking studies, ensuring the potential of this technology is fully realized.

## 798 Conclusions

799 This work highlighted the steps required to process webcam eye-tracking data collected via Gorilla,  
800 showcasing the potential of webcam-based eye-tracking for robust psycholinguistic experimentation. With a  
801 standardized pipeline for processing eye-tracking data we hope we have given researchers a clear path forward  
802 when collecting and analyzing visual word webcam eye-tracking data.

803 Moreover, our findings demonstrate the feasibility of conducting high-quality online experiments,  
804 paving the way for future research to address more nuanced questions about L2 processing and language  
805 comprehension more broadly. Additionally, further refinement of webcam eye-tracking methodologies could  
806 enhance data precision and extend their applicability to more complex experimental designs. This is an  
807 exciting time for eye-tracking research, with its boundaries continuously expanding. We eagerly anticipate  
808 the advancements and possibilities that the future of webcam eye-tracking will bring.

## 809 References

- 810 Allaire, J. J., Teague, C., Scheidegger, C., Xie, Y., Dervieux, C., & Woodhull, G. (2024). *Quarto* (Version  
811 1.6) [Computer software]. <https://doi.org/10.5281/zenodo.5960048>

- 812 Allopenna, P. D., Magnuson, J. S., & Tanenhaus, M. K. (1998). *Tracking the time course of spoken word*  
813 *recognition using eye movements: Evidence for continuous mapping models* (pp. 419–439).
- 814 Altmann, G. T. M., & Kamide, Y. (1999). Incremental interpretation at verbs: Restricting the domain of  
815 subsequent reference. *Cognition*, 73(3), 247–264. [https://doi.org/10.1016/S0010-0277\(99\)00059-1](https://doi.org/10.1016/S0010-0277(99)00059-1)
- 816 Anderson, C. A., Allen, J. J., Plante, C., Quigley-McBride, A., Lovett, A., & Rokkum, J. N. (2019). The  
817 MTurkification of Social and Personality Psychology. *Personality & Social Psychology Bulletin*, 45(6),  
818 842–850. <https://doi.org/10.1177/0146167218798821>
- 819 Anwyl-Irvine, A. L., Massonnié, J., Flitton, A., Kirkham, N., & Evershed, J. K. (2020). Gorilla in our  
820 midst: An online behavioral experiment builder. *Behavior Research Methods*, 52(1), 388–407. <https://doi.org/10.3758/s13428-019-01237-x>
- 822 Barrett, M. (2021). *Ggokabeito: 'Okabe-ito' scales for 'ggplot2' and 'ggraph'*. <https://CRAN.R-project.org/package=ggokabeito>
- 824 Blasi, D. E., Henrich, J., Adamou, E., Kemmerer, D., & Majid, A. (2022). Over-reliance on English hinders  
825 cognitive science. *Trends in Cognitive Sciences*, 26(12), 1153–1170. <https://doi.org/10.1016/j.tics.2022.09.015>
- 827 Bramlett, A. A., & Wiener, S. (2024). The art of wrangling. *Linguistic Approaches to Bilingualism*.  
828 <https://doi.org/https://doi.org/10.1075/lab.23071.bra>
- 829 Bylund, E., Khafif, Z., & Berghoff, R. (2024). Linguistic and geographic diversity in research on second  
830 language acquisition and multilingualism: An analysis of selected journals. *Applied Linguistics*, 45(2),  
831 308–329. <https://doi.org/10.1093/applin/amad022>
- 832 Carter, B. T., & Luke, S. G. (2020). Best practices in eye tracking research. *International Journal of Psy-  
833 chophysiology*, 155, 49–62. <https://doi.org/10.1016/j.ijpsycho.2020.05.010>
- 834 Cooper, R. M. (1974). The control of eye fixation by the meaning of spoken language: A new methodol-  
835 ogy for the real-time investigation of speech perception, memory, and language processing. *Cognitive  
836 Psychology*, 6(1), 84–107. [https://doi.org/10.1016/0010-0285\(74\)90005-X](https://doi.org/10.1016/0010-0285(74)90005-X)
- 837 Corporation, M., & Weston, S. (2022). *doParallel: Foreach parallel adaptor for the 'parallel' package*.  
838 <https://CRAN.R-project.org/package=doParallel>
- 839 Csárdi, G., Hester, J., Wickham, H., Chang, W., Morgan, M., & Tenenbaum, D. (2024). *Remotes: R pack-  
840 age installation from remote repositories, including 'GitHub'*. <https://CRAN.R-project.org/package=remotes>
- 842 Dahan, D., Magnuson, J. S., & Tanenhaus, M. K. (2001). Time course of frequency effects in spoken-word  
843 recognition: Evidence from eye movements. *Cognitive Psychology*, 42(4), 317–367. <https://doi.org/10.1006/cogp.2001.0750>
- 845 Degen, J., Kursat, L., & Leigh, D. D. (2021). Seeing is believing: Testing an explicit linking assumption  
846 for visual world eye-tracking in psycholinguistics. *Proceedings of the Annual Meeting of the Cognitive  
847 Science Society*, 43.
- 848 Dolstra, E., & contributors, T. N. (2023). *Nix* (Version 2.15.3) [Computer software]. <https://nixos.org/>
- 849 Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G\*Power 3: A flexible statistical power analysis  
850 program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39(2), 175–  
851 191. <https://doi.org/10.3758/BF03193146>

