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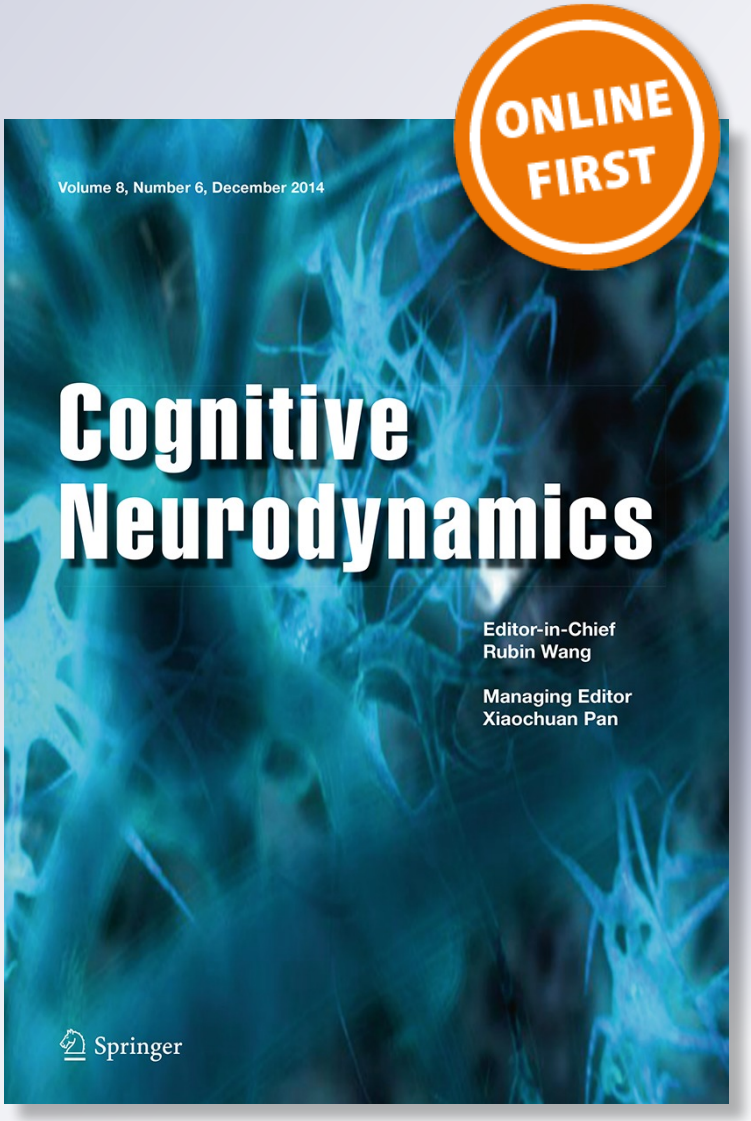


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RESEARCH ARTICLE

# Neural bases of syntax–semantics interface processing

**Evguenia Malaia · Sharlene Newman**

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**Abstract** The binding problem—question of how information between the modules of the linguistic system is integrated during language processing—is as yet unresolved. The remarkable speed of language processing and comprehension (Pulvermüller et al. 2009) suggests that at least coarse semantic information (e.g. noun animacy) and syntactically-relevant information (e.g. verbal template) are integrated rapidly to allow for coarse comprehension. This EEG study investigated syntax–semantics interface processing during word-by-word sentence reading. As alpha-band neural activity serves as an inhibition mechanism for local networks, we used topographical distribution of alpha power to help identify the timecourse of the binding process. We manipulated the syntactic parameter of verbal event structure, and semantic parameter of noun animacy in reduced relative clauses (RRCs, e.g. "The witness/mansion seized/protected by the agent was in danger"), to investigate the neural bases of interaction between syntactic and semantic networks during sentence processing. The word-by-word stimulus presentation method in the present experiment required manipulation of both syntactic structure and semantic features in the working memory. The results demonstrated a gradient distribution of early components (biphasic posterior P1–N2 and anterior N1–P2) over function words "by" and "the", and the verb, corresponding to facilitation or conflict resulting from the syntactic (telicity) and semantic (animacy) cues in the preceding portion of the sentence. This was followed by assimilation of power distribution in the α band at the second noun. The flattened distribution of α power during the mental manipulation with high demand on working memory—thematic role re-assignment—demonstrates a state of α equilibrium with strong functional coupling between posterior and anterior regions. These results demonstrate that the processing of semantic and syntactic features during sentence comprehension proceeds in highly integrated fashion using gating of attentional resources to facilitate rapid comprehension, with attentional suppression of global alpha power to facilitate interaction of local networks.

**Keywords** Neurolinguistics · Syntax · Semantics · Interface · Binding

## Introduction

The question of how information from semantic and syntactic modules of the linguistic system is integrated is as yet unresolved. The remarkable speed of language processing and comprehension (Pulvermüller et al. 2009) suggests that at least coarse semantic information (e.g. noun animacy) and syntactically-relevant information (e.g. verbal template) are integrated rapidly to allow for "good enough" comprehension (Ferreira and Patson 2007). Parallel Architecture theory (Jackendoff 2007; Malaia 2014) proposed parallel constraint-based formalisms for independent linguistic modules, such as syntax and semantics, treating them as individual items stored in long-term memory, and assembled in working memory, with direct competition from alternative structures. However, the

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proposal lacked a plausible neural implementation. The present study manipulated verbal event structure and noun animacy in reduced relative clauses (RRCs, e.g. "*The witness/mansion seized/protected by the agent was in danger*"), to investigate the neural bases of the interaction between syntactic and semantic networks during sentence processing.

Recent advances in analyses of oscillatory activity in the human brain propose α-band-based global inhibition as a gating principle for binding distributed local networks (Haegens et al. 2010; Jensen and Mazaheri 2010; Voytek et al. 2010). Rhythmic brain waves around 10 Hz (α) are the dominant EEG component during conditions of mental rest; during cognitive effort, α amplitudes are typically reduced (Klimesch 1997). Obleser and Weisz (2012) suggested that relative decline in alpha power is likely to reflect an increase in mental operations performed on the speech signal, and more-attentive active cognitive processing. Additionally, Sauseng et al. (2005) found that during manipulation of information in working memory, alpha power exhibits a more topographically flat distribution over the scalp, as compared to a simple mental retention task, suggesting global binding of local networks at alpha frequency. We thus hypothesized that mental manipulation of syntactic and semantic information in working memory will lead to an assimilation in the alpha power distribution over the scalp during the assignment of a thematic role to the second (Agent) noun, indicating the binding of distributed syntactic and semantic portions of the language network at the alpha frequency.

During the processing of an English sentence, the first argument encountered is assumed to be the prototypical agent and the subject of the sentence (Kuperberg et al. 2007; Townsend and Bever (2001); Weckerly and Kutas 1999). When this assumption is incorrect, such as in sentences with reduced object relative clauses (e.g. "*The lawyer escorted by the governor arrived on time"*), the coarse processing is no longer sufficient: the comprehender has to quickly re-assign the thematic roles to proceed with sentence parsing. This re-analysis can be modulated by the introduction of semantic or morphological features biasing a specific syntactic structure such as animacy, which biases an Agentive interpretation of a noun (e.g. Hirotani et al. 2011; Grewe et al. 2006; Clifton et al. 2003).

