Running head: PAST TENSE

Irregular and regular verbs elicit identical morphological decomposition ERPs

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Abstract

[...to be written…]

1. Introduction

As a rule, past tense on verbs is expressed by adding /-ed/ to the stem; this is the *regular*, or rule-based inflection. The alternative type, *irregular* inflection, expresses past tense by replacing the "base word" with another word altogether (suppletion), as in *go* vs. *went*. The form 'went' is not predictable from the form 'go', hence the term irregular—it cannot be predicted by a rule. Between these two extremes, English also has a hybrid type of semi-regular patterns applying to small classes of verbs, such as vowel changing rules like 'swim/swam', 'ring/rang', and 'sing/sang' (/i/→ /a/); and 'wring/wrung', 'sling/slung', 'fling/flung', (/i/→ /u/), etc. For the current purpose, we define irregular inflection as any pattern that requires memorization of a form or a small set of forms. Hence, 'go' requires memorizing 'went'; and 'swim' requires memorizing that the verb belongs to a small set of verbs that undergo the /i/→ /a/ vowel change rule[1].

Along with this theoretical or grammatical description, there are two approaches in the literature as to how this distinction translates into psycholinguistic and neurolinguistic processing. The "dual route" theory is that only regular verbs derive their past tense forms by rule, and that all irregular forms are stored in the lexicon (including the verbs that exhibit non-productive general phonological change patterns that make the word forms look analytic) (Clahsen, 1999; Clahsen et al., 1992, 2003; Pinker & Ullman, 2002a). In contrast, theories of "full decomposition" posit that even irregular forms like 'went' are represented at some level of mental representation as a stem (e.g., 'go') combined with an abstract [PAST] morphosyntactic feature (Halle & Marantz, 1994; Stockall & Marantz, 2006a).[2] Recently, (Morgan & Levy,

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[1] A question we are not addressing is whether there is a 3-way distinction between truly regular vs. truly irregular suppletion (go/went, is/was) vs semi-irregular with specific vowel change patterns (e.g., swim/swam).

[2] We have omitted discussion here of neural network approaches (Plunkett & Marchman, 1991; Rumelhart et al., 1986), which make graded, rather than categorical predictions about the measures used in the current study.

2016) have provided evidence for a hybrid approach where both compositionality and holistic forms are represented in a graded, probabilistic fashion.

The second question concerns processing. As different theoretical solutions require different algorithms for computation, can we measure the computational processes and determine which theory provides a better fit to the data? According to the Declarative/Procedural model (Clahsen et al., 1992; Pinker & Ullman, 2002a; Ullman, 2001, 2004), also known as the Dual Route theory, the answer is “yes”, in that regular vs. irregular verbs activate distinct neurophysiological memory mechanisms in the brain. According to (Ullman, 2004), regularly inflected verbs are derived using procedural memory structures, engaging a basal ganglia network, whereas irregularly inflected verbs activate declarative memory structures in the left temporo-parietal region. The predictions of the Dual Route theory are in stark contrast to Full Decomposition models, such as Distributed Morphology, which predicts that the same brain networks will be activated in process regular and irregular marked forms (Halle & Marantz, 1994)). Evidence from a study using Magnetic Encephalography (MEG) supported this hypothesis (Stockall & Marantz, 2006b). The MEG measures revealed that both irregular and regular verbs equally activated the verb stems and that this activation occurred in the same time frame. This finding supports a model in which inflected irregulars undergo rule application at some stage of processing, just like regular verbs.

Pinker & Ullman (2002b) in their “Rules and Words” analysis, discuss a wide range of Dual Route predictions for clinical neuropsychology and cognitive neuroscience, and we focus here on their predictions for event-related brain potentials (ERPs). In an expectation violation paradigm, the type of ERP response observed has often been interpreted as evidence for the underlying nature of the violation, based on the history of experimental results rather than explicit neuro-computational linking theories. For example, Osterhout & Mobley (1995) observed that agreement violations, as in ‘They likes to run’ or antecedent-reflexive agreement violations ‘she likes himself’ lead to an increased negativity over left anterior sites compared to grammatical utterances (called LAN (left anterior negativity) responses). Other studies have also observed LAN-like responses to ungrammaticality (Gunter et al., 2000; Neville et al., 1991; Osterhout & Mobley, 1995). This LAN response occurs early in time (within 300 ms of the violation) and before the lexical-semantic information is fully accessed. A P600 response is sometimes also observed to ungrammatical structures involving tense agreement (Dragoy et al., 2012), but this response is quite late in time (600 ms), well after semantic information is accessed. Thus, the LAN response is particularly relevant for testing the Dual-Route model and will be used here as the index of tense expectancy violations (Baggio, 2008).

. In a processing model where predictions are made on the fly, for instance encountering ‘kick-ed’ when past tense is not expected, requires recognition that a rule has been applied when it should not have been. If LAN reflects computations related to morphosyntactic rules, this should result in a LAN response. Alternatively, an unexpected irregularly inflected verb form, according to the Dual Route theory, is on a par with encountering an unexpected word form. If ‘swam’ is encountered rather than ‘swim’, lexical lookup finds “swam” in the lexicon with a built-in past tense feature. If present tense was expected, this then “counts” as a lexical semantic error, i.e. encountering an unexpected atomic word, which is associated with the N400 response.

These predictions were tested in Newman et al. (2007), which presented participants visually with written sentences, as in the incongruent “Yesterday, I walk to school” and “Yesterday, I eat a banana,” compared to congruent “Yesterday, I walked to school” and

"Yesterday, I ate a banana." This experiment also contained phrase structure violations and lexical semantic violations, designed to elicit ERP profiles for rule-based vs. word-based violations. The phrase structure and lexical violations elicited LAN/P600 and N400 respectively. The regular verbs in the present tense elicited a LAN response, but the irregular verbs did not. Both verb classes also elicited P600 responses. The authors interpreted this pattern of results as evidence for the Dual Route theory as follows: Although the irregular verbs did not bear out the prediction of an N400, the absence of a LAN for irregular verbs and presence of LAN for regular verbs, combined with a main effect P600 for both verb classes, was taken as evidence that irregular verbs did not elicit a rule-based violation response.

There are several problems with this conclusion, however. First, it rests on a null effect: the absence of a statistically significant LAN for irregular verbs. This is not the same as the presence of an N400, which was predicted by the Dual Route theory. Furthermore, lexical-semantic violations would not be expected to also elicit a P600 in classical N400 experiment designs (ref?). One could argue that the experiment failed to measure responses to *past* tense inflection, as the ungrammatical sentences were all in the present tense, which is not marked by overt morphophonology in English (except in the 3rd person singular). One possibility is that the parser computes the past tense form as part of determining that the present tense is the wrong form (you have to know what the right form looks like to determine that another form is incorrect), but this difference between "commission error" vs. "omission error" has not been examined in the ERP studies on the Dual Route. Finally, the Newman et al study did not control for inherent differences in brain responses to past and present inflected forms. Specifically, it is possible that the different ERP patterns to the past and present tense verbs used in the study were related to morphophonological properties rather than to a violation of tense. The current study aimed to address all of these issues.

1.1 The current study

The purpose of the current study was to differentiate between the Dual Route model vs. Full Decomposition, by using ERPs to test their predictions to *both* present tense as well as past tense as ungrammatical . (Newman et al. (2007) only tested present tense as ungrammatical). Essentially, the question is whether regular inflection results in a LAN whereas irregular inflection leads to an N400, or a LAN, as expected to regularly inflected forms. The second question is whether past and present tense as ungrammatical both tap into the predicted difference between regular versus irregular past tense patterns and the associated distinction between procedural vs. declarative memory.

Starting with the latter, if hearing a present tense as ungrammatical does *not* tap into the difference between procedural and declarative memory, then ungrammatical present tense regulars and irregulars should elicit the same ERP response (e.g. LAN) even under the Dual Route Model; whereas ungrammatical *past* tense should differentiate between verb types, with N400 to irregulars and LAN to regulars. If hearing present tense as ungrammatical *does* tap into the difference between procedural and declarative memory processes, ungrammatical present tense should either elicit a LAN for regulars and no LAN for irregulars (as observed in Newman et al., 2007)) or a LAN for regulars and an N400 for irregulars (the model prediction under Dual Route).

