BRAIN POTENTIALS DURING LANGUAGE PRODUCTION IN CHILDREN AND ADULTS: AN ERP STUDY OF THE ENGLISH PAST TENSE

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Abstract

The current study examines the neural correlates of eight-to-twelve-year-old children and adults producing inflected word forms, specifically regular versus irregular past-tense forms in English, using a silent production paradigm. ERPs were time-locked to a visual cue for silent production of either a regular or irregular past-tense form or a 3rd person singular present tense form of a given verb (e.g., *walked/sang* vs. *walks/sings*). Subsequently, another visual stimulus cued participants for an overt vocalization of their response. ERP results for the adult group revealed a negativity 300-450ms after the silent-production cue for regular compared to irregular past-tense forms. There was no difference in the present form condition. Children’s brain potentials revealed developmental changes, with the older children demonstrating more adult-like ERP responses than the younger ones. We interpret the observed ERP responses as reflecting combinatorial processing involved in regular (but not irregular) past-tense formation.
1. Introduction

The recognition and comprehension of morphologically complex words has been investigated extensively by behavioral studies, neuroimaging studies that relate functional aspects of morphological processing to areas within the brain, and electrophysiological studies that examine the time course of morphological processing (e.g., Bozic & Marslen-Wilson, 2010; Havas, Rodriguez-Fornells, & Clahsen, 2012). However, there has been relatively little research on the processes involved in the production or generation of morphologically complex words, and even less on developmental changes of these processes from child to adult. Previous psycholinguistic research has largely relied on behavioral measures, such as production latencies and error rates, to examine children’s performance with inflected words (e.g., Marcus, Pinker, Ullman, Hollander, Rosen, & Xu, 1992; Clahsen, Hadler & Weyerts, 2004). Thus, details of the time course of producing or generating morphologically complex words, particularly in children, have remained largely unknown. To achieve more detailed insights into the temporal aspects of morphological processing during production, the current study demonstrates how the processing of regular and irregular inflected word forms in children's on-line production can be investigated by means of temporal imaging techniques, specifically by event-related brain potentials (ERPs).

1.1 ERP studies of morphological processing

Evidence from previous electrophysiological studies has shown differences between regular and irregular morphology both in terms of the spatial distribution and temporal parameters of ERP components. Priming studies on inflectional phenomena in different languages have revealed a reduced N400 component for regular compared
to irregular word forms. For example, in an ERP priming study on English past-tense inflection, Münte, Say, Clahsen, Schiltz, and Kutas (1999) found that stem forms (e.g., walk) primed by regularly inflected past-tense forms (e.g., walked) showed a reduced N400 component relative to unprimed stems. Verb stems taking an irregular past-tense form (e.g., give/gave) and morphologically unrelated controls where the prime-target pairs shared the same degree of phonological or orthographic overlap (e.g., yellow/yell) showed no such effect. Münte et al. (1999) suggested that the reduced N400 reflects ease of lexical access of the target word (e.g., walk) due to the corresponding prime word being decomposable into their stem forms plus affix (e.g., [walk] + -ed) whereas for irregular prime-target pairs, such as fall-fell, this is not possible. This effect has also been shown for German (Weyerts, Münte, Smid, & Heinze, 1996) and Spanish (Rodriguez-Fornells, Münte, & Clahsen, 2002).

In other ERP comprehension studies (e.g., Penke, Weyerts, Gross, Zander, Münte, & Clahsen, 1997; Weyerts, Penke, Dohrn, Clahsen, & Münte, 1997; Gross, Say, Kleingers, Münte, & Clahsen, 1998; Rodriguez-Fornells, Clahsen, Lleo, Zaake, & Münte, 2001; Morris & Holcomb, 2005; Lück, Hahne, & Clahsen, 2006; Newman, Ullman, Pancheva, Waligura, & Neville, 2007), morphologically incorrect word forms have been found to elicit an anterior negativity at around 300 to 400ms when compared to the corresponding correct forms. This is sometimes followed by a late positive component around 500-800ms (labeled as P600 or Syntactic Positive Shift), which is associated with additional computational resources required by processing grammatically incorrect, ambiguous, or otherwise grammatically complex stimuli (e.g., Osterhout, 1994; Featherston, Gross, Münte, & Clahsen, 2000; Fiebach, Schlesewsky, & Friederici, 2002; Kaan & Swab, 2003). In the ERP study by Lück et al. (2006), for example, in which participants listened to correctly and incorrectly
inflected noun plurals of German, over-applications of the regular -s plural form elicited a left anterior negativity (LAN) when compared with the correct irregular form, whereas unexpected irregular plural forms (e.g., incorrect –n plurals of surnames) led to an increased N400 component when compared to the correct form. This contrast in ERP responses is thought to reflect the distinction between combinatorial processing for regularly inflected forms (signaled by the LAN) and lexical look-up for irregular word forms (signaled by the enhanced N400). Both violations also elicited a P600/SPS component, which Lück et al. (2006) interpreted as signaling a reanalysis and repair process for the violating conditions. In a study investigating English past-tense inflection (Newman et al., 2007), participants were required to read sentences that were either correct or had violations of past-tense inflection. Results revealed a left anterior negativity for violations of regular but not of irregular past-tense inflection whilst late positivities (P600/SPS) were elicited for both violations. Newman et al. (2007) suggest that these results reflect distinct neural correlates for processing regular and irregular past-tense forms.

Whilst morphological processing in adults has been the subject of a number of ERP studies covering a range of different languages, to our knowledge there is only one ERP study on morphological processing in children. This study (Clahsen, Lück & Hahne, 2007) examined ERPs to correct and incorrect German noun plurals during listening in three age groups of children (age range: 6;5 to 12;1 ; n=20 in each group) and an adult control group. Two groups of children (the eight-to-nine-year olds and the eleven-to-twelve-year olds) showed an anterior negativity in response to -s plural over-regularizations similar to adults, whereas the younger children displayed a more widespread negativity. Although the negativity in the adult group had an earlier onset (500ms compared to 600ms for the children), and was more strongly left-lateralized
than in the children, the anterior negativities that were found for the eight-to-twelve-year old children fall within the range of variation that has been observed in studies with adults. These anterior negativities have been interpreted as an index of morphological decomposition processes by which an over-regularized form is recognized as an illegal [stem+affix] combination. Clahsen et al. (2007) concluded from their results that these processes are also available to children of the age range tested. Note, however, that this conclusion was based on grammatically incorrect stimuli, and that it remains to be shown whether it also holds for morphologically correct word forms.

