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An ERP investigation of quantifier scope ambiguous sentences: Evidence for number in events

Veena D. Dwivedi [a, b, *], Raechelle M. Gibson [b, 1]

[a] Department of Applied Linguistics, Brock University, Niagara Region, 1812 Sir Isaac Brock Way, St. Catharines L2S 3A1 ON, Canada
[b] The Centre for Neuroscience, Brock University, Niagara Region, 1812 Sir Isaac Brock Way, St. Catharines L2S 3A1 ON, Canada

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ABSTRACT

We used event related potentials (ERPs) in order to investigate how sentences, semantically ambiguous with respect to number, are understood. Although sentences such as (i) *Every kid climbed a tree* lack any syntactic or lexical ambiguity, two possible meanings are available, where either many trees or just one tree was climbed. Previous behavioural studies showed a plural preference, whereas ERP and behavioural experiments conducted in our lab have not. In this work, we further investigate sentences as in (i), called quantifier scope ambiguous sentences, and compare them to unambiguous sentences, (ii) *Every kid climbed the trees*. Participants read sentences presented in 1- and 2-word chunks, and judged, at the target word *tree(s)*, whether 1 or 2 words appeared on the computer screen (Berent *et al*., 2005). Previously, interference effects resulted for judgments that 1 word was on the screen when it was marked plural (e.g., *trees*) versus singular (e.g., *tree*). Interestingly, Patson and Warren (2010) also showed that this was the case for judgments made for singular words, e.g., *tree,* in quantifier ambiguous sentences, confirming the plural preference. The current ERP study did not replicate their behavioural findings. Difficulty for "1" responses was not observed for *trees* in (ii) nor was it observed for *tree* in quantifier scope sentences (i). Instead, a P300 effect was found at the target word *tree(s)*, where amplitudes differed depending on congruency in number interpretation for subjects and direct objects. Results are discussed in terms of heuristic first sentence processing mechanisms, and relevant features of event knowledge.

1. Introduction

All human languages have a way of distinguishing between individuals and sets of individuals. As such, understanding how people comprehend the singular-plural distinction is a crucial facet in explaining our effortless capacity for language. This facile capacity is even more remarkable given that some sentences are ambiguous with respect to number interpretation.

For example, quantifier scope ambiguous sentences such as *Every kid climbed a tree* are ambiguous in terms of numerical interpretation—either one or several trees are inferred (see Fig. 1). Despite this ambiguity, these sentences are often interpreted the same way across readers/listeners, where the plural interpretation is preferred. The preference in interpretation

* Corresponding author. Department of Applied Linguistics, Brock University, Niagara Region, 1812 Sir Isaac Brock Way, St. Catharines L2S 3A1 ON, Canada.
E-mail address: vdwivedi@brocku.ca (V.D. Dwivedi).
[1] Raechelle M. Gibson is now at the Department of Psychology and The Brain and Mind Institute, Western University, London, ON, Canada, N6A 5B7.

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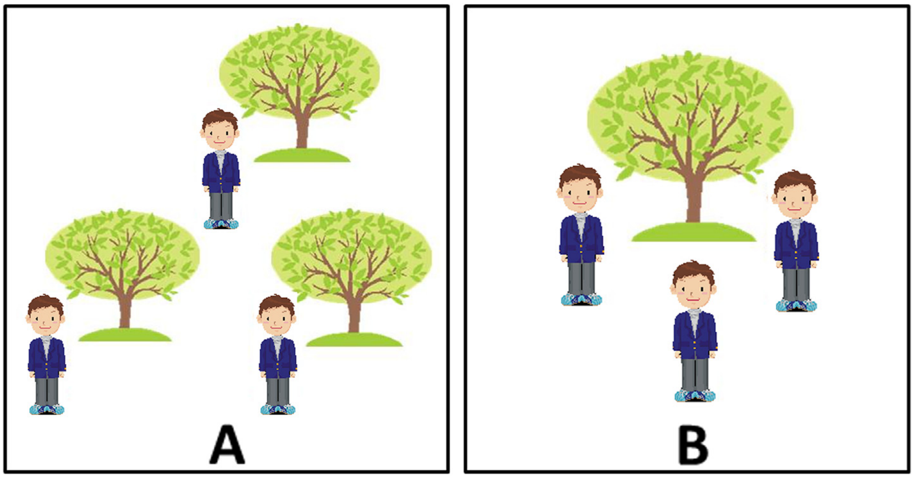

Fig. 1. *Possible interpretations of quantifier scope ambiguous sentences*. A graphical representation of the two possible interpretations of the quantifier scope ambiguous sentence, *Every kid climbed a tree*, according to plural (A) and singular interpretation (B).

has been accounted for via the preferred application of an abstract semantic rule, called quantifier ordering (May, 1985; Russell, 1905). A number of psycholinguistic investigations (Bott & Schlotterbeck, 2015; Filik, Paterson, & Liversedge, 2004; Kurtzman & MacDonald, 1993; Paterson, Filik, & Liversedge, 2008; Patson & Warren, 2010; Raffray & Pickering, 2010) have empirically found the plural preference[2] and have attributed this preference to the application of the abstract rule of quantifier ordering.

In a recent Event Related Potential (ERP) study, (Dwivedi, Phillips, Einagel, & Baum, 2010), as well as three behavioural experiments reported in Dwivedi (2013), we examined quantifier scope ambiguous sentences, such as *Every kid climbed a tree,* and did not find the plural preference as participants read. Measurements were taken at sentences such as *The tree was in the park*, or *The trees were in the park*, which followed quantifier scope sentences. Neither brain wave patterns, nor word-by-word reading time patterns, indicated an on-line preference for the plural interpretation, in any of the experiments. We claimed that quantifier scope ambiguous sentences are interpreted using "Heuristic first, algorithmic second" processing mechanisms. That is, in real-time, people do not use deep "algorithmic" semantic rules for sentence interpretation. Instead, they primarily use associative word-based heuristic strategies (cf. Kahneman, 2011). Our claim that quantifier scope ambiguous sentences are interpreted via heuristic strategies flies in the face of the majority of psycholinguistic studies examining these sentences (see above), which assume that the linguistic rule of quantifier ordering is primary in their comprehension.

In an attempt to reconcile our findings, we add to this debate by using an innovative method recently discussed in a behavioural study by Patson and Warren (2010). Briefly, as described below, their method allows for a direct measure at quantifier scope sentences, which is also sensitive to number judgments. We note that in our previous ERP work, (Dwivedi et al., 2010), we did not query participants about their number judgments, in order to avoid potential ERP artefacts (Kaan & Swaab, 2003). Presently, we extend Patson and Warren's (2010) methods, via ERP measurements, in order to potentially induce algorithmic processing of scope, which would result in a plural preference.

Patson and Warren (2010) examined the on-line interpretation of quantifier scope ambiguous sentences, such as *Each of the men carried a box*. In sentences of this type, the direct object *box* is interpreted as plural. In contrast, sentences using subjects beginning with *Together,* as in *Together the men carried a box,* result in a singular interpretation for the direct object *box*. Their study used self-paced reading methodology with a twist: words appeared on the screen in one-versus two-word chunks, and if a word was presented in blue font, participants had to judge how many words were on the screen. Participants did so by pressing either "1" or "2" on the keyboard. Following Berent, Pinker, Tzelgov, Bibi and Goldfarb (2005), Patson and Warren hypothesized that participants would be slower to press "1" when the word was plural (*e.g.*, *boxes*) versus when it was singular (*e.g.*, *box*). To this end, two plural control conditions were included: *Each of the men carried some boxes* and *Together the men carried some boxes.* Results confirmed their hypothesis: response times for pressing "1" to *boxes* were indeed longer than those for pressing "1" to *box*. These results show that the cognitive act of counting and pressing the "1" button can be interfered with by plural number marking at the direct object *boxes*. Furthermore, they found that *box* in the (quantifier scope) *Each* condition also resulted in longer "1" button pressing times. They concluded that this task is sensitive not only to plural interpretation due to overt morphology at the direct object, but also due to (covert) conceptual number interpretation—as a result of the quantified subject *Each*.

[2] For ease of exposition, we will refrain from using the terms surface scope reading, as consistent with the plural interpretation, and inverse scope reading, as consistent with the singular interpretation. Please see Dwivedi (2013), and references cited therein, for further discussion of quantifier scope theory.

Table 1
Overview of experimental conditions.

Object Type		Quantified Subject Type				
Singular	(i)	***Quantified***				
		Every kid/	climbed a/	tree/ **TW**	in the/	autumn./
	(ii)	***Non-quantified***				
		The kid/	climbed a/	tree/ **TW**	in the/	autumn./
Control Singular	(iii)	***Quantified***				
		Every kid/	climbed the/	tree/ **TW**	in the/	autumn./
	(iv)	***Non-quantified***				
		The kid/	climbed the/	tree/ **TW**	in the/	autumn./
Plural	(v)	***Quantified***				
		Every kid/	climbed the/	trees/ **TW**	in the/	autumn./
	(vi)	***Non-quantified***				
		The kid/	climbed the/	trees/ **TW**	in the/	autumn./

Note: TW= target word position

We incorporated the above paradigm, building on our previous experiments, and investigated whether the direct object *a tree* in quantifier scope ambiguous sentences would be interpreted as plural, in sentences using quantified subjects with *Every* versus sentences starting with non-quantified *The*. We also included two plural conditions: *Every kid climbed the trees* and *The kid climbed the trees.* We predicted an empirical difference at the target word *trees* for number judgments when just one word was on the screen; we expect that overt plural marking on the direct object should intrude on the "1" judgment. In addition, we expect difficulty for the singular direct object *tree* in sentences with subjects containing *Every* versus non-quantified *The*. We note that this comparison (like that in the Patson and Warren study discussed above) is confounded by the fact that the plural direct object *the trees* is compared to the indefinite singular *a tree* which not only differs due to a lack of plural marking –*s* but due to differences in the definite *the* versus indefinite article[3] *a.* A control singular direct object condition was therefore created in order to ensure that differences observed are indeed due to the plural versus singular distinction, and not the fact that the direct objects are preceded by two different types of articles, definite versus indefinite. This within-subjects study was defined by two independent variables: Quantified Subject Type (Quantified or Non-quantified) and Object Type (Singular, Control Singular and Plural). Refer to Table 1 for an overview of the experimental conditions.

