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**TITLE:**

Eye Tracking during Visually Situated Language Comprehension: Flexibility and Limitations in Uncovering Visual Context Effects

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**SHORT ABSTRACT:**

The present article reviews an eye-tracking methodology for studies on language comprehension. To obtain reliable data, key steps of the protocol must be followed. Among these are the correct set-up of the eye tracker (*e.g.*, ensuring good quality of the eye and head images) and accurate calibration.

**LONG ABSTRACT:**

The present work is a description and an assessment of a methodology designed to quantify different aspects of the interaction between language processing and the perception of the visual

world. The recording of eye gaze patterns has provided good evidence for the contribution of both the visual context and linguistic/world knowledge to language comprehension. Initial research assessed object-context effects to test the theories of modularity in language processing. In the introduction, we describe how subsequent investigations have taken the role of the wider visual context in language processing as a research topic in its own right, asking questions such as how our visual perception of events and of speakers contributes to the comprehension informed by the comprehenders' experience. Among the examined aspects of the visual context are actions, events, a speaker's gaze, and emotional facial expressions, as well as spatial object configurations. Following an overview of the eye-tracking method and its different applications, we list the key steps of the methodology in the protocol, illustrating how to successfully use it to study visually-situated language comprehension. A final section presents three sets of representative results and illustrates the benefits and limitations of eye tracking for investigating the interplay between the perception of the visual world and language comprehension.

## INTRODUCTION:

Psycholinguistic research has highlighted the importance of eye movement analyses in understanding the processes implicated in language comprehension. The core of inferring comprehension processes from the gaze record is a hypothesis that links cognition to eye movements<sup>5</sup>. There are three major types of eye movements: saccades, vestibulo-ocular movements, and smooth pursuit movements. Saccades are fast and ballistic movements that happen mostly unconsciously and have been reliably associated with the shifts in attention<sup>6</sup>. The moments of relative gaze stability between saccades, known as fixations, are considered to index current visual attention. Measuring the locus of the fixations and their duration in relation to cognitive processes is known as the 'eye-tracking method'. Early implementations of this method served to examine reading comprehension in strictly linguistic contexts (see Rayner<sup>7</sup> for a review). In that approach, the duration of inspecting a word or sentence region is associated with processing difficulty. Eye tracking has, however, also been applied to examine spoken language comprehension during the inspection of objects in the world (or on a computer display<sup>2</sup>). In this 'visual world' eye-tracking version, the inspection of objects is guided by language. When the comprehenders hear *the zebra*, for instance, their inspection of a zebra on the screen is taken to reflect that they are thinking about the animal. In what is known as the visual world paradigm, a comprehender's eye gaze is taken to reflect spoken language comprehension and the activation of associated knowledge (e.g., listeners also inspect the zebra when they hear *grazing*, indicating an action performed by the zebra)<sup>2</sup>. Such inspections suggest a systematic link between language-world relations and eye movements<sup>2</sup>. A common way to quantify this link is by computing the proportion of looks to different pre-determined regions on a screen. This allows the researchers to directly compare (across participants and trials) the amount of attention given to different objects at a particular time and how these values change in millisecond resolution.

Research in psycholinguistics has exploited eye tracking in visual worlds to tease apart competing theoretical hypotheses regarding the architecture of the mind<sup>1</sup>. Eye fixations on depicted objects have, moreover, revealed that comprehenders can—assuming a sufficiently restrictive linguistic context—perform incremental semantic interpretation<sup>8</sup> and even develop expectations about

upcoming characters<sup>9</sup>. Such eye gaze data have also shed light on a range of further comprehension processes, such as lexical ambiguity resolution<sup>10,11</sup>, pronoun resolution<sup>12</sup>, the disambiguation of structural and thematic role assignment by means of information in the visual context<sup>13,14,16</sup>, and pragmatic processes<sup>15</sup>, among many others<sup>4</sup>. Clearly, the eye movements to objects during language comprehension can be informative of the implicated processes.

The eye-tracking method is non-invasive and can be used with infants, young, and older language users. A key advantage is that, unlike punctate responses to probes or response button presses in verification tasks, it provides insights over time in a millisecond resolution into how language guides attention and how the visual context (in the form of objects, actions, events, a speaker's gaze, and emotional facial expressions, as well as spatial object configurations) contributes to language processing. The continuity of the measure during sentence comprehension complements well with other post-sentence and post-experiment measures such as overt picture/video-sentence verification, comprehension questions, and memory recall tasks. Overt responses in these tasks can enrich the interpretation of the eye gaze record by providing insight into the outcome of the comprehension process, memory, and learning<sup>2</sup>. Combining eye tracking with these other methods has uncovered to which extent different aspects of the visual context modulate visual attention and (immediate, as well as delayed) comprehension across the lifespan.

The presentation of language (spoken or written) and scenes can be either simultaneous or sequential. For instance, Knoeferle and collaborators<sup>17</sup> presented the scene 1,000 ms before the spoken sentence, and it remained present during the comprehension. They reported evidence that clipart depictions of action events contribute to the resolution of local structural ambiguity in German subject-verb-object (SVO) compared with object-verb-subject (OVS) sentences. Knoeferle and Crocker<sup>18</sup> presented a clipart scene before a written sentence and tested the incremental integration of clipart events during the sentence comprehension. They observed incremental congruence effects, meaning that the participants' reading times of sentence constituents were longer when these mismatched (vs. matched) the event depicted in the preceding scene. In another stimulus presentation variant, the participants first read a sentence describing a spatial relationship and then saw a scene of a particular spatial arrangement involving object line drawings<sup>19</sup>. This study assessed the predictions of computational spatial language models by asking the participants to rate the fit of the sentence given to the scene, with the eye movements being recorded during the scene interrogation. The participants' gaze patterns were modulated by the shape of the object that they were confronted with—partially confirming the model predictions and providing data for model refinement.

While many studies have used clipart depictions<sup>17-23</sup>, it is also possible to combine real-world objects, videos of these objects, or static photographs with spoken language<sup>1,21,24-26,44</sup>. Knoeferle and colleagues used a real-world setting<sup>24</sup> and Abashidze and colleagues used a videotaped presentation format for examining action events and tense effects<sup>25</sup>. Varying the precise content of the scenes (*e.g.*, depicting actions or not)<sup>22,27,36</sup> is possible and can also reveal visual context effects. A related study by Rodríguez and collaborators<sup>26</sup> investigated the influence of videotaped visual gender cues on the comprehension of subsequently presented spoken sentences.

Participants watched the videos displaying either male or female hands performing a stereotypically gender-related action. Then, they heard a sentence about either a stereotypically male or female action event while simultaneously inspecting a display showing two photographs side by side, one of a man and the other of a woman. This rich visual and linguistic environment allowed the authors to tease apart the effects of language-mediated stereotypical knowledge on comprehension from the effects of the visually presented (hand) gender cues.

