Running head: the variability of the LAN effect

Is the LAN effect in morphosyntactic processing an ERP artifact?

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Abstract

The left anterior negativity (LAN) is an ERP component that has been often associated with morphosyntactic processing, but recent reports have questioned whether the LAN effect, in fact, exists. The present project examined whether the LAN effect, observed in the grand average response to local agreement violations, is the result of the overlap between two different ERP effects (N400, P600) at the level of subjects (n=80), items (n=120), or trials (n=6160). By-subject, by-item, and by-trial analyses of the ERP effect between 300 and 500 ms showed a LAN for 55% of the participants, 46% of the items, and 49% of the trials. Many examples of the biphasic LAN-P600 response were observed. Mixed-linear models showed that the LAN effect size was not reduced after accounting for subject variability. The present results suggest that there are cases where the grand average LAN effect represents the brain responses of individual participants, items, and trials.

Keywords: ERP, LAN, morphosyntax, individual differences

1 Introduction

Neural processes of sentence comprehension can happen very quickly after the presentation of linguistic input. Electrophysiological techniques, such as EEG or MEG, can monitor brain responses as they unfold over time and identify neural activity associated with cognitive mechanisms. The left anterior negativity (LAN) is a negative evoked component typically observed around 400 ms after the presentation of a target word embedded in a sentence, with a focus at left and anterior electrodes for commonly-used reference locations (i.e., mastoids). The LAN effect is an increased average negative potential which can be observed in response to a morphosyntactic violation as compared to the corresponding correct sentence (it has also been observed with increasing morphological complexity in the absence of violations; e.g, Krott & Lebib, 2013). This effect is usually followed by a greater posterior positivity (P600) and it has been reported in response to local agreement violations in morphologically rich languages (Molinaro, Barber, & Carreiras, 2011; Molinaro, Barber, Caffarra, & Carreiras, 2015; but see: Wicha, Moreno, & Kutas, 2004). The LAN effect has high theoretical relevance in some models of sentence comprehension, being related to morphosyntactic analysis (Friederici, 2002). Regardless of its functional significance, the existence of the LAN as a real ERP effect has been recently questioned[1]. Multiple ERP studies have highlighted the lack of correspondence between the LAN effect obtained after averaging the ERP responses across items and subjects (i.e., grand average) and the patterns that have been observed on a single-subject basis (Osterhout, McLaughlin, Kim, Greenwald, & Inoue, 2004; Tanner & van Hell, 2014). These findings have suggested that the LAN might be a spurious effect due to averaging procedures. Given the fact that the LAN is relevant in the sentence comprehension literature, and that averaging over subjects and items is a standard procedure in the ERP analysis, it becomes important to model the variability of this ERP effect.

The present study investigates the variability of the LAN effect that has been observed in the grand average waveforms in response to local agreement violations (determiner-noun gender agreement) in a morphologically rich language (Spanish). Three different claims supporting the idea that the LAN effect is an artifact will be explored in a large ERP dataset (80 subjects; 120 items per condition).

The first claim states that individual subjects and individual items do not consistently show a LAN effect, although this effect is evident in the grand average waveforms (Osterhout, 1997; Osterhout et al., 2004). According to this view, around 400 ms after stimulus onset the individual ERPs show a continuum between two distinct ERP effects, neither of which are LAN effects, but rather the N400 and the P600. The N400 is a negative component that (also) peaks around 400 ms after stimulus onset but has a focus over central-posterior electrodes (Kutas & Federmeier, 2011), rather than left anterior electrodes. As we have described, the P600 is a posterior positivity (which can be right lateralized; Tanner & Van Hell, 2014) that is usually observed 500 ms after stimulus onset, although there is certain variability in the timing of its onset (Osterhout & Mobley, 1995), with some subjects showing an earlier onset, and some a later onset. Specifically, the first claim is that during averaging over subjects, the spatial and temporal overlap of these two qualitatively different effects would reduce the original N400 effect over (right-) posterior sites, producing a residual (left-) anterior negative effect in the grand average (Osterhout, 1997; Osterhout et al., 2004; Tanner & Van Hell, 2014)[2]. This claim will be tested by quantifying the LAN, the N400 and the P600-like effects at the subject as well as the item level between 300 and 500 ms. Since the same argument can be applied to single trials within the same participant, similar analyses will be carried out over small sets of trials.

The second claim is that there is a low co-occurrence of the LAN and the P600 effects across individuals (Osterhout et al., 2004; Tanner & Van Hell, 2014). Single subjects would typically show negative-dominant or positive-dominant responses, rather than biphasic responses. According to this view, the sub-population of participants with large negative effects tend to show small P600 effects, while the sub-population having a clear P600 effect would show small early negativities. Hence, the co-occurrence of negative and positive effects would be present in a small subset of participants and it would mainly arise from averaging over participants. This claim will be tested by calculating the correlation between early dominant negative effects and later posterior positive effects across subjects. Since the same argument can be applied to single items, similar analyses will be carried out across items.

The third claim is related to those described above and it frames the idea that the LAN is the result of subject variability in general. Note this is independent of whether there is a biphasic LAN-P600 response or rather monophasic LAN and P600 responses. The logic is the following: If the effect observed in the grand average is driven, at least in part, by individual differences (Osterhout et al., 2004; Tanner & Van Hell, 2014) then a model that includes specific terms for subject variability should provide a better fit than a model without those terms, subject to a penalty for the additional terms. Also, a model that accounts for subject variability should account (at least partially) for the LAN effect size, which is defined as the fixed effect coefficient over its SE (Gelman & Carlin, 2014). Hence, a reduction of the LAN effect size should happen through a reduction of the fixed effect estimate and/or through an increase of the relative SE. This claim will be tested by fitting linear mixed effects models on the LAN voltage and comparing them. Similar models will be also fit for the P600 voltage in order to see whether individual differences specifically account for the LAN effect.

1.1 The present study

The above-mentioned claims were tested using a multi-level modeling approach that characterizes the statistical properties of both subject and item level. We used an ERP dataset from three previous experiments focused on the LAN effect (Caffarra & Barber, 2015; Caffarra, Barber, Molinaro, Carreiras, 2017). The experimental materials and designs in these studies were always the same and included gender agreement violations between a prenominal determiner and a target noun, a morphosyntactic violation that often elicits a LAN effect in the grand average of highly-proficient subjects (Molinaro et al., 2011; but see: Wicha, Moreno, & Kutas, 2004). The ERPs time-locked to the target noun were calculated across each item, each participant, subset of trials, and overall (for methodological details see below). The ERP effects were defined as the difference between the disagreement and the agreement condition.

According to the first claim, between 300 and 500 ms after the target onset there should be a discrepancy between the ERP effect observed in the grand average and the ERP effects of single subjects (or single items, or small sets of trials). The topographies of by-subject, by-item, and by-trial effects should mainly show central-posterior negative effects (N400) and posterior positivities (P600). The LAN effects were not expected to be elicited by the majority of participants (or items, or trials).

According to the second claim, most of the participants (or items) should show either a positive or a negative dominant response, with a minority showing some degree of biphasic response (between 5% and 35% according to Tanner, 2015; Tanner & Van Hell 2014). A strong correlation should be observed between the dominant negative effects seen between 300 and 500 ms at the individual level and the late positive effects (500-800 ms), so that in subjects where one effect is larger, the other effect should be smaller (0.59<|r|<0.74; in ~~the~~ case the dominant effects seen at the individual level have the same posterior location; Tanner, Inoue & Osterhout, 2014; Tanner, McLaughlin, Herschensohn, & Osterhout, 2013; Tanner & Van Hell, 2014).

The third claim predicts that LAN effect size estimate should be reduced and/or the SE should increase after including in the model a term for subject-specific violation effects. Adding this random effect should also lead to an improvement of the model fit, as this would provide evidence for some subject-to-subject variability in the LAN effect.

2 Material and Methods

Eighty Spanish speakers highly-proficient in Spanish participated to the studies (45 female; mean age=25 y; mean Spanish AoA=1.4 y; average proficiency score=4.9/5.0). They read 240 Spanish sentences that were presented word by word in rapid serial presentation. Half of the sentences contained article-noun gender agreement violations and half were grammatically correct. After each trial they performed a grammaticality judgement task (mean accuracy=95.4 %; SD=3.0). Further details about the participants, the procedure, the EEG recording and preprocessing can be found in the original papers (Caffarra & Barber, 2015; Caffarra et al., 2017; for the EEG preprocessing we followed the pipeline described in Caffarra & Barber, 2015[3] and data from Caffarra et al., 2017 were down-sampled to 250 Hz). ERPs from two experimental conditions (agreement and disagreement) were considered. Overall, 8.7% (SD=6.1) of trials were excluded due to artifacts or incorrect behavioral responses. The number of remaining trials did not differ between conditions (*t*(79)=1.3, *p*>.05).

Grand average waveforms, by-subject, and by-item ERPs were calculated for each condition. For the first analysis, the topographies of the ERP effects (i.e., disagreement-agreement voltage difference) between 300 and 500 ms were obtained at the subject and item level. In order to reduce the potential artifacts generated by averaging procedure, multiple ERP effects were also calculated on the smallest possible trials sets (size range: 1-2 trials) for each participant (total number of sets: 6160, see Supplementary Materials A).

The number of subjects, items and trial sets showing a LAN, an N400, or a positive effect was calculated. The presence of a LAN effect was defined as a negative effect over a representative left-anterior site (F3), which was greater than the effect registered over a posterior site (Pz). The presence of a N400 effect was defined as a negative effect over a posterior site (Pz) being greater than the effect over a left-anterior site (F3). Any other case where both F3 and Pz showed a positive ERP difference was categorized as a positive effect[4]. As an aside, note that the distinction between LAN and N400 effect is based on topographical distribution features (Kemmerer, 2015), which are not straightforwardly related to neural sources in the absence of an adequate forward model (Hallez et al., 2007). Hence, our results should not be read in terms of ERP source modelling.

For the second analyses, the Pearson correlations were calculated between the LAN voltage difference (disagreement-agreement ERP difference at F3 between 300 ms and 500 ms) and the P600 voltage difference (disagreement-agreement ERP difference at Pz between 500 and 800 ms) across subjects and items. Similar correlations were calculated between the N400 voltage difference (disagreement-agreement ERP difference at Pz between 300 ms and 500 ms) and the P600 voltage difference (as in Tanner et al. 2013, 2014; Tanner & Van Hell, 2014).

For the third analysis, mixed-linear models (Baayen, Davidson & Bates, 2008) were fit using the LAN-time-window voltage (ERP average amplitude at F3 between 300 ms and 500 ms) as the dependent variable and agreement as a fixed effect factor at the level of individual trials. By-item and by-subject random intercepts, as well as random slopes for agreement were incrementally added to model variability in the LAN responses at the level of individual subjects and individual items, in addition to the variability of individual trials already modeled by the fixed effect terms. The contribution of each random effect to the model fit was assessed using likelihood ratio statistics (Pinheiro & Bates, 2000; Bates et al. 2014) by comparing the respective model with one that was identical except for the effect in question. Similar analyses were carried out using the P600 voltage (ERP average amplitude at Pz between 500 ms and 800 ms) as a dependent variable. A final model on the LAN voltage was also performed including the subject-specific N400 violation effect term. Dummy coding was used to label the levels of the categorical predictor (0=agreement; 1=disagreement). Analyses were carried out using the *lme4* package (Bates, Maechler, Bolker & Walker, 2014). *P*-values for the coefficients of the linear mixed-effect models were calculated treating the *t*-statistic as if it were a *z*-statistic[5]. Note that inferences about model fit were not based exclusively on likelihood ratio statistics, *p*-values or confidence intervals, but also on a variety of other factors (Loken & Gelman, 2017).

