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The bigger your pupils, the better my comprehension: an ERP study of how pupil size and gaze of the speaker affect syntactic processing

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Abstract

Gaze direction and pupil dilation play a critical role in communication and social interaction due to their ability to redirect and capture our attention and their relevance for emotional information. The present study aimed to explore whether the pupil size and gaze direction of the speaker affect language comprehension. Participants listened to sentences that could be correct or contain a syntactic anomaly, while the static face of a speaker was manipulated in terms of gaze direction (direct, averted) and pupil size (mydriasis, miosis). Left anterior negativity (LAN) and P600 linguistic event-related potential components were observed in response to syntactic anomalies across all conditions. The speaker's gaze did not impact syntactic comprehension. However, the amplitude of the LAN component for mydriasis (dilated pupil) was larger than for miosis (constricted pupil) condition. Larger pupils are generally associated with care, trust, interest, and attention, which might facilitate syntactic processing at early automatic stages. The result also supports the permeable and context-dependent nature of syntax. Previous studies also support an automatic nature of syntax (fast and efficient), which combined with the permeability to relevant sources of communicative information, such as pupil size and emotions, is highly adaptive for language comprehension and social interaction.

Keywords: language comprehension; pupil dilation; gaze direction; LAN; P600

Introduction

The human eye is characterized by a larger white sclera in comparison to other primates (Kobayashi and Kohshima 2001). Tomasello, among other authors (Herrmann et al. 2007), proposes that it is an evolutionary adaptation favouring interpersonal communication and social interactions. The gaze direction has a critical influence on social communication due to its ability to redirect and capture our attention and its relevance to emotional information (Jessen and Grossmann 2014). Looking at a person implies a communicative intention (Farroni et al. 2002) to the point that eye contact can modulate concurrent cognitive and behavioural responses (Senju et al. 2013). Recent evidence shows that pupil responses are coordinated by highly interconnected neural circuits implicated in light response but more intriguingly in attention, alertness, arousal, and executive functions (Strauch et al. 2022). Further, there is an intermixed relationship between eyes and emotions (Spezio et al. 2007, Bradley et al. 2008, Kret 2018, Prochazkova et al. 2018). In a pioneering study, Hess (1975) already observed that individuals with large pupils are perceived more positively than individuals with small pupils in a communicative context. Larger pupils usually mean care, interest, and attention (positive impression), while small pupils involve the opposite (negative impression) (Kret 2018).

It is largely assumed that language evolved as a social and cultural tool to facilitate communication (Pinker and Jackendoff 2005, Dunbar 2017). Therefore, it is not surprising that, in the last decade, it has been demonstrated that extralinguistic information relevant to communication (such as emotions, speakers'

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and readers' facial expressions, self-reference, and social context) seems able to affect language comprehension, including syntactic processing (Martín-Loeches et al. 2012, Vissers et al. 2013, Verhees et al. 2015, Espuny et al. 2018a, Hinchcliffe et al. 2020, Jiménez-Ortega et al. 2020, 2021a, 2021b, Rubianes et al. 2024). In this framework, it can be expected that gaze direction and/or pupil size might be among the extralinguistic cues affecting language comprehension. Accordingly, this study aimed to investigate how speaker gaze direction and pupil dilation affect syntactic processing using event-related potentials (ERPs).

ERPs provide a fine-grained method for studying how linguistic processes unfold. Two language-related ERP components, relatively specific for syntactic processing, have been described in the literature: left anterior negativity (LAN) and P600. The LAN is a negative deflection appearing in left frontal areas ∼300–500 ms after the occurrence of a morphosyntactic mismatch (Steinhauer and Connolly 2008) that has been proposed to reflect first-pass syntactic processes (Hahne and Friederici 1999, Molinaro et al. 2011) and the difficulty of morphosyntactic integration (Friederici 2002). On the other hand, the P600 is a centro-parietally positive component to linguistic anomalies peaking ∼600 ms after stimulus onset. The syntactic P600 reflects a general marker for structural processing and reanalysis (Steinhauer and Connolly 2008, Friederici 2011, Brouwer et al. 2012). Generally, an increased LAN/reduced P600 pattern is interpreted as more efficient syntactic processing as observed in good comprehenders and conscientious participants (Coulson and Kutas 2001, Tanner and Van Hell 2014, Jiménez-Ortega et al. 2021b).

Behavioural studies found that the speaker's gaze may regulate language comprehension either at the lexico-semantic stages (e.g. Holler et al. 2014, Abashidze and Knoeferle 2021) or at the syntactic level (e.g. Knoeferle and Kreysa 2012). Particularly, these authors asked participants to verify whether the post-video template matched or not a previous sentence cued with a gaze. Differences were observed depending on the congruence/incongruence between the direction of the gaze and the sentence meaning and depending on the sentence structure (subject–verb–object versus object–verb–subject). It has also been demonstrated that the speaker's gaze direction can modulate the N400 and P600 semantic components depending on the congruence between the speaker's gaze direction to a given scene and the meaning of an ongoing sentence Jachmann et al. 2019. However, a recent study presenting speech accompanied by either a static picture or a video of the speaker's face did not find significant effects of eye movements on the N400 Hernández-Gutiérrez et al. 2018. Consequently, the authors suggested manipulating gaze direction in future research. Furthermore, syntactic processing remained unexplored in their study.

During social interactions, large pupils are perceived as positive, beautiful, and trusting, while small pupils are perceived as cold, distant, and less trusting (Hess 1975; Kret 2018, Kret and De Dreu 2019). The pupillary response might reflect emotional valence, arousal, and even cognitive emotion regulation (Babiker and Malik 2013, Kinner et al. 2017). Specifically, the authors have investigated pupil dilation during language comprehension of the listener (Hubert and Järvikivi 2019, Hubert 2020). However, while dilated pupil might promote positive affect or emotions in the observer, to the best of our knowledge, there is a lack of studies investigating the effect of the speaker's pupil dilation on the listener's language comprehension using ERP. Nevertheless, emotional effects on language comprehension, specifically in syntax, have been previously observed (Jiménez-Ortega et al. 2012, Espuny et al. 2018a, Padrón et al. 2020). The observed LAN emotional modulations may indicate that emotional information can impact syntactic processing at its early—and presumably automatic—stages (Hasting and Kotz 2008, Jiménez-Ortega et al. 2012, Batterink and Neville 2013, Lucchese et al. 2017), while P600 modulations reflect controlled processes at later stages (Vissers et al. 2007, Verhees et al. 2015). However, how emotional information affects syntax is still a matter of debate. It has been postulated that differences in the arousal levels (closely related to pupil response) elicited by the materials, in interaction with their valence (Citron et al. 2013, Padrón et al. 2020), processing styles promoted by the type of task and individual differences, among others (Jiménez-Ortega et al. 2021b) might explain, at least partly, these differences.

