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When Events Change Their Nature: The Neurocognitive Mechanisms underlying Aspectual Coercion

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Abstract

The verb 'pounce' describes a single, near-instantaneous event. Yet, we easily understand that, "For several minutes the cat pounced…" describes a situation in which multiple pounces occurred, even though this interpretation is not overtly specified by the sentence's syntactic structure or by any of its individual words—a phenomenon known as 'aspectual coercion'. Previous psycholinguistic studies have reported processing costs in association with aspectual coercion, but the neurocognitive mechanisms giving rise to these costs remain contentious. Additionally, there is some controversy about whether readers commit to a full interpretation of the event when the aspectual information becomes available, or whether they leave it temporarily underspecified until later in the sentence. Using event-related potentials (ERPs), we addressed these questions in a design that fully crossed context type (punctive, durative, frequentative) with verb type (punctive, durative). We found a late, sustained negativity to punctive verbs in durative contexts, but not in frequentative (e.g. explicitly iterative) contexts. This effect was distinct from the N400 in both its time course and scalp distribution, suggesting that it reflected a different underlying neurocognitive mechanism. We also found that ERPs to durative verbs were unaffected by context type. Together, our results provide strong evidence that neural activity associated with aspectual coercion is driven by the engagement of a morphosyntactically unrealized semantic operator rather than by violations of real-world knowledge, more general shifts in event representation, or event iterativity itself. More generally, our results add to a growing body of evidence that a set of late-onset sustained negativities reflect elaborative semantic processing that goes beyond simply combining the meaning of individual words with syntactic structure to arrive at a final representation of meaning.

1. Introduction

One of the key features of human language is that it can be used to convey an unlimited number of unique utterances using only a finite set of basic rules and concepts. Early theoretical accounts of semantics proposed that overall sentence meaning could be derived based solely on the surface structure of a sentence—the meaning of individual words and their syntactic combination (so-called Fregean compositionality; see Jackendoff, 2012,

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chapter 12 and Partee 1995). For example, in 1a below, the verb *prowl* describes an action which can continue for an arbitrarily long time, and it therefore combines readily with the temporal context "for several minutes" to yield an overall event representation of a cat continuing to prowl for the time specified. However, consider 1b. below. A *pounce,* by definition, is nearly instantaneous and it therefore cannot last for several minutes. Yet, rather than interpreting this sentence as anomalous, we readily understand it to mean that the cat made a series of pounces over the course of several minutes.

1a. For several minutes the cat prowled about the yard.

$[_S$ $[_{PP}$ for $[_{NP}$ several minutes]] $[_{NP}$ the cat] $[_{VP}$ prowled $[_{PP}$ about $[_{NP}$ the yard]]]]

1b. For several minutes the cat pounced on the toy.

$[_S$ $[_{PP}$ for $[_{NP}$ several minutes]] $[_{NP}$ the cat] $[_{VP}$ pounced $[_{PP}$ on $[_{NP}$ the toy]]]]

1c. After several minutes the cat pounced on the toy.

$[_S$ $[_{PP}$ after $[_{NP}$ several minutes]] $[_{NP}$ the cat] $[_{VP}$ pounced $[_{PP}$ on $[_{NP}$ the toy]]]]

This interpretation poses a challenge to simple compositionality. Syntax alone is insufficient to generate this iterative meaning, as both 1a and 1b are syntactically identical. Nor is the meaning of the verb *pounce* sufficient, as it does not carry with it an iterative interpretation, as can be seen in 1c. Therefore, the iterative meaning in 1b cannot be arrived at based on surface structure alone. Instead, it relies on a morphosyntactically unrealized mechanism. This is usually referred to as *enriched* composition (see Culicover & Jackendoff 2002, for extensive discussion), and the type of enriched composition illustrated in 1b. is usually referred to as *aspectual coercion* (Talmy, 1978, Moens & Steedman, 1988, Jackendoff, 1991) [1].

Several psycholinguistic studies report costs in processing sentences like 1b relative to 1a. For example, Piñango, Zurif, and Jackendoff (1999) presented participants with spoken sentences such as "The insect hopped/glided effortlessly until it reached the garden", in which the main verb was either punctive (*hopped)* or durative (*glided).* Letter-string probes appeared on the screen 250ms after the offset of critical durative words (e.g. *until)* and participants were required to make a lexical decision (decide whether the probe was a word or a non-word). The authors found that it took longer to make lexical decisions to probes in sentences containing punctive verbs than durative verbs.

Similarly, others have shown that, during self-paced reading, it takes longer to process verbs in sentences like 1b than 1a, both when participants make explicit judgments about plausibility (Todorova, Straub, Badecker, & Frank, 2000a; Brennan & Pylkkänen, 2008; Experiment 1) or when they simply read the sentences for comprehension (Husband, Bretta, & Stockall, 2006).

[1]The term, 'aspectual coercion' has been used to refer to the derivation of any aspectual representation of an event which does not follow from simple composition, regardless of mechanism. In addition to the example provided here, it also includes *additive coercion*, *subtractive coercion* and *inchoactive coercion*. For example, as discussed by Brennan and Pylkkänen (2010), in the sentence, "Within ten minutes the child was asleep," the action described is not simply that of a child sleeping, but also the transition from wakefulness to sleep. For a more in-depth discussion, see Van Lambalgen and Hamm (2005) or Croft (2012). For simplicity, in the current manuscript we will primarily use the term *aspectual coercion* to describe the differences in interpretation between 1a and 1b.

1.1. Cognitive mechanisms driving the processing costs of aspectual coercion

In their original report, Piñango, Zurif, and Jackendoff (1999) argued that the processing costs incurred during aspectual coercion were driven by the engagement of a morphosyntactically unrealized plurality/iterativity operator within the semantic composition system (Jackendoff, 1997; Pustejovsky, 1991; Smith, 1991; de Swart, 1998). This iterativity operator is proposed to repeat the punctive action to fill the time specified by the context. In this manuscript, we will refer to this account as the *iterativity operator* hypothesis.

However, other mechanisms could also account for the processing costs associated with sentences like 1b versus 1a. For example, Dölling (1995; 1997; 2003) proposed that sentences such as 1b are, in fact, first interpreted through simple composition. Because this results in a meaning that is incongruous with real-world knowledge (e.g. a pounce that lasts several minutes), comprehenders then re-interpret the sentence as meaning that multiple iterations of the action have occurred (e.g. multiple pounces). We will refer to this as the *real-world incongruity* hypothesis.