3 Results

The grand average waveforms showed a clear LAN-P600 biphasic response (Figure 1; Caffarra & Barber, 2015; Caffarra et al., 2017).

--- Figure 1---

The analysis of the subject topographies revealed that 55% of the participants showed a LAN effect, 25% a N400 effect and 20% a positive effect (Figure 2). The by-item topographies showed that 46% of the items elicited a LAN, 29% an N400 effect and 25% a positive effect. Similar percentages were observed after calculating ERP effects on small sets of trials for each participant (LAN: 49%, N400: 29%, positive effect: 22%, see Supplementary Materials A). Negative effects at F3 were present in 71% of the participants and 66% of the items (Figure 2).

---Figure 2---

In the second analysis, 66% of the participants and 62% of the items showed an early negative effect at F3 followed by a later positivity (Figure 3, first row, quadrant IV corresponds to the presence of biphasic responses). The LAN effect and the P600 effect were uncorrelated across participants (*r*=0.04; *p*=0.72). However, there was a positive weak correlation across items (*r*=0.25; *p*<0.001), suggesting that for items where the P600 effect was smaller, the LAN effect was larger. When similar correlations were computed on the ERP voltage differences at the same representative electrode (Pz) larger correlations were found (by-subject: *r*=0.48; *p*<0.001; by-item: *r*=0.64; *p*<0.001).

--- Figure 3 ---

In the third analysis, an initial mixed-linear model was fit on the LAN voltage including agreement as a fixed predictor and a by-item random intercept (model A: intercept=0.04; SE=0.10; β=-0.62; SE=0.13; *t*=-4.94, *p*<0.001, for more details see Supplementary Materials C). Note that the agreement condition average voltage is near zero (0.04) and that the average LAN (disagreement) effect is a negative modulation of about half a microvolt (-0.62). The standard error of the LAN effect (0.13) is small relative to the size of the effect, leading to a relatively large *t*-ratio. Compared to this baseline model, adding additional random effect terms would be expected to affect the standard error of the fixed effects, and possibly the fixed effect coefficients.

Adding a by-subject random intercept (model B: intercept=0.05; SE=0.28; β=-0.62; SE=0.12; *t*=-5.13, *p*<0.001) led to an improvement of the model fit ($\chi^2(1)$=1167, *p*<0.001) and an increase of the SE (from 0.10 to 0.28). This is consistent with larger subject variability in the LAN-window voltage in the control condition (Figure 4). To assess whether a subject-specific and/or an item-specific violation effect improved the fit, two additional models were compared: one in which a by-subject random slope was added to model B (model C: intercept=0.05; SE=0.27; β=-0.62; SE=0.13; *t*=-4.61, *p*<0.001), and one that also included a by-item random slope (model D: intercept=0.05; SE=0.27; β=-0.62; SE=0.14; *t*=-4.57, *p*<0.001). Note first that the fixed parameters and the SEs remain unchanged. Second, neither of these models led to improvements in fit over the corresponding nested comparison (model C: $\chi^2(2)=2.96$, $p=0.23$; model D: $\chi^2(2)=2.44$, $p=0.30$). These model comparisons, along with plots of the distributions of the model random effects, as well as plots of the raw subject averages, suggest that the LAN effect was not subject to a great deal of subject-to-subject or item-to-item variability, although variability in the effect was clearly observed. Importantly, the estimates of the LAN effect (-0.62 μV, SE=0.13 μV) did not change substantially after accounting for subject variability. Finally, we also fit a model that included the amplitude of the N400 effect (at Pz) as a predictor. In this case, the estimate of the LAN effect was not reduced and the SE remained unchanged (-0.65 μV, model E: intercept=0.32; SE=0.26; β=-0.65; SE=0.13; $t=-4.97$, $p<0.001$).

The models A, B, C, and D were also fit to the P600 voltage (500-800 ms time window; for more details see Supplementary Materials C). All models had substantially equivalent estimates of the baseline voltage (about 0.8 μV) as well as P600 violation effect (about 3.7 μV; model A: intercept=0.81; SE=0.11; β=3.69; SE=0.14; $t=26.89$, $p<0.001$; model B: intercept=0.79; SE=0.25; β=3.70; SE=0.13; $t=27.59$, $p<0.001$; model C: intercept=0.81; SE=0.19; β=3.68; SE=0.28; $t=13.20$, $p<0.001$; model D[6]: intercept=0.81; SE=0.18; β=3.67; SE=0.29; $t=12.71$, $p<0.001$).

Similar to the LAN, adding a by-subject random intercept improved the fit over model A ($\chi^2(1)=629.55$, $p<0.001$), with an increase of the SE (from 0.11 to 0.25). In addition, including a by-subject random slope led to an improvement of the fit over model B ($\chi^2(2)=182.72$, $p<0.001$) and a concomitant increase of the SE (from 0.13 to 0.28). Thus, there is evidence of subject-to-subject variability in the P600 control condition, as well as in the P600 violation effect (Figure 4).

--- Figure 4 ---

4 Discussion

The present study examined and modeled the variability of the LAN effect elicited by local agreement violations in a morphologically rich language. Three different hypotheses related to the claim that the LAN effect in the grand average is a spurious effect were examined. A large ERP dataset showing a LAN-P600 biphasic response after grand averaging was analyzed at the subject, item, and trial level.

First, individual ERPs were calculated by-item, by-subject and by-trial sets to examine how often the ERP responses resembled the grand average for (a) single subjects (over all items), (b) single items (over all subjects), and (c) small sets of trials. This analysis clearly showed that LAN effects could be observed in individual subjects, items, and trial sets. Moreover, these effects were more consistent than the N400 or positive effects at the level of subjects, items and small sets of trials. The grand average LAN effect was, thus, more representative of what occurred to most subjects, items, and trials than the proposed alternatives. Note that even when the effects of averaging were kept to the minimum (in the by-trial analysis ERP averages were either not computed or computed over two trials) the LAN was still the most consistent ERP effect. This is difficult to reconcile with the claim that the LAN effect depends on the averaging procedure.

These findings do not support the claim that the averaging procedure is artificially producing a left anterior negativity (Osterhout, 1997; Osterhout et al., 2004), at least when the LAN effect is elicited by local agreement violations in a morphologically rich language with highly-proficient readers. A remaining possibility is that there is a difference between violation types, languages, and participant language background. Note that although the LAN was the most consistently reported effect, it was not present in all subjects, items, and trials. Electrophysiological effects (even well-established ones, such as N1 or P2) do not likely appear at every by-subject and by-item average (Cooper, Osselton, & Shaw, 1969; Sörnmo &

Laguna, 2005). The relative size of the effect together with the amount of measurement variability and measurement noise[7] can make the effect difficult to be detected at every observation. Crucially, although the LAN has a relatively small size (around 0.5 µV) as compared to the N400 and the P600 effects (which are typically over 1 µV), it was consistently detected. As to the impact of measurement variations, the first analysis cannot tell us whether subject (or item) variability partially accounts for this ERP patterns. This was specifically tested by the third analysis.

Second, the correlations between LAN (which was the dominant negative effect based on the results of the previous analysis) and P600 single effects were calculated to examine how the biphasic responses covary over the sample of subjects or items. The results revealed that most of the participants and most of the items show both early negative and late positive effects. There was no clear relation between individual subject LAN and P600 effects, but there was a weak correlation across items. As the by-item LAN effect increased the by-item P600 effect decreased. When similar correlations were calculated on the same posterior spatial location they were stronger and compatible with those reported in previous studies (Tanner et al., 2013, 2014; Tanner & Van Hell, 2014).

These findings speak against the presence of prominent monophasic responses at the subject level (Osterhout et al., 2004), as well as at the item level. These results show weak support for the covariance of the two components of the biphasic responses. The LAN effects (which were the most frequent ERP negative effects observed in individual subjects and items) did not show a strong relation with the subsequent positive ERP effects, while ERP effects of individual items showed only a weak relation. Note that the correlations calculated here regarded different topographic locations (F3 and Pz), as the first analysis showed that early negative effects were most frequently left anteriorly distributed. However, when the same posterior topographic location was considered (as done in previous studies: Tanner et al., 2013, 2014; Tanner & Van Hell, 2014), the correlations were stronger, suggesting that the covariance of two subsequent ERP magnitude differences increases with spatial contiguity. These higher correlations at the same topographic locations are probably due to a shared random effect and measurement noise at the same electrode.

Third, mixed-linear models were fit to estimate ERP effects after accounting for subject and item variability. The results showed that larger subject variability was present in the LAN responses to correct sentences, as well as in the P600 responses to correct and incorrect sentences. The estimate of the LAN fixed effect parameter was not reduced and the SE remained unchanged after accounting for subject-specific LAN effect and for subject-specific N400 effect.

These findings provide evidence of subject-to-subject variability in the LAN responses. However, this is not a peculiarity of the LAN and it can also be observed in the P600 responses (even to a larger extent). These results do not strongly support the idea that the subject variability accounts for the LAN effect reported in the grand average[8]. In addition, the distributions of the random effects relative to the LAN control condition and violation effect (see Supplementary Materials C) do not cluster into distinct groups that would be associated with qualitatively different effects (i.e., N400 and P600), but they rather appear to be unimodal distributions.

Overall, these results argue against the possibility that the LAN effect is consistently and systematically an artifact of averaging. Note that this is true regardless of how the LAN effect is functionally interpreted. The present findings cannot tease apart different functional interpretations of the LAN effect (e.g., morphosyntactic analysis vs. working memory demands). Instead, the present work provides evidence that there are cases where the grand average LAN effect is representative of~~,~~ by-subject, by-item and by-trial responses. The type of violation considered here (i.e., determiner-noun gender agreement violation in a morphologically rich language) has been often associated with LAN effects in the published literature[9] on first language comprehension (Molinaro et al., 2011; but see: Hagoort, 2003; Wicha, Moreno, & Kutas, 2004). It is still not clear whether the present results can be generalized to other experimental designs where the grand average LAN effect seems to be less representative of single ERP responses (e.g., subject-verb agreement violations in morphologically poor languages; Tanner & Van Hell, 2014; violations where there is a longer time interval between agreeing constituents; Roll, Gosselke, Lindgren, & Horne, 2013).

A potential contribution of the present work is providing useful methodological tools to examine both the properties of the ERP grand average and individual responses. The updated scripts for the present analyses are available online at https://github.com/dvdsn/218594. Estimation of different sources of variability and larger sample sizes will help us to have a better measure of ERP effect sizes and its systematic variation (see a recent debate on sample size in Friston 2012; Lindquist, Caffo, & Crainiceanu, 2013; and also the discussion in Loken & Gelman, 2017). Note however, that there remains a great deal of work to be done, as even the best-fitting models reported here~~,~~ did not account for very much variability (in the sense of R^2).

To conclude, the present study described multiple ways of exploring the relation between grand average waveforms and ERPs of single subjects, items, and trials. It provided evidence that the grand average LAN effect can accurately reflect individual brain responses.