Altogether, this study aims to investigate whether auditory language comprehension, particularly in the syntactic domain, is affected by the speaker's pupil dilation and gaze direction. To this end, participants listened to sentences that could be correct or contain a syntactic anomaly while the static face of a speaker presented on a screen was manipulated in terms of gaze direction (direct, avert) and pupil dilation (miosis, mydriasis). Based on previous findings, we expect that pupil size and gaze direction will affect syntactic processing and its components, independent of the sentence meaning. Nevertheless, the direction of these modulations is difficult to predict, particularly for gaze direction, as there is no previous literature in this regard. If pupil size and gaze direction impact morphosyntactic processing, we should observe a differential electrophysiological pattern for morphosyntactic violations. An increased LAN followed by a reduced P600 component would indicate a possible facilitation effect. In contrast, the opposite pattern might indicate enhanced difficulties in processing the syntactic computations or the lack of resources to establish the agreement relations.

Methods

Participants

Thirty-two Spanish-native speakers (12 males) participated in the experiment. However, data inspection revealed an outsider that was eliminated, so that 31 participants were finally included in the data analyses. Their age ranged from 18- to 26-year olds (mean: 20.4 years). All participants were right-handed (mean score: +70, range: +40 to + 100) according to the Edinburgh Handedness Inventory (Oldfield 1971). Participants had normal or corrected-to-normal vision, no hearing difficulties, and no previous history of neural or psychiatric disorders. Following the Declaration of Helsinki, they gave their informed consent before the experiment, as approved by the ethics committee of the Faculty of Psychology of the Complutense University of Madrid (Ref. 2016/17-021) and were reimbursed afterwards.

Material

The linguistic stimuli consisted of 480 sentences in Spanish with 3 different structures previously used in Hernández-Gutiérrez et al. (2021). Depending on sentence structure, there could be a 'noun-adjective' mismatch (Structure 1) or a 'determiner-noun' mismatch (structures 2 and 3). The length of target words varied between two and five syllables, and linguistic characteristics like word frequency, concreteness, imageability, familiarity, and emotional content were controlled by presenting every word across all experimental conditions. An example of the sentences by type of structure is given in Table 1.

The sentences were acoustically presented with eight different voices, four men and four women. Two voices were recorded

Table 1. Structure types and examples of sentences used in the experimental procedure.

Structure types (*n* = 90 per type)	**Correct**	**Incorrect**
(1) [Det]-[N]-[Adj]-[V]-[Prep]-[N]	*El pañuelo*$_{\text{Masc/Sing}}$***bordado***$_{\text{Masc/Sing}}$ *era de mi abuela.* (The **embroided** $_{\text{Masc/Sing}}$ cushion $_{\text{Masc/Sing}}$ belonged to my grandmother)	*El pañuelo* $_{\text{Masc/Sing}}$***bordada***$_{\text{Fem/Sing}}$ *era de mi abuela.* (The **embroided** $_{\text{Fem/Sing}}$ cushion $_{\text{Masc/Sing}}$ belonged to my grandmother)
(2) [Det]-[N]- [V]-[Det]-[N]- [Adj]	*Los turistas habían fotografiado los* $_{\text{Masc/Plur}}$***glaciares***$_{\text{Masc/Plur}}$ *árticos.* (The tourists had photographed the $_{\text{Masc/Plur}}$ arctic **glaciers** $_{\text{Masc/Plur}}$)	*Los turistas habían fotografiado los* $_{\text{Masc/Plur}}$***glaciar***$_{\text{Masc/Sing}}$ *árticos* *(The tourists had photographed the* $_{\text{Masc/Plur}}$ *arctic* ***glacier***$_{\text{Masc/Sing}}$*)*
(3) [Det]-[N]- [V] -[Prep]-[Det]-[N]-[Prep]-[Det]-[N]	*Las hojas son recogidas durante el* $_{\text{Masc/Sing}}$***otoño***$_{\text{Masc/Sing}}$ *por los barrenderos* (The leaves are picked by the sweepers during the $_{\text{Masc/Sing}}$ **autumn** $_{\text{Masc/Sing}}$)	*Las hojas son recogidas durante el* $_{\text{Masc/Sing}}$***otoños***$_{\text{Masc/Plur}}$ *por los barrenderos.* (The leaves are picked by the sweepers during the $_{\text{Masc/Sing}}$ **autumns** $_{\text{Masc/Plur}}$)

Literal translations (noun–adjective order inverted) into English, where m., masculine; f., feminine; sg., singular; pl., plural. Bold words represent critical words.

by a male and a female speaker (see details in Hernández-Gutiérrez et al. 2021), while the remaining six were obtained, thanks to manipulating the tone of the two originals using GoldWave software. To ensure that the voices were distinguishable but natural, 10 individuals—different from those participating in the experiment—evaluated 12 different voices in terms of naturality (6 males, 6 females), from which the 6 different voices were finally chosen. All audio files were matched in intensity using Audacity software. Since the critical information for morphosyntactic violations relates to the gender/number markers, triggers were set on critical words at the offset of the lexeme, just before the gender/number declension. To this aim, three independent researchers set the ERP triggers of each target word separately with GoldWave software considering the auditory information and the sound waves' visual (spectrogram) patterns. This procedure has been successfully employed in previous work (Hernández-Gutiérrez et al. 2021).

Each voice was paired with a face. Identities were kept constant throughout the study. The eight portraits were selected from the Radboud Faces Database (Langner et al. 2010), being homogeneous in terms of brightness, background, size, etc., as well as standardized regarding face alignment and eye distance. Their facial expression was neutral; for each face a direct gaze picture and for the other, a half-lateral one was selected (oriented at 45° from the observer's eyes, right and left versions). The pupils of the faces were manipulated using the Adobe Photoshop editor to create more dilated (mydriasis) and constricted (miosis) pupils, i.e. there was a replica of each photograph: one exhibited mydriasis (visual angle 0.48° of diameter) and another miosis (visual angle of 0.29°), corresponding to the normal visual angle of an average pupil between 0.3 and 0.5 cm at 60 cm of distance (see Fig. 1), that is between the physiological range of 0.3–0.7 cm of the pupil (Kret et al. 2015). Additionally, a naturality test of the modified images was performed before the electroencephalogram (EEG recordings, where seven co-authors blindly judged among a pool of images (30 modified and 30 non-modified) to determine which ones were natural, and the used images were the ones that were judged as natural by all co-authors. Although this procedure is less accurate than scoring each face for naturality, it efficiently discards possible unnatural stimuli.

In sum, the same 480 sentences in their different versions of voices and faces were used for all experimental conditions presented in a counterbalanced design across participants. Therefore, although each participant listened to each sentence just once, at the end of the data collection, all sentences were presented the same number of times according to the three main factors: Correctness (Correct, Incorrect) × Pupil Size (miosis, mydriasis) × Eye Gaze Direction (direct, averted).