Some support for the *real-world incongruity* hypothesis comes from a magneto-encephalography (MEG) study by Brennan and Pylkkänen (2008, Experiment 2) which revealed increased neural activity between 340-380ms and 440-460ms after the onset of critical punctive verbs (e.g. *beeped*) following durative contexts ("For 25 seconds…") versus punctive contexts ("After 25 seconds…"). Although the early effect between 340-380ms was shorter lived than the N400 component that is typically evoked by words that are incongruous with real-world expectations (Hagoort, Hald, Bastiaansen, & Petersson, 2004; Kutas & Federmeier, 2011; Paczynski & Kuperberg, 2012), it partially localized to a region that had previously been implicated as a neuroanatomical source of the N400 (Halgren et al., 2002). The authors therefore interpreted this effect as reflecting participants' detection of a real-world incongruity at the point of the critical verb.

It is also possible that previously reported costs associated with aspectual coercion were driven, at least in part, by more general processes that are distinct from aspectual coercion itself. One possibility is they were driven by a *shift* in the aspectual representation of the central verb, which goes from having no meaningful temporal dimension to conveying an event that does have a clear temporal duration. This type of aspectual shift is theoretically dissociable from enriched composition itself. Consider, for example, the sentence, "Several times the cat pounced on the toy." Just like sentence 1b, this sentence describes a cat engaging in a series of pounces. Unlike sentence 1b, however, the frequentative phrase, "several times" explicitly specifies the iterative nature of the overall event representation, and so the meaning of the sentence follows from simple compositionality—the combination of the meaning of individual words and syntactic structure; there is no additional requirement for a semantic operator. On the other hand, just like sentence 1b, the overall event described has a non-trivial temporal dimension, and it is possible the shift in the aspectual interpretation of the verb itself is associated with additional processing. We will refer to this as the *aspectual shift* hypothesis.

Support for the *aspectual shift* hypothesis comes from Todorova, Straub, Badecker, & Frank (2000b) who observed longer reading times to frequentative post-verbal modifiers ("sent a check every year") than to non-frequentitive modifiers ("sent a check last year"). The former condition requires an aspectual shift whereas the latter does not. To date, however, there have been no psycholinguistic studies directly contrasting sentences that require aspectual coercion with those that only require an aspectual shift.

Another more general account of processing costs associated with aspectual coercion is that they are driven by event iterativity itself. If one assumes some type of embodied cognition during language comprehension, simulating multiple events might be associated with more processing costs than simulating a single event.[2] This account can be dissociated from both the *iterativity operator* and the *aspectual shift* hypotheses described above. Consider, for example, the sentence, "Several times the cat prowled about the yard." Similar to sentence 1b, this sentence describes a series of actions. However, the iterative meaning is explicitly provided by the phrase "several times," precluding the need for enriched composition. Additionally, the verb *prowled* is durative, and so there is no aspectual shift. Nonetheless, simulating multiple prowls may lead to more processing costs than simulating a single prowl. We will refer to this as the *event iterativity* hypothesis.

It should be noted that the *aspectual shift* and the *event iterativity* hypotheses are not mutually exclusive with either one another, or with the *iterativity operator* hypothesis. Indeed, it is possible that previous costs of aspectual coercion were driven by more than one of the mechanisms outlined above.

1.2. The time course of neurocognitive processes associated with aspectual coercion

The questions raised above pertain to the cognitive mechanisms that drive costs associated with aspectual coercion. There also remain open questions about its time course—both its onset and duration.

Some insights come from a follow-up study by Piñango and colleagues (2006) in which the timing of the onset of the lexical probes was varied in relation to the offset of the durative phrases. The authors replicated their earlier finding of longer lexical decision times to probes in the aspectually coerced versus non-coerced sentences. This, however, was only true when the probes were presented 250ms after the offset of the critical words that licensed coercion, but not when they were presented immediately at offset of these words. Assuming that the each word lasted approximately 200-300ms, this slowdown corresponds to approximately 450-550ms after the onset of the critical words. Thus, these findings suggest that the neurocognitive mechanisms driving coercion are evident at a fairly late stage of processing.

At first glance, these relatively late costs of coercion may seem to contradict the MEG findings of Brennan and Pylkkänen (2008) which, as discussed above, reported some increased neural activity prior to 500ms following the onset of critical words. However, as

[2]Here, we do not differentiate between a strong embodied cognition hypothesis in which event simulation is *necessary* for language comprehension, or a weak embodied cognition hypothesis, in which language comprehension is *augmented* by event simulation, see Clark (2008) and Dempsey and Shani (2012) for recent discussion.

noted above, these early MEG effects were quite short-lived and the authors did not examine activity after 500ms. It is therefore possible that neural activity associated with aspectual coercion was maximal past the time windows examined. Consistent with this idea, three recent event-related potential (ERP) studies report neural activity past 450ms in association with processing other types of complex event representations.

First, Bott (2010) observed a sustained anteriorly distributed negativity beginning at 500ms in association with another type of aspectual coercion—'additive coercion'. Here, the combination of a prepositional phrase and verb implied an event in addition to the one that was explicitly stated (e.g. original German: "In zwei Stunden hatte der Förster die Falle entdeckt"; English translation: "Within two hours, the ranger had discovered the trap". Here, the 'searching for the trap' event is implied but not explicitly stated. Second, Baggio, Lambalgen, and Hagoort (2008) reported a sustained anteriorly distributed negativity beginning at approximately 450ms after the onset of sentence-final verbs that signaled the need to shift an aspectual representation of an event from one that was ongoing to one that was prematurely terminated (e.g. original Dutch: "Het meisje was een brief aan het schrijven toen haar vriendin koffie op het papier morste"; English translation: "The girl was writing a letter when her friend spilled coffee on the paper"). Here, the non-completion of the letter-writing event is again inferred, but not explicitly stated. And, third, we (Wittenberg, Paczynski, Wiese, Jackendoff, & Kuperberg, 2014) recently observed a sustained negativity effect starting at 500ms after the onset of verbs in light verb constructions (e.g. original German: "Als die Stewardess eine Ansage machte…"; English translation: "When the stewardess made an announcement…"). Here, once again, the interpretation of the event cannot be based on surface structure alone: in order to come to a full interpretation of the 'announcing event', the subject must act both as the Agent of the main verb (e.g. 'made') as well as of the subsequent direct object argument (e.g. 'announcement')—a phenomenon known as 'argument sharing', which is also predicted to evoke additional processing due to semantic composition mechanisms (Culicover & Jackendoff, 2005).