A further application of this paradigm has targeted developmental changes in language processing. Eye movements to objects during spoken language comprehension revealed the effects of depicted events in 4 - 5-year olds<sup>27,28</sup> and in older adults<sup>29</sup> in real time, but somewhat delayed compared to young adults. Kröger and collaborators<sup>22</sup> examined the effects of prosodic cues and case marking within an experiment and compared these across experiments in adults and children. Participants inspected an ambiguous action-event scene while listening to a related unambiguously case-marked German sentence. Eye movements revealed that the distinct prosodic patterns helped neither the adults nor the 4- or 5-year-olds when disambiguating who-does-what-to-whom. Sentence-initial case marking, however, influenced adults' but not children's eye movements. This suggests that a 5-year-olds' understanding of case marking is not sufficiently robust to enable thematic role assignment (see the study by Özge and collaborators<sup>30</sup>), at least not when action events did not disambiguate thematic role relations. These results are interesting, given that they are in contrast with previous results of prosodic effects on thematic role assignment<sup>31</sup>. Kröger and collaborators<sup>22</sup> proposed that the (more or less supportive) visual context is responsible for the contrasting findings. To the extent that these interpretations hold, they highlight the role of the context in language comprehension across the lifespan.

The eye-tracking method combines well with the measures from picture- (or video-)sentence verification tasks<sup>18,20,26</sup>, picture-picture verification tasks<sup>32</sup>, corpus studies<sup>24</sup>, rating tasks<sup>19</sup>, or post-experimental recall tasks<sup>25,33</sup>. Abashidze and collaborators<sup>34</sup> and Kreysa and collaborators<sup>33</sup> investigated the interplay of speaker gaze and real-world action videos<sup>34</sup> and speaker gaze and action depictions<sup>33</sup>, respectively, as cues for upcoming sentence content. By combining the tracking of eye gaze in a scene during language comprehension with a post-experimental memory task, they gained a better understanding of the way in which the listeners' perception of a speaker's gaze and the depicted actions interact and affect both immediate language processing and memory recall. The results revealed the distinct contribution of actions *versus* speaker gaze to real-time comprehension *versus* post-experiment memory recall processes.

While the eye-tracking method can be employed with great flexibility, certain standards are the key. The following protocol summarizes a generalized procedure that can be adjusted to different types of research questions according to the researchers' specific needs. This protocol is a standardized procedure employed in the Psycholinguistics Laboratory at the Humboldt-Universität zu Berlin, as well as in the former Language and Cognition Laboratory at the Cognitive Interaction Technology Excellence Cluster (CITEC) at Bielefeld University. The protocol describes a desktop and a remote setup. The latter is recommended for use in studies with children or older adults. All experiments mentioned in the **Representative Results** use an eye tracker device which

has a sampling rate of 1,000 Hz and is used together with a head stabilizer, a PC for testing the participants (Display PC) and a PC for monitoring the experiment and the participants' eye movements (Host PC). The main difference of this device to its predecessor is that it allows for binocular eye tracking. The protocol is intended to be sufficiently general for use with other eye-tracking devices that include a head stabilizer and make use of a dual PC setup (Host + Display). However, it is important to keep in mind that other setups will likely have different methods for handling problems such as calibration failures or track loss, in which case the experimenter should refer to the user manual of their specific device.

## **PROTOCOL:**

This protocol follows the ethics guidelines of the institution where the data was collected, *i.e.*, the Cognitive Interaction Technology Excellence Cluster (CITEC) of Bielefeld University and Humboldt-Universität zu Berlin. The experiments conducted at Bielefeld University were approved individually by the Bielefeld University's ethics committee. The psycholinguistics laboratory at the Humboldt-Universität zu Berlin has a laboratory ethics protocol that was approved by the ethics committee of the Deutsche Gesellschaft für Sprachwissenschaft, the German Linguistics Society (DGfS).

### **1. Desktop Setup**

Note: The following are the key steps in an eye-tracking experiment.

#### **1.1. Instrument preparation**

1.1.1. Turn on the eye-tracking camera and the Host PC (see **Figure 1** for an illustration of the in-lab data collection and the pre-processing setup).

1.1.2. Initiate the eye tracker software.

1.1.3. Turn on the Display PC. Open the folder that contains the experiments.

1.1.4. Start the 'deployed' version with a .exe extension by double-clicking it.

1.1.5. Depending on the setup, a prompt for selecting an experimental list might appear, which is typically a tab-delimited .csv/.txt file containing the conditions, sound file names, written sentences, and/or images that a participant will be exposed to. Select the list, and the program will start. Name the output file where the results will be stored.

Note: The output file is saved on the Display PC and a back-up is saved on the Host PC.

1.1.6. Leave the first screen of the experiment (the introduction or welcome screen) open.

1.1.7. Remove the protective cover from the eye tracker camera.

221 1.1.8. For hygienic purposes, place a tissue on the chin holder.

222  
223 1.1.9. Optional: Prepare a response pad and/or a keyboard as required by the experiment.

224  
225 1.1.10. Optional: If presenting auditory stimuli, adjust the volume of the speakers and test them  
226 prior to running the experiment. Alternatively, test the functionality of the headphones to be  
227 used by the participant.

228  
229 1.1.11. Prepare the necessary forms to be signed by the participant.

230  
231 1.1.12. Adjust the light intensity in the laboratory in order to have a dimly lit room with a constant  
232 luminance for the entire duration of the data collection process.

## 233 234 **1.2. Preparation for the participants**

235  
236 1.2.1. After the participants have arrived, introduce yourself.

237  
238 1.2.2. Place a **Do not disturb** sign on the laboratory door.

239  
240 1.2.3. Ask the participant to take a seat.

241  
242 1.2.4. Guide the participant through the information sheet and the necessary consent and  
243 demographic forms.

244  
245 1.2.5. Let the participant read and sign the consent form.

246  
247 1.2.6. Briefly explain the general aspects of the experiment and its duration. Do not provide too  
248 much information prior to the experiment, since this might influence the participant's gaze  
249 behavior and the resulting data.

250  
251 1.2.7. Provide written instructions and give the participant the opportunity to ask questions.

252  
253 1.2.8. Briefly explain the function of the eye tracker.

254  
255 1.2.9. If necessary, clarify the task and point out any buttons/keys that will need to be pressed  
256 during the experiment.

257  
258 1.2.10. Explain how the chin rest is intended to minimize head movement during the experiment.  
259 Mention that the device functions best if the participant avoids any movements.

## 260 261 **1.3. Setting up the eye tracker**

262  
263 1.3.1. Prepare the participant for the experiment: ask them to sit at the table and place their chin  
264 on the chin rest. Ask them to lean their forehead against the headrest.

