The Costs of Zero-Derived Causativity in English: Evidence from Reading Times and MEG

Lisa Levinson and Jonathan Brennan

Abstract

This paper investigates the processing of lexical causative verbs in English as a means to provide insight into long-standing debates in this domain and to explore methods for comparison of words which are phonologically-identical but vary at other levels of representation. Verbs such as *melt* can be used in both transitive and intransitive contexts, which have been argued to vary not only in the number of thematic arguments, but also in semantic, morphological, and syntactic representation. Hypothesizing that the transitive variants contain additional causativity, we predicted that they would induce greater processing cost that could be attributed to greater lexical semantic complexity. In order to test this prediction, we included in each study pairs of activity verbs which alternate in transitivity but not causativity. Two self-paced reading studies confirmed our prediction, demonstrating an interaction such that transitive verbs in the causative condition took significantly longer to process than intransitive verbs, a pattern that was not reflected in the activity condition. A further magnetoencephalography study tested for neural activity associated with different levels of linguistic processing and provides insight into the nature of the behavioral delay. The behavioral findings suggest that the transitive variants in the lexical causative alternation are more complex than the intransitives at some level of representation, despite their phonological identity. The MEG study provides a profile which is suggestive of a link with lexical or morphological complexity.

1 Introduction

At the core of any pursuit of understanding language and linguistic processing is the representation of the basic units of computation. One of the central issues in identifying the atomic units of lexical representation is the difficulty of establishing the degree of semantic and morphological complexity at the sublexical level. One such problematic case is in the domain of the cross-linguistic lexical causative alternation, exemplified by the English example in (1):

(1) a. The sun melted the ice.
    b. The ice melted.

Linguists have observed that many languages contain pairs of transitive and intransitive verbs such as these where the transitive verb appears to contribute additional causative meaning. In languages like English this alternation is realized without any change in the phonological form of the verb. This has led to the transitive forms being called 'zero-derived causatives.' However, the transitive verbs in this alternation do not share all of the properties of either periphrastic (2) or synthetic 'syntactic' causatives, marked with causative affixes, found in other languages (3):

(2) The teacher made the student take the exam.

(3) Hanako-wa Yoshi-o ik-ase-ta
    Hanako-T Yoshi-A go-**CAUSE**-past
    'Hanako made Yoshi go.' (Japanese syntactic causative, Kuroda (1965))

Unlike the class of syntactic causatives, the transitive variants in this alternation do not introduce a causative event which is completely independent from the caused event, and accordingly do not permit as wide a range of independent syntactic modifiers of the causing and caused event as do syntactic causative verbs (Shibatani 1976). Thus Shibatani calls this alternation the 'lexical' causative alternation, since it has been argued that the derivation of the causative verb is a lexical, rather than than syntactic, process. This terminology will be adopted here informally, without any assumption that the process is indeed an operation in the lexicon. Along with these syntactic and semantic differences, the lexical alternation differs from other causative alternations in being potentially realized without overt morphological distinctions, as in English. Since Lakoff's (1965) Generative Semantics analysis of lexical causatives, there has been much debate regarding the representation of the variants in this alternation, and especially the status of this 'lexical' causativity and its relation to the syntactic derivation and compositional semantics.

Semantically, the observation that sentences such as (1a) entail sentences with the intransitive counterpart such as (1b) has led many to analyze the transitive as semantically containing the same core meaning of the intransitive and adding a causative component, sometimes described as a predicate named CAUSE. This type of analysis might break down the two verbs into a root and predicates as in (4)[1]. Here the idiosyncratic meaning of the verb *open* is represented as a root (set in lowercase letters) which is compatible with both transitive and intransitive contexts. The predicates CAUSE and BECOME combine with this root to produce the different variants of the verb.

(4) a. [BECOME [open]] = intransitive *open*
    b. [CAUSE [BECOME [open]]] = transitive *open*

Here the BECOME predicate contributes the change-of-state semantics usually found in the lexical causative alternation. Although the details of this type of analysis vary, many have proposed analyses which assume this type of contrast in semantic complexity (McCawley 1968, Dowty 1979, Parsons 1990, Pesetsky 1995, Harley 1995, Pylkkänen 2002, Alexiadou et al. 2006, Rappaport Hovav and Levin to appear)[2]. We will describe such analyses as *causativization* theories.[3]

On the other hand there are also *anticausativization* theories, which posit that causativity is contained in both variants, but that a reflexivization operation or other process derives the intransi-

---

[1] The semantic predicate representations given here are greatly simplified and collapse over many possible finer-grained distinctions regarding the semantics of the predicates themselves for the sake of exposition.