In all three studies, the authors interpreted these late and prolonged negativity effects as reflecting the costs of computing or maintaining complex event representations within working memory (for other work linking sustained negativity effects with increased working memory demands during online language comprehension, see King & Kutas, 1995; Kluender & Kutas, 1993; Nieuwland & van Berkum, 2008a; Nieuwland & van Berkum, 2008b; van Berkum et al., 2003). Similar working memory costs may be incurred during aspectual coercion.

Others have argued that, during more naturalistic comprehension, aspectual coercion may be delayed still further. Pickering et al. (2006) point out that, in most of the behavioral studies described above, participants carried out a secondary task (for example, cross-modal lexical decision or plausibility judgment, although see Husband, Bretta, & Stockall, 2006), and that the additional working memory demands imposed by these tasks led participants to make an artificially early commitment to an aspectual interpretation.

Support for this idea comes from a series of four experiments reported by Pickering and colleagues (2006). Reading times and eye-tracking measures were examined as participants read the stimuli from Piñango et al. (1999) and Todorova et al. (2000b), but with no additional task demands. No coercion costs were observed either at the critical word (where aspectual coercion first became licensed), or at the three subsequent words. The authors suggested that, during word-by-word reading, in the absence of a superimposed task, comprehenders left the aspectual interpretation of the event underspecified until a later point when such information became needed.

1.3. The Present Study

In this study, we used event-related potentials (ERPs) to examine the neurocognitive mechanisms driving aspectual coercion. To date, there has only been one study using a direct neural measure to examine aspectual coercion—the MEG study by Brennan and Pylkkänen (2008). As discussed above, however, this study did not examine neural activity past 500ms after the onset of critical words where coercion costs may be maximal. Also, because MEG and EEG do not necessarily pick up on the same neural signals (MEG is less sensitive to radial sources than EEG, see Sharon, Hämäläinen, Tootell, Halgren, & Belliveau, 2007, for discussion), it is important to use both techniques to explore any particular neurocognitive mechanism. Here, we used ERPs to address two main questions. First, is any increased neural activity associated with aspectual coercion specific to enriched composition itself, or is it driven by real-world incongruities, aspectual shift or event iterativity? Second, without secondary task demands, at what point during online processing does the language parser engage in aspectual interpretation?

To exhaustively investigate the potential source(s) of activity associated with aspectual coercion within a single study, we utilized a 3 (context type) by 2 (verb type) design (see Table 1). The three types of contexts used were: punctive ('After several minutes'), durative ('For several minutes'), and frequentative/explicitly iterative ('Several times'). The two types of verbs used were: punctive and durative. Examples of sentences containing critical manipulations are shown in Table 1. Each critical sentence was embedded within a short narrative such that each was preceded by a sentence providing situational context and followed by a sentence describing a subsequent occurrence.

Both the *iterativity operator* and *real-world incongruity* hypotheses predict more activity to punctive verbs following durative contexts (*For several minutes the cat pounced…*, condition B, Table 1) than following either punctive (*After several minutes…*, condition A) or frequentative (*Several times…*condition C) contexts. However, whereas the *iterativity operator* hypothesis predicts a sustained negativity effect, reflecting the requirement to maintain, manipulate and/or select representations of event structure in working memory, (e.g. Bott, 2010; Baggio, Lambalgen, & Hagoort, 2008), the *real-world incongruity* hypothesis predicts an N400 effect, reflecting the mismatch between stored real-world knowledge and the meaning of the incoming word (Hagoort et al., 2004; Paczynski & Kuperberg, 2012). This N400 effect might then be followed by a P600, a posteriorly-distributed positive going component starting approximately 500ms post stimulus onset, which has previous been reported to severe violations of real-world knowledge (see Kuperberg, 2007, for review).

The *aspectual shift* hypothesis also predicts more neural activity to punctive verbs following durative contexts than those following punctive contexts. In addition, it also predicts more activity to punctive verbs following *frequentative* contexts. This is because both durative and frequentative contexts require a shift to an event representation with a non-trivial duration. This shift might also engage working memory resources, leading to a sustained negativity effect, similar to that reported by Baggio, Lambalgen, and Hagoort (2008) to shifts the event representation.

The *event iterativity* hypothesis makes the same predictions as the *aspectual shift* hypothesis. However, it also predicts increased neural activity to durative verbs following frequentative contexts. In other words, it predicts an effect on (a) punctive verbs following durative contexts, (b) punctive verbs following frequentative contexts, and (c) durative verbs following frequentative contexts. This is because all three cases require the simulation of multiple events, rather than a single event. Because such simulation would presumably engage working memory resources, it might also be associated with a sustained negativity effect. A summary of predictions made by all four hypotheses is given in Table 2.

Thus far, we have framed our predictions in terms of effects that are time-locked to the critical verb. However, as discussed above, Pickering et al. (2006) suggested that, when participants simply read for comprehension, aspectual information can remain underspecified and that costs associated with coercion only become apparent later, once comprehenders commit to an interpretation. Previous work from our group looking at a different type of enriched composition, complement coercion (Kuperberg et al., 2010), found an N400 effect at the point where coercion was first licensed, followed by an anterior *positivity* on the sentence-final word, which we interpreted as reflecting the retrieval from memory of a specific unstated event (e.g. in a sentence such as “The author started the book….,” this might mean retrieving “writing” as the unstated event). This finding suggests that, in some situations, comprehenders might indeed leave some aspects of event interpretation underspecified, only resolving it at the final word of the sentence. Thus, it is possible that some, or all, the differences between the conditions in our study would manifest *not* at the critical verb, where aspectual coercion is first licensed, but at the sentence-final word.

