Semantic context and body position shape pupillary effort in word acquisition

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Abstract

Language processing and learning are cognitively demanding activities that engage significant mental effort. Body position, specially standing, has been associated with increased cortical activation and attentional control. This study investigated whether body position influences the effort required to learn low-frequency words from context. Seventeen young adults read 168 Brazilian Portuguese sentences containing 28 low-frequency nouns (10–15 letters), each presented in six contexts (3 rich, 3 neutral), while either sitting or standing. Eye movements were recorded at 120 Hz, and task-evoked pupillary response (TEPR) was defined as baseline-corrected mean pupil diameter during reading of the target noun word. A linear mixed-effects model predicted TEPR from Body Position (sitting, standing), Text Context (rich, neutral), and their interaction, controlling for standardized word length and word index, with by-participant random intercepts and a random slope for context. Preliminary results showed that the standing body position significantly increased TEPR relative to sitting; and an interaction between body position and text context showed that TEPR was highest at the standing-rich and lowest at the sitting-rich. These findings suggest that cognitive load during word learning might be modulated by body position, with standing increasing mental effort as indicated by TEPR. While rich semantic context typically reduces effort, this supportive effect was diminished (or even reversed) when participants were standing, suggesting that postural demands may interfere with the benefits of contextual support.

Introduction

In psycholinguistic research, various evidence has highlighted the role of cognitive effort and attentional demands in language comprehension. Studies have shown that increased syntactic complexity and lower lexical frequency elevate processing demands, as reflected in physiological and behavioral indicators of effort. For instance, Chapman and Hallowell (2021) found that more syntactically complex sentences elicited heightened cognitive effort during comprehension tasks, particularly in populations with aphasia. Similarly, Häuser *et al.* (2019) demonstrated that sentence predictability influenced attentional load, with unexpected continuations requiring greater mental resources. Other research has shown that lexical characteristics such as frequency and word length modulate effort during auditory processing (McLaughlin *et al.*, 2022; Schmidtke, Bsharat-Maalouf, & Degani, 2024). Notably, many of these studies employed pupillometry as a sensitive, real-time index of cognitive effort and attentional fluctuations during linguistic tasks (Schmidtke, 2018; Ryan, Hamrick, & Miller, 2017). The convergence of findings suggests that linguistic complexity and lexical properties systematically shape cognitive resource allocation during language processing.

Beyond linguistic variables, recent research has begun to explore how motor and body position impact cognitive workload. Body position refers to the physical orientation or configuration of the body such as sitting, standing, or balancing i.e. varying degrees of musculoskeletal control and stability. Maintaining postural control while standing when compared to sitting, requires continuous sensorimotor coordination and can increase cognitive demands, especially under conditions of instability or sensory restriction (Kahya *et al.*, 2018; Rosker *et al.*, 2024; Strauch *et al.*, 2022). In fact, standing on unstable surfaces, performing unipedal stances, or having visual feedback occluded, led to greater pupil dilation, i.e. higher mental effort compared to more stable or less demanding postural conditions, such as standing on firm ground with full visual input. These findings highlight that body position and/or the maintenance of stance themselves can act as modulators of cognitive load. The study of the effects of alternating between sitting and standing body positions on cognition, recently has emerged as a relevant area of research (Cherigui *et al.*, 2025; Bouquet *et al.*, 2025). Alternating body positions has been discussed as relevant with respect to concerns over the health risks associated with sedentary behavior and the potential for simple interventions to enhance workplace productivity and well-being (Wilkerson *et al.*, 2023).

A few studies have investigated whether body positions, such as sitting versus standing, affect cognitive effort during linguistic learning tasks. Given that standing has been associated with increased cortical activation and attentional control (Kahya *et al.*, 2018), it raises the question of whether body position may impact on contextual richness in word learning, thereby impacting the cognitive cost of acquiring new words. To our knowledge, no research has yet combined task-evoked pupillary response of word learning with manipulations of both linguistic context and body position. The present study addresses this gap by investigating whether body position (sitting vs. standing) influences the acquisition of words presented in phrases with rich versus neutral contexts, using pupillometry (pupil diameter on TEPR) as the primary measure of cognitive effort. By examining how body position and linguistic context jointly affect word learning, this work aims to shed light on the embodied dimensions of cognitive load during language acquisition and the potential interplay between body position and semantic processing efficiency.