Authors Notes

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Footnotes

1. This is not the first debate about the functional nature of ERP components associated to sentence comprehension. In the past years, at least another similar debate has been proposed, which was focused on the nature of the P600 and the possibility to reduce it to a P300 (Coulson et al., 1998; Osterhout & Hagoort, 1999).
2. It is worth noting that the coexistence of the LAN with a positivity does not necessarily inform on potential component overlaps. In fact, a negative effect on the scalp is always accompanied by a positive counterpart (although not always within the sensor array) since the sum of potentials around the head should be zero in ideal conditions.
3. Using the ERP pipeline described in Caffarra et al. (2017) led to similar results (Mendoza, 2017).
4. Other ways of categorizing the effects (using clusters of three electrodes instead of one representative electrode and calculating laterality and anteriority indexes based on 26 electrodes) led to similar pattern of results (i.e., presence of LAN effects at the subject and item level, greater proportion of LAN effects than any other alternatives, see Supplementary Materials B).
5. Correlations and mixed-linear models were calculated also using clusters of electrodes instead of a single representative electrodes (LAN: F3, F7, FC5; N400/P600: Pz, P3, P4) and the results were similar to those presented here. For the mixed-linear models, the results of the model comparisons were the same after fitting the same models using sum coding (-0.5/0.5). Model comparisons with leave-one-out cross validation after fitting the equivalent Stan models using the *rstanarm* package (available online at https://CRAN.R-project.org/package=rstanarm) resulted in similar conclusions.
6. The model did not converge, but coefficient estimates were similar to the models that did converge.

7. Measurement noise refers to a pattern that would not repeat with re-test, while measurement variability refers to a pattern that does repeat with re-test, but is different from the population central tendency.
8. The results from the mixed-linear models might seem to be at odd with the scatter plots of correlation analyses, where more variability seems to be present in the case of the LAN than the P600 effect. However, it should be kept in mind that the scatterplots do not represent the same type of information conveyed by the mixed-linear results. In the mixed-linear models not all variability has been modeled, but only that which is related to item and subject identity (both residuals and R^2 coefficients of mixed-linear models showed that there is still a considerable portion of unmodeled activity). In addition, unlike the scatterplots, mixed-linear models model the different source of variability for LAN and P600 voltages for each condition (and not for their difference). Finally it is worth noting that the magnitude of these two effects is different (3 μV against 0.5 μV), with the larger effect being more easily modeled against the measurement variability and noise.
9. We do not know the number of studies that have looked for the LAN but have not found it --not least because of the publication bias for statistically-significant results (see Caffarra et al., 2015 for similar concerns). Even in the case the publication bias contributes overestimating the LAN effects reported in the literature, the present dataset still represents a case where the LAN effect observed in the grand average can be observed also in individual brain responses. Future studies are needed to check how far the present findings can be generalized.

Figure Captions

Figure 1. The upper panel shows grand average waveforms for the agreement and the disagreement condition (blue and red line, respectively). Positive voltage is plotted upwards. The bottom panel shows the topographic distribution of each experimental condition and of their difference in the two time windows of interest: 300-500 ms and 500-800 ms. Y-axes units are microvolts, x-axes are ms, and the topography color-scales are microvolts. The greatest magnitude LAN effect is at F3, and the greatest P600 effect is at Pz.

Figure 2. The upper panel shows the topographic distributions of the ERP effects between 300 ms and 500 ms for each participant. The topographies are ordered to show the LAN effects (44, from the greatest effect to the smallest one), the positive effects (20) and the N400 effects (16, from the smallest effect to the greatest one), respectively. The bottom panel shows the ERP voltage recorded at F3 for the agreement and the disagreement condition. Blue lines marked a negative ERP effect, while red lines marked a positive effect.

Figure 3. Top row: by-subjects and by-item correlations between the LAN voltage difference (disagreement-agreement ERP difference at F3 between 300 ms and 500 ms) and the P600 voltage difference (disagreement-agreement ERP difference at Pz between 500 and 800 ms). Bottom row: by-subjects and by-item correlations between the N400 voltage difference (disagreement-agreement ERP difference at Pz between 300 ms and 500 ms) and the P600 voltage difference (disagreement-agreement ERP difference at Pz between 500 and 800 ms). Each quadrant is displayed with its relative number.

Figure 4. Density plots of the variance parameters estimated from models C. Y-axis are kernel density estimates, and x-axis units are microvolts. The curves represent the estimates of the population probability distribution based on the given sample of points. The upper panel shows the LAN and the P600 average response to the control condition (vertical dashed line), and variability due to subject (blue distribution) and item (red distribution). The lower

panel shows the ERP average response to the control condition (Mean Agr: blue dashed line) and the ERP average size of the violation effect (Mean DisE: green dashed line) with the relative variability due to subjects. For a comparison between the distribution of the observed data and the distribution of the fitted random effect coefficients see Supplementary Materials D.

- We studied whether the LAN effect is due to component overlap
- A large ERP dataset was considered (80 participants, 120 items)
- The LAN effect was consistently observed at the individual level
- Most individual ERP responses were biphasic
- Adding individual variability terms did not improve the LAN model fit

Running head: the variability of the LAN effect

Is the LAN effect in morphosyntactic processing an ERP artifact?

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Abstract

The left anterior negativity (LAN) is an ERP component that has been often associated with morphosyntactic processing, but recent reports have questioned whether the LAN effect, in fact, exists. The present project examined whether the LAN effect, observed in the grand average response to local agreement violations, is the result of the overlap between two different ERP effects (N400, P600) at the level of subjects (n=80), items (n=120), or trials (n=6160). By-subject, by-item, and by-trial analyses of the ERP effect between 300 and 500 ms showed a LAN for 55% of the participants, 46% of the items, and 49% of the trials. Many examples of the biphasic LAN-P600 response were observed. Mixed-linear models showed that the LAN effect size was not reduced after accounting for subject variability. The present results suggest that there are cases where the grand average LAN effect represents the brain responses of individual participants, items, and trials.

Keywords: ERP, LAN, morphosyntax, individual differences

1 Introduction

Neural processes of sentence comprehension can happen very quickly after the presentation of linguistic input. Electrophysiological techniques, such as EEG or MEG, can monitor brain responses as they unfold over time and identify neural activity associated with cognitive mechanisms. The left anterior negativity (LAN) is a negative evoked component typically observed around 400 ms after the presentation of a target word embedded in a sentence, with a focus at left and anterior electrodes for commonly-used reference locations (i.e., mastoids). The LAN effect is an increased average negative potential which can be observed in response to a morphosyntactic violation as compared to the corresponding correct sentence (it has also been observed with increasing morphological complexity in the absence of violations; e.g, Krott & Lebib, 2013). This effect is usually followed by a greater posterior positivity (P600) and it has been reported in response to local agreement violations in morphologically rich languages (Molinaro, Barber, & Carreiras, 2011; Molinaro, Barber, Caffarra, & Carreiras, 2015; but see: Wicha, Moreno, & Kutas, 2004). The LAN effect has high theoretical relevance in some models of sentence comprehension, being related to morphosyntactic analysis (Friederici, 2002). Regardless of its functional significance, the existence of the LAN as a real ERP effect has been recently questioned[1]. Multiple ERP studies have highlighted the lack of correspondence between the LAN effect obtained after averaging the ERP responses across items and subjects (i.e., grand average) and the patterns that have been observed on a single-subject basis (Osterhout, McLaughlin, Kim, Greenwald, & Inoue, 2004; Tanner & van Hell, 2014). These findings have suggested that the LAN might be a spurious effect due to averaging procedures. Given the fact that the LAN is relevant in the sentence comprehension literature, and that averaging over subjects and items is a standard procedure in the ERP analysis, it becomes important to model the variability of this ERP effect.

The present study investigates the variability of the LAN effect that has been observed in the grand average waveforms in response to local agreement violations (determiner-noun gender agreement) in a morphologically rich language (Spanish). Three different claims supporting the idea that the LAN effect is an artifact will be explored in a large ERP dataset (80 subjects; 120 items per condition).

The first claim states that individual subjects and individual items do not consistently show a LAN effect, although this effect is evident in the grand average waveforms (Osterhout, 1997; Osterhout et al., 2004). According to this view, around 400 ms after stimulus onset the individual ERPs show a continuum between two distinct ERP effects, neither of which are LAN effects, but rather the N400 and the P600. The N400 is a negative component that (also) peaks around 400 ms after stimulus onset but has a focus over central-posterior electrodes (Kutas & Federmeier, 2011), rather than left anterior electrodes. As we have described, the P600 is a posterior positivity (which can be right lateralized; Tanner & Van Hell, 2014) that is usually observed 500 ms after stimulus onset, although there is certain variability in the timing of its onset (Osterhout & Mobley, 1995), with some subjects showing an earlier onset, and some a later onset. Specifically, the first claim is that during averaging over subjects, the spatial and temporal overlap of these two qualitatively different effects would reduce the original N400 effect over (right-) posterior sites, producing a residual (left-) anterior negative effect in the grand average (Osterhout, 1997; Osterhout et al., 2004; Tanner & Van Hell, 2014) [2]. This claim will be tested by quantifying the LAN, the N400 and the P600-like effects at the subject as well as the item level between 300 and 500 ms. Since the same argument can be applied to single trials within the same participant, similar analyses will be carried out over small sets of trials.

The second claim is that there is a low co-occurrence of the LAN and the P600 effects across individuals (Osterhout et al., 2004; Tanner & Van Hell, 2014). Single subjects would typically show negative-dominant or positive-dominant responses, rather than biphasic responses. According to this view, the sub-population of participants with large negative effects tend to show small P600 effects, while the sub-population having a clear P600 effect would show small early negativities. Hence, the co-occurrence of negative and positive effects would be present in a small subset of participants and it would mainly arise from averaging over participants. This claim will be tested by calculating the correlation between early dominant negative effects and later posterior positive effects across subjects. Since the same argument can be applied to single items, similar analyses will be carried out across items.

The third claim is related to those described above and it frames the idea that the LAN is the result of subject variability in general. Note this is independent of whether there is a biphasic LAN-P600 response or rather monophasic LAN and P600 responses. The logic is the following: If the effect observed in the grand average is driven, at least in part, by individual differences (Osterhout et al., 2004; Tanner & Van Hell, 2014) then a model that includes specific terms for subject variability should provide a better fit than a model without those terms, subject to a penalty for the additional terms. Also, a model that accounts for subject variability should account (at least partially) for the LAN effect size, which is defined as the fixed effect coefficient over its SE (Gelman & Carlin, 2014). Hence, a reduction of the LAN effect size should happen through a reduction of the fixed effect estimate and/or through an increase of the relative SE. This claim will be tested by fitting linear mixed effects models on the LAN voltage and comparing them. Similar models will be also fit for the P600 voltage in order to see whether individual differences specifically account for the LAN effect.

1.1 The present study

The above-mentioned claims were tested using a multi-level modeling approach that characterizes the statistical properties of both subject and item level. We used an ERP dataset from three previous experiments focused on the LAN effect (Caffarra & Barber, 2015; Caffarra, Barber, Molinaro, Carreiras, 2017). The experimental materials and designs in these studies were always the same and included gender agreement violations between a prenominal determiner and a target noun, a morphosyntactic violation that often elicits a LAN effect in the grand average of highly-proficient subjects (Molinaro et al., 2011; but see: Wicha, Moreno, & Kutas, 2004). The ERPs time-locked to the target noun were calculated across each item, each participant, subset of trials, and overall (for methodological details see below). The ERP effects were defined as the difference between the disagreement and the agreement condition.

According to the first claim, between 300 and 500 ms after the target onset there should be a discrepancy between the ERP effect observed in the grand average and the ERP effects of single subjects (or single items, or small sets of trials). The topographies of by-subject, by-item, and by-trial effects should mainly show central-posterior negative effects (N400) and posterior positivities (P600). The LAN effects were not expected to be elicited by the majority of participants (or items, or trials).