We have two sets of predictions. The first prediction is about the paradigm, and the second is about sentence interpretation. First regarding the paradigm: following Patson and Warren (2010), it is expected that participants will have the most difficulty at the target word *trees*, for the "1" judgment, versus *tree* in the singular and control singular object conditions. Therefore, at the face of it, behavioural and electrophysiological responses at the plural object condition should differ from both singular conditions. With reference to the form of the empirical effects, behavioural measures should exhibit less accuracy and/or longer response times at the plural condition. As to the form of the ERP effect, we might observe a sustained negative-going wave at the plural object *trees*, since slow going negative waveforms are argued to be representative of cognitive difficulty (King & Kutas, 1995; Rösler, Heil, & Röder, 1997; Ruchkin, Johnson, Mahaffey, & Sutton, 1988). Furthermore, we observed these waveforms in our previous ERP experiment (Dwivedi et al., 2010) on quantifier scope sentences.

The second prediction is relevant to theories of sentence interpretation, that is, does the algorithmic rule of quantifier ordering apply immediately, or not. If it does, then the prediction is that the direct object *tree* in the quantified subject condition (i) *Every kid climbed a tree* would be interpreted as conceptually plural, in contrast to its non-quantified subject control (ii), *The kid climbed a tree*. Thus, at the target position *tree,* conditions (i) and (ii) should differ empirically from each other, both behaviourally and electrophysiologically, where responses to (i) should show increased difficulty; in other words, results at this condition should mirror those at the plural object condition. Such a result would falsify our previous claims of sentence processing occurring via Heuristic first, algorithmic second mechanisms. Regarding the form of this ERP effect,

[3] For ease of exposition, we will use the more familiar terms of definite and indefinite article versus the linguistic terms of definite and indefinite determiner. Furthermore, we note that the indefinite determiner is also an existential quantifier; for further discussion, see Heim (1982) and Fodor and Sag (1982). Finally, note that Patson and Warren did not control for differences in determiners in their study; we will address this in our Discussion below.

again, we might observe a sustained negative-going wave at the target word *tree*, for condition (i) *Every kid climbed a* ***tree*** versus its control (ii) *The kid climbed a* ***tree***.

No other empirical differences are predicted at other word positions in the sentence, nor for other conditions.

Alternatively, given that this experiment uses a secondary target discrimination task for all conditions (i.e., identify words in blue font, count, and respond via button press), a P300 effect could be elicited in the electrophysiological data (Donchin, 1981; Johnson & Donchin, 1982). Moreover, this ERP component would be elicited at all six conditions. If this were indeed the case, then what would this reveal in terms of theories of sentence interpretation? Polich (2007) discussed P300 amplitude differences in terms of differences in attentional resources: "as primary task difficulty is increased, P300 amplitude from the [secondary] task decreases" (p. 2130). In the context of the current experiment, the primary task is reading sentences, and the secondary task is target identification. Thus, as difficulty in the primary task of sentence interpretation increases, fewer resources would be available for the secondary task, resulting in a P300 amplitude difference between sentence types (see also Luck, 1998). In the current experimental design, the only sentence pairs expected to differ in terms of interpretive complexity are conditions (i) versus (ii). This is because (i) starts with a quantified subject *Every* and continues with an indefinite singular object *a tree*, resulting in quantifier scope ambiguity. In contrast, (ii) does not exhibit ambiguity due to the non-quantified subject, *The*. The other conditions do not exhibit any ambiguity differences, and therefore should not differ from their controls in terms of interpretive complexity.

2. Methods

2.1. Participants

Twenty-four native speakers of English (18 female, mean age 21.58 years, range 18–29 years) were recruited at Brock University and were either paid for their participation or received partial course credit. All subjects had normal or corrected-to-normal vision and were right handed, as assessed by the Handedness Inventory (Briggs & Nebes, 1975). No participants reported any neurological impairment, history of neurological trauma, or use of neuroleptics.

This study received ethics approval from the Brock University Bioscience Research Ethics Board (BREB) prior to the commencement of the experiment (REB 10–025). Written, informed consent was received from all participants prior to their participation in the experiment.

2.2. Materials

The experimental stimuli consisted of 156 sentence scenarios for the six conditions described in Table 1. In order to reduce repetition effects, the stimuli were divided into six counterbalanced lists, such that each participant saw an equal number of sentence pairs from each condition, resulting in 26 trials per experimental condition per list. Each experimental list consisted of 456 sentences (156 critical trials and 300 filler trials) divided into one and two-word chunks. Across each list, there was an approximately equal number of one- and two-word chunks, and each participant made approximately equal numbers of one and two-word judgments throughout the task. Each list was pseudo-randomized using the Mix utility (van Casteren & Davis, 2006) such that no two sentences of the same condition appeared consecutively, no two experimental sentences appeared consecutively, and the first five sentences of each list were filler sentences. See Supplementary Material Online for a full list of experimental and filler stimuli.

2.2.1. Critical conditions

2.2.1.1. Subject noun phrase type. The subject noun phrase was either quantified or not. Quantified subjects always used the universal quantifier *every*, in contrast to Non-quantified subjects, which always used the (non-quantified) definite article *the*[4].

2.2.1.2. Object noun phrase type. The direct object noun phrase was of three types: singular, as in *a tree*; control singular, as in *the tree*; or plural, as in *the trees*. Thus, this 2 × 3 design resulted in 6 conditions, as outlined in Table 1.

2.2.1.3. Sentence structure. All experimental sentences consisted of simple declarative sentences (e.g., subject^verb^object), modified from Dwivedi et al. (2010) for the current experiment. In each sentence, the subject was always an animate noun (e.g., *kid, jeweller, etc.*). The remainder of the sentence consisted of an active verb in the past tense (e.g., *climbed, appraised, etc.*) followed by an inanimate object noun (e.g., *tree, diamond*, *etc.*) and a three-word prepositional phrase (e.g., *in the autumn, before being certified*, etc.). Care was taken to select prepositional phrases that did not modify the direct objects in order to ensure an indefinite, non-specific reading for the direct object. The majority of the prepositional phrases pertained to manner (e.g., *with much difficulty*), time (e.g., *in the morning*), instrument (e.g., *with a pen*), or event (e.g., *during the robbery*). Sample final sentences include *Every kid climbed a* ***tree*** *in the autumn,* and *Every jeweller appraised a* ***diamond*** *before being certified*.

[4] Technically, *the* can be termed non-quantificational, or referential. For ease of exposition, we will be referring to it as non-quantified.

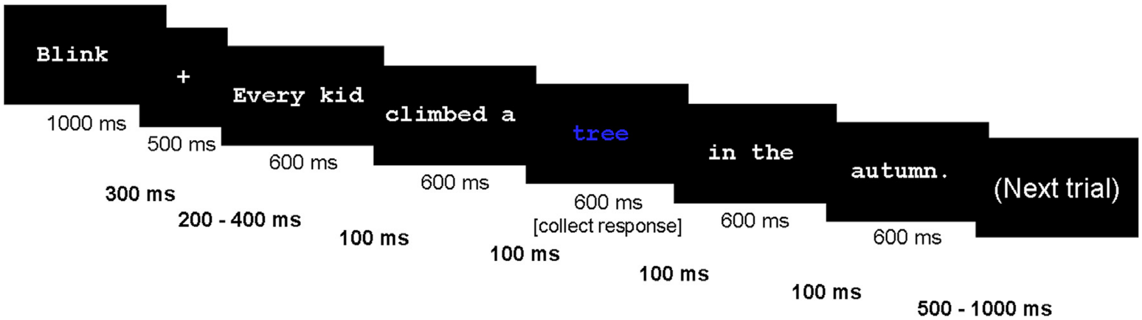

Fig. 2. *Sample trial procedure*. Number judgments were made at the critical word (here, *tree*), which was presented in blue font as indicated in the figure. Time values in bold represent inter-stimulus intervals, and time values in regular font represent the duration of stimulus presentation on the screen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2.2. Filler conditions

The experiment included 300 distractor sentences in addition to the critical sentences to reduce predictability, incorporate number judgments for pairs of words, and elicit standard ERP components. Word pairs always consisted of determiner-noun or adjective-noun combinations as in Patson and Warren (2010).

2.2.2.1. Filler quantifier sentences. Eighty sentences that began with subjects other than *every* were included. Of these 80 sentences, 40 began with a plural quantifier (e.g., *many, most, etc.*) and 40 began with *the*. Number judgments were always made on word pairs (resulting in a “2” button press), and, as in the critical conditions, the target word pairs were always the third chunk of the sentence presented on the screen. Half of the judgments were made on singular word pairs, and half of the judgments were made on plural word pairs, for a total of 40 singular and 40 plural word judgments in this condition. Sample sentences for this condition include *Many investors lost a* ***small fortune*** *during the depression*, and *The newscaster announced the* ***winning numbers*** *in the evening.*

2.2.2.2. Standard ERP component sentences. A total of 160 sentences were included to elicit standard ERP components and to introduce variability into the task. Forty sentences (from Dwivedi et al., 2010) with grammatical violations were included to elicit the P600, a marker of syntactic anomaly (e.g., *The nurse was/*were dressing a wound*). Forty sentences (from Connolly, Phillips, & Forbes, 1995) with anomalous words were also included to elicit a standard N400 effect (Kutas & Hillyard, 1980; Kutas & Van Petten, 1994, pp. 83–143) using semantically anomalous sentences (e.g., *Ned has a daughter and a cloud*). Finally, 80 coherent, unambiguous sentences were included to provide a baseline for the ungrammatical and anomalous sentences. There were no number judgments made on any of these fillers[5].