Literature background

Linguistics

Lexical frequency

The difficulty associated with recognizing a word is inversely related to its frequency of occurrence, a phenomenon already indexed by pupil dilation (Kuchinke *et al.*, 2007; Schmidtke, 2014; Shechter & Share, 2021). Research publications using tasks such as the Lexical Decision Task (LDT) demonstrated that low-frequency words elicit significantly greater pupil dilation than high-frequency words (Haro *et al.*, 2017; Kuchinke *et al.*, 2007; Kuchinke *et al.*, 2011; Rojas *et al.*, 2024). This result suggests an effect of lexical processing that is independent of response execution mechanisms accessory to the LDT (Haro *et al.*, 2017; Rojas *et al.*, 2024).

For reading, cognitive effort is crucial because proficiency hinges on effortless word recognition, allowing the limited resources of the processing system to be allocated primarily toward comprehension (Perfetti, 2007; LaBerge & Samuels, 1974). The degree of effort invested in reading is highly sensitive to lexical characteristics (Shechter & Share, 2021; Chapman & Hallowell, 2015). In visual word recognition tasks, cognitive effort is modulated by the familiarity of the stimuli (Shechter & Share, 2021; Shechter, Hershman, & Share, 2022).

Syntactic complexity

In sentence processing, historically, the reading of sentences structured with greater syntactic complexity has been linked to larger pupil sizes compared to sentences of equivalent length but simpler syntactic structure (Just & Carpenter, 1993; Schluroff, 1982). Meanwhile, when younger adults listened to sentences varying in syntactic complexity (subject-relative vs. object-relative) for later recall, they demonstrated a significant increase in mean pupil size during the retention interval for the more syntactically complex object-relative sentences (Piquado *et al.*, 2010). This main effect of syntax reflects a larger mean pupil size, and thus greater cognitive effort, for object-relative than subject-relative sentences (Piquado *et al.*, 2010).

Word length

The physical or structural dimensions of a word, such as its length, are consistently found to influence cognitive effort, especially when processing unfamiliar items. Some published studies already showed that cognitive effort was interacting with word familiarity (real words vs. pseudowords) (Shechter & Share, 2021; Shechter *et al.*, 2022).

Previous studies have confirmed a general pattern that more cognitive effort is invested in pronouncing longer letter strings (i.e., a sequence of characters that represents a text) (Shechter & Share, 2021). This effect is often significantly magnified for unfamiliar strings. Researchers predicted and confirmed a strong familiarity-by-length interaction: the length effects on pupillometric measures were consistently stronger for pseudowords than for real words (Shechter & Share, 2021; Shechter *et al.*, 2022). This outcome holds across different populations (skilled adult readers and school-age children) and modalities (oral and silent reading) (Shechter & Share, 2021; Shechter *et al.*, 2022). For example, among university students, relative changes in pupil size were significantly larger for five-letter strings than for three-letter strings, with a markedly greater length effect observed for pseudowords (Shechter & Share, 2021).

Within this context of processing auditory novel words (pseudowords), the number of syllables also significantly modulates pupillary activation, with tetrasyllabic pseudowords producing significantly larger pupil dilations, suggesting significantly greater cognitive effort required for their short-term retention in the phonological loop (López-Ornat *et al.*, 2018). These converging results support the hypothesis that reading unfamiliar strings, particularly longer ones, relies on effortful, sequential letter-by-letter processing (Shechter & Share, 2021; Shechter *et al.*, 2022).

The index of effort in novel words

Efficient word recognition is characterized not only by speed but also by minimal effort (Shechter & Share, 2021; Shechter *et al.*, 2022). As such, studies showed that processing unfamiliar lexical items demands significantly more cognitive resources than familiar words. For instance, tasks requiring the reading of pseudowords (unfamiliar letter strings) elicit larger and more sustained pupillary responses compared to real, familiar words in both adults and children, reflecting greater cognitive effort (Shechter & Share, 2021; Shechter *et al.*, 2022).