- 852 Fields, E. C., & Kuperberg, G. R. (2019). Having your cake and eating it too: Flexibility and power with  
853 mass univariate statistics for ERP data. *Psychophysiology*. <https://doi.org/10.1111/psyp.13468>
- 854 Firke, S. (2023). *Janitor: Simple tools for examining and cleaning dirty data*. <https://CRAN.R-project.org/package=janitor>
- 855 Frossard, J., & Renaud, O. (2021). *Permutation tests for regression, {ANOVA}, and comparison of signals: The {permuco} package*. 99. <https://doi.org/10.18637/jss.v099.i15>
- 856 Geller, J., & Prystauka, Y. (2024). *webgazeR: Tools for processing webcam eye tracking data*. <https://github.com/jgeller112/webgazeR>
- 857 Geller, J., Winn, M. B., Mahr, T., & Mirman, D. (2020). GazeR: A package for processing gaze position and  
858 pupil size data. *Behavior Research Methods*. <https://doi.org/10.3758/s13428-020-01374-8>
- 859 Godfroid, A., Finch, B., & Koh, J. (2024). Reporting Eye-Tracking Research in Second Language Ac-  
860 quisition and Bilingualism: A Synthesis and Field-Specific Guidelines. *Language Learning*, n/a(n/a).  
861 <https://doi.org/10.1111/lang.12664>
- 862 Gosling, S. D., Sandy, C. J., John, O. P., & Potter, J. (2010). Wired but not WEIRD: The promise of the  
863 Internet in reaching more diverse samples. *Behavioral and Brain Sciences*, 33(2-3), 94–95. <https://doi.org/10.1017/S0140525X10000300>
- 864 Green, P., & MacLeod, C. J. (2016). SIMR: an R package for power analysis of generalized linear mixed  
865 models by simulation. *Methods in Ecology and Evolution*, 7(4), 493–498. <https://doi.org/10.1111/2041-210X.12504>
- 866 Henrich, J., Heine, S. J., & Norenzayan, A. (2010). Most people are not WEIRD. *Nature*, 466(7302), 29.  
867 <https://doi.org/10.1038/466029a>
- 868 Hooge, I. T. C., Hessels, R. S., Niehorster, D. C., Andersson, R., Skrok, M. K., Konklewski, R., Stremplewski,  
869 P., Nowakowski, M., Tamborski, S., Szkulmowska, A., Szkulmowski, M., & Nyström, M. (2024). Eye  
870 tracker calibration: How well can humans refixate a target? *Behavior Research Methods*, 57(1), 23.  
871 <https://doi.org/10.3758/s13428-024-02564-4>
- 872 Hopp, H. (2013). Grammatical gender in adult L2 acquisition: Relations between lexical and syntactic  
873 variability. *Second Language Research*, 29(1), 33–56. <https://doi.org/10.1177/0267658312461803>
- 874 Huang, Y., & Snedeker, J. (2020). Evidence from the visual world paradigm raises questions about unac-  
875 cusativity and growth curve analyses. *Cognition*, 200, 104251. <https://doi.org/10.1016/j.cognition.2020.104251>
- 876 Huettig, F., & McQueen, J. M. (2007). The tug of war between phonological, semantic and shape information  
877 in language-mediated visual search. *Journal of Memory and Language*, 57(4), 460–482. <https://doi.org/10.1016/j.jml.2007.02.001>
- 878 Huettig, F., Rommers, J., & Meyer, A. S. (2011). Using the visual world paradigm to study language pro-  
879 cessing: a review and critical evaluation. *Acta Psychologica*, 137(2), 151–171. <https://doi.org/10.1016/j.actpsy.2010.11.003>
- 880 Ito, A., & Knoeferle, P. (2023). Analysing data from the psycholinguistic visual-world paradigm: Compar-  
881 ison of different analysis methods. *Behavior Research Methods*, 55(7), 3461–3493. <https://doi.org/10.3758/s13428-022-01969-3>
- 882 Ito, A., Pickering, M. J., & Corley, M. (2018). Investigating the time-course of phonological prediction in