[2] For Alexiadou et al. (2006), the additional complexity in the English transitive is analyzed not as the addition of a CAUSE head as represented in (4), but the addition of a voice head which introduces the external argument. Both forms would contain CAUSE and neither would have a separate BECOME predicate.

[3] We do not intend by use of the term 'causativization' that the transitive form must be derived from the intransitive form via a causativizing operation per se, or vice versa for anticausativization theories discussed below. The theories cited vary in whether they follow such an approach or whether one form is simply a more semantically complex representation built up from the same root as the other. See Piñón (2001) for discussion of independent derivation of the transitive and intransitive.

tive form. Such an operator would bind the external argument or causer which is overtly expressed only in the transitive (Chierchia 1989, Levin and Rappaport-Hovav 1995, Reinhart 2002), as in (5):

(5) a. [REFL [CAUSE [(BECOME) [open]]]] = intransitive *open*

b. [CAUSE [(BECOME) [open]]] = transitive *open*

The third logical possibility is that the two variants are equally semantically complex. Although this could be viewed as the null hypothesis, there is a more nuanced interpretation of this possibility as well. One type of analysis which roughly falls into this group is that of Piñón (2001). Piñón argues that neither variant is derived from the other, but that both are derived directly from a complex root either in combination with causative or inchoative semantics. A simplified sketch his theory would be as in (6).

(6) a. [BECOME [open]] = intransitive *open*

b. [CAUSE [open]] = transitive *open*

However, Piñón's actual analysis is much more semantically detailed and the representations equivalent to BECOME and CAUSE are not equally complex themselves. If evaluating by the number of arguments and quantificational operators involved, the intransitive appears to be more semantically complex, which would reduce the analysis to an anticausativization analysis for our current purposes.

As can be seen from the wide variety of references, this topic is one of long-standing and frequent debate. The fact that questions involving "silent" alternations in meaning have proven challenging to resolve with "traditional" linguistic data suggests an opening for alternative approaches to understanding the lexical causative alternation in English. To this end, our objective in this study was to determine whether we could find experimental evidence in support of either side of the debate and establish a foundation for contributing to these theoretical debates with new kinds of data.

1.1 Levels of Complexity

Another dimension of the continuing debate regarding the linguistic representations of such verbs is the level of representation at which a difference in complexity might be observed. Some theories posit that this complexity is present solely at the level of lexical semantic representation. Levin and Rappaport-Hovav's (1995) theory would fall into this category, as differences between the intransitive and transitive variants would be represented in the lexicon. In their view, the lexicon is not only a locus of representations but also of operations. Bittner (1999) attributes the difference in complexity to a higher-level semantic operation. She proposes that lexical causatives involve a semantic shift operation.

Other theories, such as those of Pesetsky (1995), Harley (1995) and Pylkkänen (2002), propose that additional semantic complexity in the transitive variant is reflected at the level of morphology and syntax. That is, the causative semantics are introduced by a syntactic head which is realized as a silent causative affix. Alexiadou et al. (2006) also propose an analysis in this vein, whereby the additional morpheme in the transitive is a voice head which introduces the agent argument, rather than a head introducing causative semantics which they analyze as being present in both the intransitive and transitive variants. Analyses which posit that the intransitive variant is more complex, such as that of Chierchia (1989), typically are based on languages in which there is an additional reflexive morpheme for that variant. Thus one might posit that there is an additional unpronounced reflexive morpheme in languages such as English.

These debates have also been ongoing in the literature and are not easily addressed in behavioral experiments. For this reason, we further aimed to establish the neural profile of the processing of verbs in this alternation such that they could be evaluated in the context of previous work identifying neural correlates of lexical, morphological, syntactic, and semantic processing.