Constructionist approaches to event structure (Ramchand 2008) suggest that telic verbs, which identify a change of state in the undergoer, require activation of a more complex event structure than atelic verbs, as shown in Fig. 1a. Earlier ERP studies, which investigated the effect of event structure on sentence comprehension, demonstrated that telic event templates prime the Undergoer argument as the argument affected by the end-state of the event (Malaia et al. 2009, 2012).

Undergoer priming facilitates online thematic role assignment and ameliorates the cognitive load during sentence processing. The effect of event template-induced (syntactic) facilitation was most pronounced in the N1–P2 biphasic component over the determiner of the second noun, suggesting rapid access to coarse semantic categorization (e.g. animate–inanimate) of the first argument for correct thematic role assignment (cf. Nakano et al. 2009; (Kuperberg et al. 2007). However, since noun features were not manipulated in other studies examining event structure effects on online processing, the neural basis of syntax–semantics interface processing remained unclear. In the present study, noun animacy (semantics) and verbal event structure (syntax) were both manipulated in order to explore the neural bases of their interaction during thematic role assignment.[1]

We hypothesized that telic verbs would facilitate thematic role assignment during reading, while animate nouns in the first argument positionwould increase the difficulty of thematic role assignment. When two arguments—animate and inanimate—are available for a transitive verb, the animate one is biased to assume the Agent thematic role as the Subject of the sentence (Weckerly and Kutas 1999); a violation of animacy expectations interferes with appropriate thematic role assignment. When the first verb is encountered, the plausibility of inanimate arguments as Agents is reduced further. Violations of thematic-semantic plausibility expectations have been shown to elicit N400 or P600 effects, depending on the experimental task (Kuperberg et al. 2007; Nakano et al. 2009; Weckerly and Kutas 1999); however, no prior studies have investigated whether the event structure of the verb might interact online with thematic role assignment.

Prior ERP studies of syntactic tasks have elicited an enhanced frontocentral N1, indicative of increased attentional effort to processing more syntactically complex stimuli (Neville et al. 1991; Malaia et al. 2009, 2013a), and syntax–semantics integration (Yamada and Neville 2007). This increase in the processing load is typically followed by the higher amplitude of positive deflection P2, previously related to phrase structure re-analysis (Osterhout et al. 1994; Malaia and Wilbur 2011; Malaia et al. 2014). We expected that in the present study, these components might appear as early as the first verb in the relative clause, reflecting automatic attempts at phrase-structure building early in the sentence. In the studies manipulating verbal cues to thematic role assignment (Malaia et al. 2009), the biphasic N1–P2 component in RRCs was first observed at the point of

[1] Telicity is also sometimes referred to as a semantic feature, depending on its realization in a specific language (cf. Malaia et al. 2013b). In contemporary Engish, it is treated as syntactic feature (Kratzer 2004).

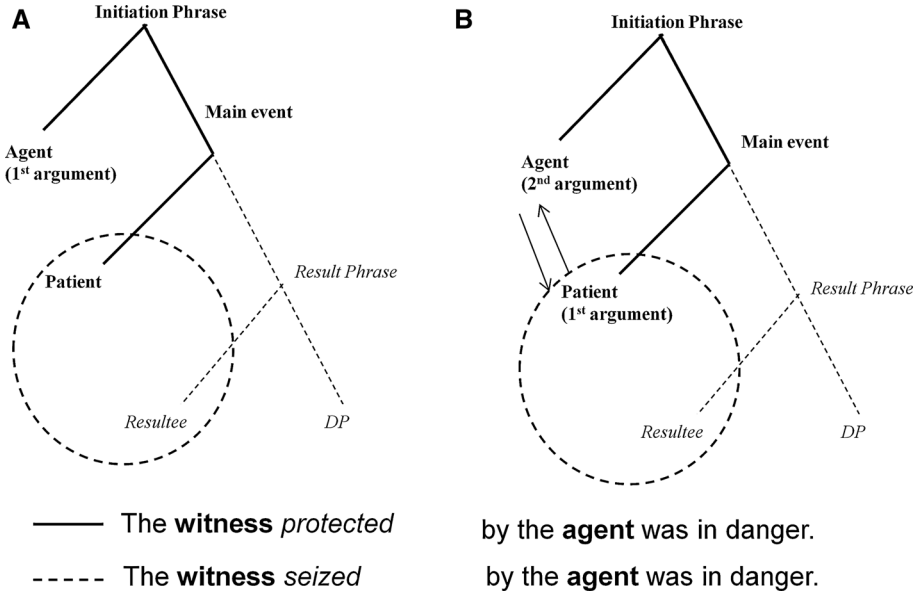


**Fig. 1** Schematic representation of event structure activated by obligatorily transitive telic and atelic verbs in working memory. Telic verbs (*dotted line*) activate an expanded event structure, inclusive of end-point (result phase) and Patient and Resultee argument roles. Upon introduction of the second argument, prior activation of both Agent and Patient roles by telic verbs simplifies re-assignment of thematic roles

syntactic disambiguation—the determiner of the second noun. In the present study, we expected the inanimate first noun to serve as an early cue for the need for thematic role re-assignment, leading to an early N1 effect related to general semantic categories and their combinability. We thus expected animacy and telicity to interact to facilitate sentence processing, such that sentences with inanimate first nouns (likely Patient/Resultee) and a telic verb would elicit the least cognitive load, with the smallest deflections in the N1–P2 time window. The inanimate atelic condition, on the other hand, was expected to elicit the greatest cognitive load, due to initial absence of a Resultee syntactic position (Fig. 1b), later coerced by the need for the assignment of a thematic role for the inanimate argument. Finally, in sentences with animate first noun and telic verb, the syntactic and semantic cues were expected create a conflict in coarse thematic role assignment, with the first animate noun competing for the Agent position, and telic verb requiring assignment of the Patient thematic role. The latter was expected to produce early left anterior negativity (ELAN), indicative of such conflicts (Yamada and Neville 2007).

## Materials and methods

### Participants

Thirteen healthy volunteers (7 male, aged 20–27, mean 21.5, SD = 2) took part in the study. They had normal or corrected-to-normal visual acuity, no language impairments, and no psychiatric or neurological history. All participants were native speakers of English, which was their sole native language. All participants were right-handed (as assessed by Oldfield 1971, inventory). Written informed consent was obtained from all participants. Indiana University IRB approved the experimental protocol. Participants completed the reading span test (RST, Daneman and Carpenter 1980); mean working memory span was 3.09, SD = 0.7. Participants underwent a training session prior to EEG session. During the training session a description of the task was provided, and practice trials were completed.

### Stimuli

Stimulus sentences with reduced relative clauses (RRCs) were constructed using 30 items from each of the following groups: animate nouns, inanimate nouns, telic verbs, atelic verbs. Telicity (telic/atelic) of the verb and animacy of the first noun in reduced relative clauses (RRCs) were manipulated. The stimulus set for this pilot study was constructed as a 2 × 2 paradigm, contrasting verbal event structure (telicity) and the order of animate and inanimate arguments in garden-path inducing object reduced relative clauses. The rest of the lexical material in the sentences was identical, and the second argument was animate in all conditions:

1. The *witness seized* by the agent was in danger (Animate Subject; telic verb).

2. The *mansion seized* by the agent was in danger (Inanimate Subject; telic verb).
3. The *witness protected* by the agent was in danger (Animate Subject; atelic verb).
4. The *mansion protected* by the agent was in danger (Inanimate Subject; atelic verb).