Procedure

The experiment was performed in an electrically shielded cabin. Participants were seated in a comfortable chair facing a computer screen (1680 × 1050 pixels) at a viewing distance of 60 cm. The auditory stimuli were presented through a pair of shielded speakers placed on both sides of the screen. The sound pressure level was the same for all participants (50 dB measured at head level with 4 in 1, DT-8820 audiometer), who confirmed it was comfortable. The pictures of the speakers' faces (900 × 600 pixels, visual angle: 19° × 20.9°) were presented in the centre of a 240 Hz-HP-LCD screen using the Presentation® software.

Participants were told that the experiment aimed to investigate how people process grammatical errors contained in an acoustic sentence while watching the speaker's face, where each voice was assigned to a face. Their task was to indicate whether the acoustic sentence was grammatically correct or not by pressing one of two buttons with their index finger. The hand and the assignment of the correct button were counterbalanced. Participants performed a training session with 10 sentences that were not presented in the experiment at the beginning of the session. They were also instructed to avoid blinking and head movements during the sentence presentation.

EEG recording and data processing

EEG data were recorded from 59 scalp and 2 mastoid electrodes using the standard 10/20 system with a sampling rate of 250 Hz and a bandpass of 0.01–100 Hz. Scalp electrodes were referenced online to the left mastoid electrode—M1. They were later re-referenced offline to the average mastoids and re-filtered with a bandpass filter of 0.01–30 Hz. The recorded activity of bipolar vertical and horizontal electrooculograms monitored eye-related activity, such as eye movements and blinks. Electrode impedance was kept <5 kΩ.

The EEG data were analysed with Brain Vision Analyzer® software. The continuous EEG recordings were divided into segments of 1200 ms, starting at 200 ms to the offset of the critical word lexeme. The ocular correction was performed through Independent Component Analysis (Jung et al. 2000) as implemented in the software. The remaining artefacts were semi-automatically rejected by eliminating epochs exceeding ±100 μV in any of the channels. Epochs that contained incorrect responses were removed from the data analysis. The average number of artefact-free trials correctly

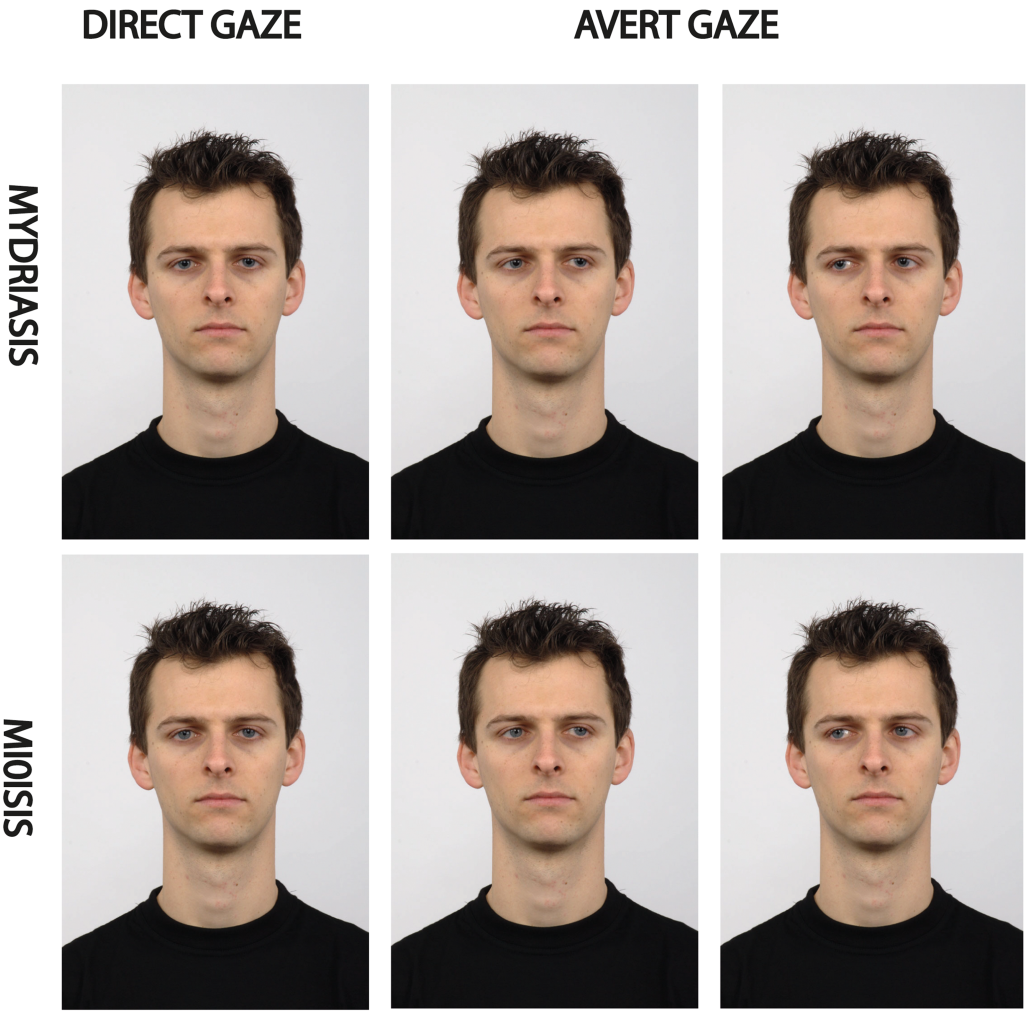

Figure 1. Example of the six portraits of one of the (fictitious) speakers. They are selected and adapted from the Radboud Faces Database (Langner et al. 2010). Half of the presented faces have a direct gaze (50%) and the other half an averted gaze (25% left gaze, and 25% a right gaze).

answered per condition was 52.6, with no differences across conditions according to a Correctness (2) × Pupil size (2) × Eye Gaze Direction (2) repeated-measures analyses of variance (ANOVA) (all F's < 1.08, P's >.3).

Data analysis

Behavioural data

Error rates and reaction times were analysed in SPSS® 26 using a Correctness (correct, incorrect) × Pupil Size (mydriasis, miosis) × Eye Gaze Direction (averted, direct) repeated-measures ANOVA.

EEG data

Factorial cluster analyses seem to estimate successfully and objectively time windows for ERP components (for further details, see: Groppe et al. 2011a, 2011b, Brusini et al. 2017, Fields and Kuperberg 2020). In turn, time-windows analyses might facilitate comparison with previous results, simplifying *post hoc* analyses. Thus, time-windows analyses were calculated guided by cluster analysis, and further confirmed by visual inspections.

Cluster-based permutation analyses were calculated by using the Mass Univariate Toolbox developed by Groppe et al. (2011b) using Matlab® 2017. It shows good statistical power when *a priori* time segments are used (Fields and Kuperberg 2020). For factor Correctness (Correct, Incorrect), an exploratory cluster-based permutation analysis was performed between 0 and 1000 ms, each with 10 000 iterations and an alpha level of 0.05.