- native and non-native speakers of english: A visual world eye-tracking study. *Journal of Memory and Language*, 98, 1–11. <https://doi.org/10.1016/j.jml.2017.09.002>
- Izura, C., Cuetos, F., & Brysbaert, M. (2014). Lextale-Esp: a test to rapidly and efficiently assess the Spanish vocabulary size. *PSICOLOGICA*, 35(1), 49–66. <http://hdl.handle.net/1854/LU-5774107>
- Kaduk, T., Goeke, C., Finger, H., & König, P. (2024). Webcam eye tracking close to laboratory standards: Comparing a new webcam-based system and the EyeLink 1000. *Behavior Research Methods*, 56(5), 5002–5022. <https://doi.org/10.3758/s13428-023-02237-8>
- Kamide, Y., Altmann, G. T. M., & Haywood, S. L. (2003). The time-course of prediction in incremental sentence processing: Evidence from anticipatory eye movements. *Journal of Memory and Language*, 49(1), 133–156. [https://doi.org/10.1016/S0749-596X\(03\)00023-8](https://doi.org/10.1016/S0749-596X(03)00023-8)
- Kumle, L., Võ, M. L.-H., & Draschkow, D. (2021). Estimating power in (generalized) linear mixed models: An open introduction and tutorial in R. *Behavior Research Methods*, 53(6), 2528–2543. <https://doi.org/10.3758/s13428-021-01546-0>
- Lakens, D. (2022). Sample size justification. *Collabra: Psychology*, 8(1). <https://doi.org/10.1525/collabra.33267>
- Leeuw, J. R. de. (2015). jsPsych: A JavaScript library for creating behavioral experiments in a Web browser. *Behavior Research Methods*, 47(1), 1–12. <https://doi.org/10.3758/s13428-014-0458-y>
- Magnuson, J. S., Dixon, J. A., Tanenhaus, M. K., & Aslin, R. N. (2007). The Dynamics of Lexical Competition During Spoken Word Recognition. *Cognitive Science*, 31(1), 133–156. <https://doi.org/10.1080/03640210709336987>
- Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, 164(1), 177–190. <https://doi.org/10.1016/j.jneumeth.2007.03.024>
- McMurray, B., & Kutlu, E. (n.d.). *From real-time measures to real world differences new [and old] statistical approaches to individual differences in real-time language processing*. <https://doi.org/10.31234/osf.io/2c5b6>
- McMurray, B., Samelson, V. M., Lee, S. H., & Tomblin, J. B. (2010). Individual differences in online spoken word recognition: Implications for SLI. *Cognitive Psychology*, 60(1), 1–39. <https://doi.org/10.1016/j.cogpsych.2009.06.003>
- McMurray, B., Tanenhaus, M. K., & Aslin, R. N. (2002). Gradient effects of within-category phonetic variation on lexical access. *Cognition*, 86(2), B33–B42. [https://doi.org/10.1016/S0010-0277\(02\)00157-9](https://doi.org/10.1016/S0010-0277(02)00157-9)
- Microsoft, & Weston, S. (2022). *Foreach: Provides foreach looping construct*. <https://CRAN.R-project.org/package=foreach>
- Miller, J. (2023). Outlier exclusion procedures for reaction time analysis: The cures are generally worse than the disease. *Journal of Experimental Psychology: General*, 152(11), 3189–3217. <https://doi.org/10.1037/xge0001450>
- Mirman, D., & Graziano, K. M. (2012). Individual differences in the strength of taxonomic versus thematic relations. *Journal of Experimental Psychology: General*, 141(4), 601–609. <https://doi.org/10.1037/a0026451>
- Müller, K. (2020). *Here: A simpler way to find your files*. <https://CRAN.R-project.org/package=here>
- Papoutsaki, A., Sangkloy, P., Laskey, J., Daskalova, N., Huang, J., & Hays, J. (2016). *Webgazer: Scalable*