1.2 Language production in adults

Language production is thought to involve a sequence of distinct processes (e.g. Dell, 1986; Levelt, 1999). The production of single words, for example, is said to consist of the retrieval of semantic information that incorporates a word’s conceptual and meaning representations, followed by the selection of a lemma, which is an abstract representation of a word’s lexical entry, followed by morphological encoding, then phonological encoding, and finally motor programming and articulation. Evidence from speech errors has been taken to support these different processes. Morphemic errors, such as thinly sliced – slicely thinned (Stemberger, 1982), are supposed to occur at the morphological encoding level, when lemma selection has been completed but prior to phonological encoding, as they typically violate affixation constraints, for example adjectival suffixes appearing on verbs and verbal suffixes on adjectives (Dell, 1986).

More recent evidence for the temporal sequencing of different processes during language production comes from the use of intracranial electrophysiology to
measure local field potentials. For example, Sahin, Pinker, Cash, Schomer, and Halgren (2009) required adults to either repeat a word (tapping simple lexical access) or to produce an inflected word form or a bare stem (tapping morphological and/or phonological encoding). Sahin et al. (2009) identified distinct markers of lexical (~200ms), morphological (~320ms), and phonological (~450ms) processing with a temporal sequence consistent with that proposed by language production models.

Compared to the numerous ERP studies that have used priming and violation studies, there are only relatively few ERP studies of language production (see Ganushchak, Chrisstoffels, & Schiller, 2011 for a review). One reason for this disparity is that the muscle activation involved in articulation distorts the EEG. To address this, studies have tried to investigate the processes involved in language production without requiring participants to overtly articulate their response. Some studies (e.g., Van Turennout, Hagoort, & Brown, 1997; Schmitt, Münte, & Kutas, 2000; Abdel Rahman, Van Turennout, & Levelt, 2003) which have used the picture naming paradigm, in which instead of speaking the name of the picture, participants are required to respond to go/no go trials, claim to tap into language production processes. However, these paradigms involve other processes, such as decision-making and planning of motor activation for button pressing, that are not normally involved in language production. Also, these studies are not particularly suitable for studies involving children, as they require metalinguistic judgments. Other studies using overt production in picture naming have tried to detect ERP correlates of language production processes that are thought to take place prior to articulation (Indefrey & Levelt, 2004), such as lexical access (Costa, Strijkers, Martin, & Thierry, 2009; Strijkers, Costa, & Thierry, 2010), morphological encoding (Koester & Schiller, 2008) and phonological encoding (Eulitz, Hauk, & Cohen, 2000). Furthermore,
Lagarano and Perret (2011) compared EEGs in single word production for an immediate and a delayed picture naming task. Whilst these studies have provided insight into the time course of aspects of language production, it should be noted that picture naming is not equivalent to speaking and so it is highly desirable to develop experimental techniques that come closer to real language production and are at the same time suitable for taking electrophysiological measures. We suggest that the silent production paradigm employed for the present study meets these criteria.

An ERP study comparing the production of regular and irregular past-tense forms in English (Lavric, Pizzagalli, Forstmeier and Rippon, 2001) reported significant differences between regular and irregular past-tense production during an early time window (288-321 ms) with irregular forms eliciting a more negative waveform than regular ones, except for frontal electrodes which showed the opposite trend (Lavric et al. 2001, p1840). Furthermore, source localization was used to demonstrate distinct cortical regions involved in producing inflected words, with regular forms showing more activity in prefrontal and right temporal areas and irregular forms showing more activity in left temporal regions. Although Lavric et al. interpret these findings as corroborating dual-mechanism models of inflection (e.g., Pinker, 1999), the possibility that the reported ERP contrasts for regular and irregular past-tense formation are at least in part due to lexical differences cannot be ruled out. This is because Lavric et al. compared different lexical items in their regular and irregular conditions. Furthermore, the critical items to elicit production of inflected verbs were not ‘regular and irregular stems’ as the authors believe (Lavric et al. 2011, p1836), but instead ambiguous forms, such as fight which could be a verb or a noun. Finally, the time window for which the effect was found was extremely short (= 33 ms) and was identified through a timeline analysis using multiple comparisons for the
same data; hence the reported effect might be an artifact. Given these problems of Lavric et al.’s study, it is not clear whether their conclusions can be maintained.

1.3 Language production in children

Children’s language production has been examined mainly using behavioral data. To investigate whether language production models developed for adults are also appropriate for children, Budd, Hanley and Griffiths (2011) showed that Foygel and Dell’s (2000) model of adult speech production provides a good simulation of children’s speech errors. Budd et al. (2011) concluded that differences between adults’ and children’s speech production systems were quantitative rather than qualitative. For inflectional morphology, many studies of child language have reported differences between regular and irregular inflection in children’s speech from an early age. For example, the over-application of regular forms has been found to be more common than the over-application of irregulars. Past-tense over-regularizations (e.g., draw-ed instead of drew) are thought to indicate that children learn and productively apply morphological rules such as ‘Add –ed’ (Pinker, 1999). These errors persist into the early school years until morphological inflection appears to become adult-like (Marcus et al., 1992).

Several experimental studies of children’s language production have used the speeded production task in which participants are asked to produce as quickly and accurately as possible a particular word form, such as the inflected form walked from the presented verb stem walk (e.g., Clahsen, Hadler, & Weyerts, 2004; Fleischhauer & Clahsen, 2012, for German; Walenski, Mostofsky & Ullman, 2007, for English). Accuracy and production latencies are measured, the latter of which provide the crucial time-course information. In these studies, high-frequency irregulars were
produced faster than low-frequency irregulars, while there was no corresponding frequency effect for regulars. This has been taken to indicate that irregular (but not regular) forms are directly retrieved from memory and do not involve morphological computation.