In contrast, Full Decomposition, which assumes abstract morphosyntactic suffixation for both tenses, predicts a LAN for both regular and irregulars, no matter whether present tense or past tense is ungrammatical. According to this theory (Stockall & Marantz, 2006a), the mental representations of verbs are as in Table 1, where √ denotes the abstract root of the word:

		Tense	
		Present	Past
Verb inflection type	Regular	*/kick–Ø/* √*kick* [*pres*]	*/kick–ed/* √*kick* [*past*]
	Irregular	*/teach/* √*teach* [*present*]	*/taught/* √*teach* [*past*]

Table 1: Full Decomposition model (Stockall & Marantz, 2006b)

Specifically, the present tense is the result of a compositional rule, just like past tense. The difference is that the morphophonological exponent of the morphosyntactic feature is a null suffix for both regulars and irregulars. The null suffix is an entity that is independently required in grammar (Pesetsky, 1995). Written like classical context sensitive rules, they can be stated as below, where the competition between rule (ii) and (iii) is regulated by the Elsewhere Principle (Kiparsky, 1982) and the Strict Cycle Condition (Chomsky, 1965):

i. [present] → /∅/ / [$_V$ X _
ii. [past] → /-id/ / [$_V$ X _
iii. [past] → /taught/ / [$_V$ teach] _

Full Decomposition cannot escape the lexicon: irregular verbs do contain a memory component, linking a specific word form as the exponent of past tense; therefore, irregular verbs will always require a retrieval of separate lexical form as part of irregular rule application, which would be consistent with observing both a LAN and N400.

1.2 Linking hypothesis for the grammar-brain relation

Before proceeding, it is useful to make explicit the linking hypothesis that relates ERP responses to grammatical computation. Why do specific ERPs arise when the parser is encountering and analyzing specific violations or specific rule operations? ERPs arise from the firing of neural assemblies in the brain when specific computations are executed, and/or when specific representations are built. The response measured at the scalp reflects a summation of processes indexing the computed representations and subsequent operations.. For example, encountering kick+PRESENT and “knowing it is wrong” must mean that the alternative representation kick+PAST was predicted, and thus also computed and compared to the actual representation. Thus, the ERP reflects the computation of both the observed as well as the expected representation. According to Dual Route, the process of recognizing the irregular verb error is akin to recognizing that a wrong word has been used, not that a wrong rule has produced that word. This in turn triggers lexical lookup of an alternative word form. The N400 effect indexes the continued search process for the lexical item . On the other hand, the ERP response linked to application of the ‘wrong” rule is the LAN.

One could conceivably argue that a present tense verb cannot say anything about which process produced its past tense version. If so, the underlying parsing theory must also be different. In this case, encountering ‘kick’ when ‘kicked’ was expected, or ‘give’ when ‘gave’ was expected, should then not activate any inflectional or lexical look-up processing at all. This would seem to imply a morphological theory where present tense is interpreted as a function of encountering an atomic phonological representation (modulo 3rd person singular agreement -s)—i.e., absence of inflection is interpreted as “present”. In this model, only “positively inflected" past tense verbs would differentiate between regulars and irregulars.

2. Method

2.1 Experimental design and planned comparisons

The study was designed to set up contextual tense expectations by introducing sentences with a time adverbial, generating an expectation for either a past or a present tense verb. In Experiment 1, replicating the design of Newman et al. (2007), but with spoken utterances, the adverb was "Yesterday". In this experiment that present tense verb is incongruent ("Yesterday, I walk to school"). In Experiment 2, we reversed this relationship by using the adverb "now.". As a result, the past tense is incongruent ("Now, I walked to school"). In addition, we compared regular versus irregular verbs. Violations of tense for regular verbs were hypothesized to elicit a LAN response. In contrast, violation of tense for irregular verbs was hypothesized to generate an N400 effect.

In addition, note that Newman et al. (2007) contained a confound in the comparison of past and present tense because a difference in tense correlated with a difference in grammaticality. Specifically, "Yesterday, I ate a banana" vs. "Yesterday, I eat a banana" differ not only in grammaticality but also (necessarily) in morphology. As a result, an ERP difference could reflect this difference in morphology rather than grammaticality. To examine ERP differences related to morphology alone, we added a condition by removing the adverb from the sentences to examine this possibility, for example, comparing "I ate a banana" to "I eat a banana," for both regular and irregular verbs. This part of the experiment was designed to help interpret the results of sentences including adverbs. Finally, the study design included one between-subject variable: Adverb Tense (past vs. present) (Experiment 1, "yesterday" vs. Experiment 2, "now"). In addition, Adverb-present. vs Adverb-absent, Verb type (regular vs. irregular) and Verb tense (past vs. present) were the within-subject variables, resulting in a mixed factorial repeated measures design, as shown in Table 1:

Adverb tense (between)	Adverb	Verb type	Verb tense	Congruency	Example stimulus	Total
now (present)	**with adverb**	irregular	**past**	incongruent	Now, I ate a banana	40
			present	congruent	Now, I eat a banana	40
		regular	**past**	incongruent	Now, I walked to school	40
			present	congruent	Now, I walk to school	40
	with adverb Total					**160**
	without adverb	irregular	**past**	congruent	I ate a banana	40
			present	congruent	I eat a banana	40
		regular	**past**	congruent	I walked to school	40
			present	congruent	I walk to school	40
	without adverb Total					**160**
now (present) Total						**320**
yesterday (past)	**with adverb**	irregular	**past**	congruent	Yesterday, I ate a banana	56
			present	incongruent	Yesterday, I eat a banana	56
		regular	**past**	congruent	Yesterday, I walked to school	56
			present	incongruent	Yesterday, I walk to school	56
	with adverb Total					**224**
	without adverb	irregular	**past**	congruent	I ate a banana	56
			present	congruent	I eat a banana	56
		regular	**past**	congruent	I walked to school	56
			present	congruent	I walk to school	56
	without adverb Total					**224**
yesterday (past) Total						**448**

Table 1: Design structure of the overall study, showing examples sentences and number of trials.

This design allowed us to examine three questions:

(a) Do regular and irregular verbs elicit distinct ERP responses to unexpected tense?

This is the key question of the study and can be addressed by examining the interaction between tense congruency and verb type. By tense congruency we mean whether the verb tense (past or present) is unexpected for a particular stimulus sentence, more specifically, when there is a mismatch between the implied tense of a time adverb and the tense on the verb, as in “Yesterday, I eat a banana”, or “Now, I sat in a chair”. For this question, The Dual Route theory predicts that irregulars should elicit an N400 effect whereas regulars should elicit a LAN effect. The Full Decomposition theory predicts that both verb types should elicit a LAN effect, consistent with a model of rule computation. It is also possible that the two different verb types will elicit additional ERP patterns related to grammaticality, such as the P600. We do not examine the P600 because presence or absence of this effect has no bearing on whether regular and irregular inflected verbs are processed by different mechanisms; rather, P600 is related to general ungrammaticality recognition or parsing difficulties as a result of ungrammaticality.

For statistical testing, we constructed a difference wave for each verb type, subtracting the congruent from the incongruent case in the two groups for each experiment (Now and Yesterday (Yest) (i.e., Now-irregular difference wave = Now-irregular past minus Now-irregular present; Now-regular difference wave = Now-regular past minus Now-regular present; Yest-irregular difference wave = Yest- irregular past minus Yest-irregular present; Yest-regular difference wave =Yest- regular past minus Yest-regular present,). In this way, the combined data set from both experiment contained two difference waves (regular-diff and irregular-diff), and each participant was labeled according to their group using the independent variable label "adverb tense", which was either 'past' (the "yesterday" group) or 'present' (the "now" group). With these two difference waves as dependent, within-subject measures, the Dual Route question can be answered by examining the main effect of verb type. Note that the between-subject group factor does not enter this analysis; it remains an unanalyzed fixed factor.

The second question addressed in the current study, which formed the motivation for Experiment 2, was whether this paradigm taps into two different inflectional processes independently of which tense is encountered. Newman et al. (2007) used *present* tense as ungrammatical, not past tense. One could argue that the difference between rule-based inflection and lexicalized inflection is only measurable when the *past* tense is unexpected, because only past tense is the overtly inflected form. When present tense is used incorrectly, it has no "overt" inflection done to it; raising the question of whether this triggers a rule computation or lexical computation at all.

(b) Does unexpected present tense result in the same ERP as unexpected past tense?