For the time-windows analyses, related statistical ANOVAs were performed with the SPSS® 26 software. Guided by the cluster analyses (see below and Supplementary Material for results) and visual inspections, for LAN component data analyses, electrodes F7, F5, F3, F1, FT7, FC5, FC3, and FC1 were averaged within the 350–450 ms window. Additionally, for P600 component, electrodes P5, P3, P1, Pz, P2, P4, P6, P03, and P04 were averaged for 600–800 ms windows data analyses. Thus, the ANOVA analyses at each window included three factors: Correctness (correct, incorrect), Pupil Size (mydriasis, miosis), and Eye Gaze direction (averted, direct).

Violations of the sphericity assumption were corrected if found by the Greenhouse–Heisser correction, and Bonferroni corrections were used for multiple comparisons.

Results

Behavioural data

Participants answered correctly in 92.8% of the experimental trials. The ANOVA showed that error rates were larger for correct trials than for incorrect ones (5.9 versus 2.8 respectively;

[$F(1,30) = 24.8$, $P < .001$, $\eta_p^2 = 0.45$, $\theta = 0.99$]. No further significances were found for error rates (all F's < 0.99, $P > .33$). Likewise, larger reaction times were observed for correct trials than for incorrect ones (455.1 versus 421.9 ms, respectively; [$F(1,30) = 17.4$, $P < .001$, $\eta_p^2 = 0.37$, $\theta = 0.98$]. Descriptively, reaction times were also larger for miosis than mydriasis (442.5 versus 434.5 versus ms, respectively) and a trend to significance was observed [$F(1,30) = 3.42$, $P = .07$, $\eta_p^2 = 0.45$, $\theta = 0.99$]. All other factors and interactions did not yield significant differences (all F's < 1.9, P's $> .18$) (Fig. 2).

ERP data

The exploratory cluster analyses for the Correctness factor revealed effects at ~380–400 ms approximately in anterior central electrodes, more prominent for the left hemisphere than for the right one (17 versus 12 significant sites, respectively, at 400 ms) and compatible with a LAN component. Approximately, between 600 and 900 ms a spread effect appeared involving all electrodes except for AF7, F7, F5, and FT7, which resembles a P600 component. A detailed plot of the results, including other minor effects, can be seen in the Supplementary Material (Supplementary Fig. S1).

Time window 350–450 ms: LAN component

In line with cluster analyses and visual inspections, the ANOVA analyses for the LAN component at 350–450 ms yielded significant effects for Correctness [$F(1,30) = 44.29$, $P < .001$, $\eta_p^2 = 0.59$, $\theta = 1$] and interestingly for Correctness × Pupil size interaction [$F(1,30) = 5.65$, $P = .02$, $\eta_p^2 = 0.16$, $\theta = 0.63$]. *Post hoc* comparisons subtracting incorrect to correct sentences for mydriasis and miosis revealed that the LAN component amplitude was significantly larger for mydriasis than for miosis [$F(1,30) = 5.66$, $P = .02$, $\eta_p^2 = 0.16$, $\theta = 0.64$]. All other factors and interactions did not show significant differences (all F's < 2.6, P's $> .12$) (Fig. 3).

Time window 600–800 ms: P600 component

Significant effects for Correctness [$F(1,31) = 69.98$, $P < .001$, $\eta_p^2 = 0.7$, $\theta = 1$] confirmed a P600 component for 600–800 window. All other factors and interactions did not show significant differences (all F's $< 1,25$, P's $> .27$) (Fig. 3).

Discussion

Recent pieces of evidence observed that syntactic processing is permeable to emotional and social information, such as the pupil size of the speaker. Pupils' dilation is involved in emotional and empathy processes that are crucial in communication. The present study aimed to explore whether relevant aspects in communication and social interaction, such as pupil size and gaze direction, affect auditory language comprehension. Participants listened to sentences that could be correct or contain a syntactic anomaly while seeing a static picture of the speaker's face, manipulated in terms of gaze direction (averted, direct) and pupil size (mydriasis, miosis). LAN and P600 components to syntactic anomalies were observed for all conditions. Interestingly, the LAN component for mydriasis was significantly larger than for miosis. Behavioural data suggested a facilitation effect of general language processing regardless of correctness, as reaction times were shorter for mydriasis than for miosis, although this was only supported by a statistical trend and interpretation should be taken with caution.

Regardless of the gaze direction, a larger LAN component was observed for mydriasis than for miosis. Pupil response and emotions are intermixed phenomena crucial to social interaction (Kret 2018). Large pupils without negative emotional expressions are generally associated with care, trust, interest, and attention (Kret 2018, Prochazkova et al. 2018, Kret and De Dreu 2019). Although pupil dilation information is not always consciously processed, it constitutes a piece of important information for social interaction that can affect our behaviour (Kret 2018). Therefore, it can be postulated that dilated pupils might generate a positive emotion/affection in our participants, which might affect syntactic processing. In this line, it has been observed that both emotional—even under reduced levels of awareness—and social information can modulate syntactic processing (Hasting and Kotz 2008, Batterink and Neville 2013, Lucchese et al. 2017, Hinchcliffe et al. 2020, Jiménez-Ortega et al. 2021b).

The shorter reaction times (though supported by a statistical trend) for mydriasis than for miosis, regardless of correctness, might indicate a general language processing facilitation, which could appear because of arousal and attention increases, among other factors. Similarly, an increased LAN component has been also interpreted as a facilitation or acceleration of the syntactic processing (Coulson and Kutas 2001, Tanner and Van Hell 2014, Jiménez-Ortega et al. 2021b). Facilitation of syntactic processing has been previously observed in emotional words presented previously to sentences containing syntactic anomalies and masked emotional adjectives embedded in unmasked sentences (Espuny et al. 2018b, Jiménez-Ortega et al. 2021a). Additionally, numerous studies have shown that mild positive affect facilitates thinking, problem-solving, and social interaction through increased cognitive flexibility (for a classical review, see: Isen 2009). Thus, it can be suggested that the observed syntax facilitation appeared as the result of a positive emotion/affection for the mydriasis condition.

Pupil information is often considered an implicit cue unconsciously processed (Kret 2018, Prochazkova et al. 2018), thus it could be postulated that the modulations appeared exclusively at early syntactic processing stages (LAN component) precisely because of its automatic and unaware nature (Batterink and Neville 2013, Jiménez-Ortega et al. 2014). The observed modulations by pupil size, together with previous findings of emotional syntactic modulations, suggest that syntactic processing is also context-dependent, supporting a double nature of syntax, automatic on the one hand and context-dependent on the other hand (Batterink and Neville 2013, Jiménez-Ortega et al. 2021a), in line with the current models of automaticity (Kiefer et al. 2017). Automatic processes are generally faster and more efficient since they need fewer resources and attention than controlled ones. Automatic syntax processing, combined with permeability to other relevant sources of information is probably highly adaptive for language comprehension and social interaction. Particularly, pupil dilation may play an important role in social interaction. Thus, language comprehension and more particularly syntax processing might be speeded and facilitated when interacting with an interlocutor with a dilated pupil.