Few studies have used physiological measures to investigate children’s language production. Lidzba et al. (2011) used fMRI to examine the neural representation, and specifically the lateralization, of language comprehension and production across a wide age range (6-to-24-year olds). The results indicated bilateral networks for language comprehension within the middle and temporal areas that are available from childhood onwards and become narrower during childhood and adolescence. For language production which Lidzba, Schwilling, Grodd, Krageloh-Mann, and Wilke (2011) tested through silent naming, developmental changes were reported during late childhood and adolescents from an initially bilateral towards an increasingly left-lateralized network. Other developmental brain imaging studies using fMRI or MEG to examine processes involved in language production have also found developmental changes in brain representation from late childhood to adult, for example in the frontal cortex as a whole (Everts, Lidzba, Wilke, Kiefer, Mordasini, Schroth, et al., 2009) or specifically in Broca’s area (Gaillard, Sachs, Whitnah, Ahmad, Balsamo, Petrella, et al., 2003; Szaflarski, Schmithorst, Altaye, Byars, Ret, Plante, & Holland, 2006). These findings indicate a continued maturation of brain networks involved in language production through adolescence with patterns of activity becoming narrower as the brain develops (Casey, Getz, & Galvan, 2008; Gogtay, Giedd, Luisk, Hayashi, Greenstein, Vaituzis, et al., 2004).
1.4 The current study

Brain studies of children’s production of morphologically complex words are to the best of our knowledge not yet available. To address this gap, the present study investigates brain potentials to regular and irregular past-tense inflection in 8-to-12-year-old children in comparison to adults using electrophysiological measures. Participants are asked to respond to two visual cues, the first one triggering a silent production and the second one an overt articulation of an inflected form for a given verb. We applied this paradigm to the study of processes involved in the production of regularly and irregularly inflected past-tense forms of English. ERPs were time-locked to the cue for silent production of either a regular or an irregular past-tense form or the 3rd person singular present-tense form of a given verb. As the present-tense forms are entirely regular, they function as a control condition in the present experiment to test for potential lexical differences in the experimental past-tense condition. For both children and adults, we expect distinct ERP responses for regular and irregular past-tense production (walked vs. fell) but no such dissociation for 3rd person present-tense production (walks vs. falls). A more specific prediction can be made on the assumption that results from ERP violation studies will generalize to the production of correct forms. Recall, for example, that over-applications of the regular -s plural form and the regular –t participle form in German elicited a (left) anterior negativity that, in the former case, was followed by a late positivity (Penke et al., 1997; Weyerts et al., 1997). These ERP responses were interpreted as indexing combinatorial morphological processing, in this case the incorrect application of regular affixes. If these processes are also measurable for correct regular affixation when compared to irregular inflection, then we expect to find ERP responses for the production of regular inflection similar to those reported for violation studies. Finally,
given the results of previous brain studies on children’s language production indicating developmental changes from late childhood to adult (e.g., Lidzba et al., 2011), we may expect to also find differences between children’s and adults’ brain potentials to morphological encoding for the age range tested.

2. Method

2.1 Participants

Twenty monolingual, adult native speakers of British English (10 females and 10 males, mean age 20 years and 4 months, range 18–28 years) participated in the experiment. All were right-handed, had normal or corrected to normal vision, and were paid (£10) for their participation. One participant was excluded from further analysis due to excessive artifact contamination during the EEG recording. The remaining 19 participants (10 male) had a mean age of 19 years and 4 months.

Eighty-two right-handed children (36 male) were also tested. All were native speakers of English and had normal or corrected to normal vision. Sixteen children were excluded due to high error rates (< 40% correctly answered trials) and 29 children had to be excluded from further analyses due to high artifact rates during the EEG recording. The remaining children were divided into two age groups according to age: Seventeen children (5 male) were in the older age group ‘Ch-12’ (mean age: 11;7, age range: 10;7–12;11), and 20 children (8 male) were in the younger age group ‘Ch-8’ (mean age: 8;6, age range: 7;2–9;10).

2.2 Materials

Each participant was presented with 80 different verbs: 40 verbs that require regular past-tense forms and 40 verbs that require irregular past-tense forms, henceforth ‘R-
‘verbs’ and ‘I-verbs’ respectively; see appendix A and B for a complete list of verb stimuli. The infinitive form of each verb (e.g., to walk) was presented twice, once to elicit a past-tense form and once to elicit a 3rd person singular present-tense form. Thus, 160 items were presented in total. Verbs that do not have distinct past-tense forms (e.g., cut) and verbs that have doublets (e.g., dive -> dove/dived or dream -> dreamed/dreamt) were not included.

The 40 I-verbs were matched with 40 R-verbs on both word frequency and word length. Frequency counts were taken from the Children’s Printed Word Database (CPWD, Masterson, Stuart, Dixon, & Lovejoy, 2010) in which frequency is defined as the total word frequency across children’s reading books (aged 5--9 years old) divided by the number of occurrences of words in the database multiplied by one million. The R-verbs had a mean word frequency of 161 per million (SD: 244, range: 19-1493) and the I-verbs had a mean word frequency of 166 per million (SD: 261, range: 19–1577). A paired samples t-test showed no significant difference between the R- and I-verbs on the log transformed CPWD word frequencies (t(39) = -1.1; p > .05). To check the reliability of the CPWD frequency measure, the CPWD frequencies were compared with two other frequency data bases, firstly, Brown’s verbal frequency, which takes the frequency of occurrence in verbal language derived from the London-Lund corpus of English conversation (Brown, 1994), and secondly the SUBTLEXus database, which measures the frequency of words in film subtitles (Brysbaert & New, 2009). The natural logarithms of all the frequency measures (augmented with 1.1 to avoid the log of zero) were taken for statistical analyses. There were significant correlations between the three logarithm transformed word frequency measures (CPWD – Brown’s verbal r = .45 p < .001; CPWD – SUBTLEXus r = .60 p < .001; Brown’s verbal – SUBTLEXus r = .79 p < .001), which indicates that the CPWD frequency
measure was confirmed to be comparable to these two other measures. In addition to controlling for the word frequencies of R- and I-verbs, we also matched the 40 I-verbs with a further 40 R-verbs on past-tense word-form frequencies (R-verbs: mean = 164 per million, SD = 271, range = 8-1652; I-verbs: mean = 170 per million, SD = 291, range = 3-1777). A paired samples t-test showed no significant difference between the R- and the I-verbs’ past-tense word-form log-transformed CPWD frequencies (t = .18; df = 39; p > .05).