1.2 Lexical Semantic Complexity in Processing

Previous psycholinguistic work has found processing correlates of lexical semantic complexity in verbs (McKoon and MacFarland 2000, 2002, Gennari and Poeppel 2003). McKoon and MacFarland (2000) investigated the proposed distinction in representation between English verbs denoting externally- and internally-caused events. Levin and Rappaport-Hovav (1995) proposed that some verbs are associated with causes that arise from the theme of the verb. For example, an event of blooming is caused by conditions of the plant blooming itself, rather than due to any external cause. Levin and Rappaport-Hovav argue that verbs representing such events do not encode a causative predicate. They contrast this class with verbs like *break* which typically encode events with causes external to the theme undergoing to event. These they argue do encode causativity in both intransitive and transitive contexts. With corpus studies, McKoon and MacFarland (2000) first found evidence for a distinction between the thematic arguments found with the two classes. In transitive contexts with concrete themes, verbs of external causation occurred with a broader range of subjects than those with internal causation. For example, the latter seldom occur with animate subjects. They then looked for behavioral correlates of the contrast between the two classes, predicting that verbs of external causation would induce greater processing cost due to their additional causative semantics. They predicted that the processing cost would correlate with the lexical semantics of the verb, and not factors such as probability of transitivity which would be predicted to drive processing cost in constraint-based models along the lines of MacDonald et al. (1994). In two separate experiments they confirmed their prediction. Response times to post-stimulus acceptability judgment tasks showed a significant delay for verbs of external causation in comparison with verbs of internal causation, in both transitive and intransitive contexts. McKoon and MacFarland (2002) present further evidence in support of these conclusions. These studies provide evidence for an additional complexity in external causation verbs, independent of transitivity.

Gennari and Poeppel (2003) also investigated the processing costs of lexical semantic representations with respect to event structure. They compared English eventive verbs like *break* with stative verbs such as *deserve*, testing the prediction that the former are more complex than the latter. In the first self-paced reading study, they found that eventive verbs had significantly slower response times than stative verbs. In a second visual lexical decision task they observed that eventive verbs were significantly slower to be recognized than stative verbs. These results support the hypothesis that eventive verbs have, as they say, greater “semantic-conceptual complexity.”

These previous studies, in comparing distinct verbs across conditions, do not tease apart linguistic complexity from more general conceptual complexity associated with the verb root. The lexical causative alternation provides a novel opportunity to assess the processing of verbs which are phonologically identical, yet vary in meaning and argument structure. Comparing the different variants of the same root requires special attention, however, in order to disambiguate the usage of the word. Lexical processing is often studied using words in isolation, as in lexical decision tasks, which cannot be used to tease apart the different uses of individual words. This is an important gap to be filled, however, as many verbs participate in ‘silent’ alternations of this kind (Levin 1993). Thus one goal of this paper is to contribute to the development of methods which can control for word interpretation, for example by using a disambiguating sentential context.

In this study, by comparing transitive and intransitive variants of the same verbs in English, we were able to test whether processing differences can be observed even when the conceptual ‘encyclopedic’ contributions of the stimuli are matched. Such a finding would suggest that this cost is due to linguistic factors beyond the conceptual meaning of verb roots. As discussed above, such complexity has been variously proposed to be due to a purely lexical semantic complexity, a semantic coercion operation, or an added silent morpheme and syntactic head. A further aim of this study was to use magnetoencephalography (MEG) to test for previously hypothesized neural correlates of these linguistic operations or representations in the processing of the transitive as opposed to intransitive variants.

2 Deriving Behavioral Predictions

Given that previous work has found processing costs due to lexical semantic complexity (McKoon and MacFarland 2000, 2002, Gennari and Poeppel 2003), predictions from the theories discussed above can be schematized as in Table 1.

Based on findings discussed in Levinson (2012) which support the view that the transitive

Theory	Predicted Cost
Anticausativization	Intrans > Trans
Equal Complexity	Intrans = Trans
Causativization	Intrans < Trans

Table 1: Behavioral Predictions of Linguistic Theories

variants in the alternation contain more complex causative semantics across languages, we hypothesized that the transitive variants would be semantically more complex, as in causativization theories. Thus our hypothesis predicts that transitive variants should lead to greater processing cost in comparison with the intransitive variants. These predictions were tested behaviorally with two self-paced reading experiments discussed in the following sections.

3 Experiment 1

For the first experiment we used a self-paced reading design to test for processing costs associated with causativity. Shapiro et al. (1987) found that in cross-modal priming, reaction times were delayed for verbs with a greater number of syntactic frames, and were not modulated by the number of arguments. Nevertheless, in order to control for the transitivity difference between causative and non-causative variants of alternating verbs (i.e. the different number of arguments), we also included a control condition that varied only in transitivity using activity verbs as in (7):

(7) a. She ate.

b. She ate an apple.