Rich versus neutral context for word learning

Word learning often occurs incidentally through reading or listening. The semantic, syntactic, and discourse contexts surrounding a novel word contribute to its acquisition (Bolger *et al.*, 2008; Frishkoff *et al.*, 2008; Nagy *et al.*, 1987). Learning new words based on rich context (i.e., providing strong cues or associations) versus neutral context (i.e., providing minimal or ambiguous cues) inherently varies the cognitive effort required for semantic activation and integration (Cain *et al.*, 2004; Rapaport, 2003, 2005).

Published studies have shown that the pupil response was sensitive to the difficulty of semantic processing. Processing low-frequency words requires greater dilation (Haro *et al.*, 2017; Kuchinke *et al.*, 2007). Similarly, tasks requiring semantic activation (e.g., judging semantic relatedness) showed greater pupil dilation for weakly related pairs than for strongly related pairs, demonstrating sustained cognitive effort in handling uncertain semantic relations (Geller *et al.*, 2019; Haro *et al.*, 2023; Rojas *et al.*, 2024). This principle suggests that a neutral (low-cue) context during word learning should generate greater sustained effort (larger dilation) than a rich (high-cue) context. Complementarily, the increased cognitive demand has been shown to be associated with syntactic complexity (Just & Carpenter, 1993; Piquado *et al.*, 2010).

Body position

Pupillometry as an index of postural demand

In various studies, small changes in pupil diameter were used to capture real-time cognitive effort during language processing and learning (Beatty, 1982; Kahneman, 1973; Krejtz *et al.*, 2018; van der Wel & van Steenbergen, 2018). In these studies, the Task-Evoked Pupillary Response (TEPR) protocol was used to contextualize pupil size changes related to goal-oriented tasks, thus, tracking the dimension of attention, as mental effort activates the sympathetic system, causing corresponding pupil dilation (Eckstein *et al.*, 2017; Kahneman, 1973; Shechter & Share, 2021).

Postural stability, particularly during bipedal standing, requires continuous cognitive resources, a need that is intensified when the balance task becomes more challenging (Kahya *et al.*, 2018; Kahya *et al.*, 2022; Rosker *et al.*, 2024; Woollacott & Shumway-Cook, 2002). Studies confirmed that increased balance task intensity is associated with a corresponding increase in pupil dilation, reflecting greater cognitive workload. Manipulations that increase postural instability or complexity consistently demonstrate this effect, for example, in visual occlusion i.e. challenging postural control by means of visual occlusion (standing with eyes occluded) is associated with a significantly greater cognitive workload (indexed by the Index of Cognitive Activity, ICA) in healthy young adults compared to standing with eyes open (Kahya *et al.*, 2018; Kahya *et al.*, 2022). These results suggest that removing visual feedback leads to additional neural processing to maintain posture. Additionally, the manipulation of the surface (i.e. foam vs. rigid surface) and the stance complexity (i.e., parallel stance vs. single-leg stance) elicit a measurable increase in the steady-state pupil diameter (Rosker *et al.*, 2024). This steady-state dilation is linked to tonic alertness, enabling the necessary sensorimotor integration of proprioceptive, vestibular, and visual information required for preparing corrective movements during increased instability (Peterka & Loughlin, 2004; Strauch *et al.*, 2022).

Body position in the context of cognitive tasks (sitting vs. standing)

Some studies indicate that standing may enhance selective attention and cognitive control in tasks like the Stroop test (Rosenbaum *et al.*, 2017; Smith *et al.*, 2019). In comparisons of workplace performance, sitting has been associated with greater accuracy and lower omission errors in attention tests compared to standing (Rostami *et al.*, 2022).

The present study aimed to investigate how body position influences cognitive effort during word learning and whether this effect interacts with the semantic richness of the linguistic context. Specifically, we examined whether adopting a standing posture, compared to sitting, modulates task-evoked pupillary responses (TEPR) during the acquisition of novel words presented in rich versus neutral linguistic contexts in brazilian portuguese sentences. This research contributes to the embodied cognition framework by exploring how physical postural states affect the allocation of cognitive resources during language processing. It was hypothesized that standing, due to its greater demands on postural control and attentional regulation, would increase cognitive workload relative to sitting. Additionally, it was predicted that semantically rich contexts would reduce cognitive effort during word acquisition, as they provide stronger cues that facilitate semantic integration and learning.