With respect to length matching, paired samples t-tests showed no significant difference between R- and I-verbs in either number of letters (t(39)= -.63; p > .05) or number of phonemes (M = 3.6; SD = 0.7; t(39) = .42; p > .05). All verbs were one syllable long. However, the regular and irregular past-tense forms could not be matched on either number of letters (regulars: mean = 6.0, SD=1; irregulars: mean = 4.0; SD=1) or number of phonemes (regulars: mean = 5.0, SD=1; irregulars: mean = 4.0, SD=1); because of the –ed affix, regular past-tense forms are longer than irregular forms. All irregular past-tense forms were one syllable in length and 32 regular past-tense forms had one syllable, 7 regular past-tense forms two syllables, and 1 regular past-tense form was three syllables long.

For the experiment, two presentation lists were created. While both lists included the same 40 I-verbs, list 1 contained 20 R-verbs matched with the I-verbs on word frequency and 20 R-verbs matched with the I-verbs on past-tense word-form frequency. List 2 contained the remaining 40 R-verbs, 20 matched with the I-verbs on word frequency and 20 matched with the I-verbs on past-tense word-form frequency. Participants saw trials from only one list. Lists were counterbalanced over participants.
2.3 Procedure

*Adults*

All adult participants were tested in a quiet laboratory at the Centre for Brain Science at the University of Essex. Participants sat in front of a computer screen at a distance of approximately 100cm. The experiment was presented on a Macintosh computer on a 61cm size screen using the Superlab (v4.07b) experiment presentation software. Each trial began with the presentation of a fixation cross at the centre of the screen for 100ms, followed by the presentation of the infinitive of a verb (e.g., *to walk*) in the centre of the screen for 1000ms, in comic sans, 96-point size font in black on a white background. The stimulus was followed by a blank screen which varied in presentation duration (250ms, 500ms, or 750ms). To cue the silent production of the past-tense form of the verb, a picture of a dinosaur was presented. To cue the silent production of the third person present-tense form of a verb, a picture of a dog was presented; see appendix C and D. Each cueing picture remained on screen for 2000ms. The silent production cue was followed by a 2000ms long presentation of a loudspeaker picture to cue overt production of the past-tense/present-tense form of the verb. Finally, a screen showing a ‘smiley face’ was presented for 2000ms to enable the participant to blink and relax before the next trial.

Participants received four past-tense form practice trials and four present-tense form practice trials at the beginning of the experiment. Trials were fully randomized and distributed over two blocks (80 items each). Blocks were divided by a short break (participants determined lengths) and were counterbalanced amongst participants. Participants were asked to minimize eye and muscle movements until presentation of the ‘smiley face’ in each trial. The run-time of the experiment was approximately 25
minutes. One experimental session (including EEG setup) lasted for approx 90 minutes.

Children
All children were tested in quiet rooms at different schools in the area of Colchester (Essex, UK). The oldest age group of children (Ch-12) followed the same procedure as the adults except that the testing session was shorter (75 minutes) as the set-up time for the 32 electrode cap was quicker than that of the adult 64 electrode cap. Trials for the children were also divided into four blocks rather than two, with 40 trials randomized within each block.

The younger children (Ch-8) received two pre-test training sessions that took place prior to the testing session on a different day. The first one consisted of a short introduction to past/present tense forms and the dog/dinosaur cues used in the main experiment. The children were then introduced to the format of the task without using the computer. Children were given a sticker as a reward for taking part. In a second pre-test session, the child was shown a computer version of the task. This followed the experiment protocol except that the infinitive of the verb remained on screen for 2000ms and not 1000ms as it appeared in the experiment. If the child was successful in taking part in this game, another version of the game was shown with the infinitive of the verb remaining on screen for just 1000ms, the same as the experiment protocol. All training items were different to the experimental items. Again, children were rewarded with a sticker for taking part in this session. In the EEG testing session the youngest children followed the same procedure as the adults and older children.
2.3 Electrophysiological recording

For adult participants, the EEG was recorded using Neuroscan (version 4.5) acquisition software from 64-electrode sites (FP1, FPz, FP2, AF3, AF4, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3, CPz, CP2, CP4, CP6, TP8, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO5, PO3, POz, PO4, PO6, PO8, O1, Oz, O2) according to the international 10-20 system using Ag/AgCl sintered electrodes embedded in an elastic cap (Quik-Cap, Neuromedical Supplies). Additionally, bipolar horizontal and vertical electrooculograms (EOGs) were recorded for artifact rejection purposes. Recordings were referenced online to the left mastoid. Signals were recorded continuously with an on-line band-pass filter between 0.1-70Hz and digitized at 500Hz. Electrode impedances were kept below $5\, \text{k}\Omega$. Recordings were re-referenced off-line to the average of the left and right mastoid electrodes. Recordings were off-line band-pass filtered between 0.1 Hz and 30Hz. For graphical illustration purposes only, grand average ERPs were smoothed with a 7Hz low-pass filter. For children, the EEG was recorded from only 32-electrode sites (FP1, FP2, F7, F3, Fz, F4, F8, T7, FC3, FCz, FC4, FT8, T7, C3, CZ, C4, T8, TP7, CP3, CPZ, CP4, TP8, P7, P3, PZ, P4, P8, O1, Oz, O2). Signals were recorded continuously at a sampling rate of 1000Hz with an on-line band-pass filter set between 0.15 – 30Hz. On-line recordings were referenced to the left mastoid. Offline recordings were down-sampled to 500 Hz and re-referenced to the average of the left and right mastoid electrodes.