These activity verbs are optionally transitive, but there is no shift in thematic role of the subject. In both variants, the subject is the agent. The theme object is optionally expressed. Although the number of arguments differs, the verb meaning is constant; there is no additional event represented in the transitive variant. There are aspectual distinctions between the sentences in (7), but these can be independently attributed to presence or absence of the theme and not the verb itself. Both types of verbs are assumed to participate in the same number of frames (either one or two depending one one's assumptions regarding the level of representation at which the frames are linked, as discussed for optionally transitive verbs by Shetreet et al. (2009a).) Thus these verbs serve as a control for causativity - while they also vary in transitivity, they do not vary in causativity. Causativization theories predict that transitive variants in the causative alternation will induce a processing cost due to causativity that will not be found with transitive variants in the activity alternation.

3.1 Methods

3.1.1 Participants

Thirty-two native speakers of English (twenty-one female) between ages 18 and 53 (M=25) participated in the study.

3.1.2 Stimuli

To test our predictions, it is important to directly compare reading times of phonologically identical verb variants in transitive and intransitive contexts. To do this, we used questions for stimuli sentences and preposed the object wh-phrase in transitive contexts. Preposing the object allows for disambiguation of the transitivity of the verb prior to presentation of the verb itself so that response times can be compared between otherwise identical intransitive and transitive forms. The stimuli containing intransitive verbs had preposed adjunct wh-phrases. Prior work has shown that subject animacy may bias syntactic expectations for passive or active verb phrases (Ferreira 1994). Accordingly, animacy was held constant across transitive and intransitive contexts: Inanimate subjects were paired with causative verbs and animate subjects were paired with activity verbs to ensure felicity. The experiment materials included 37 quadruplets of this kind. The four conditions were as exemplified in Table 2.[4]

---

[4] Stimuli for this and all experiments in the paper can be found at http://sites.lsa.umich.edu/cnllab/output/.

Sentence	Condition	Transitivity	Label
What did the lever open in the little dollhouse?	Causative	Transitive	TransCaus
When did the door open in the little dollhouse?	Causative	Intransitive	IntransCaus
What did the intern clean over the long weekend?	Activity	Transitive	TransAct
When did the intern clean over the long weekend?	Activity	Intransitive	IntransAct

Table 2: Experiment 1 Stimuli Examples

The 37 quadruplets were split into two lists so that no participant saw the same verb more than once. The trials were pseudorandomized to distribute the conditions and fillers evenly across the experiment.

In addition to the experimental stimuli, the study included 111 fillers. These fillers included anomalous object and adjunct wh-questions and a combination of acceptable and anomalous declarative sentences. Each subject saw 18 or 19 sentences from each experimental condition (74 total), 41 anomalous questions, 40 acceptable declarative fillers and 30 unacceptable declarative fillers. Thus the total percentage of acceptable sentences was 62%. Example filler sentences are provided in (8)-(11).

(8) The speaker said the people the story before the meal.

(9) The genius programmed the robot to dance like a ballerina.

(10) When did the attendant rain for the trip to Europe?

(11) What did the mug fancy above the counter?

3.1.3 Procedure

The study materials were presented to the participant on a 17-inch LCD monitor with 1280x1024 resolution using E-Prime software (PST Inc, PA.). The text was black on a grey background and stimuli were in size 18 courier new font.

Before the main experiment, participants completed 10 practice trials. They were required to achieve 80% accuracy on the trials before continuing to the experimental trials.

Each trial started with a fixation cross in the center of the screen. After 500 ms, a series of dashes corresponding to words in the sentence appeared on the screen. Participants used the center button of a PST three-button Serial Response Box to reveal the sentence word-by-word at their own pace. After the final word in the sentence was presented, a question mark appeared. The subject was instructed to respond to this question mark with button 1, labeled 'Y' if the sentence was natural, and with button 3, labeled 'N' if the sentence was unnatural.

Participants were instructed to read at a pace that would allow them to correctly answer comprehension questions and were given 4 seconds to complete the sensicality task presented after each sentence.

3.1.4 Data Processing

We analyzed reading times at the target verb and on the two immediately subsequent words. Only trials that were rated as acceptable were entered in to the analysis. One outlier subject with overall accuracy below 70% was removed from analysis, as were trials for four outlier items that had overall acceptability ratings below 60%. Individual reaction times below 200ms and above 2000ms were also removed as outliers (6% of all data points).