2.2.2.3. Other filler sentences. An additional 60 sentences were included to balance the number of judgments made on single words and word pairs and to vary the location of the targets to reduce predictability (note that word judgments were always made for the third chunk presented in critical trials and quantifier filler conditions). Judgments were made for word pairs at the first and second chunks on the screen in each of the 20 trials. Sample sentences include, *After* ***repeated losses*** *the gambler was very unhappy* and ***The writers*** *were picketing because of the strike.*

Finally, in order to ensure that participants paid attention to the sentences, forced-choice content questions were asked (true/false; yes/no) on all of these fillers, and half of the filler quantifier sentences. The two alternative answers were shown on the left- and right-hand side of the screen. The position of the correct answer was counterbalanced across trials. For example:

After | repeated losses | the gambler | was | very unhappy.
The gambler was excited.
(1) True (2) False

2.3. Electrophysiological measures

Electroencephalographic recordings were made using a 64-channel Active Two BioSemi system (BioSemi, Amsterdam). Data were sampled at a rate of 512 Hz and digitized with a 24-bit analog-to-digital converter. Data were polynomial

[5] In an attempt to counterbalance the presentation of one-versus two-word chunks, the verbs for grammatical versus ungrammatical fillers did not end up in the right position for analysis purposes. Hence these sentences were not analyzed and will not be discussed further. See Supplementary Material Online for classic N400 ERP waveforms elicited by filler anomalous versus filler control conditions.

Table 2
Mean accuracy and response times (RT) by object type: *a tree/the tree/the trees*.

Object Type	Accuracy (%)	RT (ms)
	M (MSE)	*M (MSE)*
Singular	82.8 (2.0)	390.6 (8.6)
Control Singular	78.2 (2.2)	390.8 (8.7)
Plural	78.3 (2.1)	393.9 (8.4)

detrended at order 3 across the whole time series in order to correct for drift across the entire recording. A bandpass filter from 0.1 to 100 Hz was used to remove high and low frequency noise, and all electrodes were re-referenced to the averaged mastoids for analysis. Prior to segmentation, eye movements artifacts and blinks were removed from the data using a spatial ocular artifact correction algorithm (Pflieger, 2001) available in the EMSE v5.5 software (Cortech Solutions, 2013) (cf. Kaganovich, Schumaker, & Rowland, 2016; Kornilov et al., 2014; Morioka, Osumi, Okamoto, & Matsuo, 2015). Epochs were created from an interval 200 ms prior to stimulus onset to 1200 ms after stimulus onset.

2.4. Procedure

Participants were tested individually in one session of approximately three hours. In each session, participants completed a short questionnaire regarding reading habits, a handedness inventory (Briggs & Nebes, 1975), and an online operation span working memory task (Unsworth, Heitz, Schrock, & Engle, 2005) before the application of the electrodes. Following a practice session of eight trials, each participant completed the experimental trials in six blocks of 76 trials per block with rest periods between each block. See Fig. 2 for a sample trial procedure.

All words were presented in light grey, 19-point Courier New font on a black background in the centre of the computer monitor. Participants pressed the response pad when they were ready to begin. Each participant was then presented with the word "Blink" for 1000 ms, followed by a fixation marker (+) for 500 ms to indicate the beginning of a new trial. Following a variable inter-stimulus interval of 200–400 ms, the participant was presented with each sentence in one- and two-word chunks in the centre of the screen. Each word or word pair was presented at a fixed rate of 600 ms per word followed by an inter-stimulus interval of 100 ms. The target word in critical trials (always the third chunk on screen) or pair of words in filler trials (the location of the critical word pairs varied; refer to section 2.2.) was presented in blue font. Participants were instructed that blue font was a cue to make the number judgment and pressed pre-specified keys with their thumbs to indicate whether one or two words were on the screen. Key assignment was counterbalanced across participants such that the key corresponding to the "one" judgment was the left key for half of the participants and the right key for the other half of the participants. The word remained on the screen for 600 ms regardless of when the response was made, although participants were taken to a feedback error screen if they responded incorrectly or failed to respond within 600 ms. As mentioned previously, the trial was always repeated in the event of any type of error. Once a correct response was obtained, the sentence continued. Participants were presented with a two-choice comprehension question (true/false; yes/no) following 110 filler trials (24% of all trials), and responded using the response pad. Following a variable inter-trial interval of 500–1000 ms, the next trial began.

3. Results

3.1. Behavioural analyses

3.1.1. Filler comprehension questions

Comprehension rates for questions at filler conditions were at 94% ($SD = 4\%$), indicating that participants were indeed paying attention to sentence materials.

3.1.2. Response times

Table 2 summarizes response times at target words for different critical conditions by object type. As in Patson and Warren's work, these were only collected for correct trials. In the present ERP work, word presentation timing was (necessarily) fixed, and would effectively time out after 600 ms. As such, response time values did not differ across critical conditions, ($F < 1$). These will not be further discussed.

3.1.3. Response accuracy

Overall, participants were 80% (SD = 9%) accurate at identifying that one word was on the screen for critical conditions (see Table 2), comparable to the accuracy rate for corresponding filler quantifier conditions [$M = 82\%$ (SD = 12%)] but in contrast with the high ceiling accuracy rate reported in Patson and Warren. Accuracy rates for plural conditions versus control singular conditions were almost identical at about 78%. It was the singular condition that differed from the other two conditions, at about 83%. A statistically significant difference in accuracy between object type conditions is evident by one-way ANOVA

Table 3
Mean accuracy for all critical conditions.

Object Type	Subject Type	Accuracy (%)
		M(MSE)
Singular	Quantified	80.9 (2.5)
	Non-quantified	84.6 (1.9)
Control Singular	Quantified	77.5 (2.2)
	Non-Quantified	78.9 (2.7)
Plural	Quantified	79.2 (2.9)
	Non-Quantified	77.3 (2.0)

($F(2,46) = 4.467$, $MSE = 0.004$, $p = 0.015$). Pair-wise analysis revealed a reliable difference ($p = 0.019$) between singular ($M = 82.8$, $SD = 10.0$) and control singular object types ($M = 78.2$ $SD = 10.7$), whereas there was a trend toward significance ($p = 0.065$) for differences between singular and plural object types ($M = 78.3$, $SD = 10.4$). In other words, there was no evidence of task difficulty for plural object types. Instead, singular *a tree* showed a facilitation effect. In order to better understand these unexpected results, accuracy rates for all six conditions are further examined in Table 3.

Table 3 shows a negligible difference at the control singular object condition between the quantified and non-quantified subject types. Regarding the plural object condition, the quantified condition is just 2% more accurate than the non-quantified condition. Finally, for the singular object condition, the quantified condition led to lower accuracy than the non-quantified condition.

3.2. *Electrophysiological analyses*

3.2.1. *ERP results for the paradigm*

The grand average ERP waveforms (time-locked to the target word *tree/trees*) for a subset of all sites are displayed in Figs. 4–10. Fig. 4 shows ERP responses by Object Type condition only, whereas Figs. 5–10 display waveforms for each Object Type at both quantified and non-quantified conditions[6]. It is clear from these figures that the typical N1-P2 response associated with visual stimuli is elicited. The purpose of Fig. 4 is to show whether the paradigm used in this experiment resulted in any evidence of difficulty, especially at the plural condition versus the other two singular conditions. Our a priori hypothesis was that difficulty judging that one word was on the screen when participants read *trees* at the plural condition would result in a slow negative waveform. This was not evident at the plural, or the other object conditions. Instead of the expected negativity, a positivity was observed. Based on the timing of this positivity, as well as its distribution, we assume that a P300 effect is evident for all three Object Type conditions at the target word. This component peaks at around 400 ms and shows the typical scalp distribution of more positive amplitude change over midlines from frontal to posterior electrodes (Johnson, 1993).

Differences in the scalp distribution of the P300 effect have been reported in the literature (Polich, 2007; Ruchkin, Johnson, Canoune, Ritter, & Hammer, 1990; Ruchkin, Johnson, Mahaffey, & Sutton, 1988). In order to test for topographical differences across conditions, we analyzed ERPs using Regions of interest (ROIs); each region contained 4–5 electrodes (see also Gisladottir, Chwilla, & Levinson, 2015). The ROIs were defined as follows: Anterior Medial (AntMed): F3, Fz, F4, FC1, FC2; Central (Cent): C3, C1, Cz, C2, C4; Posterior Medial (PosMed): P3, Pz, P4, PO3, PO4; Left Anterior (LAT): FT7, F5, F7, T7; Right Anterior (RAT): FT8, F6, F8, T8; Left Posterior (LPos): CP5, P7, PO7, O1; Right Posterior (RPos): CP6, P8, PO8, O2. See Fig. 3.

Separate repeated measure ANOVAs were performed on medial and lateral ROIs, as defined above. ERPs were analyzed using mean amplitudes in consecutive 200 ms time windows (i.e., 100–300, 300–500, 500–700, 700–900, 900–1100). That is, since we did not know in advance which kind of ERP component would be elicited, our first-pass analysis included all time windows; as such, the factor of Time was defined by 5 levels. For medial ROIs, the Anteriority factor was defined as Anterior, Central and Posterior (3 levels: Anterior Medial, Central, Posterior Medial). For lateral ROIs, factors included Anteriority (2 levels: Anterior vs. Posterior) and Hemisphere (2 levels: Left vs. Right). In addition, analyses for ERPs shown in Fig. 4 included the linguistic factor of Object Type (3 levels: Singular, Control Singular, Plural).