Note that this question hides a theoretical assumption, namely that present tense is in a sense an “uninflected” form. This therefore becomes another way to test abstract morpho-syntactic operations and is part of the current study by the introduction of another independent variable: direction of prediction. I.e., is there an interaction between tense and the incongruency effect, such that the ERP response to present tense as incongruent differ from the ERP response to past tense as incongruent? If only past tense taps into the potential difference between regulars and irregulars, then we should observe such an interaction: we should only observe the critical pattern when the adverb generates expectations of present tense but a past tense verb is encountered instead. If there is no interaction, then the assumptions in (Newman et al., 2007) were correct; namely that encountering an unexpected present tense where past is expected also triggers processes that tap into the rule vs. lexical look-up distinction. Using difference waves as dependent measure allows us to normalize the laboratory differences in absolute voltage deflections and focus on the experimental effect. In the statistics, the question is then whether there is a main effect of congruency in a verb type X tense prediction ANOVA.

As a final question, we asked what the global, main effect of an unexpected verb is, computed by the mean brain response to adverb-less past and present tense sentences including the congruent sentences with adverbs, and compared that mean to the incongruent (fewer) stimulus sentences with adverbs, we can ask one final question:

(c) What is the overall, global effect of tense (un)-expectancy?

We planned to conduct this analysis to determine what the overall mean ERP effect is to a grammatical vs ungrammatical (or unexpected) verb tense, irrespective .

2.3 Materials

For Experiment 1, the stimulus sentences were auditory (recorded by a female speaker) rather than written, in contrast to all previous studies we are aware of. Most of the sentences were identical to those used in Newman et. al. (2007), but a small number was replaced with higher frequency verb forms (because we intended to also use the sentences in a study with children). Fifty-six regular verbs and 56 irregular verbs (all monosyllabic) were used in 112 simple declarative sentence structures.[4] For each verb, four sentences were constructed by varying two conditions: whether the verb was in the past tense or present tense, and whether the sentence was preceded by “Yesterday” (the past tense context”) or by nothing (the null context). The resulting 448 sentences constituted a 2 (past vs. null context) x 2 (past vs. present tense) x 2 (irregular vs. regular) design of within-subject factors (group 1 in Table 1).

The sentences were recorded by a female speaker at a moderately slow speech rate, using 16-bit resolution and 22kHz sampling frequency. The sentences were carefully enunciated with released final consonants to minimize coarticulation cues. This allowed verbs to be spliced into

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[4]We thank Michael Ullman for sharing the stimuli materials of Newman et al. (2007) with us.

the same sentence frames and to sound natural. Pauses of approximately 100 ms were maintained before and after each word, as shown in Figure 1. As a result, past and present verb pairs were presented in the identical context.

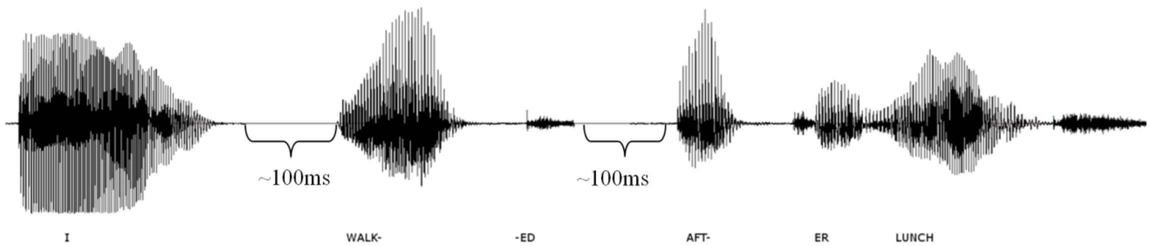

Figure 1: An auditory stimulus, with 100ms silence before and after the verb.

A pause of 300 ms was inserted after the initial adverb "Yesterday". Several different prosodic variants of "Yesterday" were recorded and used so that the sentences sounded more natural across the duration of the experiment. All 448 sentences from the two context conditions were presented in a single experimental session, resulting in 1:4 ratio of incongruent to congruent sentences.

The stimulus material and design for Experiment 2 were identical to that of Experiment 1, except the adverb "Yesterday" was randomly replaced with 15 different recordings of the adverb "Now". In addition, a subset of the stimuli were removed from the stimuli used in Experiment 1 in order to make Experiment 2 shorter, as it was planned to be replicated with young children; 18 stimuli were removed, resulting in a total of 40 verbs in each condition, for a total of 320 trials (see Appendices for details). Four lists of stimulus sentences were constructed, such that each verb occurred only once in each list. In each list, a verb would occur in one of the four possible combinations of tense and context. The order of sentences was pseudo-randomized within each list. Regular and irregular verbs and grammatical and ungrammatical sentences from the two context conditions were counter-balanced across the lists. All subjects heard the stimuli in the same order. A set of six sentences were initially presented to train the subjects in the task. The four lists of trials were then presented successively, with eight blocks of trials within each list (e.g. 14 in Experiment 1). Each block was followed by a brief pause, and each list of sentences was followed by a longer break.

2.4 Participants

The study was conducted as two separate experiments. Thirty participants (15 men and 15 women) were recruited for Experiment 1 in Manhattan via an internet bulletin board for volunteering. All participants gave informed consent and were reimbursed $10/hour for participation. After data collection, three participants were excluded because of experimenter errors. According to recording standards for ERPs (Picton et al., 2000), participants with more than a third of the trials lost to artifact may become difficult to interpret. Based on this criterion, two additional participants were excluded who had 80% and 58% loss of trials respectively. The remaining 25 participants (13 women and 12 men) had a mean age of 31 years (SD = 6.8, range 20 - 50). All were native speakers of English, with no knowledge of a second language before the age of 7 years. All reported normal hearing and normal to corrected vision, and no history of neurological impairments. One participant was lefthanded. The study was approved by the CUNY Internal Review Board.

For Experiment 2, thirty-three undergraduate students (28 women) were recruited at the University of Delaware and participated in exchange for course credit. All participants gave informed consent. Two participants were excluded because of more than a third of trials were lost to artifacts. The remaining 31 participants had a mean age of 18.8 years (SD = 1.3; range 18

- 25). Five participants were left-handed. Only 5 of the participants were male, a consequence of our sampling population being overwhelmingly female. For this reason, we tested the effect of sex in Experiment 1, where this property was balanced; no effects were found. All participants reported English as their first language, and no history of speech-language impairments. The study was approved by the Human Subjects Review Board at the University of Delaware.

2.5 Procedures

The procedure for Experiment 1 and Experiment 2 were identical. Participants were seated in an electrically shielded International Acoustics Company audiometric booth, with a PST Serial Response Box placed in front of them on a tabletop. Each stimulus sentence was presented auditorily via two speakers. In Experiment 1, one speaker was placed in front of the subject and one placed behind. In Experiment 2, two speakers were placed in front of the subject. A single trial was introduced by the sound of a tone, followed by a 300 ms pause, followed again by auditory presentation of the sentence. Upon completion of the verb in the sentence, a 1000 ms pause ensued. After this pause, the response box buttons would light up, followed by a 2000 ms response window. The purpose of this delayed response window was to prevent subjects from responding prematurely during the processing of the verb itself, as well as to prevent subjects from responding during the period after the verb during in which the ERPs of interest were measured. Subjects were instructed to press “button 1” if the sentence was about something in the present; “button 2” if the sentence was about something in the past, or “button 3” if the sentence didn’t make sense or was ungrammatical. All subjects used the right hand to respond. The subjects received no other visual input than the button box lights. After the subject responded (or timed out), a 1500 ms pause followed before the next trial. The entire recording session took between 1.5 and 2 hours.

2.6 Apparatus and EEG acquisition

Stimulus presentation and experimental control was programmed in E-Prime (Schneider, Eschman, & Zuccolotto, 2002) using the Netstation Biological Add-Ons. Accuracy and reaction time of the behavioral responses were recorded by E-Prime on a PC. In Experiment 1, EEG data was collected using an Electrical Geodesics 200 system, with a 65 channel Geodesic Sensor Net with silver/silver-chloride (Ag/AgCL) plated electrodes contained in electrolyte-wetted sponges. In Experiment 2, EEG was collected with an Electrical Geodesics 300 system, using a 128 channel Hydrocel Geodesic Sensor Net with silver chloride-plated carbon-fiber electrodes in electrolyte-wetted sponges. For both experiments, impedances were kept below 60 kOhm, which is appropriate for high-impedance amplifiers (Ferree, Luu, Russell, & Tucker, 2001). In both experiments, EEG was sampled at 250 Hz and referenced to Cz online. In Experiment 1, EEG was on-line band-pass filtered between 0.1-30.3 Hz during the recording. In Experiment 2, the EEG was on-line lowpass filtered below 100 Hz. Offline, the continuous EEG was then high-band-lass filtered between 0.1 Hz and 30 Hz using Netstation software before epoching.