2. Methods

2.1. Development of Materials

Two-hundred-and-seventy scenarios were initially created, each with six experimental conditions. Each scenario consisted of three sentences. The first sentence provided an introductory context and was the same across experimental conditions (e.g. “Lilly’s kitty was always having small adventures.”). The second sentence always began with a context, which, depending on the experimental condition, was either 1) punctive, indicating a point in time when an event occurred (e.g. “After several minutes”), 2) durative, indicating a duration of time that the event encompassed (e.g. “For several minutes”), or 3) frequentative (i.e. explicitly iterative), indicating that more than one iteration of the event occurred (e.g. “Several times”). The context was then followed by a subject noun-phrase (e.g. “the cat”), followed by a critical verb which was either 1) punctive, describing a short, near-instantaneous action (e.g. “pounced”), or 2) durative, describing an action that could continue for an indeterminate amount of time (e.g. “prowled”). The critical verb was followed by a short (1-5 word) conclusion that made the sentence plausible (e.g. “on the rubber mouse,” “about the backyard”). Note that this conclusion necessarily differed based on verb type. However, we matched the length of this conclusion between the two types of verbs. A third sentence was added to provide a plausible continuation of the situation. Again, to maintain plausibility, the third sentence differed for a given scenario depending on the critical verb type, although its length was matched across verb types. The three types of contexts were crossed with the two types of verbs, resulting in six conditions of each scenario. Examples are given in Table 1.

In order to narrow down the stimulus set to those scenarios in which the combination of contexts and verbs resulted in the intended final sentence interpretation, a rating study was conducted. Forty undergraduate participants recruited from Tufts University completed the study, which was hosted online through SurveyMonkey.com. Six lists were created using a Latin Square design, such that each list contained one version of each scenario and, across all six lists, each scenario appeared in all six conditions. Sentences in each list were pseudo-randomized to ensure that no more than two consecutive sentences belonged to the same condition. Participants read only the first two sentences of each scenario. Each scenario was accompanied by a question asking how many times an action was performed (e.g. How many times did the cat pounce?). Participants indicated their response by selecting one of four options: 1) once, 2) one long time, 3) 2-10 times, or 4) more than 10 times.

The following exclusion criteria were then used to eliminate scenarios: 1) a punctive verb following a punctive context being rated as occurring more than once, 2) a punctive verb following a durative context being evaluated as occurring either once or for one long time, 3) a durative verb following either a punctive or a durative context being rated as occurring more than once (2-10 times or more than 10 times), and 4) a punctive or a durative verb following a frequentative context being evaluated as occurring either once or for one long time. In total, 57 scenarios were eliminated as one or more participant gave ratings that met exclusion criteria for one or more versions of a scenario. In order to allow for an even distribution of the remaining scenarios across the 6 lists, an additional 3 scenarios were eliminated, yielding a total of 210 scenarios in the final stimulus set.

Six counterbalanced lists were created, using a Latin Square Design, each containing 210 scenarios. Each list contained an equal number of scenarios from each of the six conditions (35 scenarios per condition per list), with each scenario appearing once in each list and, across all 6 lists, each scenario appearing in each of the 6 conditions. Each list was ordered pseudo-randomly to ensure that no more than two consecutive scenarios belonged to the same condition.

2.2. ERP Experiment

2.2.1. Participants—Thirty-seven undergraduate native English speakers from Tufts University were initially recruited. Data from seven participants were subsequently excluded from the analysis: six due to excessive ocular or muscular artifacts, and one due to recording error, leaving a total of thirty participants (17F/13M), age 18-25 (M=19.1, SD=1.7). All participants had normal or corrected-to-normal vision, were not taking psychoactive medications, had no learning disability, no history of neurological or psychiatric disorders, and had not learned languages other than English before the age of 5. All were right-handed as assessed through a modified version of the Edinburgh handedness inventory (Oldfield, 1971). Written consent was obtained from all subjects before participation according to the guidelines of Tufts University's Human Subjects Review Board. They were paid for their participation.

2.2.2. Stimulus presentation—Each participant was randomly assigned to one of the six counterbalanced lists (five usable participants per list). Participants sat in a comfortable chair in a dimly lit room, separate from the experimenter. Stimuli were presented on a video monitor. Each trial was preceded by the word "READY" and participants pressed a button to initiate the trial, which began with the first sentence of a scenario, which was presented as a whole in the middle of the screen. Once participants finished reading this first sentence, they pressed a button at which point the sentence was replaced by a fixation-cross displayed in the center of the screen for 500ms, followed by 100ms blank screen. The second and third sentences of the scenario were then presented, one word at a time (450ms with 100ms blank screen interstimulus interval, except for the final word of sentence 2, which was followed by a 500ms blank screen, and the final word of sentence 3, which was followed by a 750ms blank screen. In 10% of the trials, the blank screen at the end of sentence 3 was followed by a comprehension question about the preceding scenario, which participants answered with a button press. Questions were unrelated to aspectual information in order to avoid overtly biasing readers in making an immediate commitment to aspectual interpretation. They were randomly distributed throughout the experiment, with half requiring a "yes" response and half requiring a "no" response. Participants were asked to refrain from blinking or moving during the word-by-word presentation portion of each trial. Stimuli were presented in seven blocks of 30 trials, with short breaks between blocks. Participants viewed five practice trials before the start of the experiment.

2.2.3. Electrophysiological Recording—Twenty-nine tin electrodes were held in place on the scalp by an elastic cap (Electro-Cap International, Inc., Eaton, OH), see Figure 1. Electrodes were also placed below the left eye and at the outer canthus of the right eye to monitor vertical and horizontal eye movements, and on the left and right mastoids. Impedance was kept below 2.5 kΩ for all scalp and mastoid electrode sites and below 10 kΩ for the two eye channels. The EEG signal was amplified by an Isolated Bioelectric Amplifier System Model HandW-32/BA (SA Instrumentation Co., San Diego, CA) with a bandpass of 0.01 to 40 Hz and was continuously sampled at 200 Hz by an analogue-to-digital converter. The stimuli and behavioral responses were simultaneously monitored with a digitizing computer.

2.2.4. Data Analysis—ERPs were formed by averaging artifact-free trials off-line, all referenced to left mastoid. Trials were rejected if voltage in any channel exceeded 70μV or any channel contained 'blocking', i.e. voltage that remained identical over 20 consecutive time points (100ms). Trials were time-locked to the onset of the critical verbs as well as to sentence-final words in the second sentence, using a −50 pre-stimulus to +50 post-stimulus onset baseline[3]. ERPs were analyzed in 100ms intervals from 100ms to 1200ms post stimulus onset in order to determine the time-course of effects. In order to examine how the modulation of the waveforms varied across the scalp, the scalp was subdivided into regions along its anterior–posterior distribution, at both mid and peripheral sites (each region contained three electrode sites, see Figure 1). Two omnibus repeated-measures ANOVAs, one covering mid-regions (dark gray in Figure 1) and another covering peripheral regions (light gray in Figure 1) across the scalp, were conducted in each time window.