Methods

Participants

Seventeen participants voluntarily participated in this study and were recruited among undergrad and graduate students attending courses at Sao Paulo State University. Eleven of them were male while seven were female. Measurements of body mass (74,5 ± 3,1 kg), height (1,74 ± 0,1 m) and age (21 ± 2,5 years) were noted. None of the participants reported neurological or musculoskeletal diseases nor vestibular problems or recurrent dizziness. All the participants had normal or correct to normal vision. Each participant signed an informed consent to this study.

Apparatus and design

For each experimental session, eye movements were recorded using a Tobii Pro Fusion eye tracker hardware (120Hz of sample rate) that was magnetically mounted on a Dell 21” flat screen display (Figure 1A). The luminance of the environment was controlled and standardized throughout all experimental sessions to i) avoid display environmental light reflections; ii) guarantee the same light conditions for pupil measurements; iii) control as much as possible the environmental lighting effects on participant’s pupil diameter. The display was positioned on a standing desk which could have its height simply adjusted, by pressing buttons (up and down arrows, raising or lowering the desk at 0.1 cm pace) (Figure 1B). A stull with 90 cm of height was used for the sitting body position conditions and it was removed accordingly whenever needed and placed back at the same position for sitting condition.

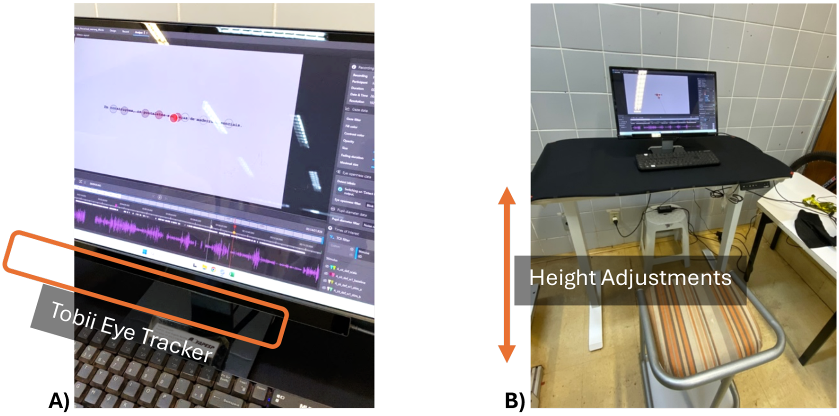

Figure 1. A: Stimuli display with the Tobii Eye Tracker magnetically attached at the bottom of the display. The sensor works at a 120Hz sampling rate. The luminance of the environment was controlled to avoid the reflections at the display. **B**: The standing desk setup has a controller which allows the desk to move up or down and these positions can be saved in one of 5 memory positions.

All participants performed reading tasks with two different sentence contexts (rich vs. neutral) either sitting on a stull or standing in front of the standing desk. The distance from the display to the participant's head and the standing table height were adjusted according to the participant's preferences, however, the right arm of the participants should rest on the standing desk close to the keyboard to avoid disturbances of body movement or participants movements unrelated to the task, characterizing a study limitation.

All the stimuli were created using Tobii Pro Lab software (full version) in which all stimuli were randomized and counterbalanced to avoid learning effects. All the sentences were created with a gray background color, bold black font color and Courrier New typographic font (Figure 2). A margin of 5% of the display resolution (1920x1080 pixels) were implemented to avoid out of depth eye fixations which could miss eye gaze toward the display depth and confuse the eye tracking system. All participants learned all words in all conditions. Likewise, all words occurred in all four conditions: by body position (sitting vs. standing) and by sentence context (rich vs. neutral). To avoid item-sentence cofounds, it was created a counterbalanced list as for each word, sentence variants were sampled without replacement so that, per participant, a different set of sentences instantiated each of the four conditions. Across participants, assignment of the 3 rich context (RC) and 3 neutral context (NC) sentences to the four conditions (RC-sitting; RC-standing; NC-sitting; NC-standing) was rotated such that each sentence variant appeared equally often in each condition. Trial order was also randomized.