1.3.2. Ask the participant to adjust the height and position of the chair if necessary: the participant should feel comfortable with their chin on the chin rest and their forehead against the headrest.

1.3.3. Explain that it is common to accidentally move the head during the experiment and that this should be avoided. Explain that the head posture might have to be corrected during the experiment.

1.3.4. If the experiment requires a button press (*e.g., via* the response pad), instruct the participant to leave their fingers resting on the buttons to be pressed and to avoid looking down at the response pad when pressing a button.

1.3.5. Ask the participant to read the welcome/introduction screen.

1.3.6. Sit in front of the Host PC. If the screen is not already on **Camera setup**, click on **Camera setup** to get to the right screen. If the protective cover has been removed from the camera lens and the participant is correctly positioned on the chin rest, the screen should show three images of the participant's eyes: a bigger image at the top, and two smaller ones at the bottom on the left and right. These smaller images show one eye each, corresponding to the left and the right eye.

1.3.7. Select the eye to be tracked. It is customary to track the participant's dominant eye. If the participant does not know which eye is dominant, conduct an ocular dominance test (step 1.3.8).

1.3.8. Determine ocular dominance. Ask the participant to stretch out one arm and align the thumb with a distant object with both eyes open. Ask the participant to alternate closing the left or right eye. The dominant eye is the one for which the thumb remains aligned with the object when the eye is open.

1.3.9. Click on **Image | Display pc** (or press **Enter**) and the images described in step 1.3.6 will also appear on the participant's display screen, but only one at a time.

1.3.10. Press the left/right arrow on either the experimenter's or the participant's computer keyboard to switch between the smaller and bigger image of the eye. Focus on the smaller image (the eye).

1.3.11. Press **A (Align eye window)** on either keyboard in order to center the search limits box on the pupil position. Then, a red square around the eye should appear with a turquoise circle [the 'corneal reflection', (cr)] near the bottom of the pupil. The pupil itself should be blue.

1.3.12. Ensure that two crosses ('crosshairs') appear on the screen—one in the center of the pupil and one in the center of the corneal reflection. The red box and the two crosses mean that the eye tracker is detecting the pupil and the cr.



Note: If the red box or the crosses are absent, the eye is not tracked—if this happens, a **no pupil** message will appear on the experimenter's computer.

1.3.13. Adjust the camera's focus by manually turning the focus lens. Be careful not to touch the front of the lens. Turn the lens until the best focus point is reached.

Note: The best focus point is reached when the turquoise circle (the corneal reflection) is as small as possible (*i.e.*, when this circle is in focus).

1.3.14. Set the pupil threshold. Ensure that only the image of the pupil is blue (*e.g.*, the eyelashes should not be blue) on the Host PC. Also, ensure that the entire pupil (not just its central part) is blue. Only worry about what is inside the red square.

1.3.15. Press **A**. This automatically sets the pupil threshold. If the pupil is not accurately displayed in blue, adjust the threshold manually using the **UP** key to increase and the **DOWN** key to decrease the amount of blue part of the image surface.

Note: Mascara (which is usually black, like the pupil) may interfere with setting the threshold—the eye tracker might take the dark eyelashes for the pupil. In this case, ask the participant to remove their makeup by providing them with makeup remover tissues.

1.3.16. Set the **cr threshold**. If **A** was pressed in step 1.3.15, the **cr threshold** should have automatically been set.

Note: Numeric values for all threshold settings should be visible. If a question mark appears in any of them, there was a problem in one of the preceding steps and the thresholds should be set manually.

#### 1.4. Calibrating the eye tracker

Note: Check whether the eye tracker can consistently identify the position of the eye when the participant looks at other parts of the screen.

1.4.1. Ask the participant to look at the four corners of the screen one at a time while the camera setup window is in view. Carefully look for any irregular reflections (these will show up as turquoise 'blobs' on the screen) that interfere with the corneal reflection when the eye gaze is directed at the corner.

1.4.2. Ask the participant to look at the center of the screen and then direct their gaze to the problematic corner if the red box around the eye and either of the crosshairs are not visible at any point during step 1.4.1. This will help determine the source of the problem.

1.4.3. Re-adjust the position of the participant's head and check if this yields any improvement.

Repeat this step if necessary. If the device is still unable to accurately track the participant's gaze after several attempts, abort the experiment.

1.4.4. Inform the participant that the eye tracker will be calibrated and that they are going to see a black circle (with a small grey dot) moving to different parts of the screen. Instruct the participant to fixate the circle until it moves to a new location. Instruct the participant to avoid straining their eyes and to focus on the small grey dot inside the black circle for optimal results.

1.4.5. Tell the participant that it is important to keep still and not to try to anticipate the position of the next circle during the calibration. Instruct them to follow the circles with their eyes and not their head. Click on **Calibrate** to start the calibration process. Normally, a 9-point calibration procedure is used in which the black circle moves to nine locations in a serial manner.

1.4.6. For an automatic calibration, press **ENTER** after the participant has accurately fixated the first dot in the middle of the screen. For manual calibration (*e.g.*, when there are problems tracking the participant's eye or when dealing with special participant groups such as children), accept each fixation by pressing **ENTER** (or by clicking **Accept fixation**/pressing the **Spacebar**).

Note: At the end of the calibration process, an almost rectangular pattern on the experimenter's screen should be visible. This represents the eye gaze patterns of the participant. Additionally, the results of a good calibration should be highlighted in green. If they are not, repeat the calibration procedure (*i.e.*, click on **Calibration**).

1.4.7. Validate the results. Tell the participant to go through the same procedure (looking at dots) in order to validate the results of the calibration process. Remind them to look at the dot and to be still.

Note: The process of validation is similar to that of calibration and both results are compared by the eye tracker software to ensure that the eye is being tracked accurately.

1.4.8. Click **Validate**.

1.4.9. Accept each fixation by pressing **ENTER** (or by clicking **Accept fixation**/pressing the **Spacebar**).

1.4.10. After the validation, the results will appear on the experimenter's screen. Pay particular attention to the two error measures, the average error (*e.g.*, 0.23°) and the maximal error (*e.g.*, 0.70°). These represent the degrees to which the tracked image deviates from the actual gaze position of a participant.

1.4.11. When using a visual world paradigm, keep the average error (the first number) under 0.5° and the maximum error (the second number) under 1°.

1.4.12. If the error values are above the threshold, ask the participant to readjust the position of

their head and restart the calibration procedure. If no improvement is observed, abort the experiment.

Note: It is common to observe high calibration errors when the participant wears contact lenses. The participant should be asked in advance to bring their prescription glasses instead of their contact lenses.

1.4.13. After successfully completing the calibration process, click **Output/Record** to start the experiment. Inform the participant that the experiment will now begin.