The ERP analyses reported below used SPSS (v.24, IBM Corp., 2013) statistical software and employed the Greenhouse–Geisser (Greenhouse & Geisser, 1959) non-sphericity correction for effects with more than one degree of freedom in the numerator. Following convention, unadjusted degrees of freedom are reported, along with the Greenhouse–Geisser epsilon value (ε) and adjusted p value. Mean square error values reported are those corresponding to the Greenhouse–Geisser correction. For ease of exposition, only significant main effects involving the linguistic factor of Object Type are reported, followed by significant interaction effects involving the non-linguistic factors of Time and/or Anteriority and/or Hemisphere.

[6] A per a reviewer's suggestion, grand average ERP waveforms shown in Figs. 4–10 do not include lateral electrodes, in order to increase figure readability. As will be shown below, lateral electrodes did not show any significant effects. See Supplementary Material Online for figures that include lateral electrodes.

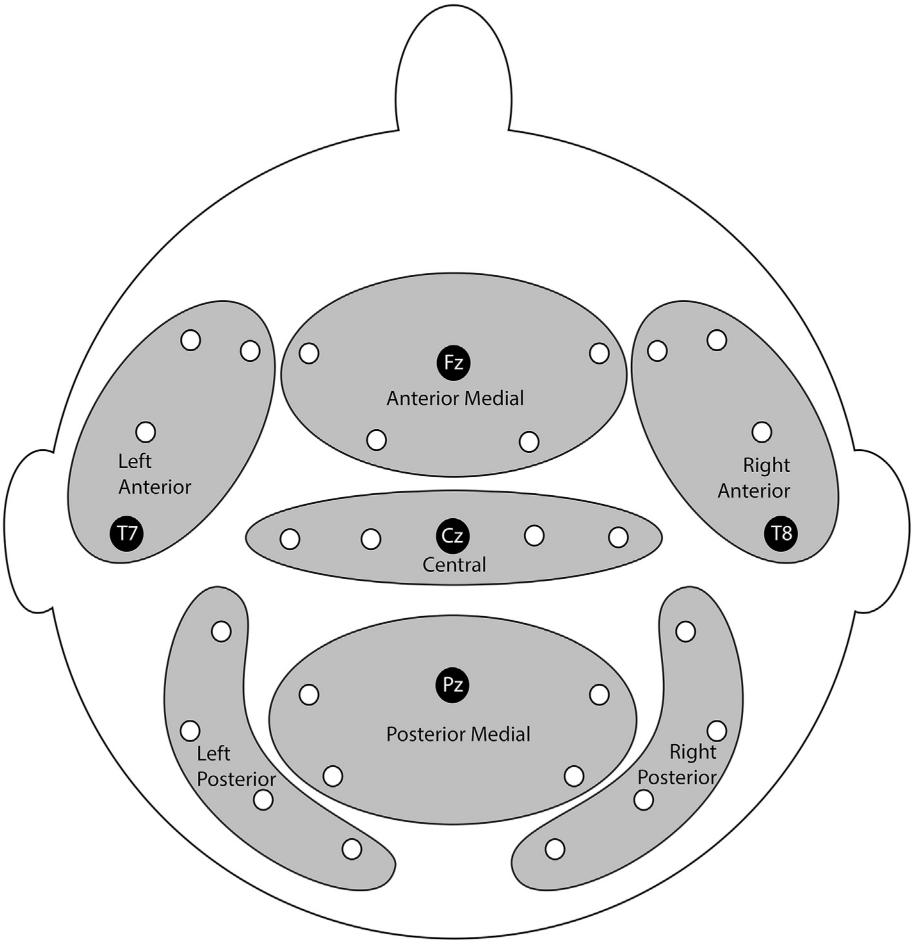

Fig. 3. *Regions used for analyses of EEG data.* Electrodes in dark circles included for orientation purposes.

Medial analyses at the target word position for Object Type and all time windows are summarized in Table 4. ANOVAs revealed no main effect of Object Type. An Object Type x Time interaction (F (8, 184) = 3.23, MSE = 7.9, p = 0.013, ε = 0.540) was found. This interaction is consistent with waveforms for each object type differing across time windows, where amplitudes were maximal in the second time window at 300–500 ms (see Fig. 4). No other interactions reached significance. The Object Type x Time interaction at lateral sites only trended towards significance (F (8, 184) = 2.24, MSE = 14.1, p = 0.096, ε = 0.351), likely due to greater variability at lateral sites. No other significant findings were revealed.

3.2.2. P300 results

The neural results are consistent with behavioural results: the plural object condition did not show difficulty, via a slow going negative waveform, as compared to the other conditions. Instead, the results show a P300 effect. For each object condition, separate repeated measures ANOVAs were conducted at each level of Quantified subject (2 levels: Quantified vs. Non-quantified) at medial and lateral ROIs as defined above, for the relevant P300 time window of 300–500 ms (see Figs. 5–10). Results are summarized in Table 5.

For the Singular condition, medial analyses revealed a main effect of Quantified subject (F (1, 23) = 6.06, MSE = 12.5, p = 0.022). That is, sentences starting with *The* showed more positive P300 amplitudes as compared to those starting with *Every*. In addition, a significant interaction with Anteriority was revealed, such that this difference was stronger at anterior medial and central medial sites (see Figs. 5 and 6). Lateral analyses did not reveal any significant effects.

As summarized in Table 5 and shown in Figs. 7 and 8, the control singular condition was a suitable control since no statistical differences were found for P300 amplitudes.

Finally, in the plural condition (see Fig. 9 and Table 5), we see the opposite pattern compared to the Singular condition (Figs. 5 and 6); for the Plural condition, sentences beginning with *Every* display greater P300 amplitudes versus sentences starting with *The*. Medial analyses revealed a trend for a main effect of Quantified subject (F (1, 23) = 3.13, MSE = 13.5, p = 0.09). Moreover, a significant interaction of Quantified subject x Anteriority was revealed (F (2, 46) = 3.54, MSE = 2.1,

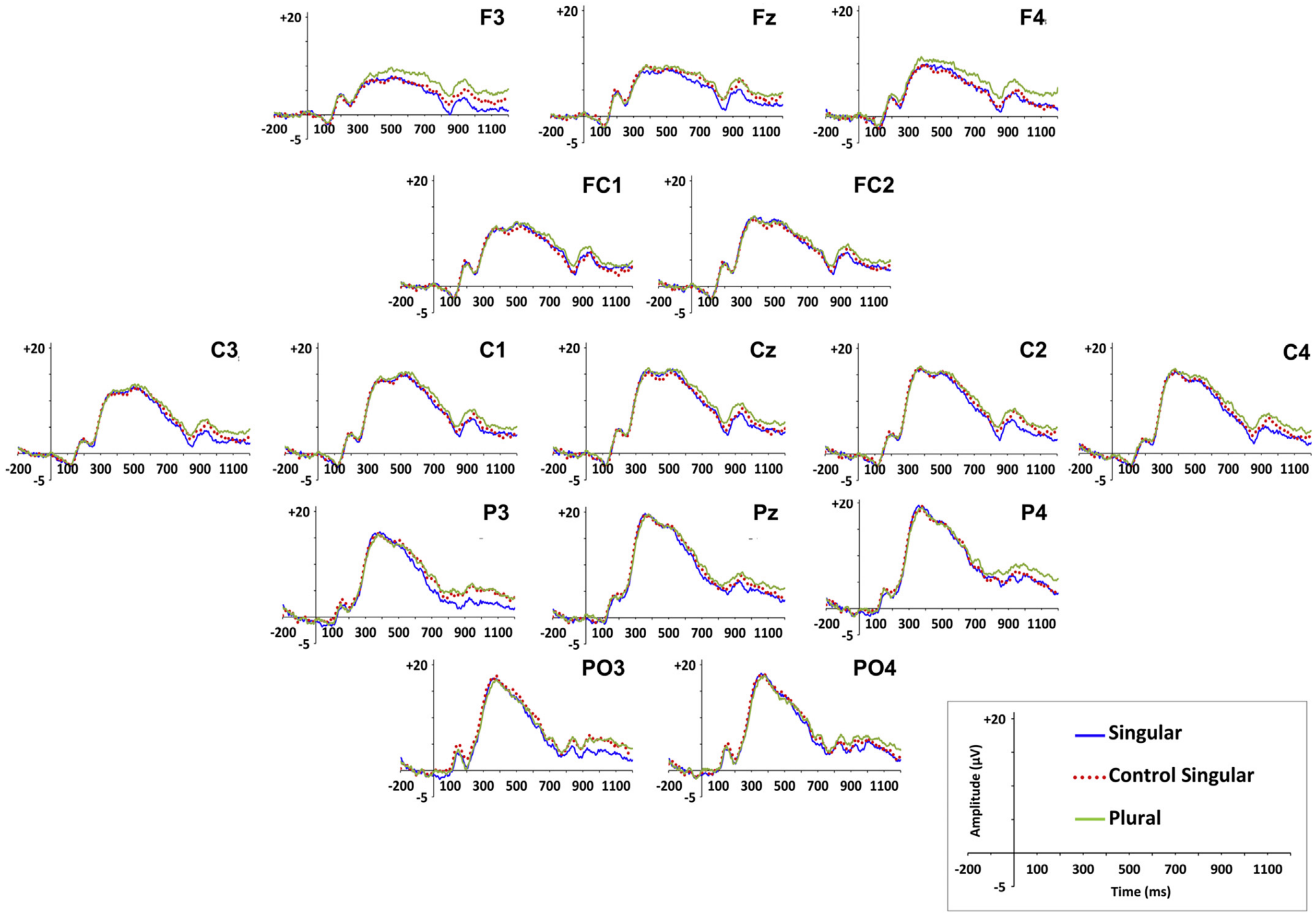

Fig. 4. *Grand average ERP waveforms for Object Type conditions*. Averages are time-locked to the onset of *tree/trees*.