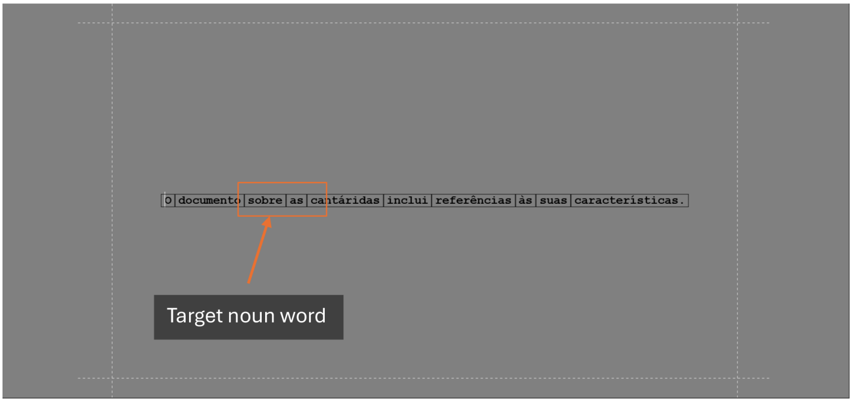

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Figure 2. Example of the design of a sentence. The target noun word would be positioned at the middle position of the sentence. The rectangles around each word are Area of Interest (AOI) drawn automatically on a reading task thus allowing to capture metrics related to phrases, words or characters within a sentence.

The sentences phrases were produced focusing on lexical, phonological and contextual features of the stimuli. A total of

28 nouns were selected from the LexPorBr lexical database, adhering to the following inclusion criteria: i) word category: all items were nouns; ii) word length: each noun contained between 10 and 15 letters; iii) lexical frequency: only nouns with a frequency of less than 0.85 occurrences per million words were retained, to ensure low familiarity and reduce frequency effects; iv) phonological simplicity: all nouns conformed to a simple syllabic structure, specifically the CVCV pattern, which minimized phonotactic complexity and facilitated reading and processing.

For each of the 28 selected nouns it was embedded six unique sentence contexts, yielding a total of 168 sentences. These were divided into two conditions: i) rich context sentences (n=84): for each noun, three sentences were created that provided semantically rich information, such as definitions characteristics functions, or descriptive cues. These sentences were designed to enhance the saliency of the target word's meaning through context; ii) neutral context sentences (n=84): for each noun, three additional sentences were constructed that provided minimal semantic support, offering grammatically correct yet contextually neutral environments. Before all presented sentences, a poll black ball with the number 8 was used as an icon positioned at the vertical middle and horizontal center of the display to standardize and baseline value for the pupil diameter prior to the sentence reading task.

Additionally, all sentences were controlled for length, containing between 9 to 11 words, to ensure consistency in syntactic complexity and processing demands. Initial sentence drafts were generated using a large language model-based AI system (e.g., ChatGPT model o3) tailored to Brazilian Portuguese. The model was prompted to generate both richly informative and neutral contexts for each noun. Subsequently, all AI-generated sentences were manually reviewed and revised by native Brazilian Portuguese speakers with linguistic training, ensuring naturalness, grammatically accuracy, and semantic appropriateness in both sentence types.

The participants performed two sentences context reading tasks (RC vs. NC), with 3 trials per task in two body positions (sitting vs. standing) for all 28 nouns. Figure 3 presents the body position of participants while performing the experiment. The conditions are explained below.

As for the body position, the order of word blocks was randomized and would be shown on the screen if it was a standing or sitting reading block. So, the experimenters would remove or place the stull in the designated position. Markings of the floor were created to ensure the right positioning of the stull.