## 1.5. During the experiment

Note: During the experiment (depending on how an individual experiment is programmed, but typically before each experimental trial), a **drift check** or **drift correct** screen will display a dot in the center of the screen. Its purpose is to report the calculated fixation error for the current trial, and, depending on the eye tracker model, to automatically adjust it.

1.5.1. During the instruction phase, the participant has been told to fixate the central dot whenever it appears. Make sure that during every drift check/drift correct phase, participants are again fixating the dot. This can be done by following the participant's gaze on the Host PC, where the participant's gaze appears as a moving green circle.

1.5.2. Once the drift check/drift correct has been completed, press **ENTER** (or the **Spacebar**) to make the dot disappear and display the next trial.

1.5.3. Determine how to deal with failure to pass the drift check phase according to the model of the eye tracker used. Depending on the model, the eye tracker will either perform an automatic **drift correction** by adjusting the gaze's coordinates to match those of the central dot, or it will make a beeping noise to prompt the experimenter to re-calibrate before continuing the experiment (**drift check**).

1.5.4. If using an automatic drift correction, keep in mind that too many drift corrections in consecutive trials and/or too large a degree of drift correction will distort the results and require a re-calibration of the device.

## 1.6. Re-calibration during the experiment

1.6.1. It is possible to re-calibrate at any time during the experiment. During the presentation of the **Drift correction/drift check** screen, click on **Camera setup**, then click on **Calibrate**. Go through the calibration and validation processes until a satisfactory value is reached, then click on **Output/record**. The experiment will resume from the exit point in the trial sequence.

## 1.7. After the experiment

1.7.1. Provide the participant with a questionnaire to assess if they were able to guess the key experimental manipulations. Here, it is also important to ask about potential strategies that could have been developed throughout the experiment.

1.7.2. Debrief the participant about the purpose of the experiment. Thank them for their participation and provide the necessary monetary compensation or assign course credit if applicable.

## **2. Remote Setup: Adjusting the Setup for Studies with Children and Older Adults**

Note: This section describes only the differences between a remote setup and a desktop setup as described in step 1. Points not explicitly mentioned here should be assumed to be identical to the procedure described in step 1.

2.1. Exchange the standard 35 mm eye tracker camera lens for a 16 mm lens.

2.2. Connect all necessary equipment (Host PC, speakers, eye tracker, and laptop if a laptop is used).

2.3. Place the laptop on a laptop stand and the eye tracker in front of it (the participant should be able to see the top 75% of the screen).

2.4. Place a “target sticker” (available from the tracker’s manufacturer) on the participant’s forehead (above the eyebrow of the right eye or on the right cheek if the forehead is too small (*i.e.*, in case of infants); this sticker replaces the chin rest of the desktop setup and it allows the eye tracker to accurately determine the position of the participant’s head.

2.5. Make sure that the participant is seated 550 - 600 mm away from the camera (the distance of the target sticker to the camera).

2.6. Make sure that the words “big angle” or “near eye” do not appear on the Host PC. If they do, it means that the position of the target sticker is not ideal. In this case, readjust the target sticker. It can also mean that the participant’s forehead is particularly small. If this is the case, place the sticker on the participant’s cheek.

Note: If the sticker is placed too close to the ear, the message “big angle” is likely to appear and the sticker must be repositioned.

2.7. Before starting the calibration process described in step 1.4, make sure that the participant is sitting comfortably. Ask them to maintain the same position throughout the whole experiment and explain that the eye tracker is very sensitive to bodily movements. Insist that they keep their head still. If the participant moves too much, the device will emit a humming noise.

Note: If the remote eye tracker setup is being used to test sensitive populations, such as children or older adults, it is advisable to use a manual calibration procedure.

### 3. Adjusting the Setup for Reading Studies

Note: When investigating visual context effects on reading, it is necessary to pay particular attention to the calibration and re-calibration processes. As opposed to visual world studies, eye tracking during reading requires a much higher degree of device precision, given the accuracy needed to track word-to-word and letter-to-letter reading patterns.

3.1. Make sure that both the average and maximum error displayed during the validation phase remain under 0.5°.

3.2. Make sure to use at least a 9-point scale for calibration. This assures a more accurate tracking of the eye gaze position, which is essential, given the small size of the areas of interest during reading.

### REPRESENTATIVE RESULTS:

A study by Münster and collaborators<sup>35</sup> investigated the interplay of sentence structure, depicted actions, and facial emotional cues during language comprehension. This study is well-suited to illustrate the advantages and limitations of the method, as it showed both robust depicted action effects and marginal effects of facial emotional cues on sentence comprehension. The authors created 5 s videos of a woman's facial expression that changed from a resting position into a happy or into a sad expression. They also created emotionally positively valenced German Object-Verb-Adverb-Subject (OVAdvS) sentences of the form 'The [object/patient<sub>accusative case</sub>] [Verb] [positive Adverb] the [subject/agent<sub>nominative case</sub>].' *Via* the positive adverb, the sentences matched the 'happy' video and mismatched the 'sad' video. Following the speaker videos, the sentences appeared with one of two versions of an agent-patient-distractor clipart scene. In one version, the agent was depicted as performing the mentioned action on the patient, while the distractor character performed a different action. The other scene version depicted no actions between the characters. Eye movements in the scene revealed the effects of the actions and of the speaker's facial expression on sentence comprehension.

The action depiction rapidly affected the participants' visual attention, meaning that the participants looked more at the agent than at the distractor when the mentioned action was (vs. was not) depicted. These looks were anticipatory (*i.e.*, occurring before the agent was mentioned), suggesting that the action depiction clarified the agent before the sentence did. The earliest effect of the action depiction emerged during the verb (*i.e.*, the verb mediated the action-associated agent). By contrast, whether the preceding speaker smiled or looked unhappy had no clear effect on the agent anticipation (**Figure 2**). The latter result could reflect the more tenuous link between a speaker's smile and a positive sentential adverb (compared with a direct verb-action reference mediating an action-associated agent). Alternatively, it could be specific to the task and stimulus presentation: perhaps emotion effects would have been more pronounced in a more socially interactive task or in one that presents the speaker's face during (rather than

before) sentence comprehension. However, presenting a smiling speaker's face during comprehension might cause participants to focus on the face at the expense of other scene content, perhaps masking otherwise observable effects of the manipulated variables (source: unpublished data).