In the mid-regions omnibus ANOVA, the within-subject variables were Verb Type (2 levels: punctive, durative), Context Type (3 levels: punctive, durative, frequentative), as well as Anterior-Posterior (A-P) Distribution (5 levels: prefrontal, frontal, central, parietal, occipital), see Figure 1. Interactions between Verb Type and Context Type were followed up by examining the effects of Context Type at each level of Verb Type.

In the peripheral regions omnibus ANOVA, the within-subjects variables were Verb Type (2 levels: punctive, durative), Context Type (3 levels: punctive, durative, frequentative), A-P Distribution (2 levels: frontal, parietal) and Hemisphere (2 levels: left, right). Interactions were followed up as described above.

The Greenhouse-Geisser correction was used in cases with more than one degree of freedom in the numerator (Greenhouse & Geisser, 1959) to protect against Type 1 error resulting from violations of sphericity assumption. In these cases, we report the original degrees of freedom with the corrected p value. In all analyses, significance level was set at 0.05. Linearly interpolated voltage maps showing differences in ERP scalp distributions within the time windows of interest were produced using EEGLab (MatLab).

3. Results

Overall accuracy on the intermittent comprehension questions was high (M:86(8)%), indicating that participants closely attended to the stimuli.

3.1 Artifact rejection

Approximately 10% of trials were rejected due to muscular, ocular, or blocking artifact [Punctive/Punctive: 10.5 (6.1)%; Durative/Punctive: 11.4 (5.3)%; Frequentative/Punctive: 10.1 (6.4)%; Punctive/Durative: 9.3 (6.7)%; Durative/Durative: 9.4 (5.5)%; Frequentative/Durative: 11.2 (5.2)%]. A 3 (Context Type) X 2 (Verb Type) ANOVA showed no main effects or interactions between these factors ($Fs < 1$, $ps > 0.37$).

[3]We used this peri-stimulus baseline for analysis because, within the first 100ms, there appeared to be slightly larger positivity on durative verbs that followed punctive contexts, relative to durative verbs that followed other contexts. We attributed this effect to artifact in the pre-stimulus presentation time window because (a) the durative verbs used were identical across conditions (such early divergence is usually due to perceptual differences between stimuli), and (b) there were no differences in ERPs on the word that preceded these verbs. Our shift in the baseline by 50ms resolved this early effect on durative verbs (i.e. there were no significant effects within the 50-100ms time window). Importantly, our analysis of *punctive* verbs, where effects of aspectual coercion would be expected, was unaffected by choice of baseline.

3.2 Critical Verb in Sentence 2

There was no main effect of Verb Type or Context Type in any time windows examined, all Fs < 2.34, all ps > 0.13. Below, we report the Verb Type by Context Type interactions.

The Verb Type by Context Type interaction was not significant in the 50-100ms, 100-200ms, or 400-500ms time-windows, all Fs < 2.37, all ps > 0.13. The interaction approached significance between 300-400ms at both the mid-regions, $F(2,58)=2.85$, $p = 0.09$, and peripheral regions, $F(2,58)=2.75$, $p = 0.09$, due to a slightly larger negativity to punctive verbs following durative contexts than punctive verbs following punctive contexts.

Starting at 500ms and continuing through to 1200ms post-critical verb onset, the mid regions ANOVAs revealed Verb Type by Context Type interactions that reached or approached significance at each 100ms time window (except between 900-1000ms), see Table 3. In the peripheral regions analysis, the Verb Type by Context interaction only approached significance at a limited number of time windows, all Fs < 2.98, ps > 0.08.

To follow up these Verb Type by Context Type interactions in the mid-regions ANOVA, we carried out ANOVAs examining the effect of Context Type on the punctive and the durative verbs separately. There were no effects of Context Type on the durative verbs in any time-window (all Fs < 2.18, ps > 0.16), as can be seen in Figure 2. For punctive verbs, however, the main effect of Context Type was significant, or approached significance, between 500ms-1200ms post-stimulus onset, except for the 100ms interval between 900-1000ms, see Table 4. As can be seen in Figure 2., punctive verbs following durative contexts evoked a sustained negativity, relative to punctive verb following punctive contexts, with ERPs evoked by punctive verbs in frequentative contexts falling between the other two conditions. Follow-up pair-wise comparisons showed that punctive verbs following durative contexts evoked a larger negativity than punctive verbs following punctive contexts in all time windows examined, except between 900-1000ms (see Table 4 as well as Figure 3 for visualization of the time-course of this effect). Additionally, punctive verbs following frequentative contexts evoked significantly more negative ERPs than those following punctive contexts between 500-600ms. Moreover, this waveform did not diverge significantly from the waveform evoked by punctive verbs following durative contexts until 800ms. These negativity effects had a fairly widespread scalp distribution, although examination of Figure 2 suggests that they had a frontal focus.

3.3. Final Word of Sentence 2

Within the recording epoch following the final word of sentence 2, there were no significant main effects of Verb Type, Context Type, or Verb Type by Context Type interactions, in any time window, in either the mid- or peripheral regions ANOVAs (all Fs < 1.20 and ps > 0.1).

4. Discussion

In this study, we used ERPs to explore the timing and neurocognitive mechanisms associated with aspectual coercion. We found that punctive verbs in durative contexts evoked a late, sustained negativity between 500-1200ms, relative to punctive verbs in punctive contexts, and a late sustained negativity between 800-1200ms, relative to punctive verbs in frequentative contexts. These sustained negativity effects had a fairly wide scalp distribution, but a frontal focus (see Figure 3). In contrast, context did not modulate ERPs evoked by durative verbs. These data help distinguish between several potential mechanisms contributing to neural activity associated with aspectual coercion. They also indicate that, even when simply reading for comprehension in a word-by-word fashion, participants can make a commitment to aspectual interpretation within a few hundred milliseconds after it becomes syntactically licensed.