EEG data were processed with EEGLab (Delorme & Makeig, 2004). The continuous EEG was epoched and baseline corrected using a 200ms pre-stimulus baseline. Epochs were extracted from 200ms before the onset of the delayed vocalization cue up to 1000 ms after cue onset.
2.4 Data Cleaning

To remove typical muscle and eye movement artifacts from the scalp recordings, an independent component analysis (ICA) algorithm (Infomax) was applied to the data. Epochs containing additional artifacts were rejected automatically using the ‘find abnormal values’ function in EEGLab. The threshold for this automatic rejection procedure was set at 70µV. Finally, data were also visually inspected for artifact rejection purposes.

2.5 Statistical analysis

Only correctly answered trials were included in the analyses. For all groups, waveforms were quantified using mean amplitude measures and grand averages were obtained for epochs beginning 200ms pre-stimulus until 1000ms post-stimulus. ERP mean amplitudes were analyzed with a repeated-measures analysis of variance (ANOVA) using the PROC GLM function in Statistical Analysis System (SAS version 9.3). The three-way ANOVA included verb type (R-verb, I-verb), tense (present-tense, past-tense), and region of interest (see below), as within-subject factors. For the adult data, four regions of interest (ROIs) were defined as left frontal ‘LF’ (F7, F5, F3, F1, FT7, FC5, FC3, FC1, C5, C3, C1), right frontal ‘RF’ (F8, F6, F4, F2, FT8, FC6, FC4, FC2, C6, C4, C2), left parietal ‘LP’ (TP7, CP5, CP3, CP1, P7, P5, P3, P1, PO7, PO5, PO3), and right parietal ‘RP’ (CP8, CP6, CP4, CP2, P8, P6, P4, P2, PO8, PO6, PO4). Midline electrodes (FZ, FCZ, CZ, CPZ, PZ, POZ) were analyzed separately. For the two child age groups, ROIs were defined as left frontal ‘LF’ (F7, F3, FT7, FC3), right frontal ‘RF’ (F8, F4, FT8, FC4), left parietal ‘LP’
(TP7, CP3, P7, P3), right parietal ‘RP’ (TP8, CP4, P8, P4), and mid-line ‘ML’ (FZ, FCZ, CPZ, PZ).

Time windows of interest for mean amplitude quantification were identified based on visual inspection and a 50-ms timeline analysis. We followed up interactions including the critical factors verb type and verb form that reached significance in at least 3 consecutive 50ms time windows by carrying out an additional statistical analysis comprising the larger time interval.

3. Results

3.1 Accuracy data

Accuracy scores for the delayed overt production task were calculated for each participant and condition. Overall, results revealed that the adult participants experienced no major problems with the task. Verb production was 83% correct in past-tense trials of I-verbs (with 8% over-regularizations of -ed), 97% correct of R-verbs, and in present-tense trials 97% correct of I-verbs and 98% of R-verbs. Separate repeated measures ANOVA which included verb type (R-verb, I-verb) and tense (present-tense, past-tense) as within-subject factors were performed for the three participant groups. For the adult group, the ANOVA revealed main effects of verb type \([F(1,18) = 18.1, p < .001]\) and tense \([F(1,18) = 30.9, p < .001]\), and a significant interaction between verb type and tense \([F(1,18) = 19.3, p < .001]\). Follow-up paired samples t-tests showed that irregular past-tense items were produced less accurately than regular ones \([t(18) = -5.1, p < .001]\), as well as less accurately than present-tense items of both I-verbs \([t(18) = -4.5, p < .001]\) and R-verbs \([t(18) = -5.2, p < .001]\). There were no significant differences between the other conditions.
Accuracy rates for the older child group (Ch-12) were lower for irregular past-tense trials than for all other conditions. Specifically, verb production was 78% correct for irregular past-tense trials (with 15% over-regularizations of -ed), 98% for regular past-tense trials, and 97% for present-tense items of I-verbs and 96% for R-verbs. The ANOVA for the Ch-12 subgroup revealed main effects of verb type \([F(1,16) = 36.7, \ p < .001]\) and tense \([F(1,16) = 34.2, \ p < .001]\), and a significant interaction between verb type and tense \([F(1,16) = 78.5, \ p < .001]\). Follow-up paired samples t-tests showed that irregular past-tense forms were produced less accurately than regular forms \([t(16) = -7.6, \ p < .001]\), as well as less accurately than present-tense items of both I-verbs \([t(16) = -7.9, \ p < .001]\) and R-verbs \([t(16) = -6.1, \ p < .001]\). There were no significant differences between the other conditions.

Accuracy rates for the younger child group (Ch-8) were again lowest for irregular past-tense forms. Verb production was 71% correct for irregular past-tense trials (with 17% over-regularizations), 89% for regular ones, and in present-tense trials 93% correct for both I- and R-verbs. The repeated measures ANOVA revealed main effects of verb type \([F(1,19) = 28.3, \ p < .005]\) and tense \([F(1,19) = 25.2, \ p < .005]\), and a significant interaction between verb type and tense \([F(1,19) = 25.6, \ p < .005]\). Follow-up paired samples t-tests showed that irregular past-tense items were produced less accurately than regular ones \([t(19) = -5.3, \ p < .001]\), as well as less accurately than present-tense items of both I-verbs \([t(19) = -6.3, \ p < .001]\) and R-verbs \([t(19) = -6.2, \ p < .001]\). There were no significant differences between the other conditions.

To determine whether accuracy scores were adult-like in the two child groups, planned comparisons were performed (Table 1). Whilst the 12 year-olds’ accuracy scores were found not to differ significantly from those of adults in any condition, the 8 year-olds were significantly less accurate than the adult group in all conditions. The
8 year-olds were also significantly less accurate than the 12 year-olds on the regular past tense and on the present tense of I-verbs, and marginally less accurate than the 12 year-olds on the irregular past-tense condition. These results indicate that the system of past-tense inflection is not yet adult-like in the younger children.

3.2 ERP data
The grand average ERP waveforms for both R- and I-verb types in both the past-tense and present-tense forms are shown in Figure 1 for each participant group. An example electrode from each region of interest is shown in the plot.

Visual inspection of the ERPs for all age groups shows an N1, followed by a P2 component (which are particularly pronounced at frontal and central electrode-sites) for both the 3rd person present and the past-tense conditions. As shown in appendix E, these components did not yield any reliable difference between the two conditions for any of the three age groups).