Transitive verbs for reduced relative clauses (40 telic and 40 atelic) were chosen based on Levin (1993), and cross-referenced with examples of allowable usage from multiple dictionary sources. The telic verbs chosen described complete (non-gradient) change, and no semelfactives or reciprocal verbs were used. Noun–verb co-occurrence frequencies were assessed using PMI measures (Recchia and Jones 2009); neither noun animacy nor verbal telicity was a significant factor in noun–verb co-occurrence. Individual frequency of noun and verb stimuli and their orthographic neighborhoods did not differ significantly among conditions. Each participant was shown the entire set of noun–verb pairs, half of which were used in RRCs, and another half in control sentences without relative clause (e.g. "*The mother changed the infant on the couch*"). Appendix provides the full list of stimuli. 80 filler sentences (conjoined active sentences of approximately the same length as the stimuli) were also included; those were constructed using a different set of verbs and nouns in order to ameliorate an effect of repetition. Participants were visually presented with stimuli and filler sentences in a word-by-word manner (500 ms per word), and a comprehension probe. Each participant read 160 experimental sentences; the order of sentences in blocks was pseudo-randomized so that no condition occurred more than twice in a row; the order of blocks among participants was counterbalanced using Latin Square design.

Each participant was seated 36 inches away from the monitor; each sentence was presented in a word-by-word manner; each word appeared on the screen for 300 ms, followed by the 200 ms blank screen. The stimuli subsumed, on average, 0.5° visual angle vertically, and 1.5°–3° horizontally. Stimuli were presented in white on a black background; arial narrow font size 32 was used. The participants were asked to respond as quickly and accurately as possible to the question, which appeared on the screen in full following the stimulus sentence. Questions were counterbalanced for correct answer (Yes/No) and argument probed (Agent/Patient) across conditions. Examples of sentence-question pairs: "*The professor criticized by the student was hard to understand.*"—"*Was the student critical of the professor?*"(correct answer—Yes; Animate Patient; atelic verb); "*The department audited by the consultant remained in good standing.*"—"*Did the consultant remain in good standing?*" (correct answer—No; Inanimate Patient; telic verb).

## EEG recording and analysis

High-density, continuous EEG data were collected using a 256-channel EGI Hydrocel Geodesic SensorNet and a Netstation EEG acquisition system. EEG data were sampled at 500 Hz/channel, band pass filtered at 0.1–250 Hz, and were referenced to the vertex. Electrode impedances were kept below 50KOhm. Stimulus onset times and participants' behavioral responses were time-stamped on a continuous EEG file. Data pre-processing was conducted on EGI Net Station software. Data were re-referenced to the average of two mastoids, and digitally bandpass filtered at 0.3–40 Hz to eliminate slow signal drifts (Wolff et al. 2008), allowing to avoid usage of additional baseline correction. EEG data were segmented relative to stimulus onset time-stamps beginning 100 ms prior to stimulus onset and continuing for 500 ms post-stimulus. Segments with artifacts due to electro-ocular and/or electromyographic activity were removed from subsequent analysis (under 15 % for each condition and each participant; the number of removed segments did not differ significantly among conditions). Electrodes with poor signal quality were identified and a 'bad channel replacement' procedure was also implemented, where activity from the surrounding channels was used to provide an interpolated signal. Baseline correction was performed on the remaining artifact-free trials, the data were averaged across each condition in each participant. A group average was generated, to enable the main ERP components to be identified, and group averaged topographic voltage maps were analyzed to identify groups of electrodes in the regions of interest based on previous literature (Lai and Mangels 2007; Malaia et al. 2009; Yamada and Neville 2007). The following ROIs were selected, as marked in Fig. 2: left posterior (electrodes 104, 105, 106,112, 113, 114, 120, 121, 122, i.e. posterior to P9 in the 10–10 system), right posterior (electrodes 169, 177, 189, 168, 176, 188, 167, 175, 187, i.e. posterior to P8 in the 10–10 system), central occipital (124, 125, 126, 136, 137, 138, 147, 148, 149, centered around Oz in the 10–10 system) left anterior (electrodes 46, 47, 48, 37, 38, 39, 32, 33, 34, surrounding AF7 in the 10–10 system), right anterior (electrodes 25, 18,19, 10, 11, 12, 2, 3, 222, surrounding AF8 in the 10–10 system), central anterior (electrodes 21, 22, 23, 14, 15, 16, 6, 7, 8, centered on Fz in the 10–10 system). None of the selected ROI electrodes were identified as "bad channels" in the artifact correction procedure.

Latency ranges were selected for four ERP components: P1 (150–200 ms post-stimulus onset), N1 (150 to 200 ms post-stimulus onset), P2 (200–300 ms post-stimulus), and N2c (200–300 ms post-stimulus), so that a semi-automated peak picker could be used to identify peak ERP component amplitudes and latencies in the averaged data in single participants over the selected electrode clusters. ERP