P600 modulations were not observed either for the pupil dilation or for the gaze eye. Similarly, previous studies investigating emotional effects on syntactic processing that employed neutral sentences containing syntactic anomalies in an emotional word observed LAN but not P600 modulations (Martín-Loeches et al. 2012, Padrón et al. 2020, Poch et al. 2023), even if emotional words are masked and processed without awareness (Jiménez-Ortega et al. 2017, 2021a). However, when emotional information (videos, words, or paragraphs) is presented before sentences containing

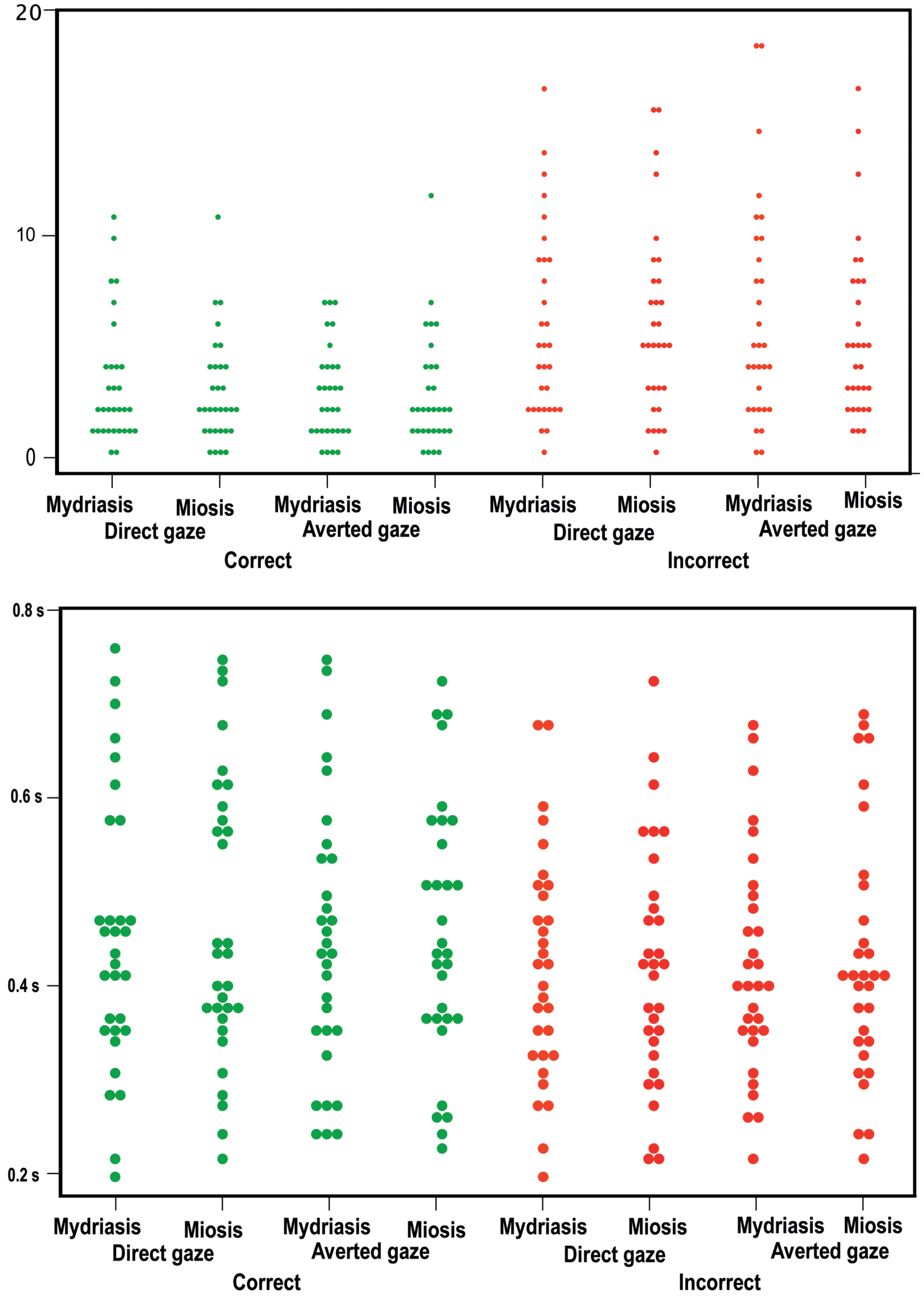

Figure 2. Dot plots show distributions of error rate percentages (top) and reaction times in seconds (bottom) for each condition: direct gaze mydriasis, direct gaze miosis, averted gaze mydriasis, and averted gaze miosis in their correct (left) and incorrect versions (right).