In a further variant of the paradigm, Guerra and Knoeferle<sup>32</sup> asked whether spatial-semantic world-language relations can modulate the comprehension of abstract semantic content during reading. Guerra and Knoeferle borrowed the idea from the conceptual metaphor theory<sup>36</sup> that spatial distance (*e.g.*, proximity) grounds the meaning of abstract semantic relations (*e.g.*, similarity). In line with this hypothesis, participants read coordinated abstract nouns faster when they were similar (*vs.* opposite) in meaning and had been preceded by a video conveying proximity (*vs.* distance; playing cards move closer together *vs.* farther apart). In a second set of studies<sup>37</sup>, sentences described the interaction between two people as intimate or unfriendly, leading to the discovery that videos of two cards approaching one another sped up the reading of sentence regions that conveyed social proximity. Note that the spatial distance affected sentence reading rapidly and incrementally even when the sentences did not refer to the objects in the video. The videos distinctively modulated reading times as a function of the congruence between spatial distance and semantic as well as social aspects of sentence meaning. These effects appeared both in first-pass reading times (the duration of the first inspection of a pre-determined sentence region) and the total time spent on that sentence region (see **Figure 3** for an illustration of the results from the studies by Guerra and Knoeferle)<sup>32</sup>. However, the analyses also revealed a substantial variation between participants, leading to the conclusion that such subtle card-distance effects may not be as robust as the effects of verb-action relations, to mention one example.

A further set of studies illustrates how variation in sentence structure can help evaluate the generality of visual context effects. Abashidze and collaborators<sup>34</sup> and Rodríguez and collaborators<sup>26</sup> examined the effects of recent actions on the subsequent processing of spoken sentences. In both studies, participants first inspected an action video (*e.g.*, an experimenter flavoring cucumbers, or female hands baking a cake). Next, they listened to a German sentence that was either related to the recent action or to another action that might be performed next (flavoring tomatoes<sup>34</sup>; building a model<sup>26</sup>). During comprehension, the participants inspected a scene showing two objects (cucumbers, tomatoes)<sup>34</sup> or two photographs of agent faces (a female and a male agent face, named 'Susanna' and 'Thomas', respectively)<sup>26</sup>. In the study by Abashidze and collaborators<sup>34</sup>, the speaker first mentioned the experimenter and then the verb (*e.g.*, flavoring), eliciting expectations about a theme (*e.g.*, the cucumbers or the tomatoes). In the study by Rodríguez and collaborators<sup>26</sup>, the speaker first mentioned a theme (the cake), and then the verb (baking), eliciting expectations about the agent of the action (female: Susanna, or male: Thomas, depicted *via* photos of a female and a male face).

In both studies, the question at issue was whether people would (visually) anticipate the theme/agent of the recent action event or the other theme/agent based on further contextual cues provided during comprehension. In Abashidze and collaborators<sup>34</sup>, the experimenter's gaze cued the future theme object (the tomatoes) from the onset of the verb (literally translated from

German: ‘The experimenter-agent flavors soon ...’). In Rodríguez and collaborators<sup>26</sup>, gender knowledge of stereotypical actions became available when the theme and the verb were mentioned (e.g., the literal translation of the German stimuli was: ‘The cake-theme bakes soon ...’). In both sets of studies, the participants preferentially inspected the target/agent of the recent action (the cucumbers<sup>34</sup> or Susanna<sup>26</sup>) over the alternative (future/other-gender) target (the tomatoes<sup>34</sup> or Thomas<sup>26</sup>) during the sentence.

This so-called ‘recent-event preference’, thus, appears to be robust across a substantial variation in sentence structure and experimental materials. It was modulated, however, by visual constraints from the concurrent scene<sup>26</sup>, such that presenting plausible photographs of verb themes in addition to gendered photographs of agents reduced the reliance on the recently-inspected action events and further modulated attention based on gender-stereotype knowledge exerted by language. **Figure 4** illustrates the main findings of the experiments by Rodríguez and collaborators<sup>26</sup>.

While this version of the visual-world paradigm yielded robust results, other studies have highlighted the complexity (and limitations) of the linking hypothesis. Burigo and Knoeferle<sup>20</sup> uncovered that participants—when listening to utterances such as *Die Box ist über der Wurst* (‘The box is above the sausage’)—mostly followed the utterance in inspecting clipart depictions of these objects. But on a proportion of trials, the participants’ gaze decoupled from what was mentioned. Upon hearing ‘sausage’ and having inspected the sausage at least once, the participants’ next inspection returned to the box on approximately 21% of the trials in speeded verification (Experiment 1) and in 90% of the trials in post-sentence verification (Experiment 2). This gaze pattern suggests that the reference (hearing ‘sausage’) guided only some (inspecting the sausage) but not all eye movements (inspecting the box). This sort of design could be used to tease apart lexical-referential processes from other (including sentence-level interpretative) processes. However, researchers must be careful when making claims about different levels of linguistic processing based on relative differences in eye movement proportions, given the ambiguity in linking eye gaze to cognitive and comprehension processes.

#### FIGURE LEGENDS:

**Figure 1: Overview of the data collection environment.** The graph shows how the different software and hardware elements used for data collection and preprocessing relate to one another.

**Figure 2: Representative results of Münster and collaborators<sup>35</sup>.** These panels show the by-subject mean log-gaze probability ratios per condition in the verb region (for the depicted action) and in the verb-adverb region combined (for the effect of emotional prime). The results show a considerably higher proportion of looks towards the target image when the action mentioned in the sentence was depicted than when it was not depicted. The results for the effect of emotional facial primes were less conclusive: they suggest only a slight increase in the mean-log ratio of looks to the target when the facial prime had a positive emotional valence (a smile) than when it had a negative valence (a sad face). The error bars represent the standard error of the mean. This figure has been modified from Münster *et al.*<sup>35</sup>.

**Figure 3: Representative results of Guerra and Knoeferle<sup>32</sup>.** This panel shows the mean first-pass reading times (in milliseconds) of the (dis)similarity adjective. The results show shorter reading times for similarity sentences after seeing two playing cards move closer together compared with farther apart. The error bars represent the standard error of the mean. This figure has been modified from Guerra and Knoeferle<sup>32</sup>.

**Figure 4: Representative results of Rodríguez and collaborators<sup>26</sup>.** This panel shows the by-subject mean log gaze probability ratios per condition in the verb region. The proportions of looks above 0 show a preference for the target agent image and the proportions below 0 show a preference for the competitor agent image. The results show that participants were more likely to inspect the target agent image when the object and the verb mentioned in the sentence matched the previous videotaped events than when they did not. Additionally, there were more looks toward the target agent image when the action described by the sentence conformed to gender stereotypes. The error bars represent the standard error of the mean. This figure has been modified from Rodríguez *et al.*<sup>26</sup>.

## DISCUSSION:

In summary, the reviewed variants of eye tracking in visual contexts have uncovered many ways in which a visual scene can affect language comprehension. This method provides crucial advantages compared to methods such as measuring reaction times. For instance, ongoing eye movements provide us with a window into language comprehension processes and how these interact with our perception of the visual world over time. Moreover, participants are not necessarily required to perform an explicit task during language comprehension (such as judging the grammaticality of a sentence *via* a button press). This allows researchers to use the method with populations that might struggle with overt behavioral responses other than eye gaze, such as infants, children and, in some cases, older adults. Eye tracking is ecologically valid in that it reflects participants' attention responses—not unlike humans' visual interrogation of communication-relevant things in the world around them during more or less attentive listening to unfolding utterances.