Adults
Following the N1/P2 early components, more negative waveforms are observed for regular past-tense form trials when compared to the irregular past-tense form trials, at approximately 300ms after stimulus onset. This contrast appears to be distributed bilaterally across frontal and central electrodes. The time-window of interest was set
at 300ms to 450ms after cue onset based on visual inspection of the data and an additional time-line analysis (see above). No differences are observed for the ERPs in the present-tense condition. Mean amplitudes were extracted for each participant at each electrode-site. After data cleaning (see section 2.4), 72% of trials were included in the statistical analyses. Similar numbers of trials were included in the past- and present-tense conditions (72% each) and also for R-verbs and I-verbs (71% and 74%).

The repeated-measurements ANOVA revealed a main effect of verb form \( [F(1,18) = 7.61, \text{MSE} = 19.97, p < .05] \), due to an overall more positive mean amplitude for the past-tense compared to the 3rd person present-tense condition. More importantly, there was a significant two-way interaction of verb type and verb form \( [F(1,18) = 11.11, \text{MSE} = 4.43, p < .01] \). Step-down analyses by verb form revealed a significant effect of verb type in the past-tense condition only \( [F(1,18) = 4.80, \text{MSE} = 13.26, p < .05] \) confirming more negative going amplitudes for regular than for irregular past-tense trials. Although there was a significant verb type and ROI interaction \( [F(1,18) = 3.97, \text{MSE} = 1.38, p < .05] \), step-down analyses by ROI showed no further significant effects.

The analysis of the midline electrodes revealed a significant two-way interaction between verb type and verb form \( [F(1,18) = 4.47, \text{MSE} = 5.36, p < .05] \) but step-down analyses by verb form showed no further significant effects of verb type. In summary, adults show a more negative-going waveform for regular compared with irregular items 300-450ms after cue onset in the past-tense condition only.

**Ch-12**

Visual inspection of the ERPs (see Figure 1) showed an N1, followed by a P2 component at frontal/central electrode sites. Following these early components, more
negative-going waveforms can be observed for regular than for irregular trials in the past-tense condition only, at the right frontal electrodes around 400ms after stimulus onset. This pattern seems to be less pronounced at left frontal electrodes. At a later point in time (around 700ms), regular past-tense trials show a more positive waveform than irregular ones at parietal electrode sites. After data cleaning, 56% of trials were included in the statistical analyses. Similar numbers of trials were included in the past and the present-tense conditions (56% and 55%) and also for R- and for I-verbs (55% and 56%). Based on a 50ms time bin analysis and visual inspection of the waveforms, two time windows of interest were identified: an early 300-550ms and a late 650-800ms time window.

In the *early time window*, the ANOVA revealed a significant three-way interaction between ROI, verb type and verb form \(F_{(4,64)} = 2.92, \text{MSE} = 3.65, p < .05\). Step down analyses by verb form and ROI revealed significantly more negative-going waveforms for regular than for irregular past-tense trials \(F_{(1,16)} = 5.37, \text{MSE} = 9.16, p < .05\) at RF electrode-sites. No other effects were significant (all \(p\) values > .05). In the *late time window*, there was a marginally significant three-way interaction \(F_{(4,64)} = 2.21, \text{MSE} = 4.25, p < .08\). Step down analyses revealed a significant more positive going waveform for regular than for irregular past-tense trials \(F_{(1,16)} = 5.94, \text{MSE} = 5.53, p < .05\) at electrode-sites in the LP region of interest. In summary, the 12 year-olds showed a significantly more negative going waveform between 300-550ms for regular than for irregular items in the past-tense condition only, which was most pronounced at right frontal electrode sites. At a later time window, 650-800ms, regular past-tense forms showed a more positive going waveform than irregular ones. By contrast, there were no significant differences between R- and I-verbs in the present-tense condition, in either time window.
The data were prepared for analysis in the same way as for the adult and the Ch-12 groups using an ICA procedure for artifact rejection followed by manual inspection. After these procedures, 56% of trials were included in the statistical analyses. Similar numbers of trials were included in the past-tense and present-tense conditions (54% and 55%) and also for R- and for I-verbs (53% and 56%). A 50ms time bin analysis over the 1000ms epoch was carried out to identify time windows of interest. No consecutive 50ms time bins revealed any significant two-way interactions between verb type and verb form, or any significant three-way interactions between ROI, verb type, and verb form. Visual inspection of the ERPs (see Figure 1) indicated a possible difference in the regular and irregular waveforms between 410ms and 460ms. This time window was followed up but revealed no significant effects. Thus, the younger age group of children did not show any significant ERP differences between verb types in either the past or the present-tense condition.

To summarize the results, adults showed a negativity between 300ms and 450ms after cue onset for regular trials when compared to irregular trials in the past-tense form only. The older children (Ch-12) showed a similar but longer lasting negativity for the regular items in the past-tense form. However, scalp distribution between the two populations differs. While the effect was broadly distributed in adult participants, the negativity is particularly pronounced at right frontal electrode-sites in the children. In addition, the children also showed a late positivity at left parietal electrodes for regular past-tense trials when compared to irregular ones. No significant differences between verb types in either condition were found for the younger children (Ch-8).
4. Discussion

This study demonstrates how electrophysiological techniques can be used to investigate processes involved in children’s and adults’ production of morphologically complex words. Our aim was to explore an experimental technique that (i) taps into morphological encoding during production, (ii) is appropriate for both children and adults, (iii) does not assign any artificial task to participants, and (iv) is suitable for measuring event-related brain potentials. We believe the silent production experiment presented here meets all these criteria.

Our test case for examining morphological encoding in production was past-tense inflection in English and the contrast between regular –ed affixation and irregular past-tense forms. As a control, the same lexical items were tested in the 3rd person singular present-tense, which does not comprise any irregular forms for main verbs in English. Consequently, we expected to find differences in the ERP responses of the past-tense (walked vs. fell) but not the present-tense condition (walks vs. falls).