Table 4
F-values for Object Type at target word for all time windows using ROIs.

Analysis	Effect (*df*)	*F*	*MSE*
Medial	ObjType (2,46)	1.738	54.002
	ObjType x AntPos (4,92)	1.446	4.720
	ObjType x T (8,184)	3.230*	7.894
	ObjType x AntPos x T (16,368)	1.255	0.894
Lateral	ObjType (2,46)	1.171	59.565
	ObjType x AntPos (2,46)	0.203	8.340
	ObjType x H (2,46)	1.475	8.993
	ObjType x T (8,184)	2.236	14.010
	ObjType x AntPos x H (2,46)	0.033	3.973
	ObjType x AntPos x H x T (8,184)	0.679	0.871

Note: ObjType = Object Type; AntPos = Anteriority; H = Hemisphere; T = Time.
$^*p < 0.05$.

$p = 0.045$, $\varepsilon = 0.852$), such that this difference was stronger at posterior medial sites (see Fig. 9). Lateral analyses did not reveal any significant effects.

In sum, judgments at the direct object resulted in a P300 effect for all object conditions. Amplitude differences were observed at the singular and plural object conditions, in the opposite direction. Whereas sentences starting with quantified subjects *Every kid* were less positive for singular conditions, these were more positive-going for plural conditions. In addition, the topography of the effects differed between conditions, where singular conditions showed more fronto-central distribution as opposed to more posterior effects for the plural conditions. These topographic differences are summarized in Fig. 11.

4. Discussion

In the present work, we recorded ERPs while participants read sentences presented in one- and two-word chunks and hypothesized that participants would find it difficult to identify that just one word was on the screen when it was interpreted as plural. We expected difficulty to be observed when the word was unambiguously plural, as in *trees,* as well as when it was interpreted as conceptually plural in quantifier scope ambiguous sentences, *Every kid climbed a tree.* That is, we tried to replicate behavioural results found in Patson and Warren (2010), which found difficulty at sentences with plural objects such as *boxes*, as well for quantifier scope ambiguous sentences of the form *Each of the men carried a box.* To date, work in our lab has not shown on-line effects that indicate a plural interpretation in quantifier scope sentences, calling into question as to whether the algorithmic rule of quantifier ordering applies in real-time to allow for the plural inference. Instead, we have proposed (Dwivedi et al., 2010; Dwivedi, 2013; Dwivedi & Curtiss, 2013, 2016) that people rely on associative-word based heuristic cues during language comprehension, and only use algorithmic rules if required. We thought that this task, sensitive to number, and a direct measurement of the quantifier scope sentence (cf. Dwivedi et al., 2010) would indeed reveal a plural reading (consistent with the quantifier ordering rule). Overall, we did not replicate Patson and Warren's findings–difficulty was not observed for unambiguous plural conditions. Instead, neurophysiological evidence at target words revealed a P300 component for all conditions. Upon further inspection, this component showed significant differences in amplitude when there was a switch in number interpretation between subjects and objects in critical sentences of interest. Moreover, the distribution of these effects differed depending on object type; singular objects showed more fronto-central effects whereas plural objects showed more posterior P300 effects. We discuss and interpret the cognitive significance of these effects in turn.

4.1. Lack of difficulty at plural condition

The findings in the present ERP work did not replicate the behavioural findings of Patson and Warren (2010). First, strikingly, the plural condition did not result in any behavioural evidence of task difficulty. This lack of difficulty does not correspond to our predictions based on the findings of Patson and Warren (2010). Instead, we found a facilitation effect for the singular condition. Why should this be the case? One plausible explanation arises from expectations regarding number interpretation in the (experimental) singular condition. Specifically, participants are given information regarding the semantic number associated with the upcoming word *before* the target word appears, only in this condition, since the indefinite article *a* precedes the presentation of the direct object (e.g., *tree* in *Every/The kid climbed a tree*). Accordingly, when the single target word *tree* appears on the screen in this condition, expectations regarding the number interpretation of the noun are confirmed–hence the facilitation effect observed. In contrast, the definite article *the,* which does not contain any information regarding number, precedes the direct object *tree(s)* in the control singular and plural conditions. As a consequence, when the single target word *tree(s)* appears on the screen in these conditions, no expectations have been built with respect to number interpretation. Interestingly, the control plural conditions in Patson and Warren's study were *Each of/Together the men carried some boxes.* Note that plural information is conveyed prior to the judgment for *boxes* by the (plural) quantifier *some* in these sentences. As such, an alternative explanation regarding the difficulty participants exhibited in number judgments for plural

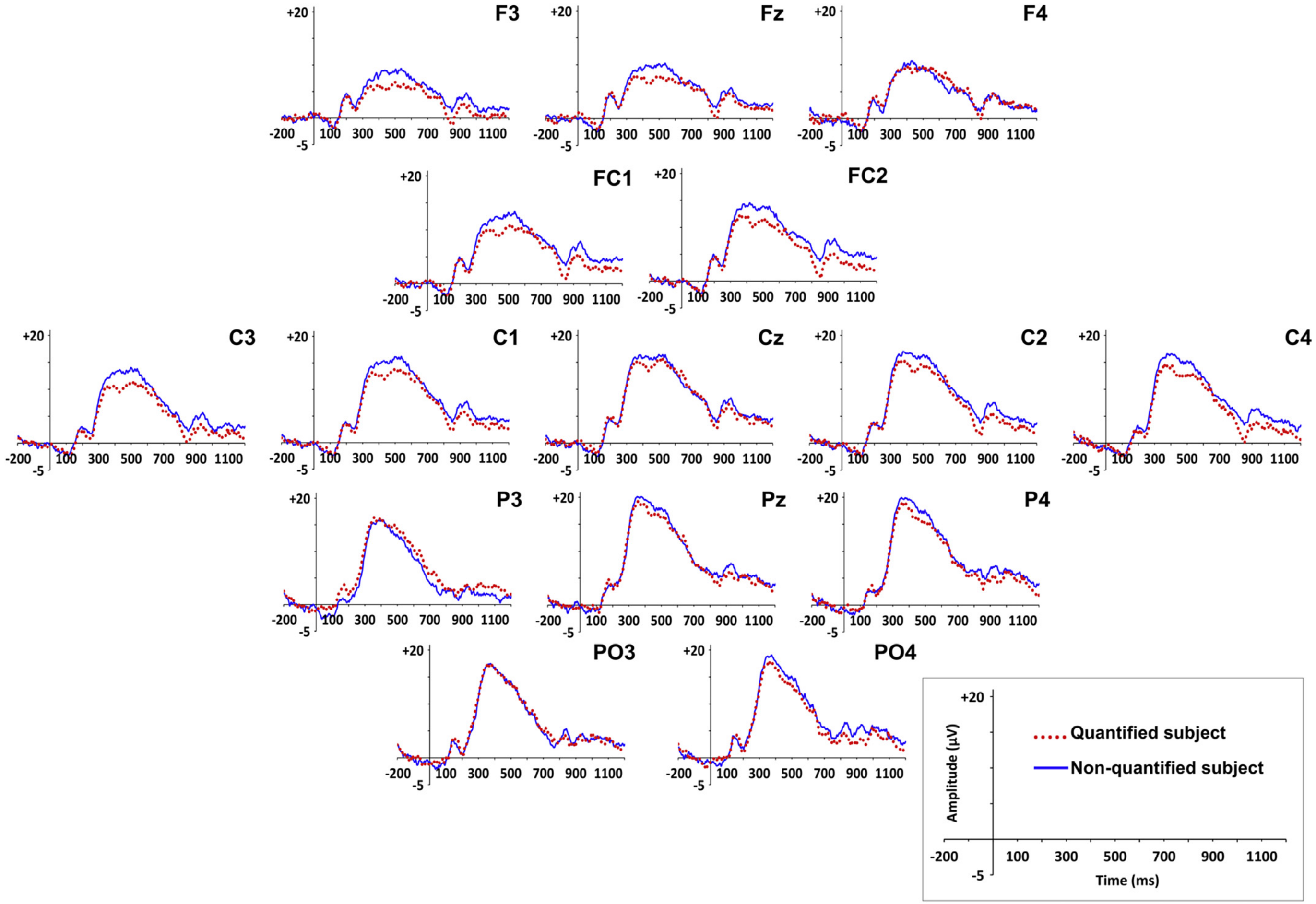

Fig. 5. *Grand average ERP waveforms for Quantified versus Non-quantified Singular condition*. Averages are time-locked to the onset of the target word *tree*.