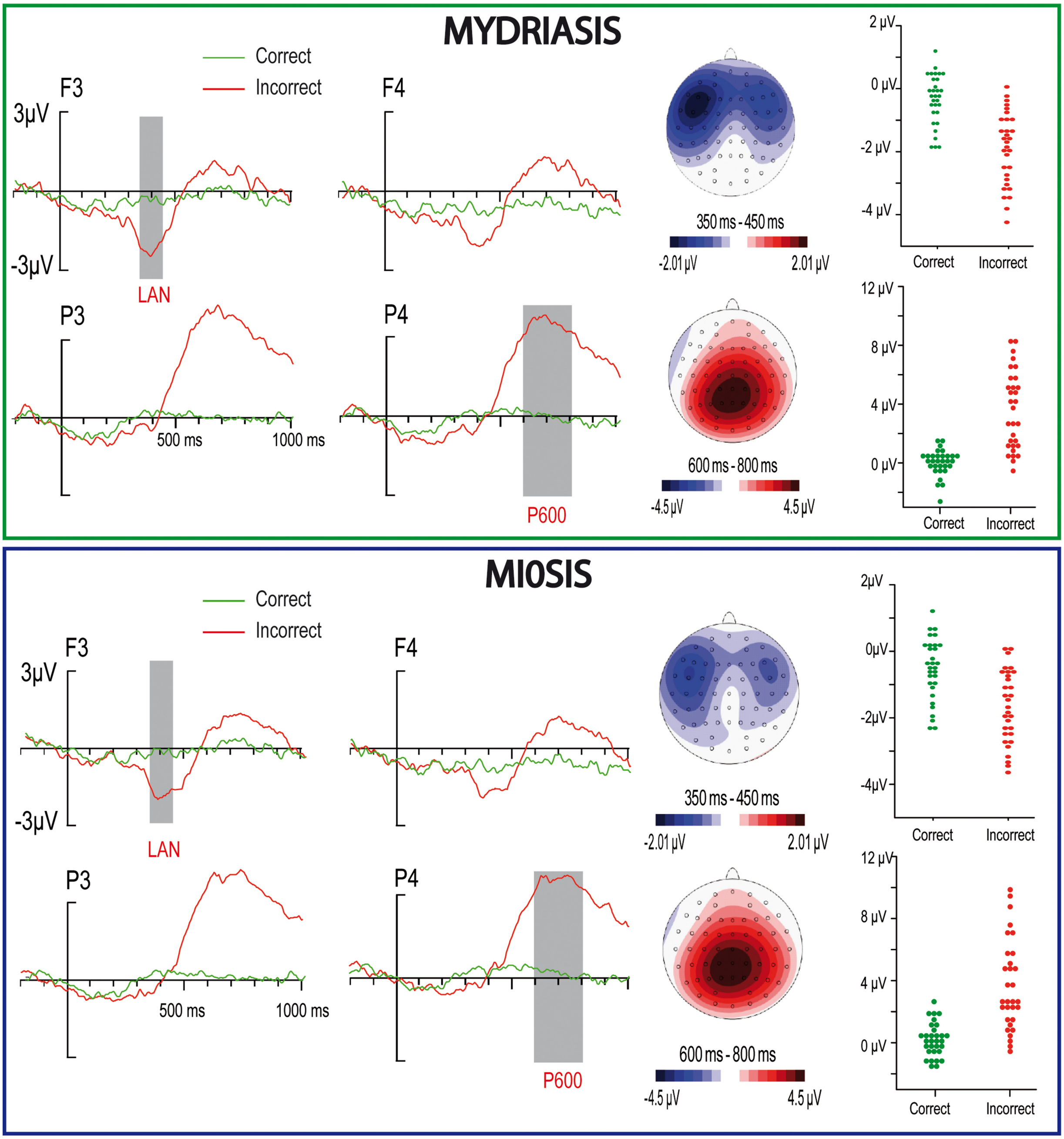

Figure 3. ERP data and topographic maps for miosis (top) (constricted pupil) and mydriasis (bottom) (dilated pupil) conditions, Next to LAN and P600 topographic maps for mydriasis and miosis conditions, dot plots represent the average activity in microvolts for correct and incorrect sentences in 350–450 ms LAN (right up) and 600–800 ms P600 windows (right bottom) of the selected electrodes for each component.

syntactic anomalies, P600 modulations have been described (Vissers et al. 2010, Jiménez-Ortega et al. 2012, Verhees et al. 2015, Espuny et al. 2018a). Recent pieces of evidence point out that the P600 might be a controlled component reflecting a continuous index of integration effort whose amplitude varies continuously with integrative effort (Aurnhammer et al. 2023), while the LAN component is believed to be a more automatic and less controlled component (Batterink and Neville 2013, Jiménez-Ortega et al. 2014). It can be therefore hypothesized that when relevant cues for communication are processed being less aware and/or in a more automatic mode, effects on language comprehension might be predominantly observed for LAN components, as in the case of emotional information within the target word or pupil size. Additionally, P600 effects might be expected when more controlled integration of information is required as in the case of previous emotional videos and paragraphs before target sentences. Although the findings here summarized seem to match harmoniously with this hypothesis, further research is needed to directly test this possibility.

Given the influence of the speaker's gaze on listener comprehension (Knoeferle and Kreysa 2012, Staudte et al. 2014), the importance of social interaction (Senju et al. 2006), and the previous findings on the effects of social presence on syntactic processing (Hinchcliffe et al. 2020), syntactic modulations by gaze direction were predicted at the LAN and/or the P600 components. However, our data did not reveal any effect of gaze direction. It can be hypothesized that, given the more automatic nature of the processes related to the LAN component (Batterink and Neville 2013, Jiménez-Ortega et al. 2014), and their ability to occur without attention and awareness, they would not be affected by gaze direction, which plays an important role in conscious attentional processes (Frischen et al. 2007). However, this would let unexplained why the P600 also appeared unaffected. Additionally, in previous studies, gaze direction was either congruent or incongruent with the sentence meaning and depending on the sentence structure (Jachmann et al. 2019), which might explain the gaze direction effects. In turn, a previous study did not find significant modulations of the semantic-related N400 component by the dynamism of the speaker's eyes (Hernández-Gutiérrez et al. 2018) consistent with our results. However, interpreting the lack of significance can be challenging. Further research is needed to determine whether dynamic information regarding gaze direction might modulate online language processing. This could be achieved through a more specific experimental design where gaze direction is not confounded with sentence meaning.

Although presenting static pictures of participants paired with the same voice was a simple procedure permitting the control of other possible confounding factors, more natural conditions would increase the ecological validity of the results. Future research is desirable, using videos or even real interactions with speakers to further confirm the influence of pupil diameter on syntax in more ecological conditions.

Conclusions

Our data support the existence of syntactic modulations by pupil size, which is an emotional cue that is often processed without awareness. Observing a speaker presenting dilated pupils facilitates syntactic processing at early stages of language processing. Therefore, pupil dilation may play an important role in social interaction, since it may denote care, trust, and interest. Thus, on the one hand, syntactic processing can be modulated by relevant contextual information, as reported here by the speaker's pupil dilation, supporting the permeable nature of syntax. On the other hand, according to previous studies, syntax processing is fast and efficient due to the minimal attentional and monitoring requirements supporting an automatic nature. Therefore, fast, efficient, and permeable syntax processing can be highly proficient for communication and social interaction.

Supplementary data

Supplementary data is available at SCAN online.

Conflict of interest

None declared.

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References

Abashidze D, Knoeferle P. Influence of actor's congruent and incongruent gaze on language processing. *Front Psychol* 2021;**12**:701742. https://doi.org/10.3389/fpsyg.2021.701742x

Aurnhammer C, Delogu F, Brouwer H *et al*. The P600 as a continuous index of integration effort. *Psychophysiology* 2023;**60**:e14302. https://doi.org/10.1111/psyp.14302

Babiker IF, Malik A. Pupillary behavior in positive and negative emotions. In: *2013 IEEE International Conference on Signal and Image Processing Applications*. IEEE, Melaka, Malaysia, 8-10 October, 2013. https://doi.org/10.1109/ICSIPA.2013.6708037

Batterink L, Neville HJ. The human brain processes syntax in the absence of conscious awareness. *J Neurosci* 2013;**33**:8528–33. https://doi.org/10.1523/JNEUROSCI.0618-13.2013

Bradley MM, Miccoli L, Escrig MA *et al*. The pupil as a measure of emotional arousal and autonomic activation. *Psychophysiology* 2008;**45**:602–07. https://doi.org/10.1111/j.1469-8986.2008.00654.x

Brouwer H, Fitz H, Hoeks J. Getting real about semantic illusions: rethinking the functional role of the P600 in language comprehension. *Brain Res* 2012;**1446**:127–43. https://doi.org/10.1016/j.brainres.2012.01.055

Brusini P, Dehaene-Lambertz G, van Heugten M *et al*. Ambiguous function words do not prevent 18-month-olds from building accurate syntactic category expectations: an ERP study. *Neuropsychologia* 2017;**98**:4–12. https://doi.org/10.1016/j.neuropsychologia.2016.08.015