3.1.5 Data Analysis

Reading times were analyzed using mixed effects models (Baayen 2007, Baayen et al. 2008) in the lme4 package (Bates and Maechler 2009) in the R statistical software environment (R Development Core Team 2006). Log-transformed reading times were modeled for each phrase with fixed effects of verb type (causative, activity) and transitivity, as well as their interaction. Also included as fixed effects in our models were phrase length (in letters), per-trial reading time on the pre-verbal region, mean by-item accuracy, trial order, verb written frequency (log transformed, from the HAL corpus via the English Lexicon Project), as well as an estimate of the relative frequency that each verb appeared in a transitive frame (based on Google hit counts in transitive and intransitive frames[5]). Random intercepts were included for both subjects and items.

Markov-chain monte-carlo (MCMC) sampling was used to estimate *p*-values for the reading

---

[5] Results were qualitatively the same when this factor was excluded.

time effects effects (Baayen 2007). The same pattern of statistical reliability was also observed using likelihood ratio tests; only likelihood-ratio tests were used to evaluate effects from logistic regressions against binomial acceptability judgments, as MCMC sampling is not yet available in the lme4 package for such models.

3.2 Results

Reading times at the verb and on the two following regions are shown in Figure 1. There was a significant interaction between verb type and transitivity at the verb, $\beta = .075, SE = .25, p_{mcmc} < .005$. Resolving the interaction showed that causative transitive verbs elicited longer reading times ($M = 557ms$) than their intransitive variants ($M = 522ms$), $\beta = .055, SE = .019, p_{mcmc} < .005$; no difference was found between transitive and intransitive activity verbs ($M = 505ms$ and $M = 516ms$ respectively, $p_{mcmc} > .2$).

A significant interaction was also observed on the phrase immediately following the verb, $\beta = .176, SE = .024, p_{mcmc} < .001$. Resolving this interaction showed longer reading times for causative transitives ($M = 482ms$) compared to intransitives ($M = 447ms$), $\beta = .086, SE = .016, p_{mcmc} < .001$, as well as shorter reading times for transitive activities ($M = 458ms$) compared to intransitives ($M = 517ms$), $\beta = -.083, SE = .018, p < .001$.

The interaction remained significant at two words after the verb, $\beta = .100, SE = .024, p_{mcmc} < .001$, however there was no pairwise effect between transitive and intransitive causative verbs ($M = 429ms$ and $M = 419ms$ respectively, $p_{mcmc} > .1$). Rather, the interaction was driven by a sustained increase in reading times for intransitive activity verbs ($M = 479ms$), compared to transitive activities ($M = 449ms$), $\beta = .070, SE = .017, p_{mcmc} < .001$.

Results from the off-line acceptability judgments are shown in Table 3. Analyses revealed a significant interaction effect for acceptability differences ($\chi^2(1) = 96, p < .001$) such that causative transitives were rated less acceptable on average than causative intransitives, while transitive activities were rated more acceptable than intransitive activities. The same trend was also reflected in the off-line reaction times, though the interaction term did not reach significance for that measure