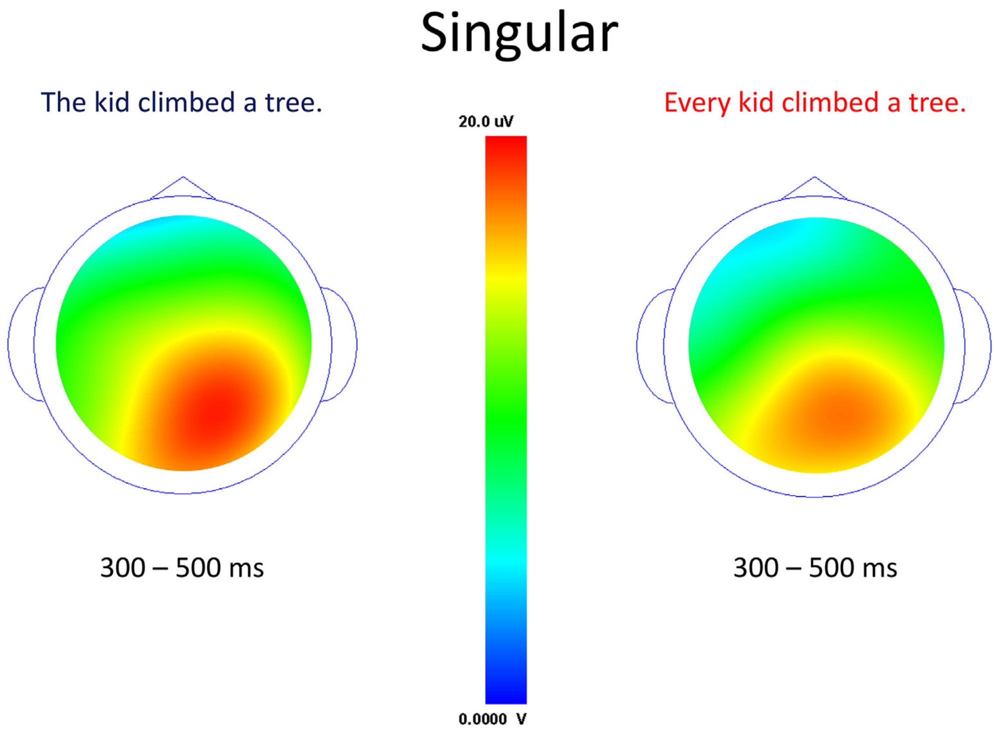

Fig. 6. Scalp distribution of P300 effect at *tree* in 300–500 ms time window for Quantified versus Non-quantified Singular condition.

target words in Patson and Warren's control conditions may have been due to expectations regarding plural number (due to the presence of *some*), rather than morphological suffixation (due to plural −*s*) on the noun.

Next, overall behavioural accuracy rates in the current work were not at ceiling, as found in Patson and Warren (2010). This is likely due to distinctions in methodology employed. First, as is standard for ERP language experiments, word presentation rates in the present work were fixed. In contrast, word presentation rate was under participants' control in Patson and Warren's self-paced reading study. Similarly, in order to maintain the fixed timing of the experiment in the current ERP study, any trial in which the participant did not respond within 600 ms was counted as incorrect. Finally, for critical trials in the current work, the target word was always presented as the third chunk of the sentence; this was not the case across all other conditions. Instead, in order to reduce predictability, we counterbalanced the sentence position for the number judgment task across other filler conditions. In contrast, judgments were always made at the sentence-final position in Patson & Warren, 2010 study. Thus, differences regarding timing and predictability would account for differences observed in accuracy rates for the number judgment task between these two experiments.

4.2. The P300 effect

The neural results in this experiment also did not indicate difficulty with the plural condition, as a slow negative-going waveform was not observed. Instead, a P300 effect was elicited in all conditions of this dual task experiment. Interestingly, P300 amplitude differences were observed in the singular and plural conditions. We argue that amplitude differences reflect that more attentional resources are available for the secondary task of counting and responding to the blue target word for sentences that are easier to interpret (Polich, 2007, 2010). Specifically, when the singular/plural distinction of the subject type matches that of the object type, sentences are easier to interpret. Such "easy" sentences leave extra cognitive resources available for the secondary task of target identification, resulting in larger P300 amplitude. For instance, *Every kid climbed the trees* (condition (v), see Table 1) is straightforward to interpret, since both the subject and object interpretations are plural. That is, the quantifier *Every* indicates that more than one entity is in the event, and the morphological marking on the direct object *trees* is unambiguously plural. Thus, there is no switch in number interpretation. In contrast, its corresponding non-quantified condition, *The kid climbed the trees,* starts with a subject that is singular, and then "switches" to plural at the object. The switch results in a cognitive cost such that fewer resources are available for the button pressing task, eliciting smaller P300 amplitudes. Thus, P300 amplitudes are smaller for sentences beginning with non-quantified subjects such as *The kid* that then "switch" to plural objects such as *trees*; amplitudes are greater for sentences starting with quantified *Every kid* and continuing with plural *trees.* The latter condition is simpler to interpret. This straightforward explanation also accounts for amplitude differences, in the *opposite* direction, for *Every kid climbed a tree* versus *The kid climbed a tree.* That is, the

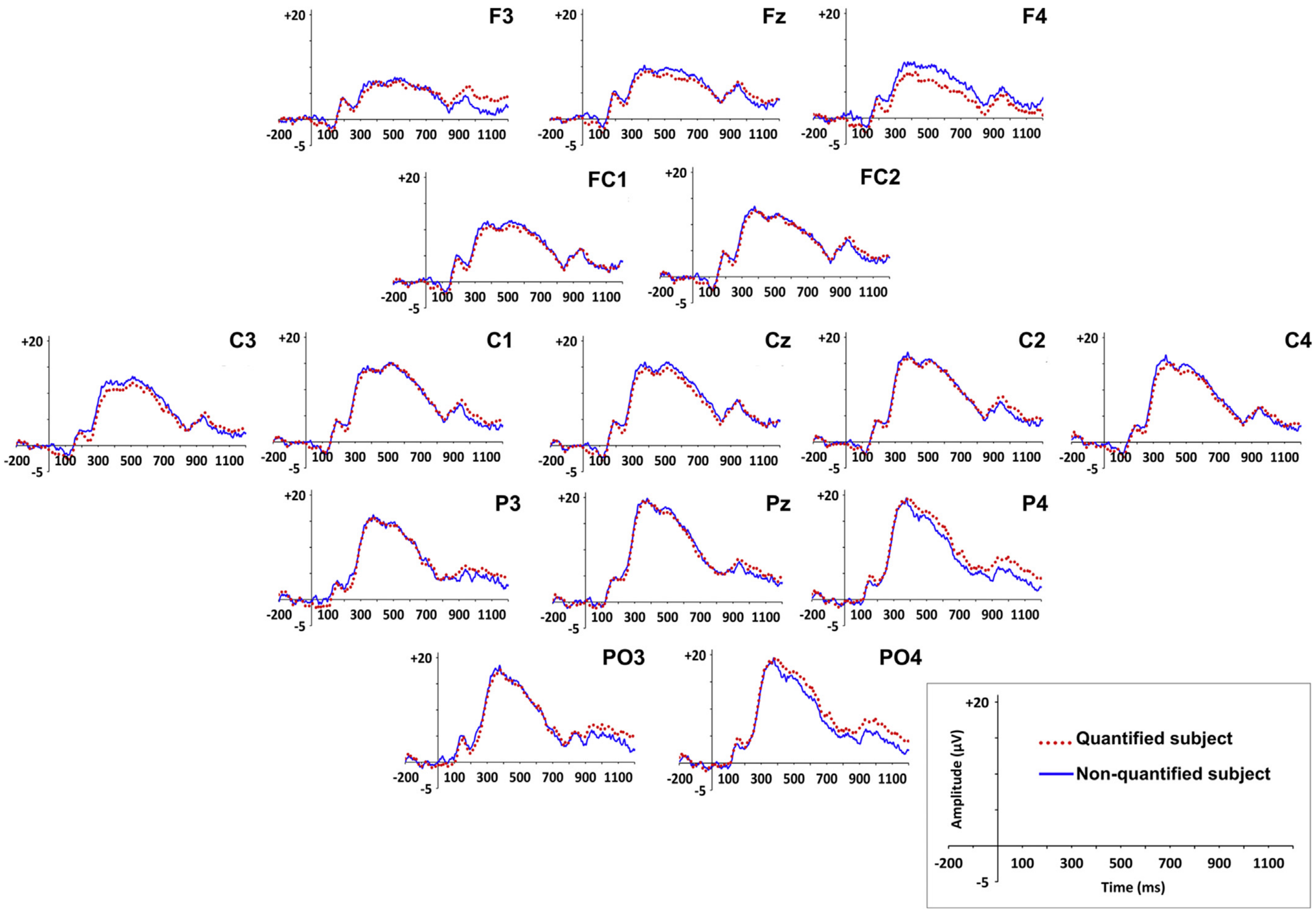

Fig. 7. *Grand average ERP waveforms for Quantified versus Non-quantified Control Singular condition*. Averages are time-locked to the onset of the target word *tree*.

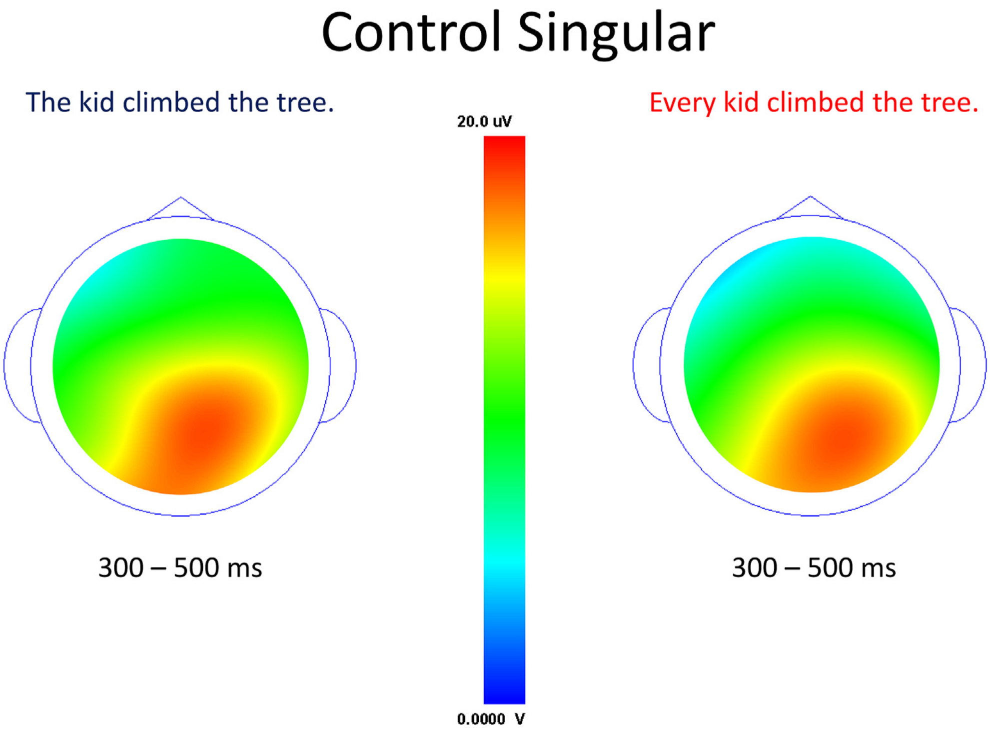

Fig. 8. Scalp distribution of P300 effect at *tree* in 300–500 ms time window for Quantified versus Non-quantified Control Singular condition.

quantified *Every* condition exhibits smaller P300 amplitudes versus its non-quantified (control) condition starting with *The kid*. This is because *Every kid climbed a tree* switches the number interpretation between subject and object, whereas *The kid climbed a tree* does not. As a result, the non-quantified condition is easier to process, resulting in greater P300 amplitude.