4.1 Distinguishing between neurocognitive mechanisms driving aspectual coercion

In the Introduction we considered four proposals that could account for previously observed online costs of aspectual coercion. The first two, which have previously been investigated, are specific to the contrast between sentence 1a and 1b. They posit that aspectual coercion costs are driven by either the engagement of a semantic iterative operator (the *iterativity operator* hypothesis*)* or the detection of real-world incongruity between the context and the verb (the *real-world incongruity* hypothesis). Additionally, we put forth two other proposals, which relate these costs more generally to either a *shift* in the aspectual representation of the verb (the *aspectual shift* hypothesis), or to the simulation of multiple events, as opposed to a single event (the *event iterativity* hypothesis). Our findings are most consistent with the *iterativity operator* hypothesis. Before discussing how our data support this account, we will first consider the three alternative hypotheses.

The *real-world incongruity* hypothesis, first put forth by Dölling (1995), states that, in processing sentences like 1b, comprehenders first attempt simple composition, which yields an interpretation that is inconsistent with real-world knowledge (e.g. a pounce lasting several minutes). Upon detecting this real-world incongruity, the interpretation is pragmatically revised to yield the appropriate final interpretation. This hypothesis predicted a centro-parietally distributed N400 effect between 300-500ms to sentence types B versus A —the effect that is classically seen to words whose semantic features mismatch expectations based on the interaction between context and real-world knowledge (e.g. Paczynski & Kuperberg, 2012). This might then be followed by a P600, an ERP associated with the detection of conflict and possibly revision of the input (see Kuperberg, 2007, for discussion). However, we saw no N400 or P600 modulation in this contrast; the divergence between the waveforms became significant only after 500ms and, at this point, we observed a sustained negativity effect with a more widespread/frontal distribution than the classic N400.

At first glance, the absence of an N400 effect in our study appears to contradict the MEG findings of Brennan and Pylkkänen's (2008). Recall that the authors observed an increase in neural activity between 340-380ms, which they interpreted as an N400 effect because its source localization overlapped with a region that had previously been implicated as a neuroanatomical source of the N400. In the present study, we did, in fact, observe a transient negativity within a similar time window (300-400ms), although it did not reach significance. However, because this effect was so short-lived and had a frontal focus, we do not think that it reflects an N400 response to violations of real-world knowledge expectations (the N400 real-world congruity effect is usually longer-lived and has a centro-parietal scalp distribution, see Hagoort et al., 2004; Paczynski & Kuperberg, 2012). It is possible that it reflected a brief detection of aspectual mismatch, which led to the later engagement of an iterativity operator. Indeed, it is worth noting that Brennan and Pylkkänen (2008) offered a similar explanation of their own transient 40ms MEG effect as a viable alternative to the *real-world incongruity* hypothesis. On this account, the late negativity effect observed in our own data reflected engagement of the iterativity operator itself to construct or select the final event structure, as discussed further below. Interestingly, although Brennan and Pylkkänen (2008) did not examine activity after 500ms, visual inspection of Figure 4 in their paper suggests the beginning of a substantial divergence in the waveforms between the coerced and non-coerced conditions starting at approximately 550ms post critical verb onset, which would be consistent with this account.

We found only limited support for the *aspectual shift* hypothesis. Specifically, the waveform produced by punctive verbs following frequentative contexts diverged from the waveform produced by punctive verbs following punctive contexts only between 500-600ms (although it did not differ significantly from the waveform evoked in the coerced condition until 800ms). It is possible that our study lacked the statistical power to detect what may have been a rather small effect of aspectual shift. Regardless, what these findings do indicate is that a shift in aspectual representation cannot, in and of itself, account for all neural activity associated with aspectual coercion.

Finally, our results rule out the *event iterativity* hypothesis. Although sentences with durative verbs following frequentative contexts described multiple iterative events, these verbs did not evoke more neural activity than durative verbs following either punctive or durative contexts.

The overall pattern of our findings across all conditions is most consistent with the *iterativity operator* hypothesis, which proposes that the costs of aspectual coercion are driven by the engagement of a plurality (Jackendoff, 1991) or iterativity (de Swart, 1998) operator, which leads to the construction or selection of a final event structure representation in which the punctive action is repeated to fill the time specified by the modifier. We suggest that the engagement of this operator required additional working memory resources to maintain, manipulate or select event structure information, and that the sustained negativity effect reflected the engagement of these resources. We return to the functional significance of this effect in the computation of complex event structures in section 4.3.

4.2. The timing of aspectual interpretation during online processing

The divergence in waveform in the aspectually coerced *versus* non-coerced sentences began soon after the onset of the critical verb that licensed coercion. This is consistent with the behavioral findings of Piñango and colleagues (1999, 2006), Todorova and colleagues (2000a, 2000b), Husband, Bretta, and Stockall (2006), and Brennan and Pylkkänen (2008), who all reported online costs soon after the aspectual interpretation was syntactically licensed. They also accord with the evidence reported by Piñango and colleagues (2006), suggesting that aspectual coercion costs manifest at a short delay, onsetting after the initial stages of lexical access.

These data, however, are less consistent with the null findings of Pickering et al. (2006) who found no evidence for coercion-related costs at, or within three words after, critical words in either reading-time or eye-tracking experiments. Importantly, however, Pickering et al. did not argue against aspectual coercion being computationally costly. Rather, they suggested that, under natural reading conditions, comprehenders leave the aspectual interpretation temporarily underspecified. They suggested that the effects of aspectual coercion seen in the studies by Piñango et al. (1999) and Todorova et al. (2000a) arose because, in these studies, the secondary tasks biased participants to make an artificial immediate commitment to an aspectual interpretation, rather than leaving it underspecified until necessary.

Our own findings of a sustained negativity effect soon after the aspectual interpretation first became licensed may, at first, appear to provide evidence against this proposal. This is because, similar to Pickering et al. (2006), participants in our study read for comprehension only. However, Pickering et al.'s stimuli did differ in one crucial respect from the stimuli used in the current experiment. In their study, the critical manipulation occurred within the first sentence presented—a stage at which one can reasonably assume that working memory demands would have been relatively low. In contrast, our critical manipulation was embedded within a larger discourse context, which is likely to have imposed more of a processing load (this is also true of many of the studies discussed in the next section, which also report sustained negativities in association with processing complex event structures). This may explain why readers made an earlier commitment to an aspectual interpretation. Future studies explicitly manipulating working memory load will be necessary to fully test this hypothesis.