One of the boundaries (or perhaps characteristics) of the visual world paradigm is that not all events can be depicted straightforwardly and unambiguously. Concrete objects and events can, of course, be depicted. But how abstract concepts are best depicted is less clear. This can limit (or define) insights into the interaction between language processing and the perception of the visual world using an eye-tracking visual world paradigm. Further challenges relate to the linking hypotheses between observed behavior and comprehension processes. Eye fixations are a single behavioral response that likely reflects many subprocesses during language comprehension (*e.g.*, lexical access, referential processes, language-mediated expectations, visual context effects, among others). Given this insight, researchers must be careful not to over- or misinterpret the observed gaze pattern. To address this problem, prior research has highlighted the role of comprehension subtasks to clarify the interpretation of the gaze record<sup>38</sup>.



One way to enhance the interpretability of eye movements is to integrate them with other measures such as event-related brain potentials (ERPs). By investigating the same phenomenon with two methods that are comparable in their temporal granularity and complementary in their linking hypotheses, researchers can rule out alternative explanations of their results and enrich the interpretation of each individual measure<sup>39</sup>. This approach has been pursued across experiments<sup>41</sup>, but, more recently, also within a single experiment (albeit in strictly linguistic contexts)<sup>42</sup>. Future research could benefit greatly from such methodological integration and continued combination with post-trial and post-experimental tasks.

The eye-tracking method can replicate established results, as well as test new hypotheses, about the interaction of visual attention in scenes with language comprehension. The procedure outlined in the protocol must be carefully followed since even minor experimenter errors can affect the data quality. In reading studies, for example, the relevant analysis regions are often individual words or even letters, meaning that even small calibration errors might distort the results (see the article by Raney and colleagues<sup>40</sup>). Steps 1.4 and 1.5 of the protocol, the calibration of the eye tracker and the drift check/drift correct, are of particular importance since they directly impact the recording accuracy. Failure to correctly calibrate the eye tracker can result in the tracker not accurately tracking eye movements to the pre-established areas of interest. Such tracking failure will lead to missing data points and a loss in statistical power which can be problematic when investigating world-to-language relationships that are very subtle and yield small statistical effect sizes (see the description of the experiments by Guerra and Knoeferle<sup>32</sup> and Münster and colleagues<sup>35</sup> among the **Representative Results**).

Given the need to maximize the power and sensitivity of the equipment, it is important that experimenters know how to deal with problems that routinely occur during an experimental session. For example, the pupil position and movement of participants wearing glasses can result in calibration difficulties due to light reflections on the lenses of a participant's glasses. One way to solve this problem is to mirror the image of the participant's eye on the Display PC and encourage them to move their head until the reflection of light on the glasses is no longer visible on their screen, meaning that it is no longer captured by the camera. A further cause of calibration failure can be pupil constriction, which may be a consequence of an overexposure to light. In that case, dimming the light in the laboratory will increase pupil dilation and, thus, help the eye tracker in accurately detecting the pupil.

As a final thought, we would like to address the potential that the visual-world paradigm has for research on second-language learning. The paradigm has already been successfully used in psycholinguistic research to investigate phenomena such as cross-language lexical and phonological interaction<sup>44-46</sup>. In addition, the close link between visual attention and language learning has frequently been highlighted in the applied-linguistics literature on second-language acquisition<sup>47-49</sup>. Future research on second-language learning will likely continue to benefit from the advantageous position of eye tracking as a method that provides an index of visual attention in a millisecond resolution.

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#### **DISCLOSURES:**

The authors have nothing to disclose.