- 932        *webcam eye tracking using user interactions.* 38393845.
- 933    Peelle, J. E., & Van Engen, K. J. (2021). Time stand still: Effects of temporal window selection on eye  
934        tracking analysis. *Collabra: Psychology*, 7(1), 25961. <https://doi.org/10.1525/collabra.25961>
- 935    Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv,  
936        J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, 51(1), 195–  
937        203. <https://doi.org/10.3758/s13428-018-01193-y>
- 938    Płużyczka, M. (2018). The First Hundred Years: a History of Eye Tracking as a Research Method.  
939        *Applied Linguistics Papers*, 25/4, 101–116. <http://cejsh.icm.edu.pl/cejsh/element/bwmeta1.element.desklight-98576d43-39e3-4981-8c1c-717962cf29da>
- 941    Prystauka, Y., Altmann, G. T. M., & Rothman, J. (2024). Online eye tracking and real-time sentence pro-  
942        cessing: On opportunities and efficacy for capturing psycholinguistic effects of different magnitudes and  
943        diversity. *Behavior Research Methods*, 56(4), 3504–3522. <https://doi.org/10.3758/s13428-023-02176-4>
- 944    R Core Team. (2024). *R: A language and environment for statistical computing* (Version 4.4.2). R Founda-  
945        tion for Statistical Computing. <https://www.R-project.org/>
- 946    Rodd, J. M. (2024). Moving experimental psychology online: How to obtain high quality data when we  
947        can't see our participants. *Journal of Memory and Language*, 134, 104472. <https://doi.org/10.1016/j.jml.2023.104472>
- 949    Rodrigues, B., & Baumann, P. (2025). *Rix: Reproducible data science environments with 'nix'*. <https://docs.ropensci.org/rix/>
- 951    Rossi, E., Krass, K., & Kootstra, G. J. (2019). *Psycholinguistic Methods in Multilingual Research* (pp. 75–  
952        99). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781119387725.ch4>
- 953    Sarrett, M. E., Shea, C., & McMurray, B. (2022). Within- and between-language competition in adult second  
954        language learners: Implications for language proficiency. *Language, Cognition and Neuroscience*, 37(2),  
955        165–181. <https://doi.org/10.1080/23273798.2021.1952283>
- 956    Semmelmann, K., & Weigelt, S. (2018). Online webcam-based eye tracking in cognitive science: A first  
957        look. *Behavior Research Methods*, 50(2), 451–465. <https://doi.org/10.3758/s13428-017-0913-7>
- 958    Simonsohn, U. (2015). Small telescopes. *Psychological Science*, 26(5), 559–569. <https://doi.org/10.1177/0956797614567341>
- 960    Slim, M. S., & Hartsuiker, R. J. (2023). Moving visual world experiments online? A web-based replication  
961        of Dijkgraaf, Hartsuiker, and Duyck (2017) using PCIbex and WebGazer.js. *Behavior Research Methods*,  
962        55(7), 3786–3804. <https://doi.org/10.3758/s13428-022-01989-z>
- 963    Slim, M. S., Kandel, M., Yacovone, A., & Snedeker, J. (2024). Webcams as windows to the mind? A direct  
964        comparison between in-lab and web-based eye-tracking methods. *Open Mind*, 8, 1369–1424. [https://doi.org/10.1162/opmi\\_a\\_00171](https://doi.org/10.1162/opmi_a_00171)
- 966    Stone, K., Lago, S., & Schad, D. J. (2021). Divergence point analyses of visual world data: applications  
967        to bilingual research. *Bilingualism: Language and Cognition*, 24(5), 833–841. <https://doi.org/10.1017/S1366728920000607>
- 969    Tanenhaus, M. K., Spivey-Knowlton, M. J., Eberhard, K. M., & Sedivy, J. C. (1995). Integration of visual  
970        and linguistic information in spoken language comprehension. *Science (New York, N.Y.)*, 268(5217),  
971        1632–1634. <http://www.ncbi.nlm.nih.gov/pubmed/7777863>