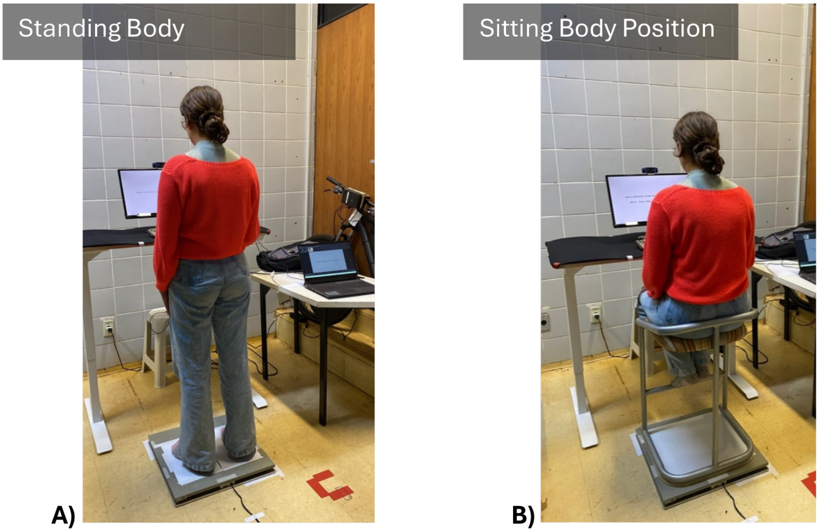

Figure 3. A: Participant performing the reading task while standing. **B:** Participant performing the reading task while sitting. The right arm of the participant is resting on the table while the left arm was resting and should not move throughout the experimental procedures.

Participants were instructed to, whenever they saw phrases appear in the center of the screen, read them very carefully, sit in front of the screen in the indicated position, and press any key to continue, noting that they would be asked questions about the phrases at the end of the experiment. No feedback was given during learning.

Procedures

Upon arrival at the experimental room, participants provided written informed consent and received an information sheet. Body mass and height were noted. Visual acuity was assessed using a Snellen chart; only participants with acuity between 20/20 and 20/25 were permitted to continue. Participants were then asked to remove their shoes before the experiment began. Prior to the experimental procedure, the standing desk table height was adjusted and saved for later use: participants alternated between sitting and standing as they would during the task to set the table to a comfortable height according to their preferences. Eye-tracker calibration was then performed. Participants with data loss less than 5% were allowed to continue; those with higher values repeated the calibration until they met the threshold. The experiment was self-paced: participants silently read sentences and advanced at their own pace until an on-screen message prompted them either to take a short break or to change body position (from sitting to standing or vice versa). After completing all 168 sentences, a message appeared thanking the participant for their participation in the experiment.

Data analysis

The pupil diameter was recorded for the entire sentence reading task. For each word inside a sentence, an area of interest was drawn (the black rectangle around each word, Figure 2). However, for the purpose of this study, the pupil diameter time series was generated only for the target noun word AOI of each condition for each of the 28 nouns. The TEPR was considered as the sentence reading, specifically, the moment the participant read the target noun word entirely.

To create a pupil outcome comparable within participants, it was applied a trial-wise baseline correction. For each participant × trial, we computed the mean baseline pupil diameter from the average pupil diameter; when a trial baseline was missing, we used participant's overall baseline computed from all their baseline rows. The dependent variable was the baseline-corrected pupil diameter.

For the analyses, we used only non-baseline rows that corresponded to word AOIs and had valid body position, context, and non-missing pupil diameter baseline corrected values. To limit undue influence of extremes (i.e., outliers) while preserving within-person scaling, the pupil diameter baseline corrected value was z-scored within participant and observations outside ±3 SD (standard deviation) were removed. Both word length and word index were standardized (mean 0, SD 1).

Statistical analysis

For statistical analyses, it was modeled trial-level baseline-corrected pupil diameter ($pupil\_diameter_{bc}$) using a linear mixed-effects model. All calculations were implemented in RStudio with R language.

The fixed-effects model was defined as:

$$pupil\_diameter_{bc} = body_{position} * text_{context} + word_{length_c} + word_{index_c} * (1 + context_c \,||\, participant)$$

With:

$pupil\_diameter_{bc}$ = baseline-corrected pupil diameter for a target word, computed as the trial/participant's current average pupil minus its baseline (millimeters). With the reference of higher values means larger dilation relative to baseline.