According to the second claim, most of the participants (or items) should show either a positive or a negative dominant response, with a minority showing some degree of biphasic response (between 5% and 35% according to Tanner, 2015; Tanner & Van Hell 2014). A strong correlation should be observed between the dominant negative effects seen between 300 and 500 ms at the individual level and the late positive effects (500-800 ms), so that in subjects where one effect is larger, the other effect should be smaller ($0.59<|r|<0.74$; in case the dominant effects seen at the individual level have the same posterior location; Tanner, Inoue & Osterhout, 2014; Tanner, McLaughlin, Herschensohn, & Osterhout, 2013; Tanner & Van Hell, 2014).

The third claim predicts that LAN effect size estimate should be reduced and/or the SE should increase after including in the model a term for subject-specific violation effects. Adding this random effect should also lead to an improvement of the model fit, as this would provide evidence for some subject-to-subject variability in the LAN effect.

2 Material and Methods

Eighty Spanish speakers highly-proficient in Spanish participated to the studies (45 female; mean age=25 y; mean Spanish AoA=1.4 y; average proficiency score=4.9/5.0). They read 240 Spanish sentences that were presented word by word in rapid serial presentation. Half of the sentences contained article-noun gender agreement violations and half were grammatically correct. After each trial they performed a grammaticality judgement task (mean accuracy=95.4 %; SD=3.0). Further details about the participants, the procedure, the EEG recording and preprocessing can be found in the original papers (Caffarra & Barber, 2015; Caffarra et al., 2017; for the EEG preprocessing we followed the pipeline described in Caffarra & Barber, 2015[3] and data from Caffarra et al., 2017 were down-sampled to 250 Hz). ERPs from two experimental conditions (agreement and disagreement) were considered. Overall, 8.7% (SD=6.1) of trials were excluded due to artifacts or incorrect behavioral responses. The number of remaining trials did not differ between conditions (*t*(79)=1.3, *p*>.05).

Grand average waveforms, by-subject, and by-item ERPs were calculated for each condition. For the first analysis, the topographies of the ERP effects (i.e., disagreement-agreement voltage difference) between 300 and 500 ms were obtained at the subject and item level. In order to reduce the potential artifacts generated by averaging procedure, multiple ERP effects were also calculated on the smallest possible trials sets (size range: 1-2 trials) for each participant (total number of sets: 6160, see Supplementary Materials A).

The number of subjects, items and trial sets showing a LAN, an N400, or a positive effect was calculated. The presence of a LAN effect was defined as a negative effect over a representative left-anterior site (F3), which was greater than the effect registered over a posterior site (Pz). The presence of a N400 effect was defined as a negative effect over a posterior site (Pz) being greater than the effect over a left-anterior site (F3). Any other case where both F3 and Pz showed a positive ERP difference was categorized as a positive effect[4]. As an aside, note that the distinction between LAN and N400 effect is based on topographical distribution features (Kemmerer, 2015), which are not straightforwardly related to neural sources in the absence of an adequate forward model (Hallez et al., 2007). Hence, our results should not be read in terms of ERP source modelling.

For the second analyses, the Pearson correlations were calculated between the LAN voltage difference (disagreement-agreement ERP difference at F3 between 300 ms and 500 ms) and the P600 voltage difference (disagreement-agreement ERP difference at Pz between 500 and 800 ms) across subjects and items. Similar correlations were calculated between the N400 voltage difference (disagreement-agreement ERP difference at Pz between 300 ms and 500 ms) and the P600 voltage difference (as in Tanner et al. 2013, 2014; Tanner & Van Hell, 2014).

For the third analysis, mixed-linear models (Baayen, Davidson & Bates, 2008) were fit using the LAN-time-window voltage (ERP average amplitude at F3 between 300 ms and 500 ms) as the dependent variable and agreement as a fixed effect factor at the level of individual trials. By-item and by-subject random intercepts, as well as random slopes for agreement were incrementally added to model variability in the LAN responses at the level of individual subjects and individual items, in addition to the variability of individual trials already modeled by the fixed effect terms. The contribution of each random effect to the model fit was assessed using likelihood ratio statistics (Pinheiro & Bates, 2000; Bates et al. 2014) by comparing the respective model with one that was identical except for the effect in question. Similar analyses were carried out using the P600 voltage (ERP average amplitude at Pz between 500 ms and 800 ms) as a dependent variable. A final model on the LAN voltage was also performed including the subject-specific N400 violation effect term. Dummy coding was used to label the levels of the categorical predictor (0=agreement; 1=disagreement). Analyses were carried out using the *lme4* package (Bates, Maechler, Bolker & Walker, 2014). *P*-values for the coefficients of the linear mixed-effect models were calculated treating the *t*-statistic as if it were a *z*-statistic[5]. Note that inferences about model fit were not based exclusively on likelihood ratio statistics, *p*-values or confidence intervals, but also on a variety of other factors (Loken & Gelman, 2017).

3 Results

The grand average waveforms showed a clear LAN-P600 biphasic response (Figure 1; Caffarra & Barber, 2015; Caffarra et al., 2017).

--- Figure 1---

The analysis of the subject topographies revealed that 55% of the participants showed a LAN effect, 25% a N400 effect and 20% a positive effect (Figure 2). The by-item topographies showed that 46% of the items elicited a LAN, 29% an N400 effect and 25% a positive effect. Similar percentages were observed after calculating ERP effects on small sets of trials for each participant (LAN: 49%, N400: 29%, positive effect: 22%, see Supplementary Materials A). Negative effects at F3 were present in 71% of the participants and 66% of the items (Figure 2).

---Figure 2---

In the second analysis, 66% of the participants and 62% of the items showed an early negative effect at F3 followed by a later positivity (Figure 3, first row, quadrant IV corresponds to the presence of biphasic responses). The LAN effect and the P600 effect were uncorrelated across participants (r=0.04; p=0.72). However, there was a positive weak correlation across items (r=0.25; p<0.001), suggesting that for items where the P600 effect was smaller, the LAN effect was larger. When similar correlations were computed on the ERP voltage differences at the same representative electrode (Pz) larger correlations were found (by-subject: r=0.48; p<0.001; by-item: r=0.64; p<0.001).

--- Figure 3 ---

In the third analysis, an initial mixed-linear model was fit on the LAN voltage including agreement as a fixed predictor and a by-item random intercept (model A: intercept=0.04; SE=0.10; β=-0.62; SE=0.13; t=-4.94, p<0.001, for more details see Supplementary Materials C). Note that the agreement condition average voltage is near zero (0.04) and that the average LAN (disagreement) effect is a negative modulation of about half a microvolt (-0.62). The standard error of the LAN effect (0.13) is small relative to the size of the effect, leading to a relatively large t-ratio. Compared to this baseline model, adding additional random effect terms would be expected to affect the standard error of the fixed effects, and possibly the fixed effect coefficients.

Adding a by-subject random intercept (model B: intercept=0.05; SE=0.28; β=-0.62; SE=0.12; t=-5.13, p<0.001) led to an improvement of the model fit ($\chi^2(1)$=1167, p<0.001) and an increase of the SE (from 0.10 to 0.28). This is consistent with larger subject variability in the LAN-window voltage in the control condition (Figure 4). To assess whether a subject-specific and/or an item-specific violation effect improved the fit, two additional models were compared: one in which a by-subject random slope was added to model B (model C: intercept=0.05; SE=0.27; β=-0.62; SE=0.13; t=-4.61, p<0.001), and one that also included a by-item random slope (model D: intercept=0.05; SE=0.27; β=-0.62; SE=0.14; t=-4.57, p<0.001). Note first that the fixed parameters and the SEs remain unchanged. Second, neither of these models led to improvements in fit over the corresponding nested comparison (model C: $\chi^2(2)=2.96, p=0.23$; model D: $\chi^2(2)=2.44, p=0.30$). These model comparisons, along with plots of the distributions of the model random effects, as well as plots of the raw subject averages, suggest that the LAN effect was not subject to a great deal of subject-to-subject or item-to-item variability, although variability in the effect was clearly observed. Importantly, the estimates of the LAN effect (-0.62 µV, SE=0.13 µV) did not change substantially after accounting for subject variability. Finally, we also fit a model that included the amplitude of the N400 effect (at Pz) as a predictor. In this case, the estimate of the LAN effect was not reduced and the SE remained unchanged (-0.65 µV, model E: intercept=0.32; SE=0.26; β=-0.65; SE=0.13; $t=-4.97, p<0.001$).

The models A, B, C, and D were also fit to the P600 voltage (500-800 ms time window; for more details see Supplementary Materials C). All models had substantially equivalent estimates of the baseline voltage (about 0.8 µV) as well as P600 violation effect (about 3.7 µV; model A: intercept=0.81; SE=0.11; β=3.69; SE=0.14; $t=26.89, p<0.001$; model B: intercept=0.79; SE=0.25; β=3.70; SE=0.13; $t=27.59, p<0.001$; model C: intercept=0.81; SE=0.19; β=3.68; SE=0.28; $t=13.20, p<0.001$; model D[6]: intercept=0.81; SE=0.18; β=3.67; SE=0.29; $t=12.71, p<0.001$).

Similar to the LAN, adding a by-subject random intercept improved the fit over model A ($\chi^2(1)=629.55, p<0.001$), with an increase of the SE (from 0.11 to 0.25). In addition, including a by-subject random slope led to an improvement of the fit over model B ($\chi^2(2)=182.72, p<0.001$) and a concomitant increase of the SE (from 0.13 to 0.28). Thus, there is evidence of subject-to-subject variability in the P600 control condition, as well as in the P600 violation effect (Figure 4).

--- Figure 4 ---

4 Discussion

The present study examined and modeled the variability of the LAN effect elicited by local agreement violations in a morphologically rich language. Three different hypotheses related to the claim that the LAN effect in the grand average is a spurious effect were examined. A large ERP dataset showing a LAN-P600 biphasic response after grand averaging was analyzed at the subject, item, and trial level.

First, individual ERPs were calculated by-item, by-subject and by-trial sets to examine how often the ERP responses resembled the grand average for (a) single subjects (over all items), (b) single items (over all subjects), and (c) small sets of trials. This analysis clearly showed that LAN effects could be observed in individual subjects, items, and trial sets. Moreover, these effects were more consistent than the N400 or positive effects at the level of subjects, items and small sets of trials. The grand average LAN effect was, thus, more representative of what occurred to most subjects, items, and trials than the proposed alternatives. Note that even when the effects of averaging were kept to the minimum (in the by-trial analysis ERP averages were either not computed or computed over two trials) the LAN was still the most consistent ERP effect. This is difficult to reconcile with the claim that the LAN effect depends on the averaging procedure.

These findings do not support the claim that the averaging procedure is artificially producing a left anterior negativity (Osterhout, 1997; Osterhout et al., 2004), at least when the LAN effect is elicited by local agreement violations in a morphologically rich language with highly-proficient readers. A remaining possibility is that there is a difference between violation types, languages, and participant language background. Note that although the LAN was the most consistently reported effect, it was not present in all subjects, items, and trials. Electrophysiological effects (even well-established ones, such as N1 or P2) do not likely appear at every by-subject and by-item average (Cooper, Osselton, & Shaw, 1969; Sörnmo &

Laguna, 2005). The relative size of the effect together with the amount of measurement variability and measurement noise[7] can make the effect difficult to be detected at every observation. Crucially, although the LAN has a relatively small size (around 0.5 μV) as compared to the N400 and the P600 effects (which are typically over 1 μV), it was consistently detected. As to the impact of measurement variations, the first analysis cannot tell us whether subject (or item) variability partially accounts for this ERP patterns. This was specifically tested by the third analysis.