Citron FM, Weekes BS, Ferstl EC. Effects of valence and arousal on written word recognition: time course and ERP correlates. *Neurosci Lett* 2013;**533**:90–95. https://doi.org/10.1016/j.neulet.2012.10.054

Coulson S, Kutas M. Getting it: human event-related brain response to jokes in good and poor comprehenders. *Neurosci Lett* 2001;**316**:71–74. https://doi.org/10.1016/s0304-3940(01)02387-4

Dunbar RI. Group size, vocal grooming and the origins of language. *Psychon Bull Rev* 2017;**24**:209–12. https://doi.org/10.3758/s13423-016-1122-6

Espuny J, Jiménez-Ortega L, Casado P *et al*. Event-related brain potential correlates of words' emotional valence irrespective of arousal and type of task. *Neurosci Lett* 2018a;**670**:83–88. https://doi.org/10.1016/j.neulet.2018.01.050

Espuny J, Jiménez-Ortega L, Hernández-Gutiérrez D *et al*. Isolating the effects of word's emotional valence on subsequent morphosyntactic processing: an event-related brain potentials study. *Front Psychol* 2018b;**9**:2291. https://doi.org/10.3389/fpsyg.2018.02291

Farroni T, Csibra G, Simion F *et al*. Eye contact detection in humans from birth. *Proc Natl Acad Sci USA* 2002;**99**:9602–05. https://doi.org/10.1073/pnas.152159999

Fields EC, Kuperberg GR. Having your cake and eating it too: flexibility and power with mass univariate statistics for ERP data. *Psychophysiology* 2020;**57**:e13468. https://doi.org/10.1111/psyp.13468

Friederici AD. Towards a neural basis of auditory sentence processing. *Trends Cogn Sci* 2002;**6**:78–84. https://doi.org/10.1016/s1364-6613(00)01839-8

Friederici AD. The brain basis of language processing: from structure to function. *Physiol Rev* 2011;**91**:1357–92. https://doi.org/10.1152/physrev.00006.2011

Frischen A, Bayliss AP, Tipper SP. Gaze cueing of attention: visual attention, social cognition, and individual differences. *Psychol Bull* 2007;**133**:694–724. https://doi.org/10.1037/0033-2909.133.4.694

Groppe DM, Urbach TP, Kutas M. Mass univariate analysis of event-related brain potentials/fields I: a critical tutorial review. *Psychophysiology* 2011a;**48**:1711–25. https://doi.org/10.1111/j.1469-8986.2011.01273.x

Groppe DM, Urbach TP, Kutas M. Mass univariate analysis of event-related brain potentials/fields II: simulation studies. *Psychophysiology* 2011b;**48**:1726–37. https://doi.org/10.1111/j.1469-8986.2011.01272.x

Hahne A, Friederici AD. Electrophysiological evidence for two steps in syntactic analysis. Early automatic and late controlled processes. *J Cogn Neurosci* 1999;**11**:194–205. https://doi.org/10.1162/089892999563328

Hasting AS, Kotz SA. Speeding up syntax: on the relative timing and automaticity of local phrase structure and morphosyntactic processing as reflected in event-related brain potentials. *J Cogn Neurosci* 2008;**20**:1207–19. https://doi.org/10.1162/jocn.2008.20083

Hernández-Gutiérrez D, Abdel Rahman R, Martín-Loeches M *et al.* Does dynamic information about the speaker's face contribute to semantic speech processing? ERP evidence. *Cortex* 2018;**104**:12–25. https://doi.org/10.1016/j.cortex.2018.03.031

Hernández-Gutiérrez D, Muñoz F, Sánchez-García J *et al.* Situating language in a minimal social context: how seeing a picture of the speaker's face affects language comprehension. *Soc Cogn Affect Neurosci* 2021;**16**:502–11. https://doi.org/10.1093/scan/nsab009

Herrmann E, Call J, Hernàndez-Lloreda MV *et al.* Humans have evolved specialized skills of social cognition: the cultural intelligence hypothesis. *Science* 2007;**317**:1360–66. https://doi.org/10.1126/science.1146282

Hess EH. The Role of Pupil Size in Communication. *Sci Am* 1975;**233**:110–119. https://doi.org/10.1038/scientificamerican1175-110

Hinchcliffe C, Jiménez-Ortega L, Muñoz F *et al.* Language comprehension in the social brain: electrophysiological brain signals of social presence effects during syntactic and semantic sentence processing. *Cortex* 2020;**130**:413–25. https://doi.org/10.1016/j.cortex.2020.03.029

Holler J, Schubotz L, Kelly S *et al.* Social eye gaze modulates processing of speech and co-speech gesture. *Cognition* 2014;**133**:692–97. https://doi.org/10.1016/j.cognition.2014.08.008

Hubert LI. It's Personal and Disgusting: Extra-Linguistic Information in Language Comprehension. Doctor of Philosophy, University of Alberta, 2020.

Hubert LI, Järvikivi J. Dark forces in language comprehension: the case of neuroticism and disgust in a pupillometry study. In: *Proceedings of the 41st Annual Meeting of the Cognitive Science Society*, vol. 1. Montreal, QC, July, pp. 450–56, 2019.

Isen AM. A role for neuropsychology in understanding the facilitating influence of positive affect on social behavior and cognitive processes. In: *Oxford Handbook of Positive Psychology*, 2nd edn. Oxford: Oxford University Press, 2009.

Jachmann TK, Drenhaus H, Staudte M *et al.* Influence of speakers' gaze on situated language comprehension: evidence from event-related potentials. *Brain Cogn* 2019;**135**:103571. https://doi.org/10.1016/j.bandc.2019.05.009

Jessen S, Grossmann T. Unconscious discrimination of social cues from eye whites in infants. *Proc Natl Acad Sci USA* 2014;**111**:16208–13. https://doi.org/10.1073/pnas.1411333111

Jiménez-Ortega L, Badaya E, Casado P *et al.* The automatic but flexible and content-dependent nature of syntax. *Front Human Neurosci* 2021a;**15**:651158. https://doi.org/10.3389/fnhum.2021.651158

Jiménez-Ortega L, Badaya E, Hernández-Gutiérrez D *et al.* Effects of reader's facial expression on syntactic processing: a brain potential study. *Brain Res* 2020;**1736**:146745. https://doi.org/10.1016/j.brainres.2020.146745

Jiménez-Ortega L, Espuny J, de Tejada PH *et al.* Subliminal emotional words impact syntactic processing: evidence from performance and event-related brain potentials. *Front Human Neurosci* 2017;**11**:1–13. https://doi.org/10.3389/fnhum.2017.00192

Jiménez-Ortega L, Hinchcliffe C, Munoz F *et al.* Language comprehension may depend on who you are: how personality traits and social presence seemingly modulate syntactic processing. *Lang Cogn Neurosci* 2021b;**37**:365–80. https://doi.org/10.1080/23273798.2021.1970201

