Portable pupillometry on a shoe-string: a sentence processing demonstration

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For contexts in which written stimuli are infeasible, pupillometry presents an attractive alternative to measures such as self-paced reading or maze tasks. However, eye-trackers are expensive and can be difficult to transport. Here, we present a novel setup for measuring pupil dilation which is affordable, portable, and yields interpretable results for sentence processing experiments (using open-source code from Jeeliz: https://github.com/jeeliz/jeelizPupillometry; components in Table 1). This is advantageous for fieldwork. Despite having a relatively low temporal resolution (~15 Hz), the setup yielded pupil radius contours that distinguished between grammatical vs ungrammatical sentences and among grammatical sentences varying in acceptability.

One hundred and four Castilian Spanish speakers rated the acceptability of Spanish sentences while pupil size was measured with the novel setup (Figs. 1 & 2). While they fixated a central grey circle, participants heard 6 different constituent orders for 30 sets of items (pseudorandomized and counterbalanced using a Latin Square, with a 1:3 experimental item to filler ratio; examples in Table 2). Here, we present the results for canonical SVO, non-canonical OSV, and ungrammatical sentences with post-nominal articles, as these three clearly differed in acceptability (Fig. 3). These differences were reflected in the pupillometry data (Fig. 5).

Raw data from two trials are shown in Fig. 4, Panel 1 (ratio of pupil to iris radius). Note the recurring value of .04, which corresponds to a blink. Before analyzing our data, 24% of samples were determined to be blinks, transient pupil misestimations or trials rendered unusable by blinks (>50% samples). Missing samples were replaced by interpolation (Panel 3). Participants whose data subsequently lacked one condition were also excluded (8% of samples; final *N*=89) since we used a Latin Square design. The mean within-trial pupil-iris ratio in the interval 1s before stimulus onset was subtracted from these values to baseline them (van Rij et al., 2019).

Data were analyzed using Generalized Additive Mixed Modeling (GAMM), which can account for both fixed and random sources of variance (cf. LMER) without carrying assumptions about the shape of the data (Baayen et al. 2016). Our model included a fixed factor of condition, a fixed by-condition smooth over time, and random subject-wise smooths over time. Our dependent variable was pupil radius (our processed pupil-iris ratio measure, before smoothing).

The model predictions for the Ungrammatical and OVS conditions are plotted in Fig. 5 (L panel) alongside canonical SVO. Significant differences between curves are marked with red underline vertical dashes. Differences in pupil diameter over time reflect processing load. For example, processing load in SVO sentences increased gradually over the sentence (mean duration: 1773 ms), peaking 4 s after stimulus onset, immediately before the rating was made.

A similar curve can be observed for the OVS condition (Fig. 5, R panel), except that the processing load is higher, compared with the canonical SVO during the interval indicated by the red vertical dashed lines. The increased processing difficulty could be due to initial misanalysis and subsequent reanalysis of the non-canonical structure. A much different curve was elicited by the ungrammatical condition. The early window of difference (cf. red lines) begins prior to the onset of the sentence and may be noise. The later window of difference is roughly analogous to that for the OVS conditions and may also reflect some attempt at reanalysis.

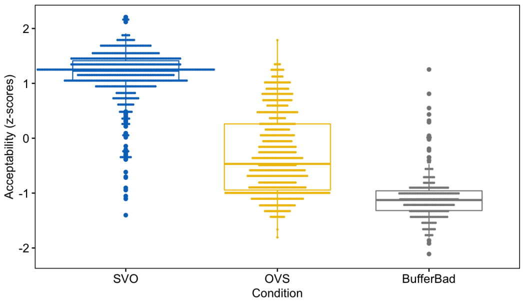
In sum, this inexpensive, portable pupillometry system is sensitive to differences in processing effort during spoken language comprehension. Comparisons to EyeLink will resume after the Coronavirus pandemic. As we refine this system, we believe it will prove valuable for expanding the languages and communities represented in processing research.

ITEM	COMMENTS, PRICE
USB camera	5-50mm Varifocal Lens HD Sony IMX179 Webcam; $76.00
Camera plate, hex screws	$9.99 & $5.64 respectively
Desk lights	Safety hazard lights; $19.99 for 3 (pupil illumination)
Head-mounted lights	Clip-on stage lights; $12.00 ea. (2 per setup; pupil illumination)
Laptop, headphones, keyboard, mouse	Linux OS preferred (more robust camera settings) Keyboard and mouse facilitate proper distance from camera

Table 1: Components and price of novel pupillometry setup

Figure 1: Front view of setup.

Figure 2: Side view of setup.



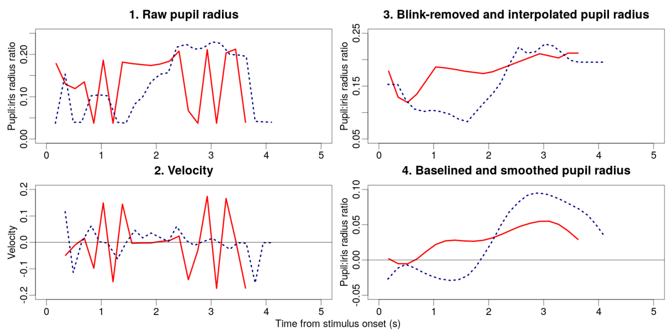


Figure 3 (left): Z-scored acceptability ratings of SVO (grammatical, canonical), OVS (grammatical, non-canonical), and unambiguously ungrammatical sentences.
Figure 4 (right): Demo of pupil data processing for two trials.

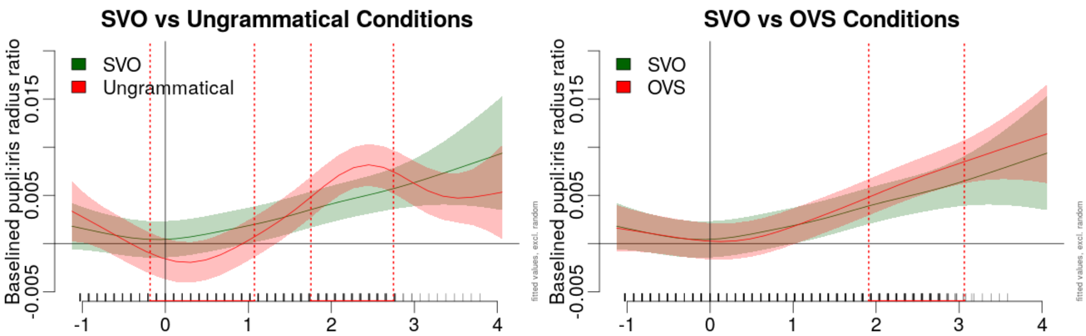


Figure 5: Comparison of SVO with Ungrammatical (L) and SVO with OVS (R) conditions. Red underline and vertical dashes indicate significant differences between curves.

CONDITION	EXAMPLE	MEAN Z-SCORED RATING
SVO	el conductor cierra la ventana the conductor closed the window	1.16 (mean 1-7 rating: 6.51)
OVS	la ventana cierra el conductor the window closed the conductor	-0.30 (mean 1-7 rating: 3.16)
Ungrammatical	escalera el repararía trabajadora el stairs the repair worker the	-1.09 (mean 1-7 rating: 1.37)

Table 2: Sample stimuli and ratings; the SVO and OVS sentences have the same truth-conditional meaning in Spanish, though the SVO order is canonical and the OVS order is infrequent and only occurs in particular discourse contexts. The Ungrammatical string is not a possible sentence in Spanish.