Second, the correlations between LAN (which was the dominant negative effect based on the results of the previous analysis) and P600 single effects were calculated to examine how the biphasic responses covary over the sample of subjects or items. The results revealed that most of the participants and most of the items show both early negative and late positive effects. There was no clear relation between individual subject LAN and P600 effects, but there was a weak correlation across items. As the by-item LAN effect increased the by-item P600 effect decreased. When similar correlations were calculated on the same posterior spatial location they were stronger and compatible with those reported in previous studies (Tanner et al., 2013, 2014; Tanner & Van Hell, 2014).

These findings speak against the presence of prominent monophasic responses at the subject level (Osterhout et al., 2004), as well as at the item level. These results show weak support for the covariance of the two components of the biphasic responses. The LAN effects (which were the most frequent ERP negative effects observed in individual subjects and items) did not show a strong relation with the subsequent positive ERP effects, while ERP effects of individual items showed only a weak relation. Note that the correlations calculated here regarded different topographic locations (F3 and Pz), as the first analysis showed that early negative effects were most frequently left anteriorly distributed. However, when the same posterior topographic location was considered (as done in previous studies: Tanner et al., 2013, 2014; Tanner & Van Hell, 2014), the correlations were stronger, suggesting that the covariance of two subsequent ERP magnitude differences increases with spatial contiguity. These higher correlations at the same topographic locations are probably due to a shared random effect and measurement noise at the same electrode.

Third, mixed-linear models were fit to estimate ERP effects after accounting for subject and item variability. The results showed that larger subject variability was present in the LAN responses to correct sentences, as well as in the P600 responses to correct and incorrect sentences. The estimate of the LAN fixed effect parameter was not reduced and the SE remained unchanged after accounting for subject-specific LAN effect and for subject-specific N400 effect.

These findings provide evidence of subject-to-subject variability in the LAN responses. However, this is not a peculiarity of the LAN and it can also be observed in the P600 responses (even to a larger extent). These results do not strongly support the idea that the subject variability accounts for the LAN effect reported in the grand average[8]. In addition, the distributions of the random effects relative to the LAN control condition and violation effect (see Supplementary Materials C) do not cluster into distinct groups that would be associated with qualitatively different effects (i.e., N400 and P600), but they rather appear to be unimodal distributions.

Overall, these results argue against the possibility that the LAN effect is consistently and systematically an artifact of averaging. Note that this is true regardless of how the LAN effect is functionally interpreted. The present findings cannot tease apart different functional interpretations of the LAN effect (e.g., morphosyntactic analysis vs. working memory demands). Instead, the present work provides evidence that there are cases where the grand average LAN effect is representative of by-subject, by-item and by-trial responses. The type of violation considered here (i.e., determiner-noun gender agreement violation in a morphologically rich language) has been often associated with LAN effects in the published literature[9] on first language comprehension (Molinaro et al., 2011; but see: Hagoort, 2003; Wicha, Moreno, & Kutas, 2004). It is still not clear whether the present results can be generalized to other experimental designs where the grand average LAN effect seems to be less representative of single ERP responses (e.g., subject-verb agreement violations in morphologically poor languages; Tanner & Van Hell, 2014; violations where there is a longer time interval between agreeing constituents; Roll, Gosselke, Lindgren, & Horne, 2013).

A potential contribution of the present work is providing useful methodological tools to examine both the properties of the ERP grand average and individual responses. The updated scripts for the present analyses are available online at https://github.com/dvdsn/218594. Estimation of different sources of variability and larger sample sizes will help us to have a better measure of ERP effect sizes and its systematic variation (see a recent debate on sample size in Friston 2012; Lindquist, Caffo, & Crainiceanu, 2013; and also the discussion in Loken & Gelman, 2017). Note however, that there remains a great deal of work to be done, as even the best-fitting models reported here did not account for very much variability (in the sense of R^2).

To conclude, the present study described multiple ways of exploring the relation between grand average waveforms and ERPs of single subjects, items, and trials. It provided evidence that the grand average LAN effect can accurately reflect individual brain responses.

Authors Notes

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Declarations of interest: none

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Footnotes

1. This is not the first debate about the functional nature of ERP components associated to sentence comprehension. In the past years, at least another similar debate has been proposed, which was focused on the nature of the P600 and the possibility to reduce it to a P300 (Coulson et al., 1998; Osterhout & Hagoort, 1999).
2. It is worth noting that the coexistence of the LAN with a positivity does not necessarily inform on potential component overlaps. In fact, a negative effect on the scalp is always accompanied by a positive counterpart (although not always within the sensor array) since the sum of potentials around the head should be zero in ideal conditions.
3. Using the ERP pipeline described in Caffarra et al. (2017) led to similar results (Mendoza, 2017).
4. Other ways of categorizing the effects (using clusters of three electrodes instead of one representative electrode and calculating laterality and anteriority indexes based on 26 electrodes) led to similar pattern of results (i.e., presence of LAN effects at the subject and item level, greater proportion of LAN effects than any other alternatives, see Supplementary Materials B).
5. Correlations and mixed-linear models were calculated also using clusters of electrodes instead of a single representative electrodes (LAN: F3, F7, FC5; N400/P600: Pz, P3, P4) and the results were similar to those presented here. For the mixed-linear models, the results of the model comparisons were the same after fitting the same models using sum coding (-0.5/0.5). Model comparisons with leave-one-out cross validation after fitting the equivalent Stan models using the *rstanarm* package (available online at https://CRAN.R-project.org/package=rstanarm) resulted in similar conclusions.
6. The model did not converge, but coefficient estimates were similar to the models that did converge.

7. Measurement noise refers to a pattern that would not repeat with re-test, while measurement variability refers to a pattern that does repeat with re-test, but is different from the population central tendency.
8. The results from the mixed-linear models might seem to be at odd with the scatter plots of correlation analyses, where more variability seems to be present in the case of the LAN than the P600 effect. However, it should be kept in mind that the scatterplots do not represent the same type of information conveyed by the mixed-linear results. In the mixed-linear models not all variability has been modeled, but only that which is related to item and subject identity (both residuals and R^2 coefficients of mixed-linear models showed that there is still a considerable portion of unmodeled activity). In addition, unlike the scatterplots, mixed-linear models model the different source of variability for LAN and P600 voltages for each condition (and not for their difference). Finally it is worth noting that the magnitude of these two effects is different (3 µV against 0.5 µV), with the larger effect being more easily modeled against the measurement variability and noise.
9. We do not know the number of studies that have looked for the LAN but have not found it --not least because of the publication bias for statistically-significant results (see Caffarra et al., 2015 for similar concerns). Even in the case the publication bias contributes overestimating the LAN effects reported in the literature, the present dataset still represents a case where the LAN effect observed in the grand average can be observed also in individual brain responses. Future studies are needed to check how far the present findings can be generalized.

Figure Captions

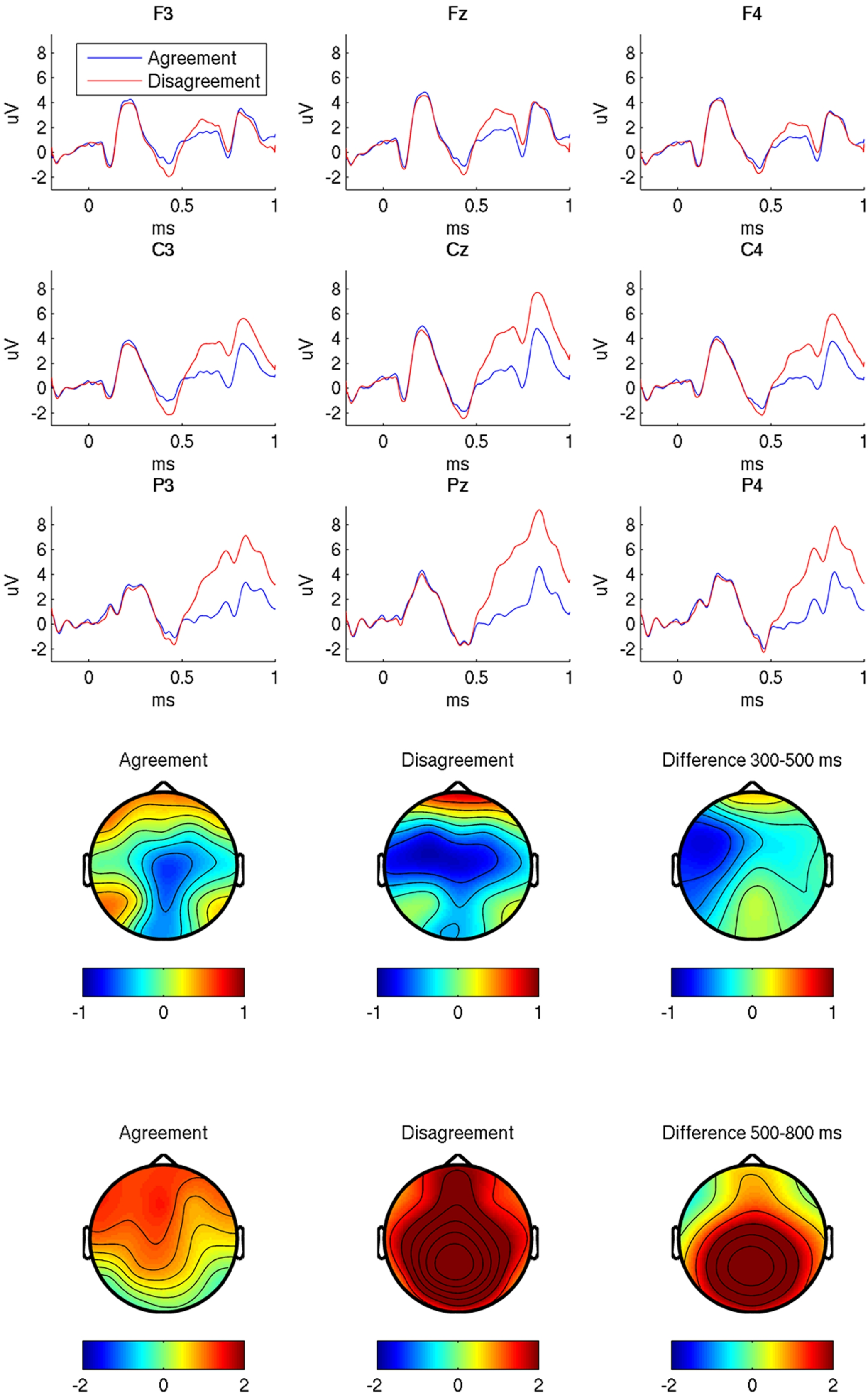
Figure 1. The upper panel shows grand average waveforms for the agreement and the disagreement condition (blue and red line, respectively). Positive voltage is plotted upwards. The bottom panel shows the topographic distribution of each experimental condition and of their difference in the two time windows of interest: 300-500 ms and 500-800 ms. Y-axes units are microvolts, x-axes are ms, and the topography color-scales are microvolts. The greatest magnitude LAN effect is at F3, and the greatest P600 effect is at Pz.