At this point, we need to address another possible explanation for differences in P300 amplitude, which has to do with subjective probability (Chwilla & Brunia, 1991; Donchin, 1981; Polich, 2007, 2010), given that P300 amplitude is an inverse function of stimulus probability. It could be argued that the P300 effect has to do with the presence of *Every,* which only occurs in half of the (156) critical trials of the experiment (78 out of 456 total trials). On this account, the presence of *Every* would result in a sort of surprise or oddball effect, and would result in a P300 amplitude difference. We note that if the amplitude difference observed were only in one direction, and that too, only for the plural condition, then this could be a plausible alternative explanation. However, the fact that this P300 amplitude difference also occurs in the condition that starts with *The*, which not only occurs in half of the critical trials but also in filler trials (and is therefore more, not less, frequent than *every*) would strongly argue against a stimulus probability explanation.

Furthermore, the number switch explanation for the ERP effect is supported by behavioural results. Although differences were small[7] accuracy rates showed that participants were more accurate in the number judgment task at precisely the conditions that showed greater P300 amplitudes (i.e., conditions that are easier to process due to a lack of number switch). Specifically, participants were more accurate at *The kid climbed a tree* (84%) versus *Every kid climbed a tree* (81%) and at *Every kid climbed the trees* (79%) versus *The kid climbed the trees* (77%). Interestingly, no significant P300 amplitudes were found for the control singular condition *Every kid climbed the tree* versus *The kid climbed the tree*; behavioural differences were also negligible. This is likely due to the fact that number is underspecified at the object (Poesio, Sturt, Artstein, & Filik, 2006); *the* yields no numerical information, and *tree* is not overtly marked as plural. Taken together, our findings provide strong evidence that overt number interpretation, when congruently specified, facilitates sentence comprehension.

Finally, we conclude with comments regarding the differences found in topography for the P300 effects observed for the (indefinite) singular object vs plural object conditions.

The singular condition exhibited larger P300 amplitude differences at fronto-central regions, whereas differences were more posterior for the plural object. Polich (2007, 2010) (see also Hartikainen & Knight, 2003; Kok, 2001; Polich, 2003) distinguish P300 components with these topographies as the P3a and P3b, respectively. Given that these different topographies arise for different semantic object types, it would seem that the interpretive properties of the objects are driving the differences in the distribution. Notably, whereas the P3a is associated with attentional focus, the P3b occurs when attentional

7 We note that in post hoc analyses, these differences were not significant (p values > 0.05).

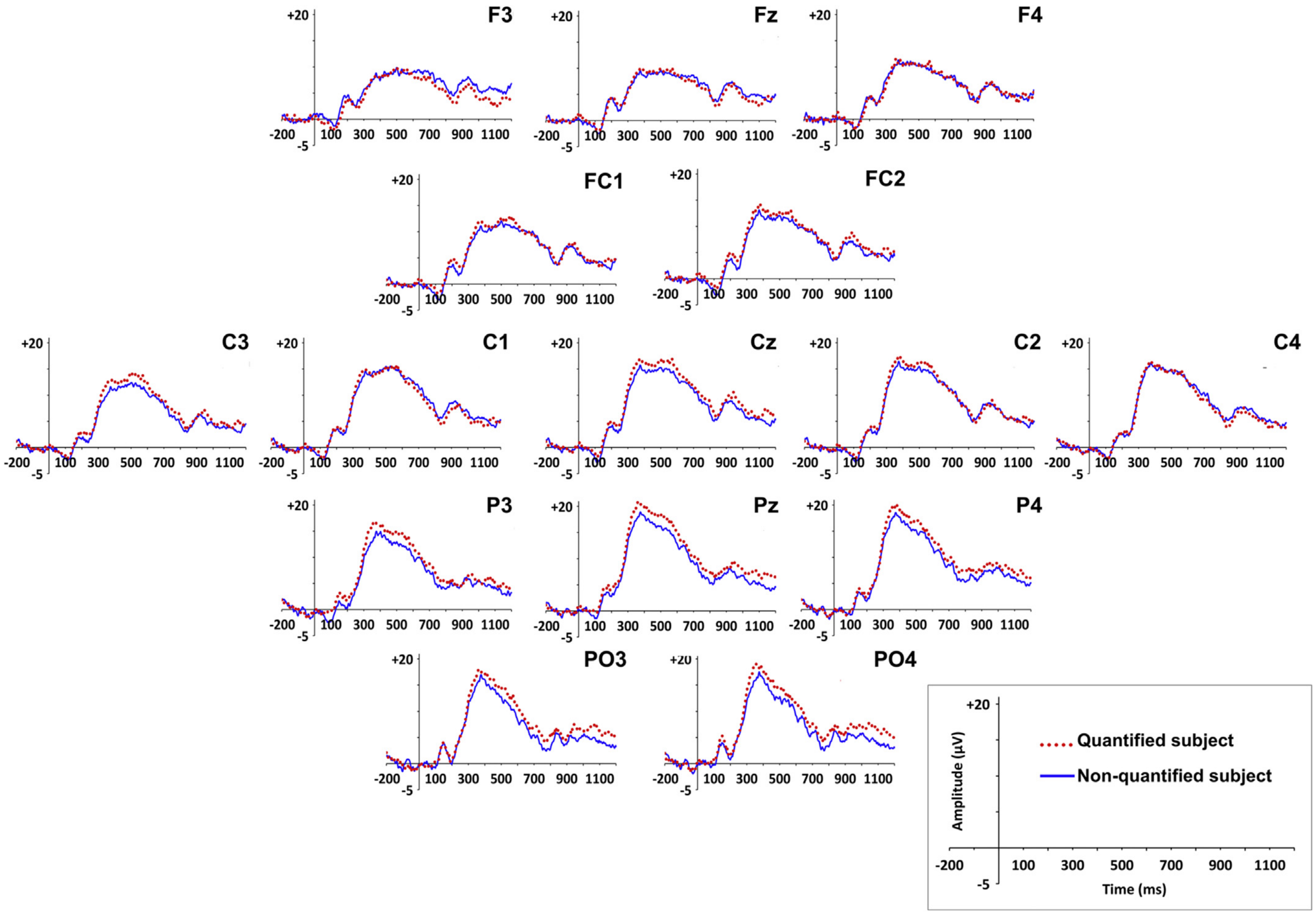

Fig. 9. *Grand average ERP waveforms for Quantified versus Non-quantified Plural condition*. Averages are time-locked to the onset of the target word *trees*.

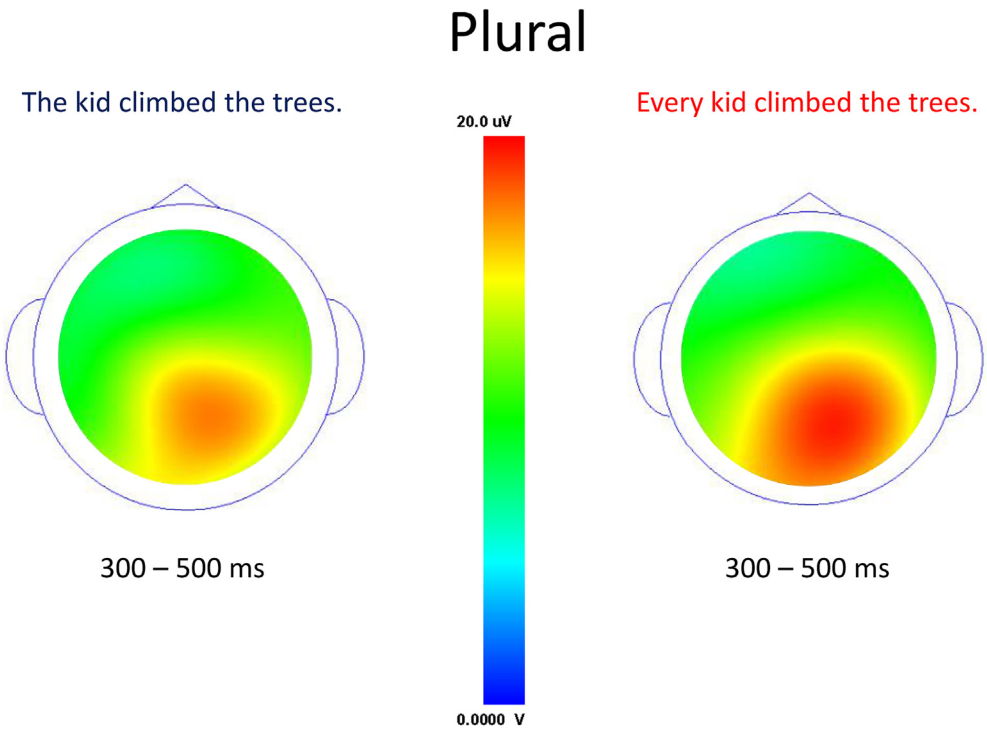

Fig. 10. Scalp distribution of P300 effect at *trees* in 300–500 ms time window for Quantified versus Non-quantified Plural condition.