2.7 EEG epochs, artifact correction and data consolidation

After recording and filtering, the continuous EEG was divided into epochs containing the verb and the following sentence material for each trial. We used two different epoching schemes: (a) by time-locking the ERP to the onset of the verb, and (b) by time-locking the ERP to the offset of the verb. The purpose was to examine whether the time course of the ERP response differed for irregular verbs and regular verbs, because the phonetic signal for tense in irregulars compared to regulars occurs earlier in the phoneme string, at vowel onset (and with coarticulation, even during the consonant frication or burst, see Mann & Repp, 1980). For offset time-locking, we used a 1000 ms epoch after verb offset, to allow measurement of a possible P600[7].The mean duration of regular verbs was 548 ms (SD=89 ms), whereas the mean duration of irregular verbs was 513 ms (SD = 95 ms). Thus, the response after the verb could be captured by about 1000 ms of EEG.

All the single trial data were then submitted to an automatic artifact correction procedure using the ERP PCA toolbox (Dien, 2010), which subtracted components related to eyeblinks, saccades and eye movement based on Independent Component Analysis. In addition, bad channels were corrected and bad trials removed, as follows: A channel in a single recording was marked as a bad channel if the fast average amplitude exceeded 200 μV, if the differential amplitude exceeded 100 μV, or if it had zero variance. Bad channels were deleted and replaced with data using the spherical spline interpolation. A trial was marked for exclusion from single subject averages if it contained more than 10 bad channels, or if it contained lateral eye movements or eye-blinks. Each epoch was then baseline corrected relative to a 200 ms baseline period, and the average for each condition per subject was computed.

The data from Experiment 2 were then remapped to the same 65 channel montage as used in Experiment 1, by interpolating the values of surrounding electrodes to estimate the corresponding voltage per channel in a 65 channel montage, using the EP tool software. The resulting averages per subject were then baseline corrected and re-referenced to the average voltage. The data were coded with adverb tense (past vs. present) as a group-level between-

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[7] We also conducted analysis of the data time-locked to verb onset, using a 1400 ms epoch from onset, plus a 200 ms baseline period (totaling 1600ms). No difference in results was observed.

subject variable, and the 8 within-subject cells for each participant derived from Table 1 above (i.e. adverb vs. no adverb, past vs. present tense, and regular vs. irregular verb type).

Following publication standards (Picton et al., 2000), three subjects in Experiment 1 and two subjects in Experiment 2 were excluded because they lost greater than one-third of the total trials to artifact rejection. After artifact correction and eyeblink subtraction, participants in Experiment 1 had on average 53 good trials out of 56 per cell, while participants in Experiment 2 had on average 37 good trials out of 40 trials per cell.

2.8 ERP dimensionality reduction

Our general approach to ERP analysis is two-step: We start with (i) temporo-spatial PCA factor decomposition (Dien, 2010, 2012; Dien & Frishkoff, 2005), followed by (ii) factor-constrained selection of combined time/space-regions (to be explained in more detail below). The PCA conducts dimensionality reduction and variance-partitioning prior to statistical analysis, and thus removes time factors and electrode factors from the ANOVA. The effect is simplifying statistical analysis to a single mean voltage measure per participant and cell for each component (LAN and N400). This approach is one of several solutions for reducing multiple comparison problems and experimenter bias, as recommended by Luck and Gaspelin (2017); the same point is made by (Dien, 2010), p. 143.

All data analyses of tense expectancy violations were conducted with difference waves representing the key contrasts. In order to have a uniform representation of incongruency, the subtraction was done differently for the two tenses: the congruous tense was always subtracted from the incongruous tense (which could be either past=present or present-past, depending on adverb). The general PCA procedure was the following: First, a temporal PCA was conducted on a matrix where each column represented a time sample, and rows represented a nesting of participants, cells, and electrodes. Using the Parallel test (Horn, 1965), the initial temporal PCA factor solution was pruned to a smaller set of factors accounting for more than random variance. In the next step, the same procedure was used to conduct spatial ICA (Bell & Sejnowski, 1995) for each temporal factor, by having electrodes as columns and participants, cells, and temporal factors as rows. Only combined temporal-spatial factors where the initial temporal factor accounted for at least 5% of the total variance were interpreted, and only the first/primary spatial subfactor within each temporal factor was interpreted as representing an ERP response.

The ERP factors thus identified formed an objecting method for selecting time windows and electrode regions in the undecomposed voltage data. A time window was defined by factor loadings above 0.6, and an electrode region was similarly defined as electrodes with spatial factor loadings above 0.6 (a decision criterion that has the effect of only including relatively highly weighted time samples and electrodes within a factor). However, because the factor scores represent weighted means of all time samples and all electrodes for a given ERP factor, we also used the factor scores as dependent measures in the same ANOVA, for checking convergence between latent factors and observed surface voltage fluctuations.

3. Results

3.1 Preliminary analysis of pure present vs. past tense contrast

Before addressing the main purpose of the study, we first address a question not raised in Newman et al., (2007), nor in previous ERP studies of regular vs. irregular inflection: Is there a different ERP pattern for past compared to present tense, in the absence of expectancy manipulations with the adverb, “yesterday” ? It is conceivable that when the parser is exposed to a verb with inflectional morphology, that processes related to rule application is triggered, leading to an ERP effect with the same timing and topography as the LAN. If so, this would confound any interpretation of a LAN triggered by incongruity.

We addressed this question by presenting participants with the same stimuli sentences but without an adverb, i.e., “I walk to the store” vs. “I walked to the store”, in a 2 (regular vs. irregular) x 2 (present vs. past tense) design. The data were analyzed by an exploratory temporo-spatial PCA/ICA analysis of the difference wave for each verb type, i.e., regular past tense minus regular present tense, and irregular past tense minus irregular present tense.

The input to the initial PCA was a matrix with time samples as columns, and participants (with laboratory/adverb group as a between-subject variable), cells and electrodes nested as rows. The initial temporal PCA solution was conducted on the covariance matrix and rotated to simple structure using Promax (Kaiser loading weighting, rotation option 3),

The temporal PCA reduced the dimensionality to 23 temporal factor using the Parallel test (Dien, 2020; Horn, 1965). The spatial PCA (on the 23 temporal factors) resulted in retention of seven factors, using the Parallel test. Of the 23 temporal factors, only TF1: 26%, TF2: 16%, and TF3: 14% accounted for greater than 5% of the variance. The1st spatial factor of each of these three temporal factors was retained for the following analysis,. For inferential statistical analysis, the factor scores per participant, cell and factor (representing a weighted difference score of all electrodes and all time samples for the given factor) for the two verb types was used as dependent measures in a one-factor ANOVA testing for significance of the intercept (i.e., whether the difference score was significantly different from zero) and a main effect of verb type (regular vs. irregular verbs, interpretable as the interaction between verb type and tense). No significant differences or interactions were observed between verb types for the three factors)TF1SF1, TF2SF1TF3SF1) (F < xxx; p > .1)