$body_{position}$ = participant body position during reading. A factor with two levels (sitting; standing).

$text_{context}$ = linguistic context type of the sentence containing the target word. A factor with two levels (neutral; rich).

$word_{length_c}$ = standardized word length of the target word (z-score). Base length is the number of characters in AOI when available.

$word_{index_c}$ = standardized ordinal position (z-score) of the target word within its sentence/phrase, where larger values mean later positions.

$1 + context_c \,||\, participant$ = participant-level random effects with a random intercept (each participant has their own overall level), and an uncorrelated random slope for $context_c$, allowing the $text_{context}$ effect to vary across participants.

Fixed-effect inference relied on Type-III ANOVA with Satterthwaite degrees of freedom. For interpretation, we estimated marginal means (EMM) for all body position × text context cells and ran Tukey-adjusted pairwise contrasts (standing vs. sitting within each context; rich vs. neutral within each body position), reporting EMMs with 95% of confidence intervals and adjusted p-values. Model-level effect sizes were summarized with Nakagawa's R^2 (marginal and conditional).

In summary, baseline-corrected mean pupil diameter was analyzed with a linear mixed-effects model fit (Satterthwaite degrees of freedom), predicting pupil diameter baseline-corrected from body position (sitting, standing), text context (neutral, rich), and their interaction, controlling for standardized word length and word index cofounds, with by-participant random intercepts and a random slope.

Results

The linear mixed-effects model fit showed a main effect of body position, with pupil diameter higher in standing when compared to sitting (larger pupils/higher TEPR), F(1,1347.44)=37.45, p<.001. The body position with text context interaction was also significant, F(1,1349.32)=8.69, p=.003, whereas the main effect of text context was not significant, F(1,15.21)=0.03, p=.876. Estimated marginal means (Kenward–Roger) were the smallest TEPR in sitting-rich (EMMs = −0.0659, SE = 0.0276) and the largest in standing–rich (EMMs = −0.0099, SE = 0.0276), with neutral conditions in between (sitting–neutral = −0.0464; standing–neutral = −0.0271). Planned contrasts indicated a larger body position effect under rich context (standing − sitting = +0.0560, p<.0001, ≈ 0.49 residual-SD units) than under neutral (+0.0194, p=.027, ≈ 0.17 SD), yielding a difference of +0.0366 (≈ 0.32 SD). Within-body position context comparisons showed rich < neutral when sitting (estimate = 0.0195 for neutral − rich, p=.0475) and a nonsignificant trend for rich > neutral when standing (−0.0172, p=.075). Covariates were not significant in this model (p≥.19).

Model fit indices suggested modest fixed-effect signal amid substantial individual variability (marginal R^2=.017); conditional R^2=.492).

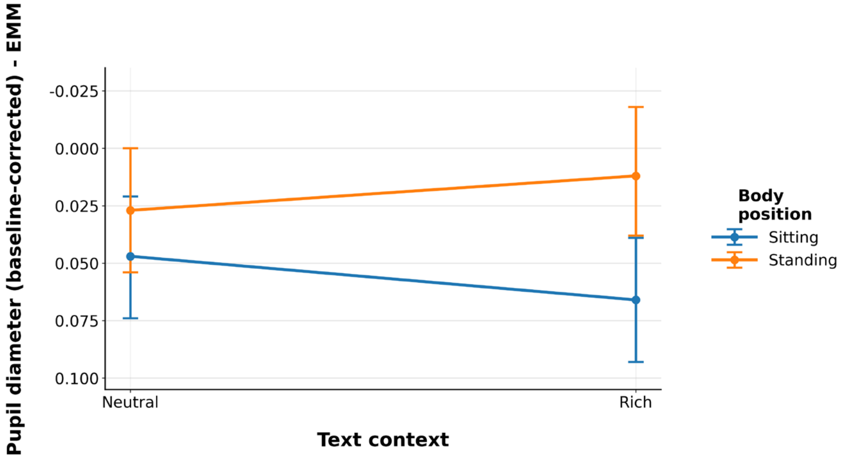

Figure 4. Mean and standard deviation of pupil diameter in the neutral and rich environment and in the sitting and standing condition. Pupil diameter was higher in standing when compared to sitting; the body position with text context interaction was also significant, with the largest pupil diameter in standing–rich and the smallest sitting-rich.