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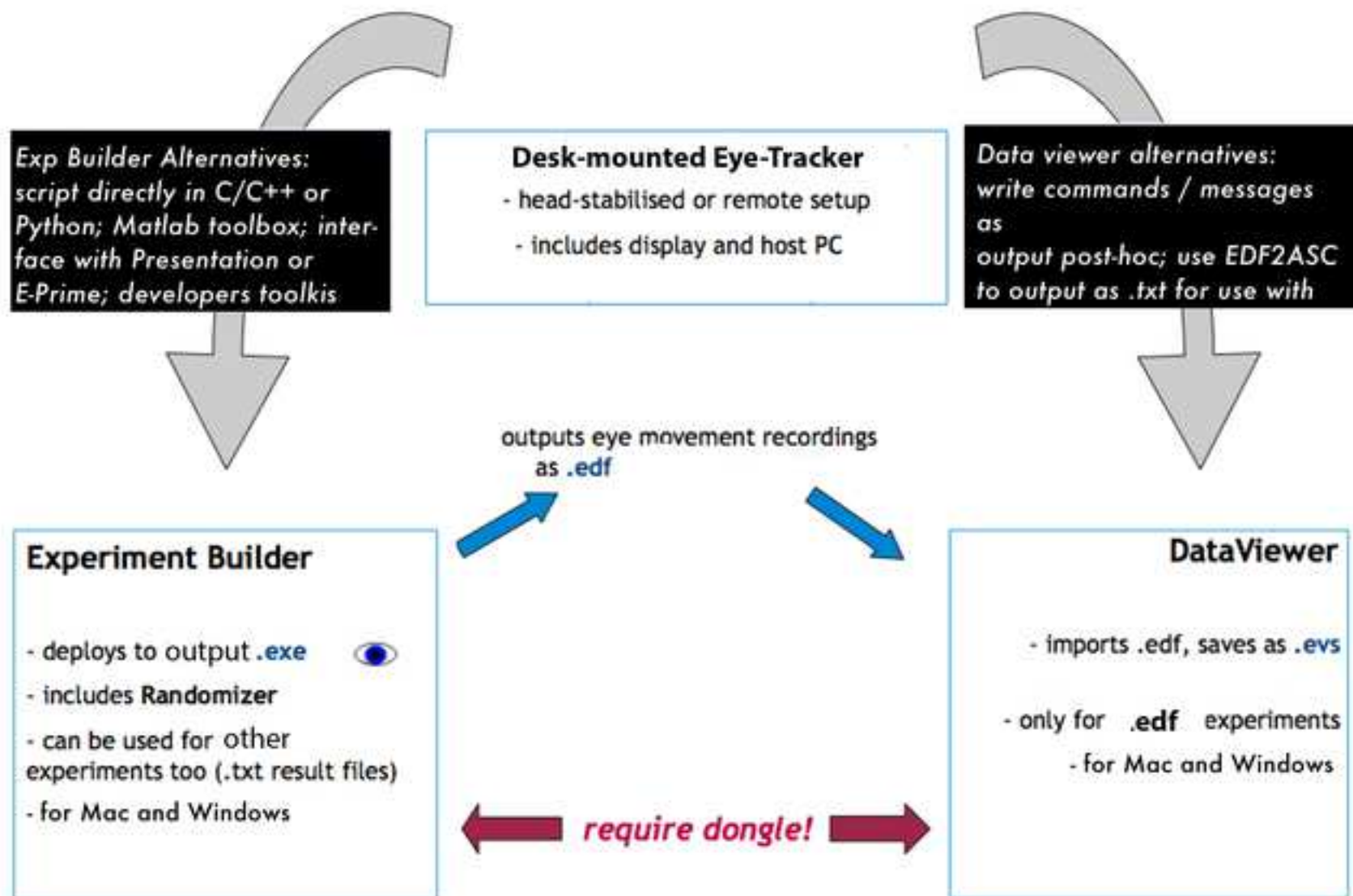
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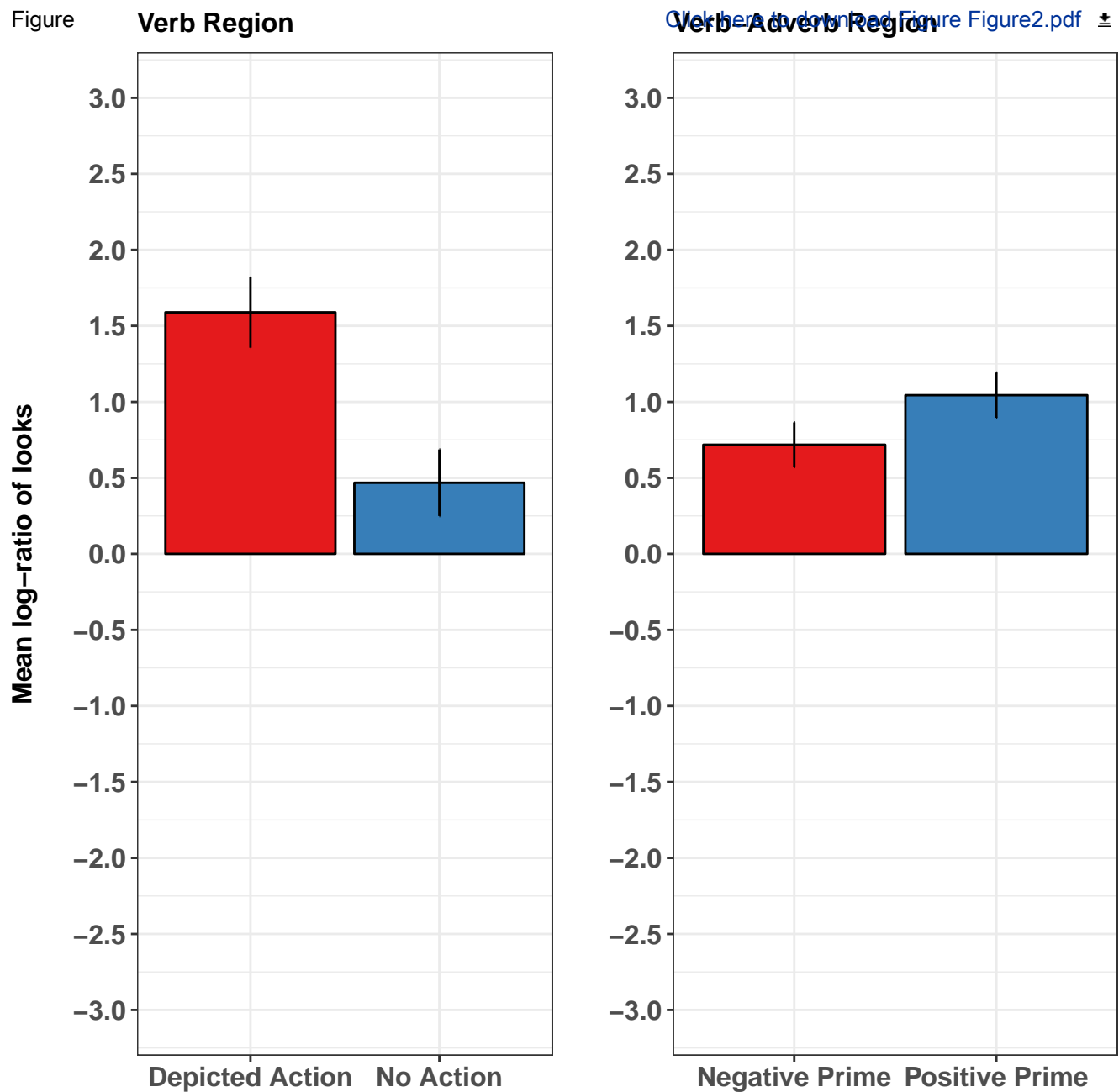
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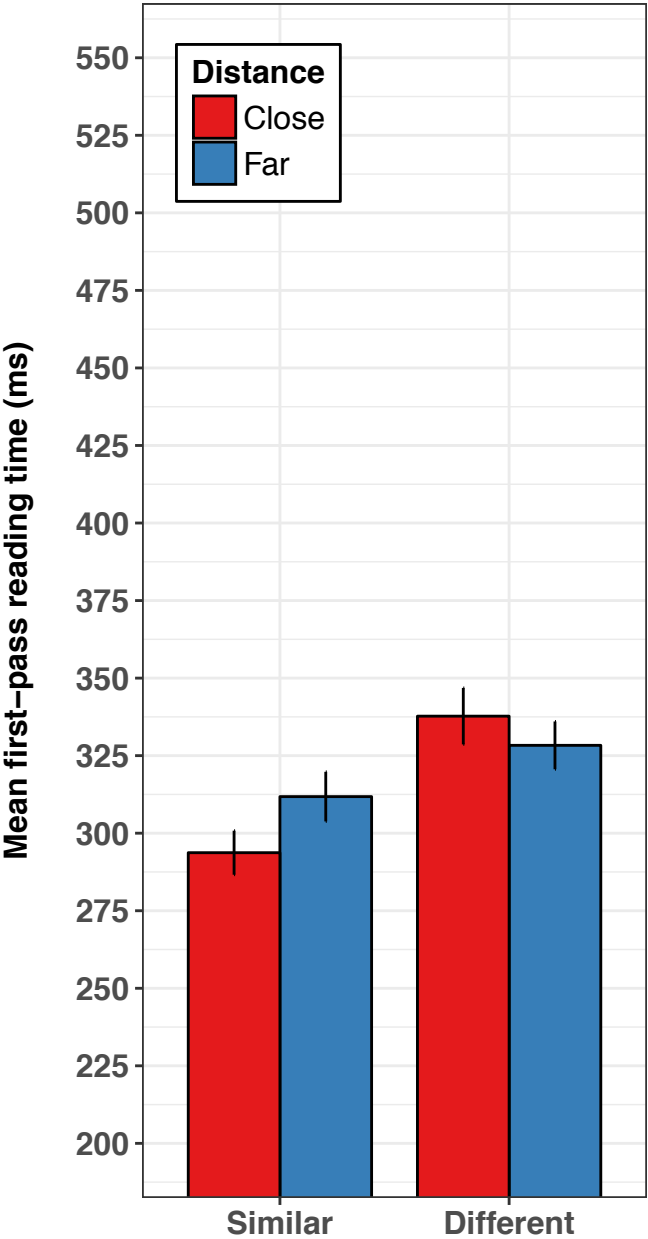