The results of the present study confirm these predictions. During silent production of past-tense forms, ERP differences were found for adults in the 300-450ms time window with regular past-tense inflection eliciting a more negative waveform than irregular past-tense forms. A similar but longer lasting effect was found in the older age group of children. No differences were observed for the production of the 3rd person present-tense forms, either for adults or for children. How can the ERP effects seen in the past-tense condition be explained?
4.1 Levels of processing inflected word forms

According to familiar psycholinguistic accounts of language production (e.g., Dell, 1986; Levelt, 1999), the production system goes through a sequence of distinct processes including conceptual encoding and lemma selection followed by form-level (morphological and phonological) encoding before actual motor execution and articulation. In terms of this framework, the ERP responses obtained for past-tense production in the current study are unlikely to reflect early stages of semantic or conceptual encoding, since for each trial the relevant conceptual and lemma information was already available from the visually presented stimulus word prior to the (silent) production task. It is more likely that they reflect later stages of form-level encoding.

We can also rule out the possibility that the observed ERP effects are due to lexical-level properties of the stimuli tested, because the same lexical items that elicited different ERP responses in the past tense did not produce any measurable effect when corresponding present-tense forms had to be produced. Instead, we attribute the electrophysiological differences obtained for the past tense to the form-level contrast between regular and irregular inflection, which affects past but not present-tense formation in English.

The ERP responses we obtained for regular (compared to irregular) past-tense formation are reminiscent of the kinds of components that have previously been reported for grammatical violations. In terms of its latency, the negativity seen for the production of regular past-tense forms in both adults and older children is similar to the kinds of morpho-syntactic negativity (sometimes followed by late positivities) elicited by syntactically incorrect forms (e.g., Friederici, 2002) and morphological over-regularizations (e.g., Penke et al., 1997, Lück et al., 2006). This negativity is
clearly different in terms of its scalp distribution from the centro-parietal N400 that has been associated with lexical-semantic processing (e.g., Kutas & Federmeier, 2007).

The time course properties of the negativity for regular past-tense production also identify this component as an index of form-level rather than semantic encoding. Recall from Sahin et al. (2009) that electrophysiological markers of morphological encoding during production were at around 300ms and of phonological encoding at around 450ms. This fits in the latency of the negativity obtained in the present study which had an onset latency of approximately 300ms for both adults and (12-year-old) children. Furthermore, some previous studies of morphological violations (e.g. Weyerts et al. 1997; Lück et al. 2006, Rodríguez-Fornells et al. 2001) reported a biphasic pattern of ERP responses for over-regularized word forms, with an early anterior negativity and a late centro-posterior positivity. In the present study, a similar kind of biphasic ERP pattern was found for the 12-year-old children as a brain response to producing correct regular past-tense forms, with the same ERP components separated both in terms of timing and distribution. Taken together, the current results suggest that silently producing regularly inflected word forms engages specific processes of form-level encoding that are distinct from those required for producing irregular word forms.

4.2 Form-level encoding

Form-level processes during production include morphological and phonological encoding. Consider first a morphological account of the current results. According to dual-mechanism morphology (Pinker, 1999; Clahsen, 2006), generating regular past-tense forms in English requires a combinatorial process, namely –ed affixation, whilst
irregulars are directly accessed from the lexicon without any affixation. Consequently, the ERP effects obtained for regular (relative to irregular) past-tense formation may be taken to reflect the additional resources required to generate an affixed word form relative to a corresponding form that involves direct lexical look-up. From this perspective, the present set of findings may be interpreted in a similar manner as results of previous ERP studies of violations of inflectional morphology which consistently show increased anterior negativities (sometimes followed by late positivities) for over-applications of regular but not of irregular inflectional processes (e.g., Penke et al. 1997, Lück et al., 2006; Newman et al. 2007).

Alternatively, the ERP responses may signal differences between regular and irregular past-tense production at the level of phonological encoding. According to slot-and-filler models of the production of inflected words (e.g., Janssen, Roelofs and Levelt, 2002), phonological codes are inserted into inflectional frames which consist of stems and affixes to spell out a complex word’s abstract morpho-syntactic feature specifications. When a verb lemma such as walk is additionally specified for the morpho-syntactic feature [+past], an inflectional frame with two slots (stem+ affix) will be generated, each of which is filled with a phonological code, one for the stem and one for the past-tense affix. An irregular past-tense form (e.g., fell) is also thought to require a two-slot inflectional frame for a stem plus a (zero) affix, for which a single phonological code will be retrieved. Thus according to this account, regular and irregular past-tense production invokes the same inflectional frames but differs in terms of phonological encoding, with two phonological codes required for regular and one for irregular inflection. It is possible that the ERP effects we obtained reflect this contrast. Note, however, that given Sahin et al.’s (2009) finding of phonological encoding occurring at around 450ms post-stimulus, the negativity reported here, with
its onset latency of approximately 300ms, is unlikely to signal pure phonological encoding. Furthermore, in order to maintain that regular and irregular forms share the same inflectional frame but differ at the level of phonological encoding, this account requires positing ‘null morphemes’, such as an invisible past-tense suffix for irregular forms like fell. Null morphemes are an unfortunate theoretical notion that many morphologists have tried to get rid of (e.g. Aronoff, 1994). Although we are not convinced by a phonological explanation of the present set of ERP results, we acknowledge that future ERP production experiments in this domain should include a phonological control condition.

4.3 Developmental changes from child to adult
The present results from both the behavioral and the ERP data reveal a number of differences between children and adults in the production of inflected word forms. Firstly, the behavioral results show that, whereas the adults and older children (Ch-12) had the same high accuracy rates across conditions, the younger children (Ch-8) were significantly less accurate than the adults in all conditions. Secondly, the ERP data for the 12-year-old children differed from those of adults in that the negativity for the regular past tense had a longer latency (300-550ms) and a more right-frontal distribution than for adults. This negativity was also followed by a late positivity at 650-800ms in the Ch-12 group, an effect that was not seen in the adult data. Thirdly, the ERP data from the younger child group (Ch-8) did not show any reliable contrast for regular versus irregular past-tense production (unlike the adult and the Ch-12 groups). How can these child/adult differences be explained?