3.2 ERP responses for regulars vs. irregular verbs, and direction of tense prediction

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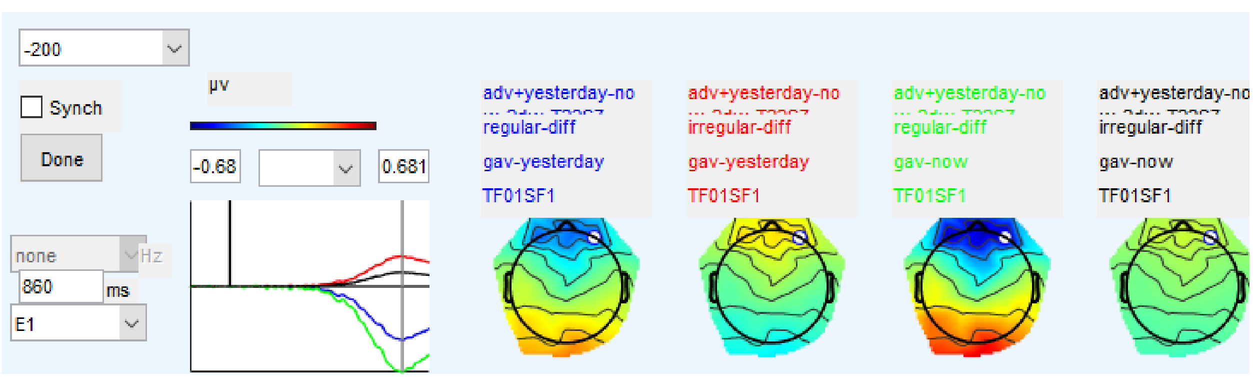
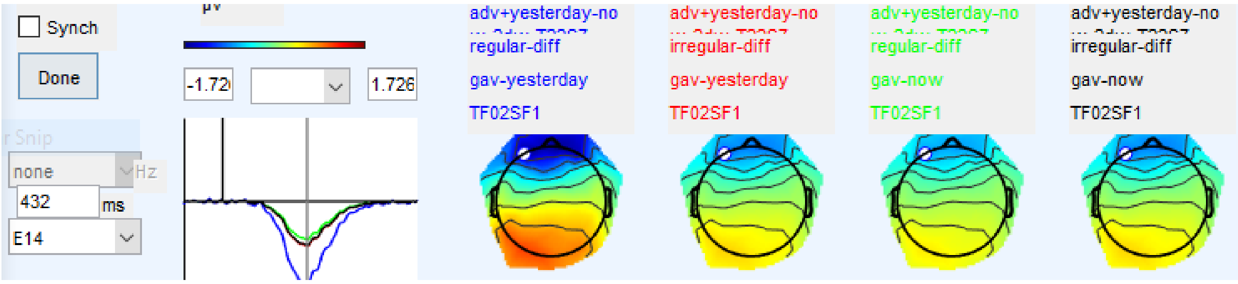
The first four initial temporal factors each accounted for at least 5% variance: TF1 (peak latency 860 ms, positive peak polarity at E63) accounted for 30% of the variance, TF2 (peak latency 432 ms, negative peak polarity at E11) for 20% variance, TF3 (peak latency 184 ms, negative peak polarity at E11) for 8% of the variance, and TF4 (peak latency 632 ms, positive peak polarity at E38) Figure 2 illustrates the timing and topography of each component for each condition (adverb and verb type)

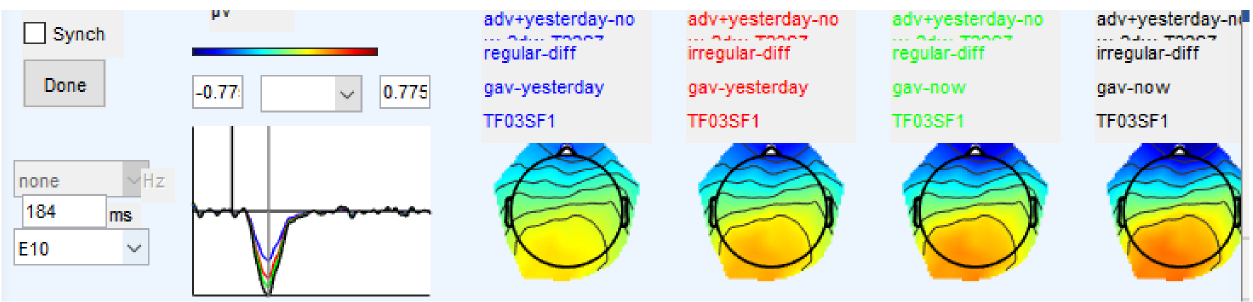
TF01SF1 (860ms)



TF02SF1 (432ms)



TF03SF1 (184ms)



TF04SF1 (632ms)

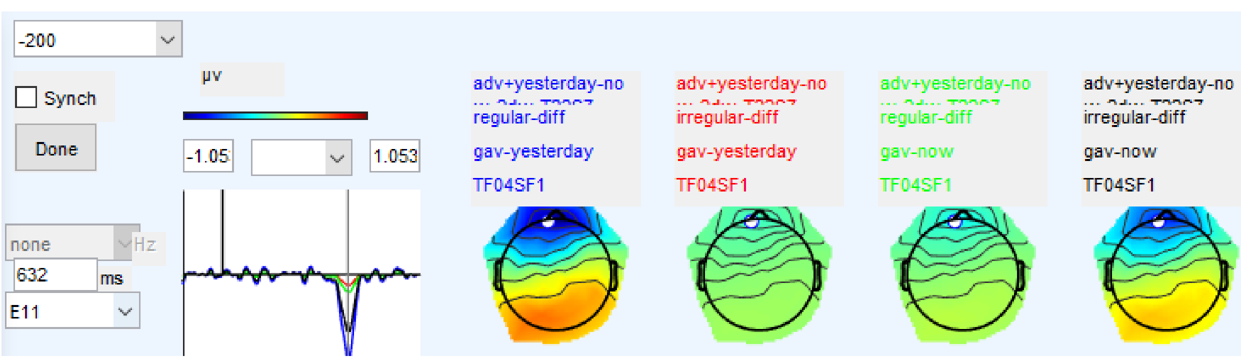


Figure: 4 primary temporo-spatial responses, by verb type (regular/irregular) and direction of tense prediction (yesterday vs. now)

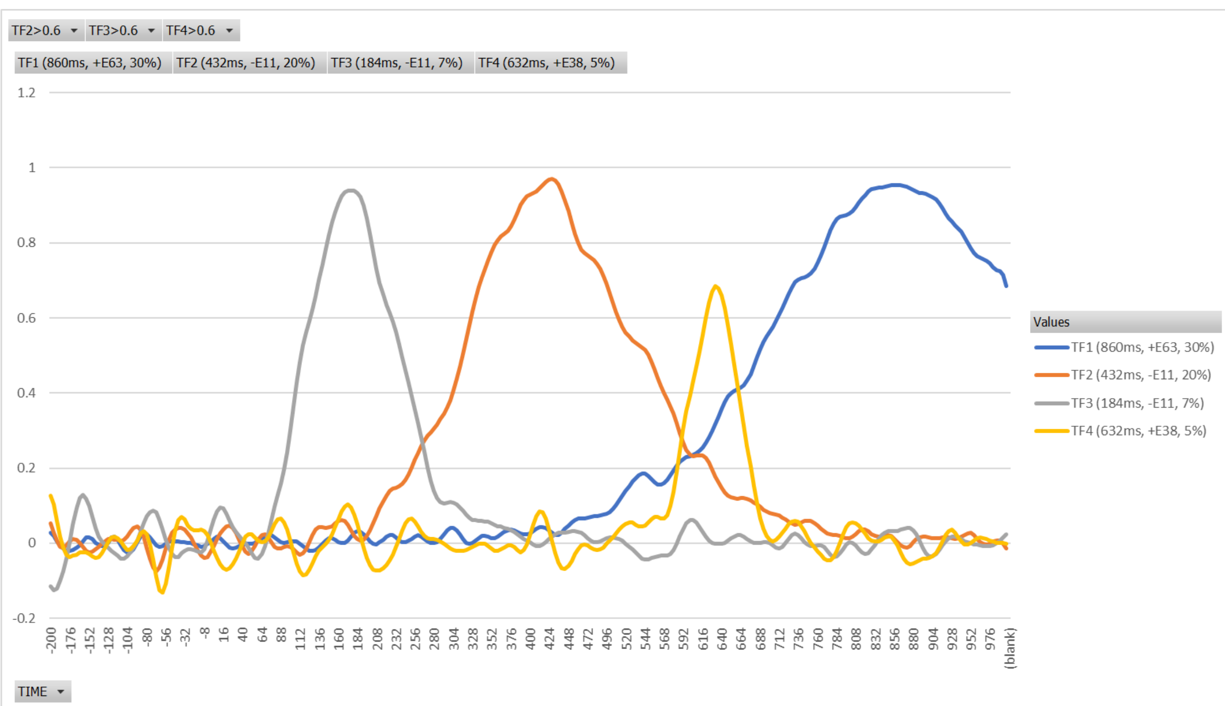
The results of the 2 x 2 ANOVA (adverb, verb type) are summarized in Table X below, with effect sizes reported as partial η^2:

Temporo-spatial brain response	Main effect of incongruency (intercept)	Main effect of direction of prediction (adverb tense)	Main effect of verb type (=congruency X verb type)	Verb type X prediction direction
ERP 1 (TF01SF1, 860 ms)	$F(1,54) = 0.7$, $p = 0.4$, $\eta^2 = 0.01$	$F(1,54) = 0.18$, $p = 0.67$, $\eta^2 = 0.003$	$F(1,54) = 2.27$, $p = 0.13$, $\eta^2 = 0.04$	$F(1,54) = 0.1$, $p = 0.89$, $\eta^2 = 0.0003$
ERP 2 (TF02SF1, 432 ms)	$F(1,54) = 18.9$, $p = 0.00005$, $\eta^2 = 0.26$	$F(1,54) = 0.9$, $p = 0.34$, $\eta^2 = 0.01$	$F(1,54) = 0.52$, $p = 0.47$, $\eta^2 = 0.009$	$F(1,54) = 0.95$, $p = 0.33$, $\eta^2 = 0.017$
ERP 3 (TF03SF1, 184 ms)	$F(1,54) = 7.7$, $p = 0.007$, $\eta^2 = 0.12$	$F(1,54) = 0.2$, $p = 0.65$, $\eta^2 = 0.003$	$F(1,54) = 0.08$, $p = 0.77$, $\eta^2 = 0.001$	$F(1,54) = 0.008$, $p = 0.92$, $\eta^2 = 0.0001$
ERP 4 (TF04SF1, 632 ms)	$F(1,54) = 6.9$, $p = 0.01$, $\eta^2 = 0.11$	$F(1,54) = 0.08$, $p = 0.76$, $\eta^2 = 0.001$	$F(1,54) = 0.32$, $p = 0.57$, $\eta^2 = 0.005$	$F(1,54) = 3.5$, $p = 0.06$, $\eta^2 = 0.06$

Table XY: Statistical results for the factors scores.

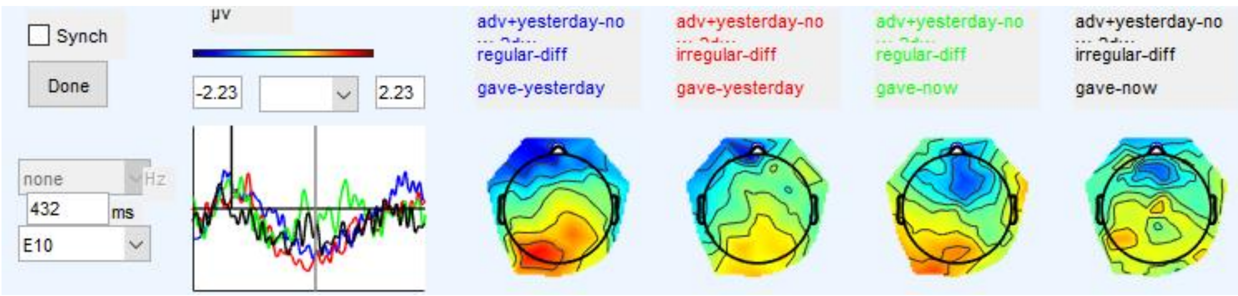
As is shown in Table XY, only factors 2, 3 and 4 exhibited significant intercepts, representing the main effect of incongruency. None of these factors exhibited a main effect of verb type, of prediction direction, or interaction between the two, although the interaction for Factor 4, at 632 ms approached significance.

We next used the information from the factor loadings in time and space to constrain selection of temporal and spatial "regions of interest" in the corresponding voltage values of the unweighted voltage distribution on the scalp. This was done by only including time samples, for a given factor, that exceeded 0.6 in factor loadings (an arbitrary decision threshold suggested by (Dien, 2010), designed to only include those time samples that exerted a strong contribution to the factor). Figure Z shows the factor loadings over time for each of the analyzed temporal factors.



Next, we used the same decision threshold to select peak electrodes from the related ICA factor, to construct an electrode region for each time window. We limit illustration here to the three factors with significant effects:

ERP 2 (based on TF02SF1, 432ms; time-window 324-512ms) + show which electrodes!



ERP 3 (based on TF03SF1, 184ms; time-window 124-228ms) + show which electrodes!

ERP 4 (based on TF04SF, 632ms; time-window 620-648ms)

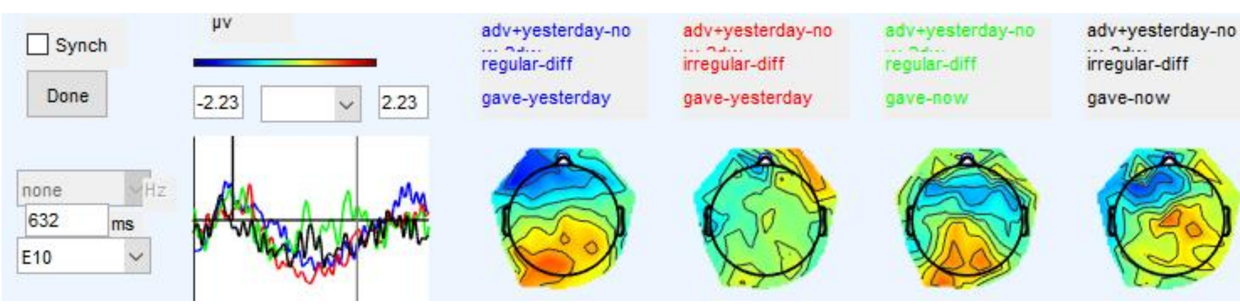


Figure XYZ. Topography plots at the peak latency for the difference wave data. The maps less uniform across condition because …

The mean voltage for the combined time window and electrode region was then calculated for each participant and cell, and used as a dependent measure in the same 2 x 2 ANOVA as above; the results are given in the Table below:

Temporo-spatial brain response	Intercept (incongruency)	Main effect of group	Main effect of verb type	Verb type X group
ERP 1: 708-996ms (based on TF01SF1)	$F(1,54)=0.01$, $p=0.9$, $\eta^2=0.0002$	$F(1,54)=0.07$, $p=0.78$, $\eta^2=0.001$	$F(1,54)=1.07$, $p=0.3$, $\eta^2=0.01$	$F(1,54)=0.14$, $p=0.7$, $\eta^2=0.002$
ERP 2: 324-512ms (based on TF02SF1)	$F(1,54)=11.6$, $p=0.001$, $\eta^2=0.17$	$F(1,54)=0.95$, $p=0.33$, $\eta^2=0.017$	$F(1,54)=0.006$, $p=0.93$, $\eta^2=0.0001$	$F(1,54)=1.57$, $p=0.21$, $\eta^2=0.028$
ERP 3: 124-228ms (based on TF03SF1)	$F(1,54)=4.97$, $p=0.029$, $\eta^2=0.08$	$F(1,54)=0.43$, $p=0.51$, $\eta^2=0.008$	$F(1,54)=0.71$, $p=0.40$, $\eta^2=0.013$	$F(1,54)=0.02$, $p=0.86$, $\eta^2=0.0005$
ERP 4: 620-648ms (based on TF04SF1)	$F(1,54)=7.95$, $p=0.006$, $\eta^2=0.12$	$F(1,54)=0.09$, $p=0.76$, $\eta^2=0.001$	$F(1,54)=0.30$, $p=0.58$, $\eta^2=0.14$	$F(1,54)=2.18$, $p=0.14$, $\eta^2=0.03$

Table Z: Statistics for the voltage ERPs

As can be seen, the temporo-spatial PCA/ICA factors and the related voltage ERPs converged in their statistical significance, which increases confidence in the combined solution. The largest effect size was observed for ERP 2, with a time window of 324-512 ms. This is the typical time range for morphosyntactic LAN responses and is interpretable as the LAN.