- 972 Trueswell, J. C. (2008). *Using eye movements as a developmental measure within psycholinguistics* (I. A.  
973 Sekerina, E. M. Fernández, & H. Clahsen, Eds.; pp. 73–96). John Benjamins Publishing Company.  
974 <https://doi.org/10.1075/lald.44.05tru>
- 975 Viviani, P. (1990). Eye movements in visual search: cognitive, perceptual and motor control aspects. *Reviews  
976 of Oculomotor Research*, 4, 353–393.
- 977 Voeten, C. C. (2023). *Permutest: Permutation tests for time series data*. [https://CRAN.R-project.org/  
package=permutes](https://CRAN.R-project.org/<br/>978 package=permutes)
- 979 Vos, M., Minor, S., & Ramchand, G. C. (2022). Comparing infrared and webcam eye tracking in the Visual  
980 World Paradigm. *Glossa Psycholinguistics*, 1(1). <https://doi.org/10.5070/G6011131>
- 981 Wickham, H. (2017). *Tidyverse: Easily install and load the 'tidyverse'*. [https://CRAN.R-project.org/  
package=tidyverse](https://CRAN.R-project.org/<br/>982 package=tidyverse)
- 983 Woods, K. J. P., Siegel, M. H., Traer, J., & McDermott, J. H. (2017). Headphone screening to facilitate  
984 web-based auditory experiments. *Attention, Perception, and Psychophysics*, 79(7), 2064–2072. [https://doi.org/10.3758/s13414-017-1361-2](https://doi.org/10.<br/>985 3758/s13414-017-1361-2)
- 986 Yee, E., Blumstein, S., & Sedivy, J. C. (2008). Lexical-semantic activation in broca's and wernicke's aphasia:  
987 Evidence from eye movements. *Journal of Cognitive Neuroscience*, 20(4), 592–612. [https://doi.org/10.1162/jocn.2008.20056](https://doi.org/10.<br/>988 1162/jocn.2008.20056)
- 989 Zehr, J., & Schwarz, F. (2018). *PennController for internet based experiments (IBEX)*. [https://doi.org/10.17605/OSF.IO/MD832](https://doi.org/10.<br/>990 17605/OSF.IO/MD832)