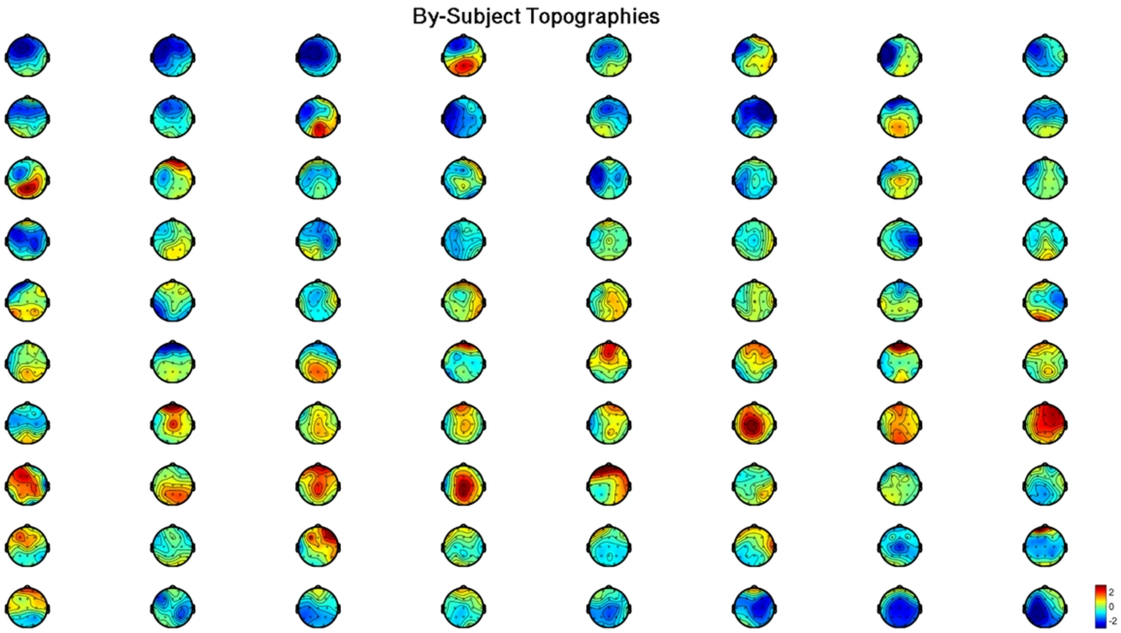
Figure 2. The upper panel shows the topographic distributions of the ERP effects between 300 ms and 500 ms for each participant. The topographies are ordered to show the LAN effects (44, from the greatest effect to the smallest one), the positive effects (20) and the N400 effects (16, from the smallest effect to the greatest one), respectively. The bottom panel shows the ERP voltage recorded at F3 for the agreement and the disagreement condition. Blue lines marked a negative ERP effect, while red lines marked a positive effect.

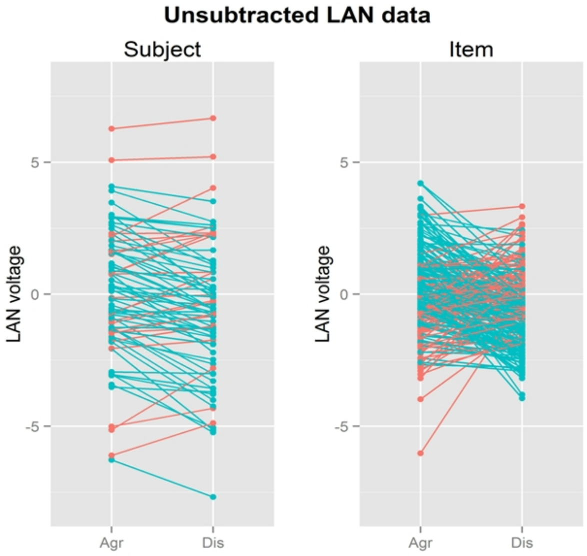
Figure 3. Top row: by-subjects and by-item correlations between the LAN voltage difference (disagreement-agreement ERP difference at F3 between 300 ms and 500 ms) and the P600 voltage difference (disagreement-agreement ERP difference at Pz between 500 and 800 ms). Bottom row: by-subjects and by-item correlations between the N400 voltage difference (disagreement-agreement ERP difference at Pz between 300 ms and 500 ms) and the P600 voltage difference (disagreement-agreement ERP difference at Pz between 500 and 800 ms). Each quadrant is displayed with its relative number.

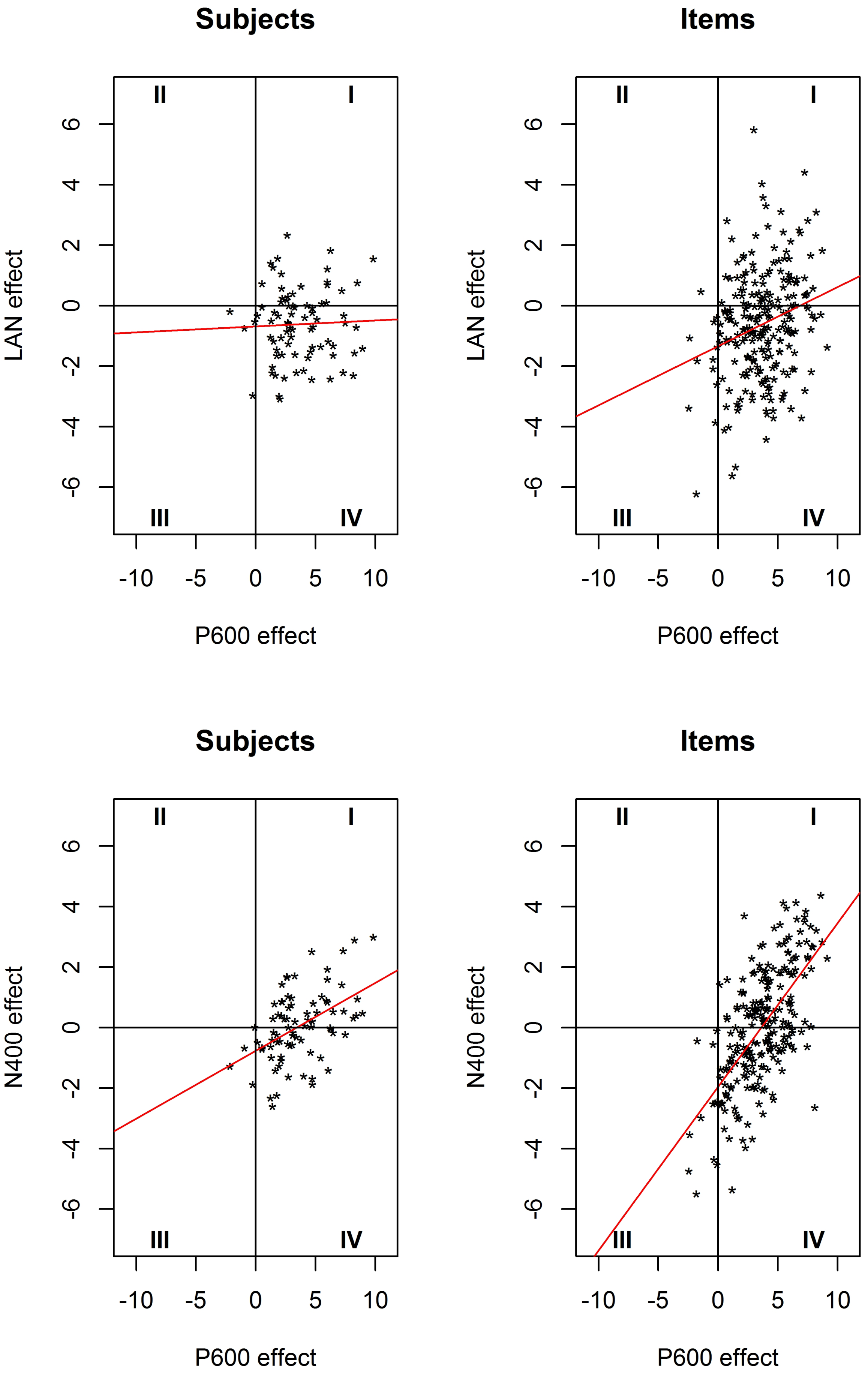
Figure 4. Density plots of the variance parameters estimated from models C. Y-axis are kernel density estimates, and x-axis units are microvolts. The curves represent the estimates of the population probability distribution based on the given sample of points. The upper panel shows the LAN and the P600 average response to the control condition (vertical dashed line), and variability due to subject (blue distribution) and item (red distribution). The lower

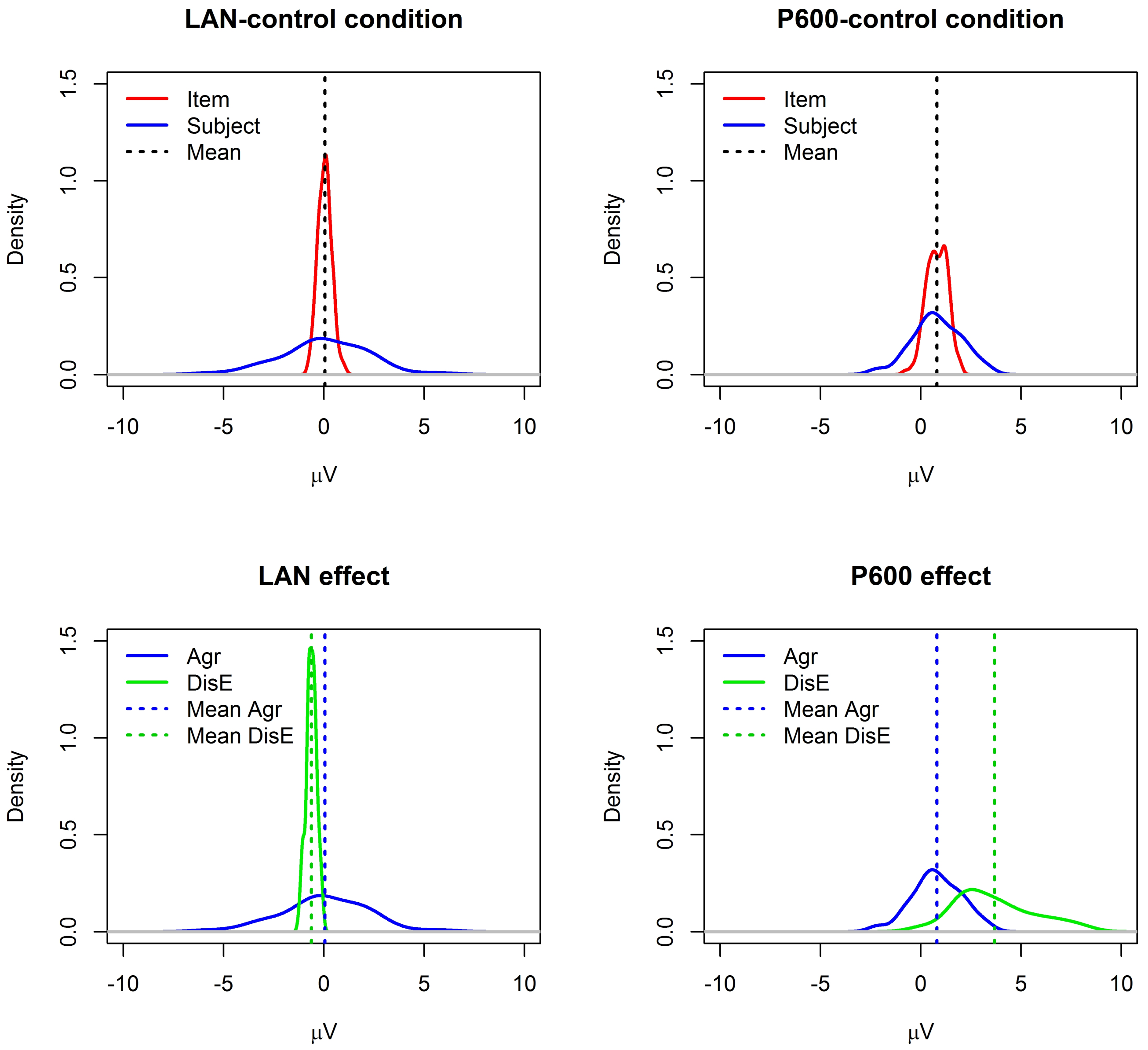
panel shows the ERP average response to the control condition (Mean Agr: blue dashed line) and the ERP average size of the violation effect (Mean DisE: green dashed line) with the relative variability due to subjects. For a comparison between the distribution of the observed data and the distribution of the fitted random effect coefficients see Supplementary Materials D.