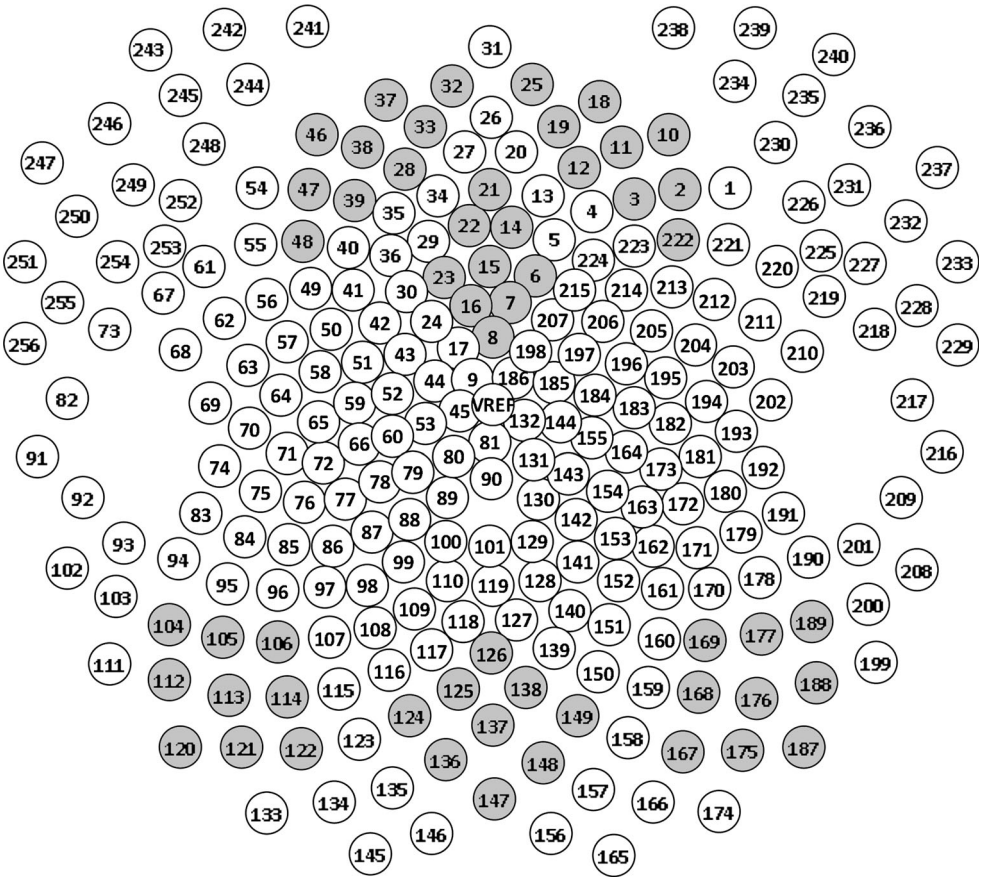


**Fig. 2** Electrode clusters of interest (ROIs) marked on the 256-channel geodesic sensor net

amplitude and latency measures were averaged over each electrode cluster.

Statistical analyses based on amplitude and latency differences as a function of condition were performed using SPSS 19. Response time data was analyzed using a 2-way repeated measures ANOVA with the following factors: telicity (telic, atelic) and animacy (animate, inanimate). EEG data was analyzed using a three-way repeated-measures ANOVA on peak amplitude and latency data of the P2, N2c, P3, and N3 components with the same factors plus scalp distribution factor (left anterior, central anterior, right anterior, left posterior, central posterior, right posterior) over each word in the relative clause: the patient noun (Patient), verb (V1), preposition "by" (BY), definite article (THE), the agent noun (Agent), and the main verb in the matrix clause (V2); Greenhouse-Geisser correction was applied and the significance level was $p < 0.05$. In cases where significant interaction with Animacy or Telicity factors was observed, step-down analyses was conducted over specific brain areas.

Frequency domain analyses were applied to epochs between 0–500 ms post-onset of each word in the RRC (250 data points). For the averaged amplitude of the nine electrodes in each ROI, we calculated amplitude spectra for each experimental condition over each word in the reduced relative clause (Patient, V1, BY, THE, Agent, V2) using fast Fourier transform. For the upper α frequency band, values between 9.8 and 12.7 Hz were bandpass-filtered using a digital elliptic filter with 0.5 decibels of peak-to-peak ripple and a minimum stop-band attenuation of 20 decibels. The mean spectral amplitude in the upper α were squared to obtain a measure of power (Sauseng et al. 2005). The power values were averaged in the frequency domain for each condition (animate telic, inanimate telic, animate atelic, inanimate atelic) and electrode cluster (left anterior, central anterior, right anterior, left posterior, central posterior, right posterior) to assess whether the experimental conditions differed in the amount of α power change over any of the electrode clusters using coefficient of variation.

## Ancillary behavioral study

A word-by-word self-paced reading task was used to assess behavioral strategies of processing RRCs. 43 undergraduate students (24 female; age M = 20.54, range 19–24) at Indiana University Bloomington participated in the study for course credit. 80 target RRC sentences, as well as 80 unreduced relative clauses (URCs, e.g. *The witness that was seized by the agent was in great danger*), and 80 filler sentences were presented on the computer screen to each

participant. The sentences were presented one word at a time, and the participants were instructed to read them, and answer probe questions as fast and accurately as possible (probes required correct thematic role assignment during comprehension). Reading times for each word, and response times for the probes were collected and analyzed using a three-way repeated measures ANOVA with the factors: sentence type (URC, RRC), telicity (telic, atelic) and animacy (animate, inanimate) The Yes/No responses and argument probes were counterbalanced across conditions. *Post hoc* analyses used Bonferroni correction for multiple comparisons.

## Results

### Behavioral results in the EEG study

#### *RRCs*

In the behavioral data from RRCs, the animacy of the first noun (the patient in the relative clause) significantly affected response accuracy [$F(1, 12) = 25.695$, $p < 0.001$, $e_p^2 = 0.682$]—participants responded with significantly higher accuracy to sentences, in which the first noun was inanimate (inanimate, accuracy $M = 87.3$, SD $= 1.57$; animate, accuracy $M = 82.7$, SD $= 1.49$).

Response times revealed main effects of both telicity [$F(1, 12) = 16.224$, $p < 0.002$, $e_p^2 = 0.575$)] and animacy [$F(1, 12) = 15.621$, $p < 0.002$, $e_p^2 = 0.566$], such that RTs to RRCs with first animate noun and telic verbs were longer (Fig. 3). No other effects or interactions were found in behavioral data [$F(1, 12) < 1$)].

### EEG results

#### *Word-by-word EEG component analysis in RRCs*

A three-way ANOVA with factors telicity (telic, atelic), animacy (animate, inanimate) and region electrode cluster (left anterior, central anterior, right anterior, left posterior, central posterior, right posterior) was performed on peak minima and maxima in 150–200 and 200–300 ms windows (P1, N1 and P2, N2c, respectively). The results are summarized in Table 1.

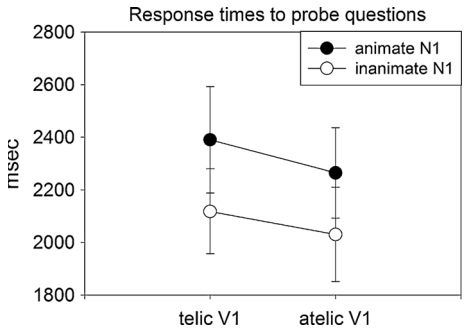


**Fig. 3** EEG study, response times results as a function of animacy and telicity conditions

*Animacy effects* Over the first noun in RRC, posterior N2c peaked significantly earlier in response to inanimate conditions.

Over the preposition "by", latencies of N1 anteriorly and N2c posteriorly were significantly affected by animacy, with earlier peaks to the animate conditions. Over the agent noun, the latency of N1 anteriorly was earlier in sentences with an animate patient (Fig. 4).

*Telicity effects* Over the verb in the matrix clause, posterior P1 showed a gradient amplitude distribution, with the animate telic condition being the most positive, followed by the inanimate atelic condition. Posterior N2c was more negative in the animate condition, as well as telic condition, although only telicity emerged as a significant factor (Fig. 5).

Over the preposition "by", anterior N1 showed a gradient amplitude distribution, with the inanimate telic condition being the least negative, and the animate atelic condition the most negative (Fig. 6). Telicity also significantly affected N1 latency anteriorly, with earlier peak latencies to telic conditions.

Finally, over the agent noun, the amplitude of P2 over left anterior cluster was more positive in the atelic condition.

*Animacy × telicity interaction* Over the determiner 'the', the amplitude of N2c posteriorly was significantly affected by the interaction of telicity and animacy, eliciting gradient amplitude distribution from animate atelic condition (the most negative), to animate telic condition (the most positive) (Fig. 7).