Table 5
F-values for Singular, Control Singular, and Plural conditions at target word for time window 300–500 ms using ROIs.

Condition	Analysis	Effect (*df*)	*F*	*MSE*
Singular	Medial	Q (1,23)	6.056*	12.539
		Q x AntPos (2,46)	3.894*	1.774
	Lateral	Q (1,23)	3.050	11.667
		Q x AntPos (1,23)	2.569	3.773
		Q x H (1,23)	1.249	4.778
		Q x AntPos x H (1,23)	4.053	0.810
Control Singular	Medial	Q (1,23)	0.692	15.326
		Q x AntPos (2,46)	2.712	2.361
	Lateral	Q (1,23)	0.599	10.826
		Q x AntPos (1,23)	1.419	4.127
		Q x H (1,23)	0.000	6.393
		Q x AntPos x H (1,23)	0.971	2.455
Plural	Medial	Q (1,23)	3.133	13.482
		Q x AntPos(2,46)	3.538*	2.115
	Lateral	Q (1,23)	0.490	21.896
		Q x AntPos(1,23)	0.961	2.279
		Q x H (1,23)	1.465	13.415
		Q x AntPos x H (1,23)	0.865	3.718

Note: Q = Quantified subject; AntPos = Anteriority; H = Hemisphere; T = Time.
*$p < 0.05$.

resources also promote memory operations (see also Knight, 1996). We account for the varying P300 topographies in the following way: the singular object condition *a tree* could be understood as a noun that requires attentional focus, perhaps because it is instantiating one tree (see also Filik, Sanford, & Leuthold, 2008, who argue for specificity effects associated with singular but not plural nouns). Next, the P3b may be generated with the plural object because plural vs. singular objects are more complex to represent for interpretive purposes; that is, there are more entities in events that include plural versus singular objects. In fact, preliminary data in our lab (Dwivedi, Rowland & Curtiss, 2015) shows that plural nouns in sentences take more time to read than their corresponding singular counterparts. We note that comments above are speculative and further research is needed in the processing of singular indefinite versus definite singular versus definite plural noun interpretation (see inter alia, Boiteau, Bowers, Nair, & Almor, 2014; Kaup, Kelter, & Habel, 2002).

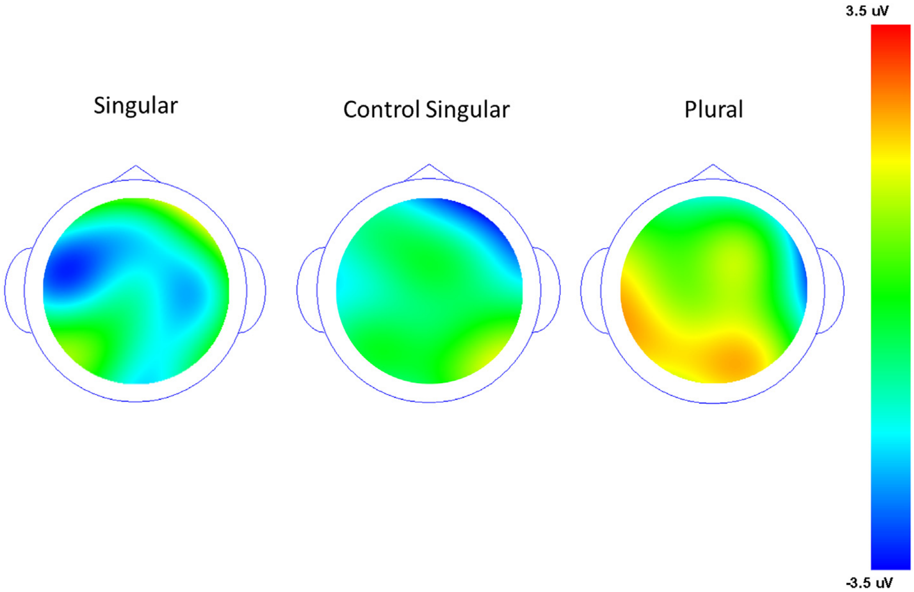

Fig. 11. Difference topography maps of P300 effects at *tree/trees* (average amplitude, 300–500 ms) for Quantified minus Non-quantified conditions at each Object Type.

4.2.1. *The heuristic significance of number*

The present work showed that participants were sensitive to number during sentence interpretation (see also Dwivedi, 2013; Dwivedi & Curtiss, 2013, 2016). We argue that number is a heuristic feature necessary for the construction of the meaning of events. Firstly, we assume that language processing occurs at a level of detail relevant to the task at hand—in a "good enough" manner (Christianson, Luke, & Ferreira, 2010; Ferreira & Patson, 2007; Ferreira, 2003; Ferreira, Christianson, & Hollingworth, 2001). Additionally, we assume that there are two routes to language processing: one route uses word-based heuristics, and the other route relies on algorithmic grammatical rules (Bever, 1970; Caplan, Hildebrandt, & Waters, 1994; Townsend & Bever, 2001)[8]. When sentences are not overly complex, one interprets sentences at a shallow level using heuristic cues from lexical items for interpretive purposes (Chwilla & Kolk, 2005). For example, it has been shown in previous ERP language work that lexical cues regarding animacy can be used to generate plausible versus implausible events (Kim & Osterhout, 2005; Kim & Sikos, 2011; Kolk & Chwilla, 2007; Kolk, Chwilla, Van Herten, & Oor, 2003; van Herten, Chwilla, & Kolk, 2006). Furthermore, in literature regarding event knowledge (Ferretti, Kutas, & McRae, 2007; Zwaan & Radvansky, 1998), it is argued that features about protagonists (under which, presumably, animacy would be subsumed), as well as space, causation, time, and intentionality, are important for interpretation. In the present work, we show that number should also be regarded as an important cue for the construction of the meaning of events (see also Dwivedi & Curtiss, 2013, 2016). When incoming numerical information (regarding the direct object) is consistent with previously posited information (regarding the subject), the direct object is more easily incorporated into the event representation of the sentence. In this way, heuristic knowledge regarding number interpretation in events is no different than other heuristic mechanisms proposed in the literature; as one constructs the mental representation of events during sentence comprehension (Rumelhart, 1980; Schank & Abelson, 1977; van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998; Zwaan, 1999), the semantic feature of number is retrieved and consulted (Katz, 1972).

Overall, the current work adds to the growing body of research concerning the mental representation of number via grammatical encoding or conceptual information (Bock, Carreiras, & Meseguer, 2012; Eberhard, 1997, 1999; Humphreys & Bock, 2005; Tanner & Bulkes, 2015). The difference here is that previous works examining the mental representation of number examined how number interfaced with the linguistic rule of subject-verb agreement. Here, we examine how number is used to understand quantifier scope ambiguous and related sentences.

4.2.2. *The significance of number in quantifier scope sentences*

Given that number judgments for "1" did not exhibit any interference effects when plural number was overtly marked on the noun (*trees*), it is unclear what we can conclude regarding quantifier scope ambiguous sentences such as *Every kid climbed a tree*. Nevertheless, we do have evidence that sentences were interpreted heuristically with respect to number, consistent

[8] Furthermore, unlike other models of language processing, we assume that the heuristic route is primary, and the algorithmic route is only used if required (see Dwivedi, 2013 for details).

with our previous claims that information regarding the number of entities in events in sentences can account for the empirical effects observed.

Additionally, how are we to explain the difference between our apparent lack of findings regarding scope computation and those of Patson and Warren (2010), who did find empirical evidence of the computation? Again, the issue of number interpretation in events plays a role. In Patson and Warren's (behavioural) work, 36 experimental sentences were used, as compared to 156 scenarios in the present ERP study. Prior to running the on-line version of their study, they conducted a norming study to ensure that all 36 sentences were strongly biased for a plural interpretation. In contrast, plural preferences for the 156 sentences in the current study varied—see discussion of number interpretation and preference in events in Dwivedi (2013) and Dwivedi and Curtiss (2013, 2016). With these factors in mind, it is unclear whether Patson and Warren's findings are driven by actual effects of quantifier scope computation, or number bias in sentence interpretation. In fact, we claim that this confound with number bias in events is likely the case with most studies on quantifier scope ambiguity (see Discussion section of Dwivedi, 2013). Overall, ERP results in the current work, supported by behavioural findings, indicated that people are sensitive to number interpretation associated with subjects and objects in events, such that when there is congruency between these, the sentence is easier to interpret.

5. Conclusion

As in our previous work (Dwivedi et al., 2010; Dwivedi, 2013; Dwivedi & Curtiss, 2013, 2016), we have shown the importance of the heuristic significance of number interpretation in events. The evidence for this claim, and our model in general, is robust, as it has been built up over several (between subject) experiments, using different methods and stimuli. In the current study, participants were sensitive to the heuristic cue of number in sentences, not the use of algorithmic rules, during interpretation. That is, as participants interpret a sentence that begins with either a singular or plural subject, and continues with a direct object that matches that number, this sentence is easier to interpret than one where there is a switch in singular/plural number interpretation. In other words, congruency of singular/plural number interpretation of entities in events determines the ease of the interpretive processes—not an algorithmic computation of quantifier scope.

It is clear that in constructing the semantic representation of events, not only do people pay attention to who, what, where and when an event occurred, but they are also interested in how many entities participated in the event. Thus, the (singular/plural) number feature should be added as another important dimension to consider for representation of meaning in text (see Zwaan & Radvansky, 1998; Zwaan, 1999). Finally, this work supports the “Heuristic first, algorithmic second” sentence processing model proposed in Dwivedi (2013). During real-time sentence interpretation, people pay attention to associative word-based cues (in this case, number) that are relevant to event interpretation. These “quick and dirty” heuristic cues are what determine ease of processing of sentences, not the application of algorithmic linguistic rules.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jneuroling.2016.11.006.

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