F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
Agreement
Disagreement
uV
ms
8
6
4
2
0
-2
0
0.5
1
Agreement
Disagreement
Difference 300-500 ms
-1
0
1
Agreement
Disagreement
Difference 500-800 ms
-2
0
2


By-Subject Topographies
2
0
-2

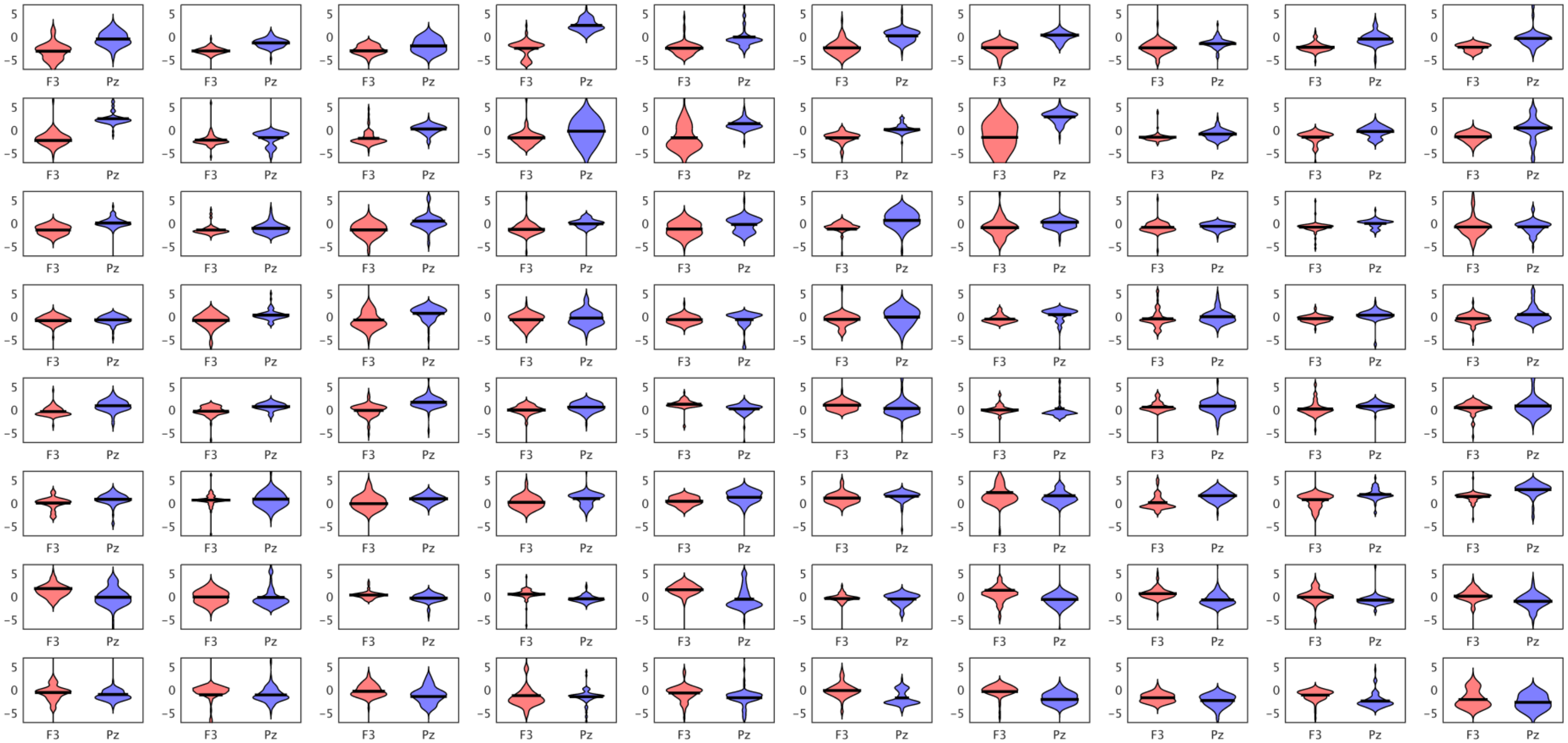

Unsubtracted LAN data
Subject
Item
LAN voltage
5
0
-5
Agr
Dis


Subjects
Items
LAN effect
P600 effect
II
I
III
IV
6
4
2
0
-2
-4
-6
-10
-5
0
5
10
Subjects
Items
N400 effect
P600 effect


LAN-control condition
Item
Subject
Mean
Density
1.5
1.0
0.5
0.0
-10
-5
0
5
10
µV
P600-control condition
Item
Subject
Mean
Density
1.5
1.0
0.5
0.0
-10
-5
0
5
10
µV
LAN effect
Agr
DisE
Mean Agr
Mean DisE
Density
1.5
1.0
0.5
0.0
-10
-5
0
5
10
µV
P600 effect
Agr
DisE
Mean Agr
Mean DisE
Density
1.5
1.0
0.5
0.0
-10
-5
0
5
10
µV

Statement of Significance

The focus of the present work represents a highly debated issue in the ERP literature nowadays and it has important methodological implications for ERP analysis procedure. For these reasons, we believe that this study will be of interest to researchers working on parsing, as well as on ERP data analysis.



The amplitude voltage between 300 and 500 ms recorded at F3 and Pz were extracted for each participant and item. The voltages of each electrode and condition were sorted based on amplitude and divided into 76 bins (as 77 was the minimum number of artifact-free items per condition, 76 bins guaranteed the fewest possible trials per bin, reducing the potential consequences of averaging procedure; each bin contained 1 or 2 trials). When two trials belonged to the same bin they were averaged, and the amplitude voltages of corresponding bins were subtracted across conditions. The resulting ERP effects calculated for F3 and Pz are plotted for each participant as violin plots (black lines represent means) in order to show the distributions of ERP effects calculated on small sets of trials. Y-axis units are microvolts. X-axis shows the electrodes of interest. The subject order is the same as Fig. 2. There is a correspondence between individual topographies shown in Fig. 2 and the distributions of ERP effects at the trial level.

Proportions of LAN and N400 effects (300-500 ms) calculated based on different criteria from those described in the paper

Effects defined on clusters of electrodes

A LAN effect was considered present when the negative effect (disagreement-agreement voltage difference) over a left-anterior cluster of electrodes (F3, F7, FC5) was greater than the effect registered over a posterior cluster (P3, Pz, P4).

A N400 effect was defined as a negative effect over the posterior cluster (P3, Pz, P4) being greater than the effect over the left-anterior cluster (F3, F7, FC5).

Any other case where both left-anterior and posterior cluster showed a positive ERP difference was categorized as positive effect.

	Subjects	Items
LANs	49%	44%
N400s	29%	32%
Positivities	23%	25%
Negative effect at F3, F7, FC5	68%	64%

Effects defined by laterality and anteriority indexes

Average ERP effects (disagreement-agreement voltage difference) were calculated for anterior (A: Fp1, Fp2, F3, F4, F7, F8, Fz, FC1, FC2, FC5, FC6), posterior (P: P3, P4, O1, O2, P7, P8, Pz, CP1, CP2, CP5, CP6), left (L: Fp1, F3, C3, P3, O1, F7, T7, P7, FC1, CP1, FC5, CP5) and right electrodes (R: Fp2, F4, C4, P4, O2, F8, T8, P8, FC2, CP2, FC6, CP6).

For each ERP effect a laterality and anteriority index was defined and an index size was quantified based on the following formulas:

Constrain	Index type	Index size
if $|L| > |R|$	Left	$L - R$
if $|L| < |R|$	Right	$R - L$
if $|A| > |P|$	Anterior	$A - P$
if $|A| < |P|$	Posterior	$P - A$

Then, each effect was classified as negative when the sign of laterality and anteriority indexes were negative and positive when the sign of both indexes were positive. Mixed effects (positive and negative) are reported aside.

		Subjects	Items
Negative effects	Left anterior (LANs)	30%	19%
	Right anterior	9%	10%
	Left posterior	13%	17%
	Right posterior (N400s)	6%	11%
Positive effects	Left anterior	3%	5%
	Right anterior	16%	13%
	Left posterior	3%	6%
	Right posterior (P600s)	15%	16%
Mixed effects	Left neg., Ant. pos.	1%	0.5%
	Left pos., Post. neg.	0%	1%
	Right pos., Post. neg.	3%	0%
	Right neg., Post. pos.	3%	0.5%

LAN (lmer)	**Model A**			**Model B**			**Model C**			**Model D**		
	β	CI	*t*	β	CI	*t*	β	CI	*t*	β	CI	*t*
Fixed Parts												
Control	0.04	[-0.15, 0.23]	0.44	0.05	[-0.50, 0.59]	0.17	0.05	[-0.48, 0.57]	0.17	0.05	[-0.49, 0.58]	0.17
Disagreement	-0.62	[-0.87, -0.38]	4.94	-0.62	[-0.86, -0.38]	5.13	-0.62	[-0.88, -0.36]	4.61	-0.62	[-0.89, -0.35]	4.57
Random Parts												
σ^2	69.83			64.40			64.33			64.30		
$\tau_{00, i}$ (SD)	0.33 (0.58)			0.39 (0.62)			0.39 (0.63)			0.61 (0.78)		
$\tau_{00, s}$(SD)				5.41 (2.32)			5.10 (2.26)			5.10 (2.26)		
$\tau_{00, dis-s}$ (SD)							0.27 (0.52)			0.27 (0.52)		
$\tau_{00, dis-i}$ (SD)										0.09 (0.30)		
ρ_{01}												
N_i	240			240			240			240		
N_s				80			80			80		
ICC_i	0.005			0.006			0.006			0.009		
ICC_s				0.077			0.073			0.073		
Observations	17523			17523			17523			17523		
R^2 / Ω_0^2	.014 / .010			.092 / .091			.094 / .093			.094 / .093		
Correlation of Fixed Effects												
	-0.65			-0.22			-0.12			-0.14		
Model comparison (χ^2)				1167.41			2.96			2.44		

LAN (stan)	**Model A**		**Model B**		**Model C**		**Model D**	
	β	Cr. I	β	Cr. I	β	Cr. I	β	Cr. I
Fixed Parts								
Control	0.04	[-0.15, 0.23]	0.03	[-0.51, 0.59]	0.04	[-0.48, 0.58]	0.05	[-0.49, 0.60]
Disagreement	-0.62	[-0.87, -0.38]	-0.62	[-0.86, -0.39]	-0.62	[-0.87, -0.35]	-0.62	[-0.89, -0.34]
Random Parts								
σ^2	69.84		64.43		64.35		64.34	
SD $\tau_{00, i}$	0.58		0.62		0.62		0.69	
SD $\tau_{00, s}$			2.37		2.29		2.29	
SD $\tau_{00, dis-s}$					0.56		0.57	
SD $\tau_{00, dis-i}$							0.35	
ρ_{01}								
N_i	240		240		240		240	
N_s			80		80		80	
Observations	17523		17523		17523		17523	
R^2	0.006		0.083		0.084		0.085	
Model comparison (elpd, SE)			666.3, 37.8		-0.6, 2.3		0.6, 0.9	

Note: CI, confidence interval; Cr. I, credibility interval.