Jiménez-Ortega L, Martín-Loeches M, Casado P *et al.* How the emotional content of discourse affects language comprehension. *PloS One* 2012;**7**:e33718. https://doi.org/10.1371/journal.pone.0033718

Jung T, Makeig S, Humphries C *et al.* Removing electroencephalographic artifacts by blind source separation. *Psychophysiology* 2000;**37**:163–78. https://doi.org/10.1111/1469-8986.3720163

Kiefer M, Liegel N, Zovko M *et al.* Mechanisms of masked evaluative priming: task sets modulate behavioral and electrophysiological priming for picture and words differentially. *Soc Cogn Affect Neurosci* 2017;**12**:596–608. https://doi.org/10.1093/scan/nsw167

Kinner VL, Kuchinke L, Dierolf AM *et al.* What our eyes tell us about feelings: tracking pupillary responses during emotion regulation processes. *Psychophysiology* 2017;**54**:508–18. https://doi.org/10.1111/psyp.12816

Knoeferle P, Kreysa H. Can speaker gaze modulate syntactic structuring and thematic role assignment during spoken sentence comprehension? *Front Psychol* 2012;**3**:538. https://doi.org/10.3389/fpsyg.2012.00538

Kobayashi H, Kohshima S. Unique morphology of the human eye and its adaptive meaning: comparative studies on external morphology of the primate eye. *J Hum Evol* 2001;**40**:419–35. https://doi.org/10.1006/jhev.2001.0468

Kret ME. The role of pupil size in communication. Is there room for learning? *Cogn Emot* 2018;**32**:1139–45. https://doi.org/10.1080/02699931.2017.1370417

Kret ME, De Dreu CKW. The power of pupil size in establishing trust and reciprocity. *J Exp Psychol Gen* 2019;**148**:1299–311. https://doi.org/10.1037/xge0000508

Kret ME, Fischer AH, De Dreu CK. Pupil mimicry correlates with trust in in-group partners with dilating pupils. *Psychol Sci* 2015;**26**:1401–10. https://doi.org/10.1177/0956797615588306

Langner O, Dotsch R, Bijlstra G *et al.* Presentation and validation of the Radboud Faces Database. *Cogn Emot* 2010;**24**:1377–88. https://doi.org/10.1080/02699930903485076

Lucchese G, Hanna J, Autenrieb A *et al.* Electrophysiological evidence for early and interactive symbol access and rule processing in retrieving and combining language constructions. *J Cogn Neurosci* 2017;**29**:254–66. https://doi.org/10.1162/jocn_a_01038

Martín-Loeches M, Fernández A, Schacht A *et al.* The influence of emotional words on sentence processing: electrophysiological and behavioral evidence. *Neuropsychologia* 2012;**50**:3262–72. https://doi.org/10.1016/j.neuropsychologia.2012.09.010

Martín-Loeches M, Fernández A, Schacht A *et al.* The influence of emotional words on sentence processing: Electrophysiological and behavioral evidence. *Neuropsychologia* 2012;**50**:3262–72. https://doi.org/10.1016/j.neuropsychologia.2012.09.010

Molinaro N, Barber HA, Carreiras M. Grammatical agreement processing in reading: ERP findings and future directions. *Cortex* 2011;**47**:908–30. https://doi.org/10.1016/j.cortex.2011.02.019

Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 1971;**9**:97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Padrón I, Fraga I, Acuña-Fariña C. Processing gender agreement errors in pleasant and unpleasant words: an ERP study at the sentence level. *Neurosci Lett* 2020;**714**:134538. https://doi.org/10.1016/j.neulet.2019.134538

Pinker S, Jackendoff R. The faculty of language: what's special about it? *Cognition* 2005;**95**:201–36. https://doi.org/10.1016/j.cognition.2004.08.004

Poch C, Diéguez-Risco T, Martínez-García N *et al.* I hates Mondays: ERP effects of emotion on person agreement. *Lang Cogn Neurosci* 2023;**38**:1451–62.

Prochazkova E, Prochazkova L, Giffin MR *et al.* Pupil mimicry promotes trust through the theory-of-mind network. *Proc Natl Acad Sci USA* 2018;**115**:E7265–74. https://doi.org/10.1073/pnas.1803916115

Rubianes M, Drijvers L, Muñoz F *et al.* The self-reference effect can modulate language syntactic processing even without explicit awareness: an EEG study. *J Cogn Neurosci* 2024;**36**:460–74. https://doi.org/10.1162/jocn_a_02104

Senju A, Johnson MH, Csibra G. The development and neural basis of referential gaze perception. *Soc Neurosci* 2006;**1**:220–34. https://doi.org/10.1080/17470910600989797

Senju A, Vernetti A, Kikuchi Y *et al.* Cultural modulation of face and gaze scanning in young children. *PloS One* 2013;**8**:e74017. https://doi.org/10.1371/journal.pone.0074017

Spezio ML, Huang PY, Castelli F *et al.* Amygdala damage impairs eye contact during conversations with real people. *J Neurosci* 2007;**27**:3994–97. https://doi.org/10.1523/JNEUROSCI.3789-06.2007

Staudte M, Crocker MW, Heloir A *et al.* The influence of speaker gaze on listener comprehension: contrasting visual versus intentional accounts. *Cognition* 2014;**133**:317–28. https://doi.org/10.1016/j.cognition.2014.06.003

Steinhauer K, Connolly JF. Event-related potentials in the study of language. In: Stemmer B (ed.), *Handbook of the Neuroscience of Language*. New York: Elsevier 1st, 2008, 91–104.

Strauch C, Wang CA, Einhäuser W *et al.* Pupillometry as an integrated readout of distinct attentional networks. *Trends Neurosci* 2022;**45**:635–47. https://doi.org/10.1016/j.tins.2022.05.003

Tanner D, Van Hell JG. ERPs reveal individual differences in morphosyntactic processing. *Neuropsychologia* 2014;**56**:289–301. https://doi.org/10.1016/j.neuropsychologia.2014.02.002

Verhees MW, Chwilla DJ, Tromp J *et al.* Contributions of emotional state and attention to the processing of syntactic agreement errors: evidence from P600. *Front Psychol* 2015;**6**:388. https://doi.org/10.3389/fpsyg.2015.00388

Vissers CT, Chwilla DJ, Kolk HH. The interplay of heuristics and parsing routines in sentence comprehension: evidence from ERPs and reaction times. *Biol Psychol* 2007;**75**:8–18. https://doi.org/10.1016/j.biopsycho.2006.10.004

Vissers CT, Chwilla UG, Egger JI *et al.* The interplay between mood and language comprehension: evidence from P600 to semantic reversal anomalies. *Neuropsychologia* 2013;**51**:1027–39. https://doi.org/10.1016/j.neuropsychologia.2013.02.007

Vissers CT, Virgillito D, Fitzgerald DA *et al.* The influence of mood on the processing of syntactic anomalies: evidence from P600. *Neuropsychologia* 2010;**48**:3521–31. https://doi.org/10.1016/j.neuropsychologia.2010.08.001

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