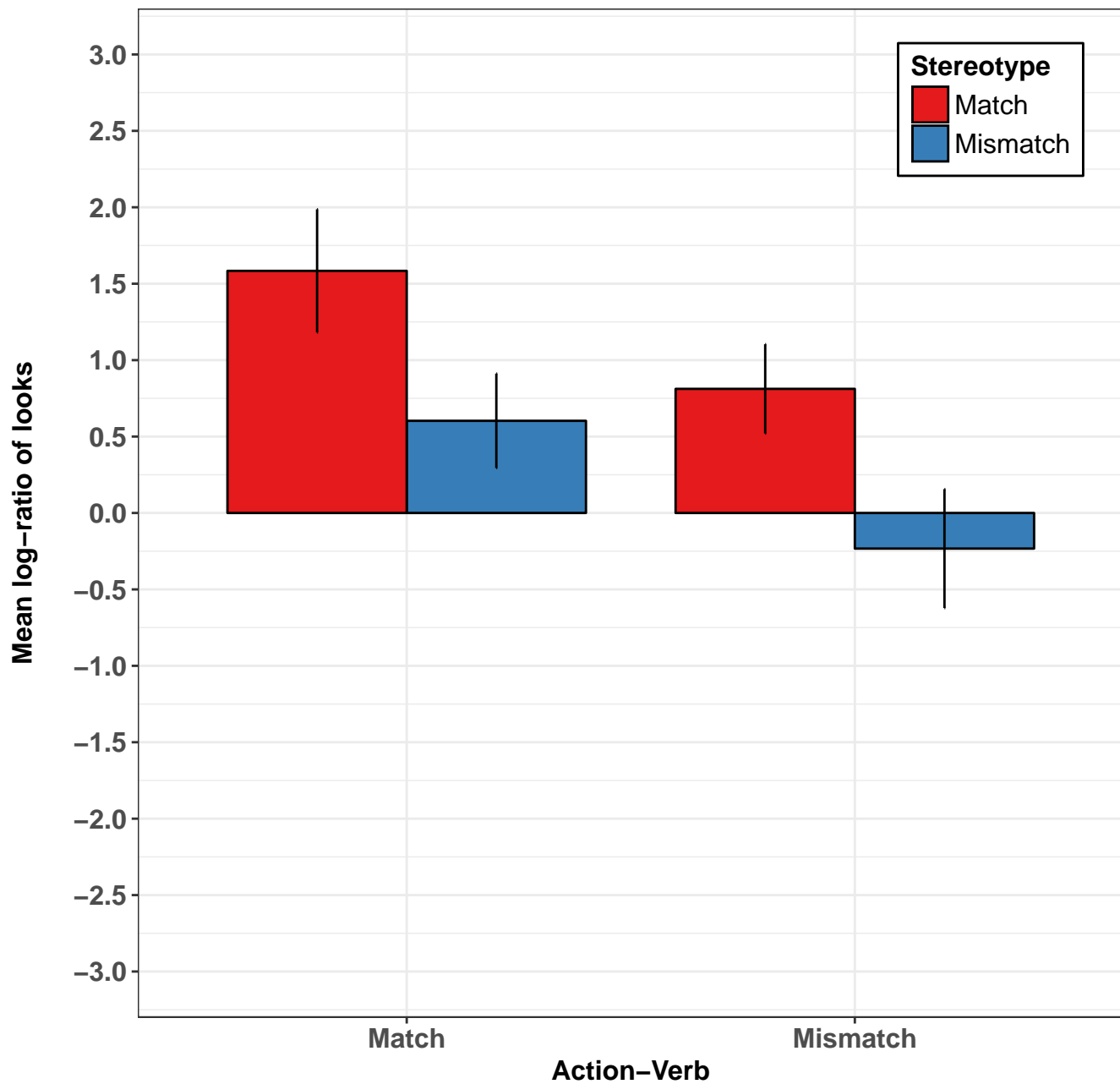




Figure

Similarity: Adjective





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Software for	SR Research	I Experiment B	<a href="http://www.sr-research.com/eb.html">http://www.sr-research.com/eb.html</a>



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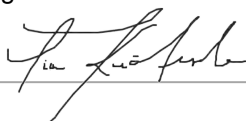
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## Editorial comments

Dear Dr. Bing Wu,

Thank you very much for the comments on our revised manuscript. We have addressed all of them in order and have included the original comments in italic black font. Our responses are in normal blue font for ease of readability. Please let us know if there is anything else that you would like us to address.

1. *Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.*

done.

2. *The short abstract is over 50-word limit.*

The abstract has now been shortened.

3. *Please use a single space between numerical values and their units.*

This has now been corrected.

4. *Please remove all headers from the Introduction.*

This has now been done.

5. *Please include an ethics statement **before the numbered protocol steps**, indicating that the protocol follows the guidelines of your institution's human research ethics committee.*

We have now created an independent section with the ethics statement before the numbered protocol steps (we had previously included it but perhaps not prominently enough).

6. *Please revise the text in Protocol to avoid the use of any personal pronouns (e.g., "we", "you", "our" etc.).*

done.

7. *Please do not highlight notes for filming.*

corrected.

8. *Step 1.3.12: Please ensure that all text is in imperative tense.*

9. *1.3.13: Please ensure that all text is in imperative tense.*

10. *1.4.1: Please ensure that all text is in imperative tense.*

11. *1.4.3: Please split this step into two steps.*

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*14. 1.5.1: Please ensure that all text is in imperative tense.*

*15. 1.5.4: Please ensure that all text is in imperative tense. Please split this step into two steps.*

*16. 2.5: Please ensure that all text is in imperative tense.*

*17. 2.6: Please ensure that all text is in imperative tense.*

*18. 3.1: Please ensure that all text is in imperative tense.*

done.

*19. Please remove all headers from Representative Results.*

The headers have been removed.

*20. Figures: Please define the error bar.*

The error bars in all figures had already been defined as representing 2 standard errors from the mean. Kindly elaborate on what you would like us to change here. If you would like us to change these to confidence intervals please let us know.