Fixed and random effect parameters are reported for lmer models (upper side) and Stan models (lower side) of LAN variability. Model comparisons were carried out using Chi-squared test in the case of lmer models and using leave-one-out cross validation in the case of Stan models (this method does not have the mathematical limitations of the likelihood ratio test, as pointed out in Bates, 2010; Demidenko, 2013; Pinheiro & Bates, 2000). The fixed effect parameter estimates are similar in the two approaches. Conclusions for the model comparisons based on either the like-hood ratio test or the leave-one-out cross validation are the same.

Here below fixed and random effect parameters are reported for lmer models of P600 variability.

P600 (lmer)		**Model A**			**Model B**			**Model C**			**Model D***	
	β	CI	*t*	β	CI	*t*	β	CI	*t*	β	CI	*t*
Fixed Parts												
Control	0.81	[0.59, 1.02]	7.40	0.79	[0.31, 1.28]	3.24	0.81	[0.43, 1.18]	4.24	0.81	[0.45, 1.17]	4.44
Disagreement	3.69	[3.42, 3.96]	26.89	3.70	[3.43, 3.96]	27.59	3.68	[3.13, 4.22]	13.20	3.67	[3.10, 4.24]	12.71
Random Parts												
σ^2		82.32			78.48			77.282			77.276	
$\tau_{00,\ i}$ (SD)		0.62 (0.79)			0.67 (0.82)			0.70 (0.84)			0.00 (0.00)	
$\tau_{00,\ s}$(SD)					3.87 (1.97)			1.95 (1.40)			1.95 (1.40)	
$\tau_{00,\ dis\text{-}s}$ (SD)								4.78 (2.19)			4.78 (2.19)	
$\tau_{00,\ dis\text{-}i}$ (SD)											1.42 (1.19)	
ρ_{01}												
N_i		240			240			240			240	
N_s					80			80			80	
ICC_i		0.008			0.008			0.009			0.000	
ICC_s					0.047			0.024			0.025	
Observations		17523			17523			17523			17523	
R^2 / Ω_0^2		.052 / .051			.100 / .099			.117 / .116			.117 / .116	
Correlation of Fixed Effects												
		-0.62			-0.27			0.02			0.02	
Model comparison (χ^2)					629.55			182.72			0.81	

Variance-Covariance matrices

LAN

Model A<-lmer(vLAN ~ agr + (1 | i),data=d)

	Control	Disagreement
Control	0.0093	-0.0079
Disagreement	-0.0079	0.0160

Model B<-lmer(vLAN ~ agr + (1 | s) + (1 | i),data=d)

	Control	Disagreement
Control	0.0765	-0.0073
Disagreement	-0.0073	0.0147

Model C<-lmer(vLAN ~ agr + (1 + agr | s) + (1 | i),data=d)

	Control	Disagreement
Control	0.0727	-0.0043
Disagreement	-0.0043	0.0181

Model D<-lmer(vLAN ~ agr + (1 + agr | s) + (1 + agr | i),data=d)

	Control	Disagreement
Control	0.0735	-0.0052
Disagreement	-0.0052	0.0184

P600

Model A<-lmer(vP600 ~ agr + (1 | i),data=d)

	Control	Disagreement
Control	0.0119	-0.0093
Disagreement	-0.0093	0.0188

Model B<-lmer(vP600 ~ agr + (1 | s) + (1 | i),data=d)

	Control	Disagreement
Control	0.0600	-0.0089
Disagreement	-0.0089	0.0179

Model C<-lmer(vP600 ~ agr + (1 + agr | s) + (1 | i),data=d)

	Control	Disagreement
Control	0.0361	0.0008
Disagreement	0.0008	0.0775

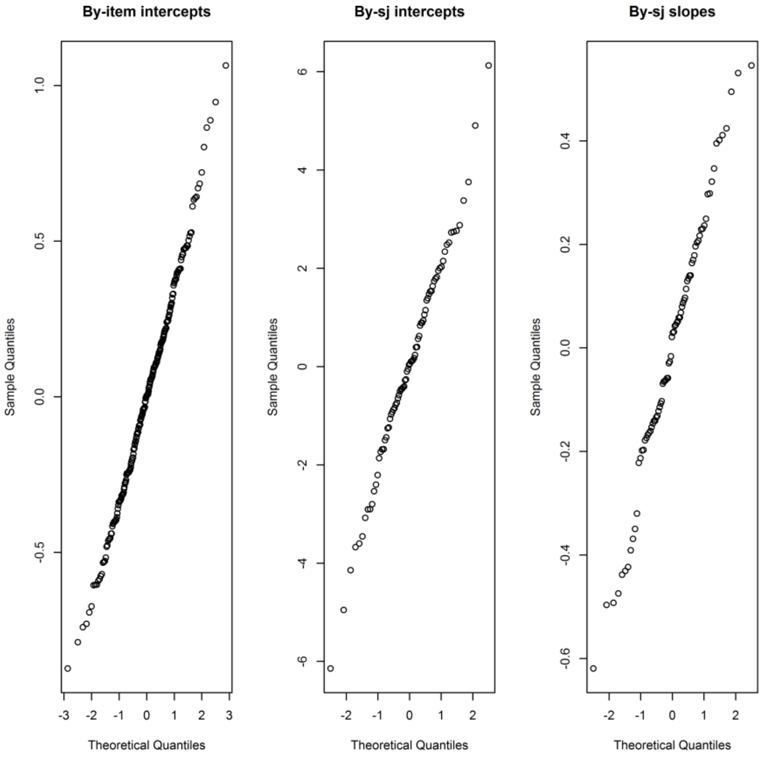
Model D<-lmer(vP600 ~ agr + (1 + agr | s) + (1 + agr | i),data=d)*

	Control	Disagreement
Control	0.0332	0.0010
Disagreement	0.0010	0.0834

*model did not converge

Random effect distributions of LAN responses

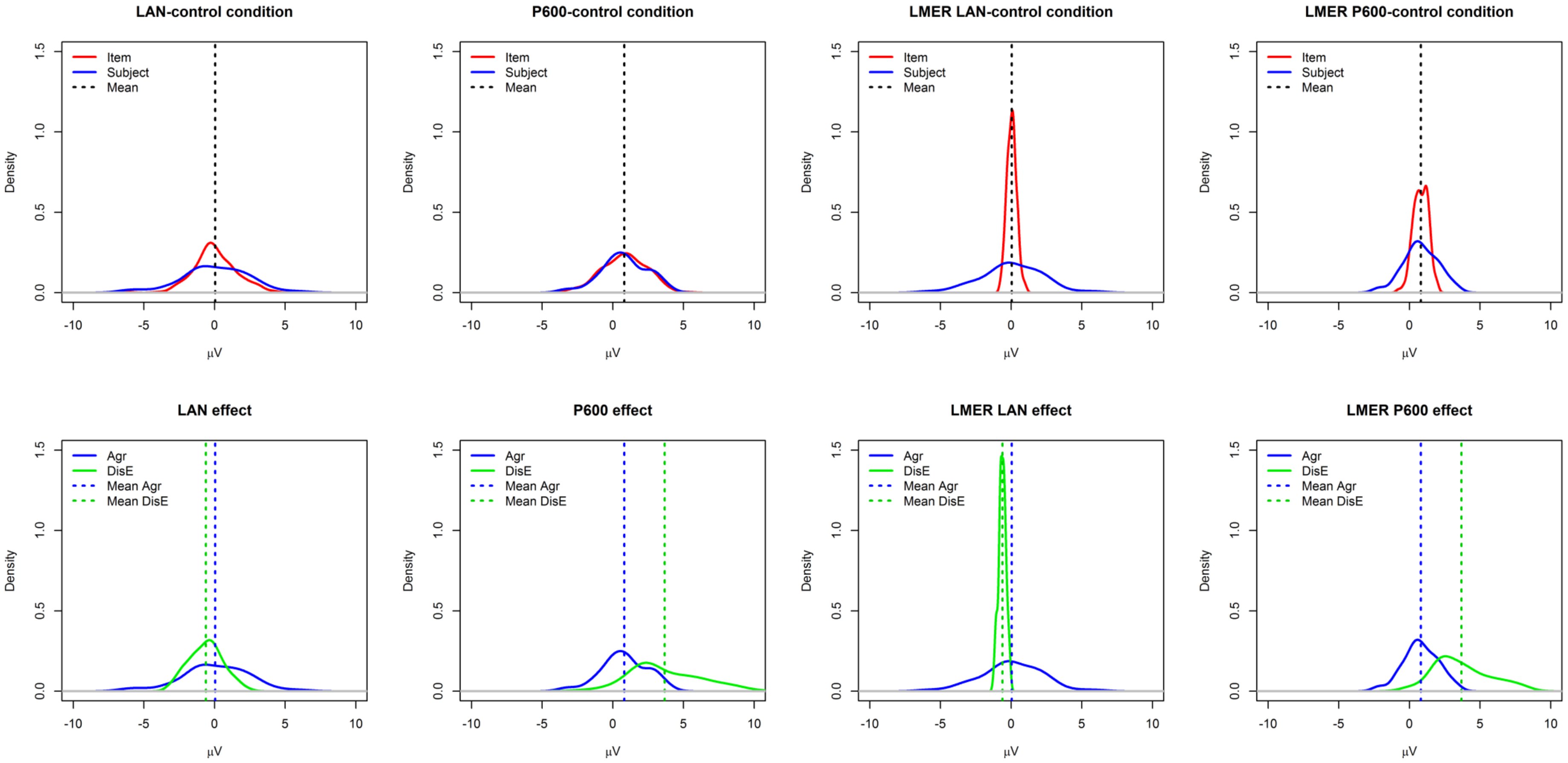
(estimates are based on Model C)



By-item intercepts

By-sj intercepts

By-sj slopes


LAN-control condition
P600-control condition
LMER LAN-control condition
LMER P600-control condition
Item
Subject
Mean
LAN effect
P600 effect
LMER LAN effect
LMER P600 effect
Agr
DisE
Mean Agr
Mean DisE
Density
0.0
0.5
1.0
1.5
-10
-5
0
5
10
µV

Density plots calculated on the real data (four graphs on the left) and on the variance parameters estimated from models C (four graphs on the right). Y-axis are kernel density estimates, and x-axis units are microvolts. The curves represent the estimates of the population probability distribution based on the given sample of points.

The upper panel shows the LAN and the P600 average response to the control condition (vertical dashed line), and variability due to subject (blue distribution) and item (red distribution). The lower panel shows the ERP average response to the control condition (Mean Agr: blue dashed line) and the ERP average size of the violation effect (Mean DisE: green dashed line) with the relative variability due to subjects.

Note that the distributions based on the estimates from the mixed-linear models show less variability as compared to those based on the real data. This is due to the different sources of variance represented here. The observed data distributions do not distinguish the sources of random effects. Thus, the variance of these distributions can include measurement variability (e.g., variations in the underlying response from subject to subject) as well as measurement noise. The mixed-linear model distributions showed only the measurement variability specifically related to items or subjects variations. Mixed-linear models have the advantage to tease apart measurement variability and measurement noise, showing the magnitude of the random effects specifically associated with individual differences.