#### *Power analysis*

The event-related power in the high α band fluctuated considerably over the course of the sentence, as did its topographic distribution (Table 2). Overall, the absolute power amplitude fell following the presentation of the patient noun (patient noun $M = 1.79$ μV; verb $M = 0.865$ μV; 'by' $M = 0.148$ μV; determiner $M = 0.117$ μV; agent noun $M = 0.216$ μV). As predicted, at the point of presentation of the agent noun, α power distribution exhibited the lowest variation in distribution over the regions of interest in all sentence types. Assimilation of the α power across brain regions appears indicative of global processing reliant on alpha-driven synchronization across brain regions, which in

**Table 1** Statistical analysis of EEG components: significant results

| Word | Component | Effect | Electrode cluster | $F$ (1, 12) | $p$ | $e_p^2$ |
|---|---|---|---|---|---|---|
| Patient noun | N2 | Animacy | Left posterior latency | 5.861 | 0.032 | 0.328 |
| Verb | P1 | Animacy × telicity | Left posterior amplitude | 10.383 | 0.007 | 0.464 |
| | N2 | Telicity | Left posterior amplitude | 9.075 | 0.011 | 0.431 |
| | | Animacy | Right posterior amplitude | 8.080 | 0.015 | 0.4 |
| BY | N1 | Animacy × Telicity | Left anterior amplitude | 9.123 | 0.011 | 0.432 |
| | | Telicity | Left anterior latency | 8.576 | 0.013 | 0.417 |
| | | Animacy | Left anterior latency | 7.291 | 0.019 | 0.378 |
| | N2 | Animacy | Left posterior latency | 12.509 | 0.004 | 0.510 |
| | P2 | Telicity | Right anterior amplitude | 5.088 | 0.044 | 0.298 |
| THE | P1 | Animacy × telicity | Left posterior latency | 4.841 | 0.032 | 0.328 |
| | N1 | Telicity | Central anterior latency | 8.664 | 0.012 | 0.419 |
| | N2 | Animacy × telicity | Central posterior amplitude | 10.137 | 0.008 | 0.458 |
| | | Animacy × telicity | Left posterior amplitude | 7.542 | 0.018 | 0.386 |
| | | Animacy × telicity | Right posterior amplitude | 8.623 | 0.012 | 0.418 |
| | | Telicity | Left posterior latency | 12.509 | 0.004 | 0.510 |
| Agent noun | P1 | Telicity | Central posterior amplitude | 5.047 | 0.036 | 0.318 |
| | N1 | Animacy | Left anterior latency | 9.910 | 0.008 | 0.452 |
| | P2 | Telicity | Left anterior amplitude | 6.686 | 0.024 | 0.358 |
| | | Telicity | Central anterior amplitude | 6.117 | 0.029 | 0.338 |
| | | Animacy | Right anterior amplitude | 8.032 | 0.015 | 0.401 |

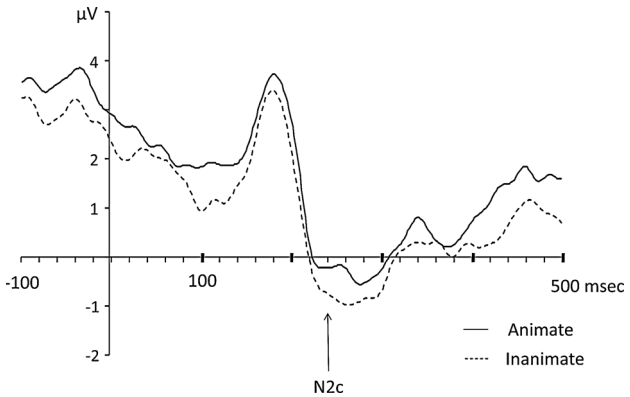


**Fig. 4** Left posterior electrode cluster ERPs to the first noun: posterior N2c peaked later in response to inanimate conditions

this case is likely associated with syntax–semantics interface processing during thematic role assignment.

## Results of the ancillary behavioral study

### *Response times to probe questions*

ANOVA on response times to probe questions (using correct responses only) demonstrated the effect of Animacy in both RRCs [$F(1, 42) = 28.234$, $p < 0.001$, $e_p^2 = 0.402$], and URCs [$F(1, 42) = 18.856$, $p < 0.001$, $e_p^2 = 0.310$], as well as a trending effect of Telicity in URCs [$F(1, 42) = 3.503, p < 0.068, e_p^2 = 0.077$]. No other effects or interactions were found in response time data [$F(1, 42) < 1$].

### *Reading times*

The ANOVA on reading times for each word in the sentence during reading demonstrated the expected effect of Sentence Type (URCs vs. RRCs) on the definite article "THE" [$F(1, 42) = 53.712$, $p < 0.018$, $e_p^2 = 0.964$], as well as interactions between Sentence Type and Animacy on the second verb [$F(1, 42) = 24.221$; $p < 0.039$ $e_p^2 = 0.924$], and Animacy on the second noun ($F(1, 42) = 22.296$; $p < 0.022$ $e_p^2 = 0.918$]. To further analyze these effects, step-down ANOVAs were conducted on RRCs and URCs separately.

A step-down ANOVA in RRCs revealed an interactive effect of animacy and telicity on the definite article 'the' before the second argument [$F(1, 42) = 62.811, p < 0.016$, $e_p^2 = 0.969$]. *Post hoc* analyses revealed significant effect of Animacy ($p < 0.031$), but not Telicity ($p > 0.05$), with Animate Telic condition eliciting significantly longer RTs, and Inanimate Telic condition elicited significantly shorter RTs, than the respective Atelic conditions (Fig. 8).

In non-garden-path conditions (in URCs), the response times to the 'by' elicited an animacy x telicity interaction [$F(1, 42) = 3072.952$, $p < 0.003$, $e_p^2 = 0.994$], such that telicity appeared to facilitate processing in the stimuli with

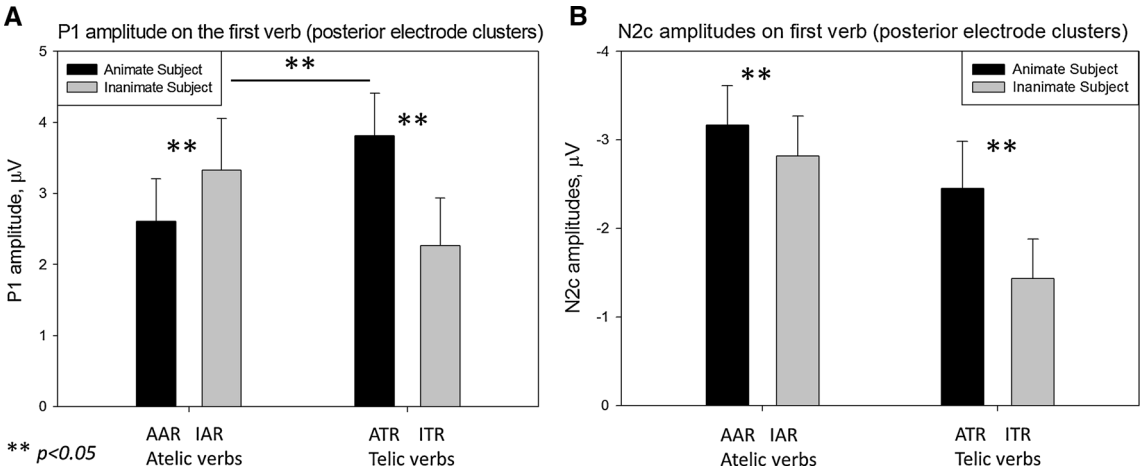


**Fig. 5** **a**. Amplitude of P1 on the verb in the reduced relative clause over left posterior electrode cluster showed a gradient amplitude distribution, with the animate telic condition being the most positive, followed by the animate atelic condition. **b**. Amplitude of N2c on the verb over posterior electrode clusters was more negative in the animate condition, as well as telic condition