3.3 Pooled data, main effect of congruency and verb type

Finally, we combined all the data into a single analysis of congruency by verb type, to take advantage of the statistical power afforded by the entire data set. This is possible because the stimulus sentences without a temporal adverb can be considered not incongruent, i.e., the tense in a simple declarative sentence comes with no presupposition and is therefore neither expected nor unexpected. In this analysis, we analyzed the data in a 2 (verbtype) x 2 (congruency) design, by collapsing all congruent and incongruent trials as illustrated in Table ZZ below:

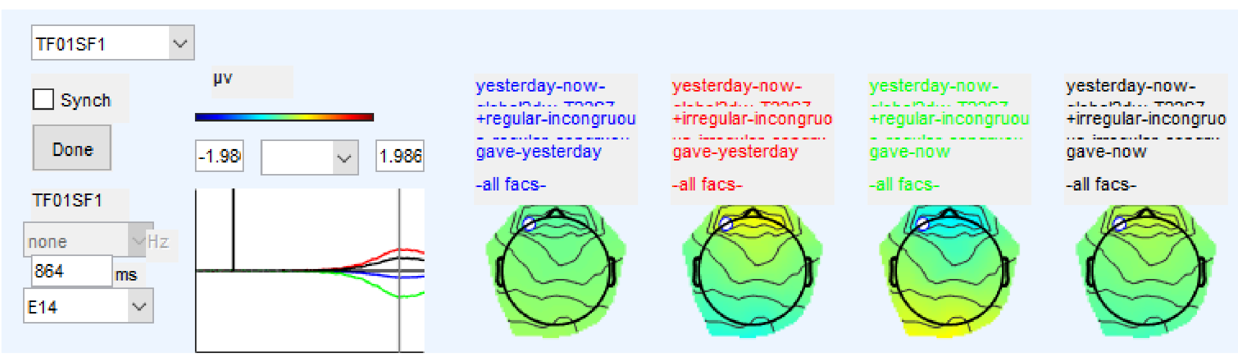
CONGRUENCY	VERB TYPE	ADVERB TENSE	example stimulus	Total
congruent	**irregular**	past (group 1)	I ate a sandwhich	56
			I eat a sandwhich	56
			Yesterday, I ate a sandwhich	56
		present (group 2)	I ate a sandwhich	40
			I eat a sandwhich	40
			Now, I eat a sandwhich	40
	regular	past (group 1)	I walk to school	56
			I walked to school	56
			Yesterday, I walked to school	56
		present (group 2)	I walk to school	40
			I walked to school	40
			Now, I walk to school	40
INCONGRUENT	**irregular**	past (group 1)	Yesterday, I eat a sandwhich	56
		present (group 2)	Now, I ate a sandwhich	40
	regular	past (group 1)	Yesterday, I walk to school	56
		present (group 2)	Now, I walked to school	40

Table ZZ

Incongruency difference waves were computed as incongruous minus congruous (so past minus present for group 2/now participants, and present minus past for group 1/yesterday participants), resulting in two incongruous waves (regular incongruity and irregular incongruity) and two congruous waves (regular congruous and regular incongruous). Two difference waves were constructed (incongruous minus congruous for each verb type) and used as dependent measures in the next processing step.

Following our data analysis procedures, the two difference waves were submitted to a temporo-spatial PCA/ICA analysis. The initial temporal PCA retained 22 factors, followed by 7 spatial factors for each temporal factor. The first four temporal factors met the criterion of accounting for at least 5% variance, and the primary (first) spatial factor in each was selected for statistical analysis. The results (unsurprisingly) pattern with the above, except providing higher statistical precision due to the larger set of trials that went into it. Figure YYY below shows each factor ERP by verb type and participant group/laboratory (to test the assumption that there was no interaction with laboratory):

ERP 1 (TF1 864ms, %variance, SF1)



ERP 2 (TF2 SF1 332ms

ERP 3 (TF3SF1 592ms

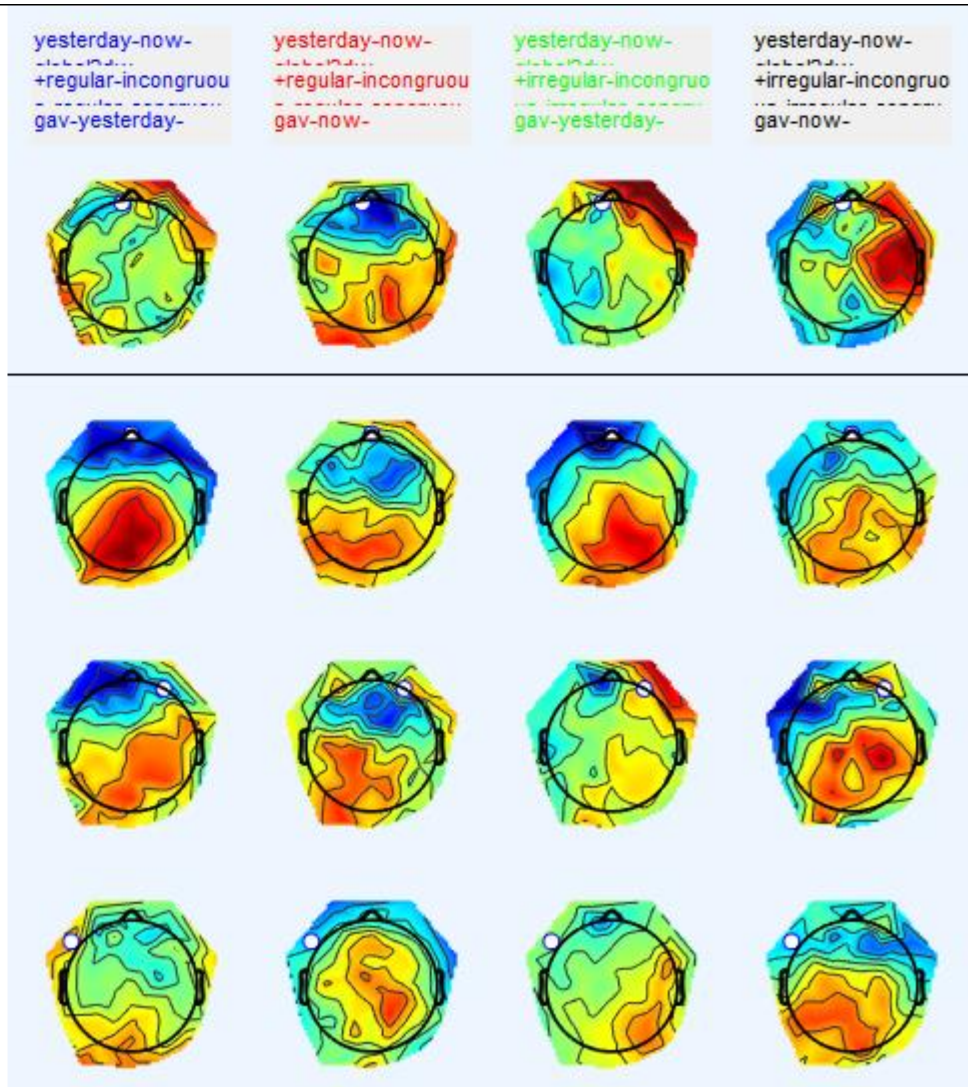
ERP 4 (TF4SF1, 140ms, % variance)

The factor scores for each factor were submitted to a 2 x 2 ANVOA (verb type X group). Temporal factors 2, 3 and 4 contained significant main effects of congruence, and no other main effects or interactions.

Temporo-spatial brain response	Intercept (incongruency)	Main effect of group	Main effect of verb type	Verb type X group
ERP 1 TF01SF1, 864ms	F(1,54)=0.001, p=0.91, η^2=0.00001	F(1,54)=0.49, p=0.48, η^2=0.009	F(1,54)=4.49, p=0.03, η^2=0.07	F(1,54)=0.12, p=0.72, η^2=0.002
ERP 2 TF02SF1, 332ms	F(1,54)=16.2, p=0.0001, η^2=0.23	F(1,54)=0.9, p=0.34, η^2=0.01	F(1,54)=0.18, p=0.66, η^2=0.003	F(1,54)=0.74, p=0.39, η^2=0.01
ERP 3 TF03SF1, 592ms	F(1,54)=8.93, p=0.004, η^2=0.14	F(1,54)=0.36, p=0.54, η^2=0.006	F(1,54)=0.76, p=0.38, η^2=0.01	F(1,54)=0.75, p=0.38, η^2=0.01
ERP 4 TF04SF1, 140ms	F(1,54)=7.8, p=0.007, η^2=0.12	F(1,54)=0.33, p=0.56, η^2=0.006	F(1,54)=0.008, p=0.92, η^2=0.0001	F(1,54)=0.64, p=0.42, η^2=0.01

As expected, the temporal properties of the factors coincide with the above analysis (except TF3 and TF4 switched order), as it contains half the same data, with the addition of the sentences repeated without the time adverbs.