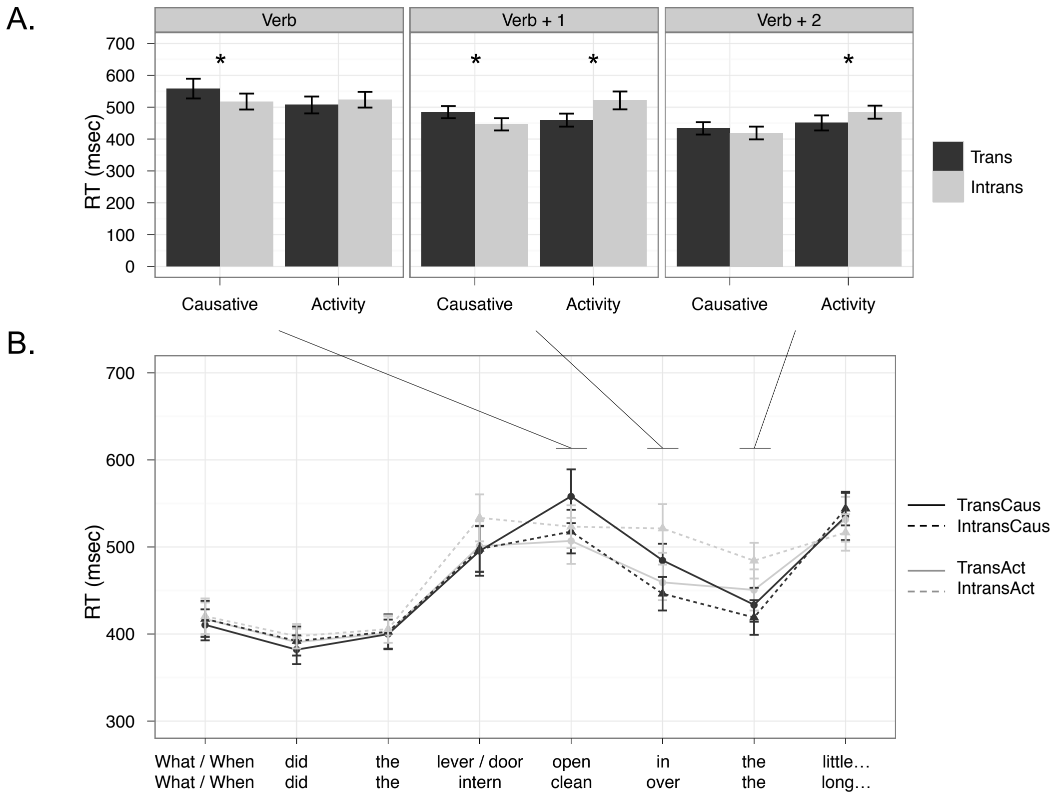

Figure 1: Reading times results from experiment one. (A) Bar-plots showing mean reading times for the verb and the two words immediately following the verb. Asterisks indicate significant pairwise effects in the context of significant interactions between verb type and transitivity. Error bars indicate standard error of the mean. (B) Word-by-word reading times from the beginning of the trial into the spill-over region for Causative (black) and Activity (grey) verbs in the Transitive (solid) and Intransitive (dotted) conditions.

($p_{mcmc} > .1$).

In summary, we found reliably longer reading times for causativization at the verb and at the region immediately following the verb.

	Trans RT, ms (SEM)	Intrans RT, ms (SEM)	Trans Acc, % (SEM)	Intrans Acc, % (SEM)
Causative	634 (34)	552 (26)	77 (3)	93 (1)
Activity	516 (24)	671 (42)	94 (1)	83 (3)

Table 3: Experiment 1 Offline Acceptability

3.3 Experiment 1 Discussion

The results of experiment 1 support causativization hypotheses for the lexical causative alternation. The interaction effect demonstrates that the longer reading times observed in transitive causatives is not due to the additional argument, which is also present in the transitive activity condition[6]. The requirement that subject animacy be matched, enforced due to previous observations that subject animacy biases verb phrase processing (Ferreira 1994), led to an acceptability mismatch between intransitive and transitive variants which could be linked with the delay in the transitive. While the statistical analysis accounted for acceptability differences between conditions in experiment 1, experiment 2 was designed to determine whether the results would persist with items that were precisely matched in terms of acceptability rather than animacy.

4 Experiment 2

The results from Experiment 1 suggest that there is a processing cost for causativity. However, the stimuli were also found to show an over-all acceptability difference such that causative transitives were rated less acceptable than their intransitive counterparts. Also, intransitive activity verbs were rated less acceptable than their transitive counterparts. An RT difference that mirrored this acceptability pattern emerged on the first word after the verb; it is possible than this acceptability difference might have contributed to the RT differences between causative transitives and intransitives on and immediately after the verb.

To address this concern, we conducted a second experiment in which acceptability was matched across conditions. To achieve this matching, it was necessary to relax the constraint that all subjects in our lexical causative sentences must have the same animacy.

---

[6] See section 5 for a discussion of the longer reading times for intransitive vs. transitive activities, which was not the driving factor for the significant interaction found at the verb and word following the verb

4.1 Methods

4.1.1 Participants

Thirty-eight native speakers of English (30 females) between ages 18 and 39 participated in the study.

4.1.2 Stimuli

The conditions for experiment 2 were the same as experiment 1 except that sentence acceptability was matched instead of controlling for subject animacy. This allowed for sentences in the transitive causative condition of experiment 1 such as “What did the explosion sink near the harbor?” to be replaced with “What did the fisherman sink in the lake?”.