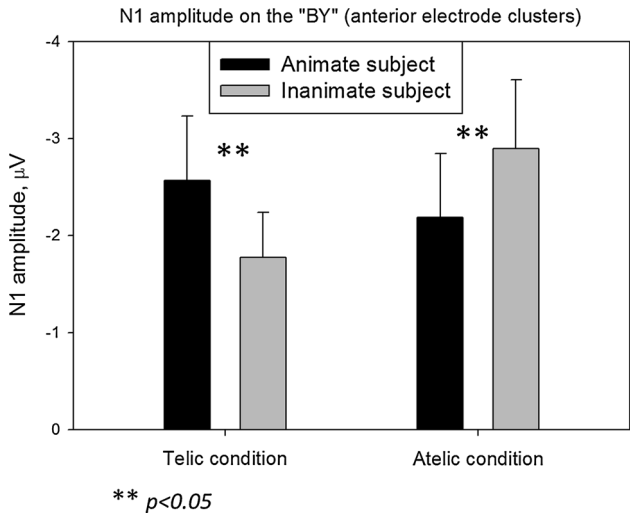


**Fig. 6** Amplitude of N1 on the preposition "by" over left anterior electrode cluster showing gradient amplitude distribution among conditions

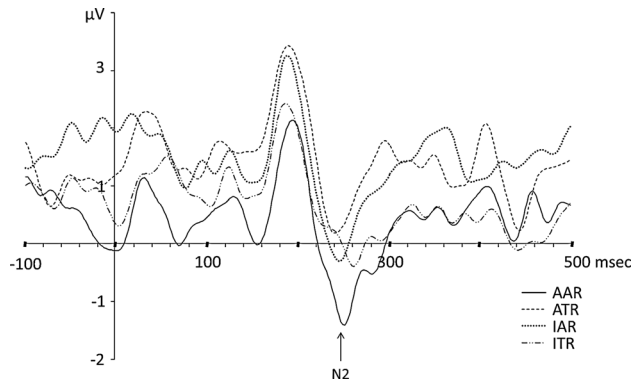


**Fig. 7** Central posterior electrode cluster ERPs to the determiner 'the': N2c showed gradient amplitude distribution from animate atelic condition (the most negative), to animate telic

inanimate first argument, but not in those with animate first argument. *Post hoc* analyses revealed significant effect of Animacy ($p < 0.022$), but not Telicity ($p > 0.05$), with faster reading times for Inanimate Telic vs. Animate Telic, but Animate Atelic vs. Inanimate Atelic (Fig. 9a).

On the second noun in URCs, effects of animacy [$F(1, 42) = 1380.819$, $p < 0.001$, $e_p^2 = 0.999$], telicity [$F(1, 42) = 21.648$, $p < 0.043$, $e_p^2 = 0.915$], and animacy × telicity interaction [$F(1, 42) = 26.292, p < 0.036, e_p^2 = 0.929$] were present. *Post hoc* analyses revealed significant effect of Animacy ($p < 0.019$), but not Telicity ($p > 0.05$), with faster reading times for Inanimate Telic vs. Animate Telic, and Inanimate Atelic vs. Animate Atelic (Fig. 9b). No other effects or interactions were found in reading time data [$F(1, 42) < 1$].

**Table 2** Coefficient of variability for the distribution of power in the low α (9.8–12.7 Hz) band in each ROI by condition over each word in the RRC

| | Patient noun | V'ed | By | The | Agent noun |
|---|---|---|---|---|---|
| ATR | 1.143462 | 0.740305 | 0.754561 | 1.57315 | 0.511023 |
| AAR | 0.778551 | 0.821326 | 0.902557 | 1.234982 | 0.50576 |
| ITR | 0.821465 | 1.195965 | 1.271679 | 1.475498 | 0.717334 |
| IAR | 0.93123 | 0.779075 | 0.753457 | 1.157406 | 0.588032 |

## Discussion

The present study investigated the effects of syntax–semantics integration on the processing load during reading for comprehension. The results demonstrated a gradient distribution of early components (biphasic posterior P1–N2 and anterior N1–P2) over function words "by" and "the", and the verb, corresponding to facilitation or conflict

resulting from the syntactic (telicity) and semantic (animacy) cues in the preceding portion of the sentence. Below we discuss the observed interaction effects, the main effects of telicity and animacy, and the possible interpretations of the EEG components affected by modulations of syntactic and semantic load during thematic role assignment.

## Early EEG components and syntax–semantics processing

The subtlety of the syntactic and semantic manipulation in the present study (i.e. all stimuli were meaningful, error-free English sentences) resulted in observation of the effects exclusively over early components. While rapid processing of linguistic information in the words has been recently demonstrated (MacGregor et al. 2012), the present study is the first one demonstrating integration of linguistic information between syntactic and semantic processing streams within 100–200 ms after the onset of the critical word. Prior studies have demonstrated early anterior negativities (such as N1 or ELAN) elicited by syntax or semantics (Yamada and Neville 2007; Hahne and Friederici 1999, inter alia). In the present study, the enhancement of the N1 component, as observed over function words, might indicate the increased cognitive effort required for syntactic integration; the shorter latency of this component suggests the facilitation of syntactic integration processes (Malaia et al. 2009; Yamada and Neville 2007; Newman et al. 2013). An alternative interpretation would suggest that the component observed over the function words might be an after-effect of earlier difference propagating from noun processing; it is, however, less likely given the timing between words and the morphology of the component.

Early posterior EEG components are less frequently analyzed in the literature on language processing; however, they are well known as indicative of perceptual processing in visual tasks (Luck and Kappenman 2011). Visual paradigms identify the posterior N2c component as an electrophysiological correlative of attention focusing; it has also been suggested that the posterior N2 might reflect the process of categorizing a stimulus (Renault et al. 1982), since its duration is increased in more demanding conditions. In the present study, syntactic and semantic manipulations affect posterior components only after the anterior effects are observed, possibly indicating the manipulation of attention in a highly demanding comprehension task.