Following our approach to data analysis, we then constructed time windows and electrode regions for these three ERPs and calculated the mean difference wave voltages for the PCA-constrained time/space regions. These means were analyzed with the same ANOVA as above for convergence. The figure below shows the verb type difference topoplot for each group at the peak latency of the factors (in the order TF1-TF2-TF3-TF4):

Peak latency of factor	Mean voltage of difference scores for each verb type, by group			
	regular/yesterday	regular/now	irregular/yesterday	irregular/now
ERP 1 TF01SF1, 864 ms				
ERP 2 TF02SF1, 332 ms				
ERP 3 TF03SF1, 592 ms				
ERP 4 TF04SF1, 140 ms				

The following table shows the inferential statistics for each ERP:

Temporo-spatial brain response	Main effect of incongruency (intercept)	Main effect of group (adverb tense prediction)	Main effect of verb type	Verb type X group
ERP 1: 756-996ms (based on TF01SF1)	$F(1,54)=0.07$, $p=0.78$, $\eta^2=0.001$	$F(1,54)=0.09$, $p=0.76$, $\eta^2=0.001$	$F(1,54)=4.42$, $p=0.04$, $\eta^2=0.07$	$F(1,54)=0.2$, $p=0.64$, $\eta^2=0.003$
ERP 2: 256-420ms (based on TF02SF1)	$F(1,54)=10.7$, $p=001$, $\eta^2=0.16$	$F(1,54)=2.1$, $p=0.14$, $\eta^2=0.03$	$F(1,54)=0.1$, $p=0.74$, $\eta^2=0.001$	$F(1,54)=0.39$, $p=0.53$, $\eta^2=0.007$
ERP 3: 532-644ms (based on TF03SF1)	$F(1,54)=5.8$, $p=0.01$, $\eta^2=0.09$	$F(1,54)=1.3$, $p=0.25$, $\eta^2=0.02$	$F(1,54)=2.6$, $p=0.1$, $\eta^2=0.04$	$F(1,54)=0.61$, $p=0.43$, $\eta^2=0.01$
ERP 4: 104-196ms (based on TF04SF1)	$F(1,54)=5.02$, $p=0.02$, $\eta^2=0.08$	$F(1,54)=0.2$, $p=0.65$, $\eta^2=0.003$	$F(1,54)=0.03$, $p=0.8$, $\eta^2=0.0006$	$F(1,54)=0.16$, $p=0.68$, $\eta^2=0.003$

Figure xxx illustrates the LAN-type effect.

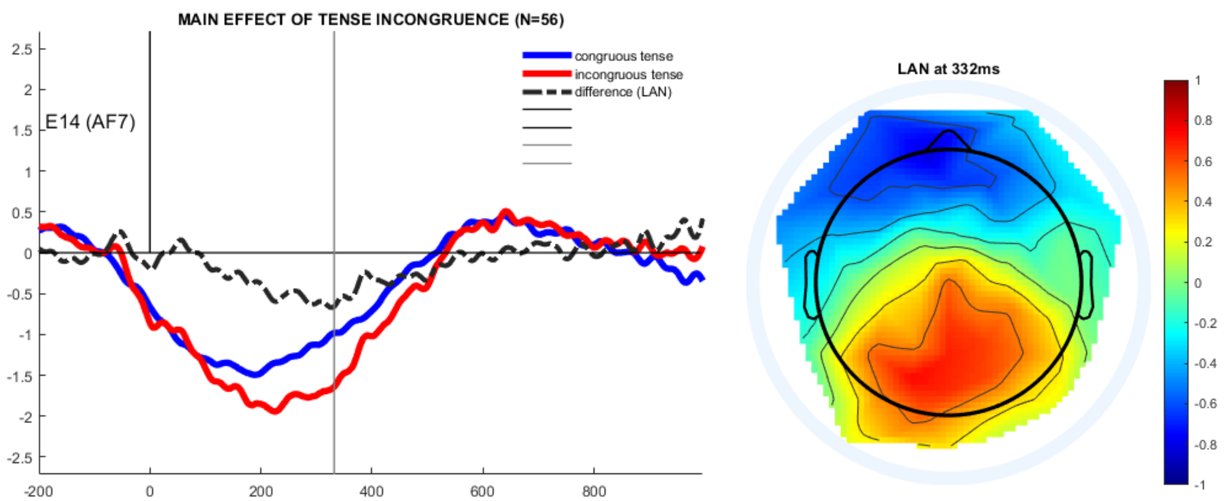


Figure: Main effect left anterior negativity

4. Discussion and conclusion

These experiments used ERPs to test predictions generated from the Dual-Route model regarding processing and representation of regular versus irregular verb forms. The study was designed to extend the Newman et al. (2007) paper by examining processing in the auditory modality. In addition, we manipulated the direction of the tense prediction so that one group heard unexpected present tense verbs, and the other group heard unexpected past tense verbs. This allowed us to determine whether an overtly non-inflected present tense verb elicited a brain response similar to an overtly inflected unexpected tense version of a verb. Second, we tested whether congruous past vs. present tense (sentences without tense-predicting adverbs) showed different ERP patterns related to the morphophonological differences (rather than to ungrammaticality). The latter comparison was undertaken to make sure that any differences observed in the experimental conditions (in which the adverb led to tense incongruity) was not the result of morphophonological differences.

The results show that an anterior negativity in the time range of the LAN observed in other studies is elicited to unexpected tense for both by commission as well as omission errors. This finding provides additional support for the interpretation of regular verb processing offered in Newman et. al. (2007). Specifically, they observed a LAN effect to the non-congruent present-marked regular verbs in the context of "yesterday".

The two studies that have compared errors of commission and omission have observed stronger effects for commission errors, but both these studies focused on children (see Dube et al., 2016), Dube et al., 2018 (Weber, Leonard paper with SLI kids). .Our study may have shown similar effects for omission and commission errors because adults may have solidified their knowledge and processing of tense markers.

Our findings of a LAN effect indicate that encountering a “wrong” present tense generates a computation of what the correct form should be; thus, at some level, adults compute a morphosyntactic feature, whether it results in a phonological element or null element.

In addition, we observed no significant ERP response when incongruous past and present tense was compared, allowing the conclusion that the basic tense difference is not a confound in this and similar experiments, and that the LAN responses we observe must be caused by abstract incongruity of tense between the sentence initial adverb and the verb.

Turning to the result of the primary question asked by the study, both regular and irregular unexpected verbs clearly elicited a series of temporally distinct anterior and/or left-anterior negativities. No N400-like effect was observed for irregular verbs, contrary to the predictions of the Dual Route or Declarative/Procedural Model (Hahne et al., 2006; Pinker & Ullman, 2002b; Ullman, 2004, 2006); rather, both verb types elicited the same, statistically non-distinct LAN response. This can be interpreted as strong support for Single Route Models (Oseki & Marantz, 2020; D E Rumelhart & McClelland, 1986; Stockall & Marantz, 2006a), and more generally, that both regular and irregular verbs are interpreted by the morphological parser as consisting of a stem plus an inflection suffix, whether overt and audible, or silent or null (Pesetsky, 1995). This conclusion does not preclude that processing of irregular verbs activate an additional process of memory retrieval, as the form of a past tense irregular verb must partially or wholly be determined by memorized unique morphophonological forms. Indeed, some studies have observed that irregular verbs activate different and/or additional brain regions during processing (Jaeger et al., 1996). The current experiment did not observe ERP effects reflecting this operation, but that does not mean that such an operation does not exist. Rather, the current experiment was sensitive to the real-time predictions about present versus past tense on the verb, generated by sentence initial time adverbs.

Some previous studies using somewhat similar designs also observed P600 effects following earlier incongruity responses. The current study saw no P600 in the data. This, lack of P600 may be due to the use of simple sentences. P600 is an ERP that reflect conscious recognition of parsing difficulties and attempts to repair and revise the analysis of a sentence (Kaan & Swaab, 2003). While an unexpected tense may rise to the awareness of the participant and lead to additional processes, that by itself provides no information about whether the error was recognized through rule application or lexical access and retrieval—the question posed by the current study. Most likely, P600 responses are related to the particular task that participants had to carry out, which makes it likely that different experiments will see differences with respect to P600, depending on task.

This finding focused on fairly high-frequency verb forms, and thus, it is possible that different patterns would be observed for regular verbs of lower frequency. Many other investigations have found data in support of the Dual Route model. Thus, it will be important to examine a wider range of stimuli (e.g., regular versus irregular plural marking) and languages (e.g., German) using a similar approach to ours before completely dismissing the Dual Route model. In addition, some studies suggest different patterns of processing across individuals; we did not find evidence of a sex difference in the first experiment, but, again, we cannot fully dismiss sex as a factor, considering findings from other studies (refs). Even so, the current study had reasonably large samples for both experiments. At a minimum, we can conclude that data from our female participants were more consistent with the single route model.

In summary, the results from the current study were more consistent with a single route model for processing tense information. We observed a LAN effect to ungrammaticality, rather than P600. The two experiments show similar patterns, despite some difference in the subject populations (younger and mostly female for experiment 2). Thus, we can have reasonable confidence in the finding. Future studies will be needed to test whether this pattern is present for other irregular grammatical patterns and for other languages.

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