As regards the older children, the results suggest that they make use of the same representations and mechanisms for producing inflected word forms as mature
speakers, but that processing these word forms may be more resource-demanding than for adults. One indication for this interpretation is the longer latency of the negativity in the Ch-12 than in the adult group. Another piece of evidence comes from the additional late positivity in the Ch-12 group for regular (compared to irregular) past-tense formation inflection which was not present in the adult group. Both in terms of its latency and distribution, this positivity is reminiscent of the P600/SPS component. Recall that this component has been associated with grammatically anomalous, ambiguous, or complex stimuli, all of which incur increased grammatical processing effort. Consequently, the late positivity seen in the Ch-12 group may be taken as an index of the additional resources that children at this age (relative to adults) require for morphologically encoding regularly inflected word forms. This interpretation is consistent with reports suggesting that even in 12-year-old children the brain networks involved in language production have not yet fully matured to adult level (e.g., Casey et al., 2008). As an alternative to this interpretation, one might regard the late effect as an enhanced negativity for irregular relative to regular past-tense forms, possibly signalling a greater working memory load for irregular compared to regular forms. Note, however, that working-memory sensitive negativities for linguistic stimuli, e.g. LAN effects, are found in earlier time windows (e.g. 300-500ms) and with a different distribution (e.g. frontal/central distribution); see, for example, Felser, Clahsen & Münte (2003). In our data, the effect occurred later, between 600-850ms, and had a more posterior distribution. We therefore maintain that the ERP component in this late time window is a P600/SPS-like effect.

Concerning the younger children (Ch-8), their behavioral data as well as their ERP responses indicate differences, to both adults and older children. In the behavioral data, there is a particularly clear contrast for regular past-tense formation,
with significantly lower accuracy scores for Ch-8 than both adults and Ch-12 (89% vs. 97% and 98%). Likewise, regular (relative to irregular) past-tense formation did not yield any significant ERP effect for the younger child group, unlike for the adult and the Ch-12 groups. These results indicate that regular –ed affixation might not yet function at adult level in these younger children. We acknowledge, however, that finding no difference between regular affixation and irregular inflection in the ERP data of the CH-8 group of children was an unexpected outcome, given previous studies of children at this age. Behavioral studies have shown differences in performance between regular and irregular inflection on a number of measures, including errors rates, error types, and production latencies (e.g. Marcus, et al., 1992, Clahsen et al., 2004). Furthermore, an ERP violation study (Clahsen et al., 2007) showed that listening to over-applications of regular inflection (relative to corresponding correctly inflected forms) elicited an anterior negativity in eight-to-nine-year-old children, similar to adults, indicating that children at this age are sensitive to misapplications of regular affixation. Yet, grammatical violations tend to yield more robust ERP effects than grammatically correct stimuli (e.g., Kaan, Harris, Gibson, & Holcomb, 2000). Thus it is possible that the ERP signals for grammatically well-formed regular (versus irregular) past-tense forms were too weak in the Ch-8 group to show a reliable contrast.

5. Conclusion
The motivation for the present study was to demonstrate how the temporal aspects of producing morphologically complex words can be investigated in both adults and children by using event-related brain potentials. ERP studies of language production are often compromised as ERP data are easily contaminated by muscle movements
elicited during articulation. Although there is a rich experimental literature on morphological processing during recognition and comprehension, little is known about the processes involved during the generation and production of inflected or derived words in real time, particularly for children. To this end, we performed a child-friendly production experiment with a group of adults and two age groups of children in which ERPs were recorded while participants were silently producing inflected word forms followed by delayed overt articulation. This paradigm thus captures the processes involved in natural language production prior to vocalization while minimizing contamination from articulatory muscle artifacts. The results of this experiment led to a pattern of ERP responses that can be interpreted to reflect processes involved in morphological encoding. The (silent) production of regular (compared to irregular) past-tense forms yielded an early negativity (followed by a late positivity in the group of older children), ERP components that are known to be elicited by morphologically complex words. We interpret the specific ERP effects obtained in the present experiment as an index of the additional computational resources needed to (silently) produce an inflected word form with internal combinatorial structure relative to an irregular form that can be directly retrieved from lexical memory. Our study also revealed a number of developmental changes suggesting that producing morphologically structure word forms may be more resource-demanding for children than for mature speakers. Although questions remain regarding the interpretation of the ERP data from the younger children, we conclude that the silent production paradigm is a viable and useful approach to capturing differences in morphological processing in real-time language production.
ACKNOWLEDGEMENTS

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References:


Appendix

A. Verbs that require regular past-tense forms (‘R-verbs’)

List 1:
to want, to use, to ask, to talk, to wash, to climb, to close, to dress, to brush, to splash,
to clear, to fit, to join, to patch, to roll, to kiss, to rake, to puff, to grip, to point, to cry,
to open, to push, to scare, to paint, to gasp, to love, to reach, to fill, to cheer, to
change, to lock, to mix, to agree, to stretch, to pump, to cross, to pack, to bake, to
peck

List 2:
to call, to start, to turn, to smile, to decide, to cover, to wait, to seem, to tie, to grab, to
chase, to sail, to dance, to add, to clean, to rub, to fix, to poke, to fry, to suck, to wish,
to cross, to plant, to race, to care, to laugh, to plan, to guess, to pick, to post, to match,
to drop, to taste, to sniff, to rush, to mend, to press, to sneeze, to block, to solve

B. Verbs that require irregular past-tense forms (‘I-verbs’)
to make, to fly, to ride, to wear, to hold, to spring, to bring, to sing, to drive, to
choose, to break, to dig, to wake, to shake, to lead, to bite, to lose, to speed, to steal, to
sting, to tell, to grow, to swim, to drink, to hide, to leave, to feed, to build, to win, to
send, to throw, to sell, to slide, to spend, to sink, to speak, to teach, to freeze, to shine,
to sweep
C. Present-tense cueing picture

D. Past-tense cueing picture
### E. ANOVA results investigating the interaction between verb type and verb form over the N1/P2 time windows

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Table 1. Planned comparisons between adult and child groups on accuracy rates

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Figure 1: Grand average ERPs of the different age groups for production of verbs in the past-tense form (left panel) and the 3rd person present-tense form (right panel). R-verbs (regular, dotted line) are plotted against I-verbs (irregular, solid line). ERPs are time-locked to the onset of the delayed vocalization cue; negative voltage plotted upwards.