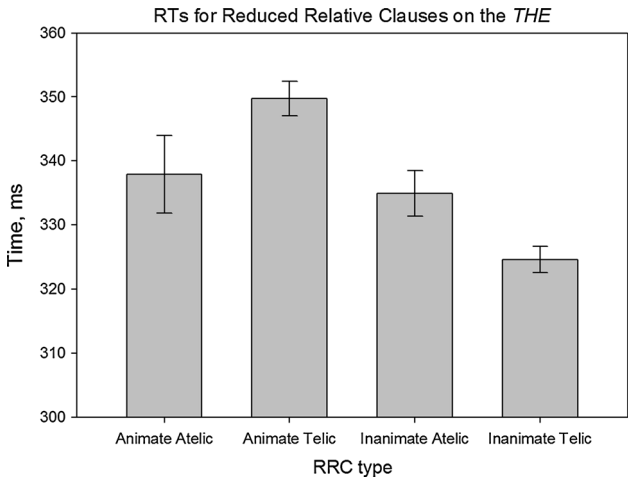


**Fig. 8** Behavioral study, response times to the THE in RRCs as a function of animacy and telicity conditions

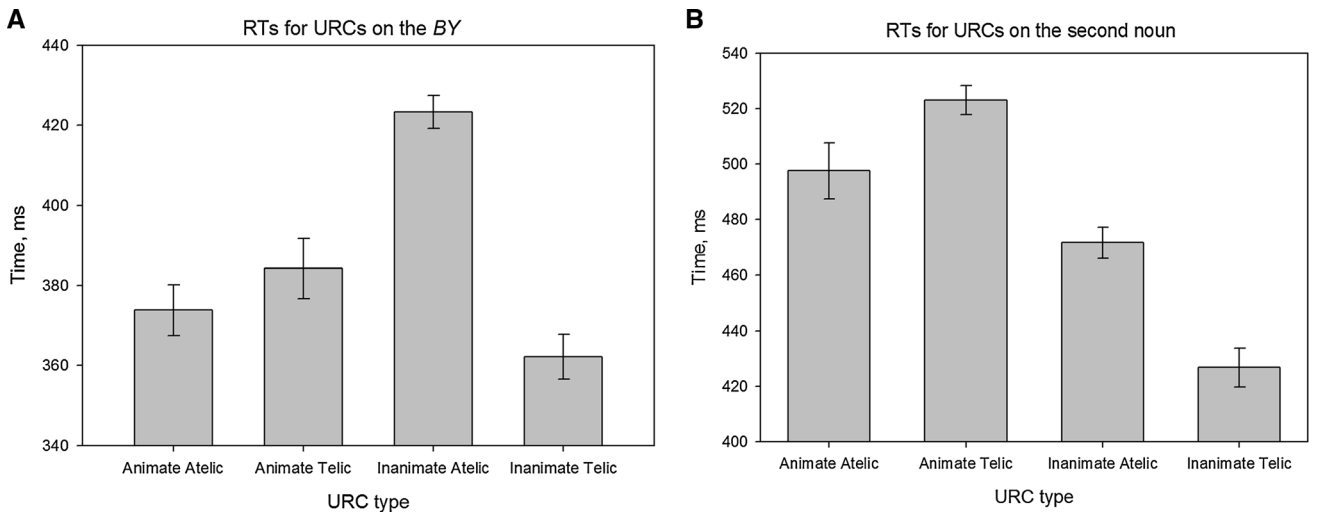


**Fig. 9** **a**. Behavioral study, response times to the BY in URCs as a function of animacy and telicity conditions. **b**. Behavioral study, response times to the second noun (Agent) in URCs as a function of animacy and telicity conditions

### Interaction effects

Both the word reading times in the behavioral experiment, and the EEG data demonstrated the interactive effects of syntactic and semantic factors on the processing of the definite article introducing the second argument. As the head of the DP, the article is a crucial node in thematic role assignment during comprehension. The consistency of the interaction of syntactic and semantic features over the determiner suggests that the participants used the same strategy in both experiments, utilizing both syntactic and semantic information during online comprehension. This observation is corroborated by the fact that over the Agent noun it was the telic conditions, along with animate ones, that elicited more difficulty in thematic role re-assignment, as predicted due to the conflict of semantic and syntactic cues.

### Telicity effects

In the present study, the telicity manipulation affected the processing of the verb in the matrix clause (as indicated by increase in the amplitude of posterior N2), as well as facilitated processing of the preposition "by" (as indicated by decreased anterior negativity, or N1). While the telicity effect on preposition processing was expected (cf. Malaia et al. 2009; Malaia and Wilbur 2011), the early effect of event structure on verb processing is a novel observation. It is possible that this attentional N2 effect over the verb arose in the present experimental design due to the manipulation of the animacy of the first noun, necessitating increased allocation of attentional resources to event structure.

### Animacy effects

In the present study, the animacy of the first argument affected the processing of the Agent noun, as well as downstream processing of the preposition "by", and the Patient (second) noun. The observation of an online animacy effect over the first noun agrees with the prior studies which showed that inanimate (non-canonical) subjects elicit an anterior negative shift (Nakano et al. 2009). While prior studies could not differentiate between immediate vs. downstream effects of animacy manipulations (cf. King and Kutas 1995), the combination of manipulated variables in the present study confirmed the downstream facilitation effect of first-noun animacy on the processing of preposition "by", introducing the syntactic adjunct phrase, as well as the processing of the second noun.

Also, during the processing of the Agent noun, the variability in power distribution in the $\alpha$ band (regardless of sentence type) dropped drastically in all conditions. The assimilation of $\alpha$ power during the mental manipulation with high demand on working memory—thematic role re-assignment—demonstrates a state of $\alpha$ equilibrium with strong functional coupling across regions. Prior research on alpha synchronization (Sauseng et al. 2005) suggests that it indicates executive control of posterior cortical activation by anterior brain regions.

### Limitations

One specific variable–semantic relatedness between the noun argument and the verb–was not controlled in this study. There is a possibility that the conditions differed with regard to this variable. Appendix lists all the stimuli for further analysis of this possibility.

## Conclusion

The results of the study suggest that the mechanism of interfacing syntactic and semantic/pragmatic domains appears to rely on subtle shifts in attentional modulation of early EEG components, especially over the function words. The interaction of noun animacy/agentive plausibility and verbal event structure over those words led to more negative ERPs in inanimate telic and animate atelic conditions, where the combination of syntactic and semantic features led to the most difficulty in creating an online syntactic model with an external argument. The gradient distribution of animacy and telicity effects suggests the neural mechanism for 'gating' the likelihood of activation for plausible syntactic structures using already received semantic information (cf. neuroimaging approach in Malaia and Newman, in press). A neurally-grounded understanding of interface processing, such as proposed above, might help explain the differences in sentence processing mechanisms across languages, which are currently under debate (Haupt et al. 2008), and allow for the development of resource-allocation-based reading strategies (see Malaia and Carnes, in press), or diagnostics for populations with language comprehension problems, such as Specific Language Impairment, or aphasias.

## Appendix

See Table 3.