4.3 Sustained late negativities during language processing

As noted in the Introduction, sustained negativity effects, similar to that seen in this study, have previously been reported in association with the processing of complex event structures, including another type of aspectual coercion. For example, Bott (2010) reported a sustained anterior negativity effect starting at 500ms after the onset of critical verbs in association with additive coercion, where an additional event is implied but not explicitly stated (e.g. a discovery event implies that a searching event must have occurred). Others have also found sustained negativities in situations requiring the elaboration of an aspectual event structure. For example, Baggio et al. (2008) reported a sustained anteriorly distributed negativity starting at 500ms following verbs that indicated that an event (e.g. a letter being written) had terminated prior to its expected completion (e.g. being interrupted by coffee spilling on the paper). And, most recently our group (Wittenberg et al., 2014) observed a late, sustained widely-distributed, but frontally focused, negativity from 500ms following verbs in light verb constructions (e.g. "Julius gave Anne a kiss")—another type of complex event structure in which the subject of the sentence acts both as the Agent of the verb and of the direct object (so-called argument sharing, cf. Jackendoff, 1974).

The common theme in all these studies is that the utterance conveys a more complex event structure than that which is evidenced in the surface event structure: in all three cases, the full interpretation of the event(s) cannot be derived purely by combining the meaning of the individual words with syntactic structure. One possibility is that these late-onset sustained negativity effects reflect the process of constructing or retrieving these more complex event structures, only after encountering the critical word itself. Another is that, prior to the critical word, comprehenders consider both a canonical and non-canonical event structure, and that the late, sustained negativity effect reflects a process of maintaining these representations and *selecting* the more complex, non-canonical event structure (i.e. enhancing its activation, and suppressing the activation of the more canonical event structure) in order to fully integrate the incoming word into its context. On either account, the late-onset sustained negativity effects are likely to reflect the increased working memory demands of maintaining and manipulating elements of the sentence, along with extra-sentential information, to construct the appropriate overall sentence meaning.

It is important to note that not all types of enriched composition are always associated with sustained negativities. For example, in previous work from our group looking at complement coercion, in which a sentence such as “The journalist began the article…,” must be interpreted as meaning “The journalist began [doing something with] the article…,” we found an N400 effect at the point of the critical word (see also Baggio et al.., 2010). This may be because, in the case of complement coercion, readers did not attempt to build a full event representation at the point of the critical NP (we found no difference in ERPs evoked by utterances with one dominant interpretation and those in which several were possible, see also Frisson & McElree, 2008). It will be necessary for future neurophysiological studies to directly compare these two types of enriched composition in the same participants.

5. Summary and Conclusions

In sum, the results of the current experiment are consistent with previous findings that iterative aspectual coercion is associated with processing costs during online comprehension. We show clear neural effects when comprehenders need to engage a morphosyntactically unrealized semantic operator to arrive at a coherent representation of a linguistically described event. During discourse comprehension, this operator is engaged approximately 500ms after the onset of verbs that first license the aspectual interpretation. Additionally, we were able to rule out a number of alternative explanations for processing costs associated with aspectual coercion. Finally, taken together with previous findings, our results add to a growing body of evidence that a set of late-onset sustained negativities reflect elaborative semantic processing that goes beyond simply combining the meaning of individual words with syntactic structure to derive the meaning of an event.

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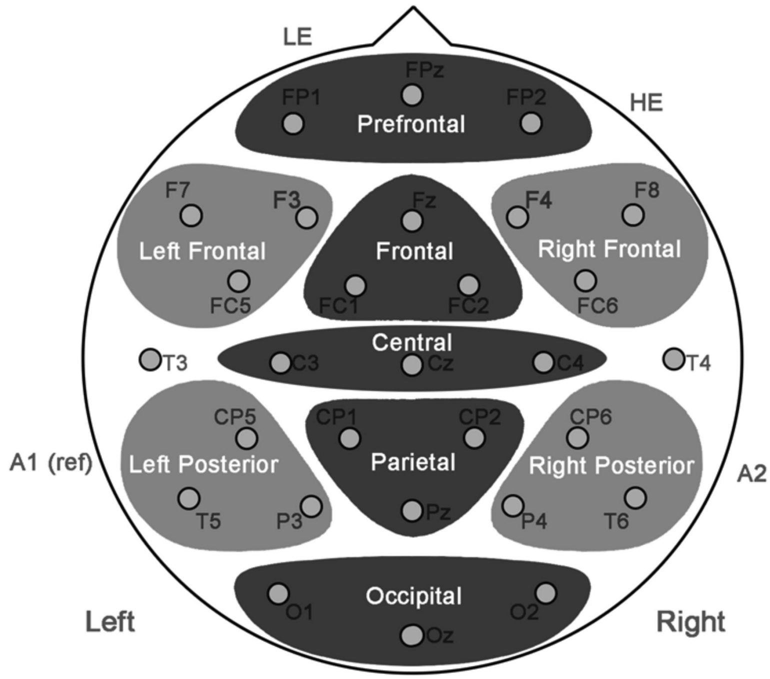

Figure 1. Electrode montage, including demarcation of regions used in analysis

For the purposes of statistical analyses, the scalp was divided into regions. Regions in dark grey were part of the mid-regions omnibus ANOVA and regions in light grey were part of the peripheral regions omnibus ANOVA.