Discussion

The present study investigated whether body position (sitting vs. standing) can influence the acquisition of new words presented in sentences varying in semantic richness (neutral vs. rich contexts), using pupil diameter (TEPR) as a physiological index of cognitive effort. The results showed that standing, compared to sitting, led to greater pupil dilation across conditions, indicating increased cognitive effort. Moreover, an interaction between body position and context revealed that rich semantic context amplified TEPR only in the standing condition, whereas in sitting, rich context reduced pupil dilation. These results suggested that body position might modulates how linguistic context affects cognitive load during word learning.

The first hypothesis posited that standing, due to its demands on postural control, would increase cognitive workload compared to sitting. This was supported by our data (Figure 4) as standing significantly elevated pupil dilation relative to sitting, across both rich and neutral linguistic contexts. These findings align with previous work showing that maintaining balance during standing requires continuous sensorimotor coordination and attentional resources, particularly under more challenging postural conditions (Kahya *et al.*, 2018; Rosker *et al.*, 2024; Strauch *et al.*, 2022). Furthermore, the steady-state pupil dilation observed in standing conditions was consistent with prior research identifying pupillometry as a reliable marker of increased postural cognitive demands (Kahya *et al.*, 2022; Rosker *et al.*, 2024). These results confirmed that even in a static standing posture, greater cognitive effort is needed relative to sitting, supporting the embodied cognition perspective that bodily states shape the allocation of cognitive resources (Kang, Lee, & Jin, 2021).

The second hypothesis suggested that semantically rich contexts would reduce cognitive effort during word acquisition, as they provide stronger cues for integration. This hypothesis was partially supported. In the sitting condition, rich context reduced TEPR, consistent with previous findings showing that semantic richness facilitates processing and reduces mental load (Cain *et al.*, 2004; Geller *et al.*, 2019; Rojas *et al.*, 2024). However, in the standing condition, the rich context increased pupil dilation (Figure 4). This unexpected result could suggest that under higher cognitive load induced by postural control, additional semantic cues may require greater integration effort.

While rich semantic context typically facilitates word learning (Cain *et al.*, 2004; Geller *et al.*, 2019), our findings suggest that in standing posture, these benefits may require increased cognitive control demands. This aligns with findings by Brock (2024), who observed that standing under added mental load amplifies pupil response, indicating elevated cognitive effort when multiple resource-intensive tasks are combined. This interpretation echoes prior models of resource allocation, in which effortful tasks (e.g., balancing and semantic integration) compete for shared attentional resources (Just & Carpenter, 1993; Bonnet & Baudry, 2016; Perfetti, 2007).

Despite its contributions, this study has several limitations. First, the sample size was limited, and replication with a larger and more diverse sample is necessary to confirm these findings. Second, only two body positions (sitting and standing) were examined. Including more demanding or dynamic conditions (e.g., balancing on foam, walking) would help clarify the relationship between postural load and language processing. Third, although pupil dilation is a validated index of cognitive effort, it is influenced by factors like luminance, arousal, and fatigue. While controls were implemented, future studies may consider additional physiological or behavioral measures (e.g., EEG, reaction time) for converging evidence. Finally, the semantic richness manipulation was sentence-level; word-level or discourse-level manipulations may yield different patterns.

These findings open several directions for future research. Most notably, they support an embodied view of language learning, wherein bodily states such as body position influences cognitive effort during word acquisition. The interaction between standing and semantic richness suggests a non-linear relationship: body position may not merely add load but could also alter the way linguistic cues are processed. Future studies could explore whether such effects extend to longer learning sessions, real-world educational environments, or dynamic movements. Additionally, investigating the neural mechanisms (e.g., with EEG or fMRI) could clarify how motor and cognitive systems co-regulate effort during language tasks. Ultimately, this research contributes to a growing literature on embodied cognition by highlighting how even subtle motor factors like body position can shape the efficiency of linguistic learning.

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