**Table 3** Animate, telic stimulus sentences with reduced relative clauses

| |
|---|
| The witness seized by the agent was in great danger |
| The sculptor nominated by the mayor was on the front page of the paper |
| The painter glimpsed by the visitor was very original |
| The candidate abandoned by the panel had some drawbacks |
| The client discovered by the advertiser was worth a lot of money |
| The mailman dispatched by the secretary arrived too late |
| The lady found by the boy was quite unusual |
| The passenger picked by the trucker was dropped off by the construction site |
| The professor recognized by the student was hard to understand |
| The defendant designated by the lawyer turned out to be unreliable |
| The singer heard by the crowd was on the top 40 in no time |
| The author quoted by the columnist was taken out of context |
| The celebrity announced by the DJ was surrounded by a crowd |
| The man spotted by the officer had been involved in the getaway |
| The lawyer sent by the governor arrived late |
| The speaker proposed by the colleague would work perfectly for the program |
| The thief identified by the victim was held in custody |
| The specialist requested by the surgeon had finally arrived |
| The contestant selected by the judge did not deserve to win |
| The prisoner grabbed by the guard was closely watched |
| The killer captured by the policeman scared the public. |
| The cashier trampled by the robber stayed in the garage |
| The detective hired by the lawyer refused to comment |
| The accountant rescued by the custodian was safe |
| The programmer alerted by the supervisor launched system check |
| The dancer joined by the host surprised the guests |
| The author lost by the publisher became famous |
| The mother pinched by the toddler was soft |
| The racer caught by the competitor disappeared from view |
| The secretary appointed by the boss impressed the customer |
| The solider disarmed by the officer stayed in the barracks |
| The engineer tenured by the manager was very productive |
| The producer struck by the musician stayed silent |
| The client mentioned by the administrator was successful |
| The teenager injured by the mentor made an impression on the committee |
| The doctor brought by the driver arrived to the hospital on time |
| The hero crowned by the journalist turned out to be fake |
| The politician dismissed by the lobbyist came to a hearing |
| The analyst audited by the consultant remained in good standing |
| The journalist released by the editor arrived in the afternoon |
| *Inanimate, telic* |
| The mansion seized by the agent was in great danger |
| The sculpture nominated by the mayor was on the front page of the paper |
| The painting glimpsed by the visitor was very original |
| The alternative abandoned by the panel had some drawbacks |
| The account discovered by the advertiser was worth a lot of money |
| The letter dispatched by the secretary arrived too late |
| The necklace found by the boy was quite unusual |
| The stone picked by the trucker was dropped off by the construction site |
| The textbook recognized by the student was hard to understand |
| The data designated by the lawyer turned out to be unreliable |
| The song heard by the crowd was in the top 40 in no time |
| The remark quoted by the columnist was taken out of context |
| The celebration announced by the DJ was surrounded by a crowd |
| The car spotted by the officer had been involved in the getaway |
| The package sent by the governor arrived late |
| The solution proposed by the colleague would work perfectly for the program |
| The jewelry identified by the victim was held in custody |
| The equipment requested by the surgeon had finally arrived |
| The recipe selected by the judge did not deserve to win |
| The gold grabbed by the guard was closely watched |
| The evidence captured by the policeman scared the public |
| The safe trampled by the robber stayed in the garage |
| The company hired by the lawyer refused to comment |
| The money rescued by the custodian was safe |
| The program alerted by the supervisor launched system check |
| The performance joined by the host surprised the guests |
| The shortlist lost by the publisher became famous |
| The toy pinched by the toddler was soft |
| The car caught by the competitor disappeared from view |
| The deadline appointed by the boss impressed the customer |
| The tank disarmed by the officer stayed in the barracks |
| The division tenured by the manager was very productive |
| The string struck by the musician stayed silent |
| The idea mentioned by the administrator was successful |
| The reputation injured by the mentor made an impression on the committee |
| The parcel brought by the driver arrived to the hospital on time |
| The image crowned by the journalist turned out to be fake |
| The bill dismissed by the lobbyist came to a hearing |
| The department audited by the consultant remained in good standing |
| The bulletin released by the editor arrived in the afternoon |
| *Animate, atelic* |
| The witness protected by the agent was in great danger |
| The sculptor praised by the mayor was on the front page of the paper |
| The painter ridiculed by the visitor was very original |
| The candidate considered by the panel had some drawbacks |
| The client handled by the advertiser was worth a lot of money |
| The mailman accompanied by the secretary arrived too late |
| The lady described by the boy was quite unusual |
| The passenger carried by the trucker was dropped off by the construction site |

**Table 3** continued

| |
|---|
| The professor criticized by the student was hard to understand |
| The defendant examined by the lawyer turned out to be unreliable |
| The singer supported by the crowd was in the top 40 in no time |
| The author bullied by the columnist was taken out of context |
| The celebrity championed by the DJ was surrounded by a crowd |
| The man chased by the officer had been involved in the getaway |
| The lawyer escorted by the governor arrived late |
| The speaker embraced by the colleague would work perfectly for the program |
| The thief scrutinized by the victim was held in custody |
| The specialist hosted by the surgeon had finally arrived |
| The contestant kept by the judge did not deserve to win |
| The prisoner chaperoned by the guard was closely watched |
| The killer tugged by the policeman scared the public |
| The cashier stalked by the robber stayed in the garage |
| The detective instructed by the lawyer refused to comment |
| The accountant guarded by the custodian was safe |
| The programmer employed by the supervisor launched system check |
| The dancer ushered by the host surprised the guests |
| The author dominated by the publisher became famous |
| The mother nuzzled by the toddler was soft |
| The racer followed by the competitor disappeared from view |
| The secretary encouraged by the boss impressed the customer |
| The solider inspected by the officer stayed in the barracks |
| The engineer counseled by the manager was very productive |
| The producer pulled by the musician stayed silent |
| The client entertained by the administrator was successful |
| The teenager fostered by the mentor made an impression on the committee |
| The doctor ferried by the driver arrived to the hospital on time |
| The hero observed by the journalist turned out to be fake |
| The politician sponsored by the lobbyist came to a hearing |
| The analyst advised by the consultant remained in good standing |
| The journalist held by the editor arrived in the afternoon |
| *Inanimate, atelic* |
| The mansion protected by the agent was in great danger |
| The sculpture praised by the mayor was on the front page of the paper |
| The painting ridiculed by the visitor was very original |
| The alternative considered by the panel had some drawbacks |
| The account handled by the advertiser was worth a lot of money |
| The letter accompanied by the secretary arrived too late |
| The necklace described by the boy was quite unusual |
| The stone carried by the trucker was dropped off by the construction site |
| The textbook criticized by the student was hard to understand |
| The data examined by the lawyer turned out to be unreliable |
| The song supported by the crowd was in the top 40 in no time |
| The remark bullied by the columnist was taken out of context |
| The celebration championed by the DJ was surrounded by a crowd |

**Table 3** continued

| |
|---|
| The car chased by the officer had been involved in the getaway |
| The package escorted by the governor arrived late |
| The solution embraced by the colleague would work perfectly for the program |
| The jewelry scrutinized by the victim was held in custody |
| The equipment hosted by the surgeon had finally arrived |
| The recipe kept by the judge did not deserve to win |
| The gold chaperoned by the guard was closely watched |
| The evidence tugged by the policeman scared the public |
| The safe stalked by the robber stayed in the garage |
| The company instructed by the lawyer refused to comment |
| The accountant guarded by the custodian was safe |
| The program employed by the supervisor launched system check |
| The performance ushered by the host surprised the guests |
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| The reputation fostered by the mentor made an impression on the committee |
| The parcel ferried by the driver arrived to the hospital on time |
| The image observed by the journalist turned out to be fake |
| The bill sponsored by the lobbyist came to a hearing |
| The department advised by the consultant remained in good standing |
| The bulletin held by the editor arrived in the afternoon |

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