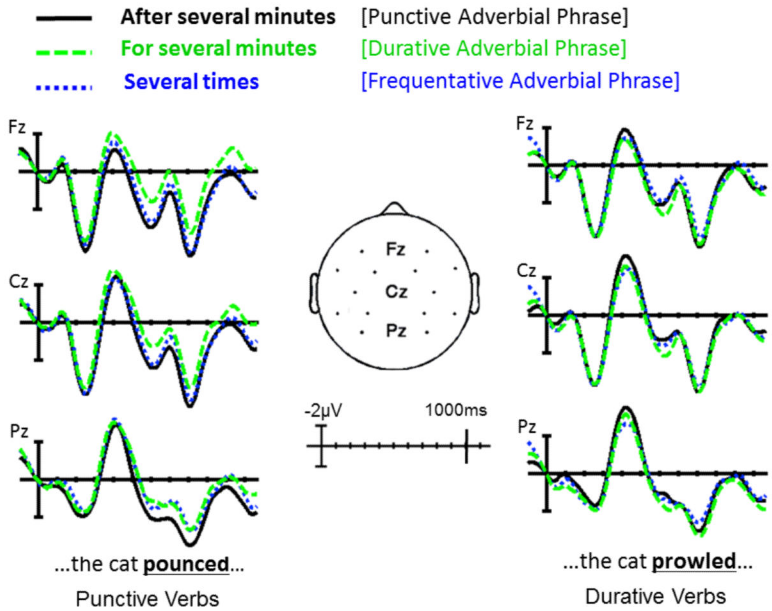

Figure 2. ERPs evoked by critical verbs at select electrode sites

ERPs to punctive verbs are presented on the left side of figure. ERPs to durative verbs are presented on the right side of figure. Solid black line indicates ERPs to critical verbs preceded by punctive adverbial phrases. Dashed green line indicates ERPs to critical verbs preceded by durative adverbial phrases. Dotted blue line indicates ERPs to critical verbs preceded by frequentative adverbial phrases. ERPs were low-pass filtered at 15Hz.

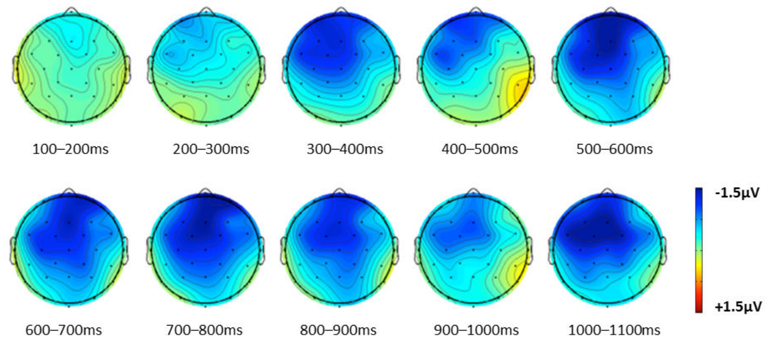

Figure 3. Voltage maps showing the time-course of the sustained negativity effect evoked by punctive verbs following durative adverbial phrases relative to those following punctive adverbial phrases

Table 1

Experimental condition.

Introductory Context Example: *Lilly's kitty was always having small adventures.*

Condition	Example Sentence with critical manipulation
A. Punctive Adverbial Phrase, Punctive Verb	*After several minutes the cat pounced on the rubber mouse.*
B. Durative Adverbial Phrase, Punctive Verb	*For several minutes the cat pounced on the rubber mouse.*
C. Frequentative Adverbial Phrase, Punctive Verb	*Several times the cat pounced on the rubber mouse.*
D. Punctive Adverbial Phrase, Durative Verb	*After several minutes the cat prowled on the rubber mouse.*
E. Durative Adverbial Phrase, Durative Verb	*For several minutes the cat prowled on the rubber mouse.*
F. Frequentative Adverbial Phrase, Durative Verb	*Several times the cat prowled on the rubber mouse.*

Table 2

Summary of predictions made by the four hypotheses about the mechanisms driving aspectual processing.

	N400	Late Sustained Negativity	P600
1. Iterativity operator hypothesis.	— —	B > A = C	— —
2. Real-world incongruity hypothesis	B > A = C	— —	B > A = C
3. Aspectual shift hypothesis	— —	B = C > A	— —
4. Event iterativity hypothesis	— —	B = C > A F > D = E	— —

X > Y: The amplitude of the specified ERP component (N400, Late Sustained Negativity, or P600) evoked by the critical verb in condition X is predicted to be larger than in condition Y.

X = Y: The amplitude of the specified ERP component (N400, Late Sustained Negativity, or P600) evoked by the critical verb in condition X. is predicted to be the same as in condition Y.

— —: No modulation of the specified ERP component is expected between any of the conditions.

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Table 3

F values for the results of the 3 (Verb Type) x 2 (Context Type) ANOVAs on the critical verb.

Time window (ms)	***Mid Regions ANOVA***				***Peripheral Regions ANOVA***		
	V	***C***	***V X C***		***V***	***C***	***V X C***
100-200	< 1	1.04	< 1		< 1	< 1	< 1
200-300	< 1	< 1	< 1		< 1	< 1	< 1
300-400	1.03	< 1	**2.85**^		< 1	< 1	**2.75**^
400-500	1.66	< 1	2.35		2.37	< 1	1.81
500-600	< 1	1.16	**4.22***		< 1	< 1	**2.98**^
600-700	< 1	< 1	**4.06***		< 1	< 1	**3.13**^
700-800	< 1	1.55	**2.51**^		2.10	< 1	1.45
800-900	< 1	< 1	**4.43***		< 1	< 1	1.94
900-1000	< 1	< 1	1.73		1.68	< 1	< 1
1000-1100	2.34	< 1	**3.51***		2.65	< 1	**2.60**^
1100-1200	1.26	< 1	**4.00***		1.28	< 1	**2.71**^

V: Main effect of Verb Type

C: Main effect of Context Type

V X C: Interaction between Verb Type and Context Type

Degrees of Freedom:

Verb Type: 1, 29

Context Type: 2, 58

Verb Type by Context Type: 2, 58

** $p < 0.01$

^ $p < 0.10$,

* $p < 0.05$,

Table 4

F values for ANOVAs on critical punctive verbs only

	Mid Regions			
Time window (ms)	***C***	***D v P***	***D v F***	***F v P***
500-600	**5.82****	**12.77****	2.30	**4.77***
600-700	**2.61**^	**4.64***	2.83	1.94
700-800	**3.96***	**4.93***	2.79	3.89
800-900	**4.46***	**9.47***	**12.31****	< 1
900-1000	1.99	— —	— —	— —
1000-1100	**4.62***	**8.14***	**12.39****	< 1
1100-1200	**4.49***	**8.47***	**5.52***	1.89

C: Main effect of Context Type

P v D: Punctive vs. Durative Context Type

P v F: Punctive vs. Frequentative Context Type

D v F: Durative vs. Frequentative Context Type

Degrees of Freedom:

C: 2, 58

P v D, P v F, D v F: 1, 29

— —: No pair-wise comparison carried out due to lack of main effects of Context Type.

^ $p < 0.10$,

* $p < 0.05$,

** $p < 0.01$