Sentence	Condition	Transitivity	Label
What did the fisherman sink in the lake?	Causative	Transitive	TransCaus
When did the paddle sink in the lake?	Causative	Intransitive	IntransCaus
What did the the couple pack for the vacation to Thailand?	Activity	Transitive	TransAct
When did the the couple pack for the vacation to Thailand?	Activity	Intransitive	IntransAct

Table 4: Experiment 2 Stimuli

In this set of stimuli, subjects in the causative condition were mixed between inanimate and animate, depending on what was most felicitous. In order to match acceptability, a web-based rating study was conducted on 80 lexical causative and 80 activity pairs (160 sentences total). 64 participants rated sentence acceptability on a scale from 1 (not acceptable) to 7 (acceptable).

From the rated stimuli, we selected 43 lexical causative pairs and 44 activity pairs that were as well matched on acceptability as possible. Averaged ratings are shown in Table 5. There was no significant interaction between verb and transitivity on judgments, $F(1, 63) = 1.7781, p > .1$, nor was there any difference between causative transitive and intransitives ($t(63) = -1.02, p > .3$). We were unable to identify an adequately sized subset of activity pairs for which there was no effect of transitivity, $t(63) = -3.29, p < .01$. As any predicted effects will be tested both for an interaction and by a pairwise comparison among causative verbs, we deemed this partial matching acceptable with respect to the specific hypotheses under consideration.

	Transitive Rating (SEM)	Intransitive Rating (SEM)
Causative	4.33 (.16)	4.25 (.16)
Activity	4.47 (.14)	4.31 (.16)

Table 5: Norming Study Results for Matched Stimuli

The quadruplets were split into two lists so that no participant saw the same verb more than once. The trials were pseudorandomized to distribute the conditions and fillers evenly across the experiment.

101 fillers were included in the experiment. As in experiment 1, these fillers included anomalous object and adjunct wh-questions and a combination of acceptable and anomalous declarative sentences. Each participant saw 21 or 22 sentences from each experimental condition (87 total), 41 anomalous questions, 45 acceptable declarative fillers and 15 unacceptable declarative fillers. 70% of the sentences were intended to be acceptable.

4.1.3 Procedure

The procedure for experiment 2 was identical to that of experiment 1.

4.1.4 Data Processing

Data pre-processing and statistical analysis followed the same procedures used for Experiment 1. Only acceptable trials were entered into the reading time analysis (86% of all trials). One subject was excluded due to overall accuracy below 70%, and six items were excluded due to overall acceptability below 60%. One additional item was excluded due to a typo in the stimulus. Individual reading times below 200ms and above 2000 ms were also removed (6% of all data points).

4.1.5 Data Analysis

The statistical procedures were identical to those used in Experiment 1.

4.2 Results

We first discuss the offline judgments to evaluate whether acceptability was successfully controlled. Table 6 shows off-line acceptability and reaction times. Acceptability judgments reflect that the conditions were relatively well matched on this property. In fact, this set of transitive causatives were rated slightly more acceptable than their intransitive counterparts. Crucially, there was no pairwise difference in acceptability between causative transitives and intransitives. There was a statistically reliable difference among the activity verbs, in-line with the results from the norming study, whereby intransitive activities were judged less acceptable than their transitive counterparts, $\chi^2(1) = 17.8, p < .001$. There were no statistically significant effects for reaction times.

	Trans R, ms (SEM)	Intrans RT, ms (SEM)	Trans Acc, % (SEM)	Intrans Acc, % (SEM)
Causative	615 (36)	623 (37)	87 (2)	85 (2)
Activity	572 (36)	672 (41)	90 (1)	84 (2)

Table 6: Experiment 2 Offline Acceptability

Turning to the on-line reading times, Figure 2 illustrates the average reaction times for each condition at and after the verb. No significant interaction was observed at the verb. A significant interaction emerged at the word immediately following the verb, $\beta = .075, SE = .022, p_{mcmc} < .001$. Resolving this interaction by verb type confirmed that the interaction was driven by a combination of reliably longer reading times for causative transitives ($M = 464ms$), compared to intransitives ($M = 440$), $\beta = .039, SE = .016, p_{mcmc} < .05$, and longer reading times for activity intransitives ($M = 480ms$) compared to transitives ($M = 455ms$), $\beta = .037, SE = .016, p_{mcmc} < .05$.

No significant effects were observed at the second word following the verb.

In summary, we found significantly longer reading times associated with causativization at the word immediately following the verb, and this result could not be explained as a function of acceptability differences between transitive and intransitive variants of the causative verbs.

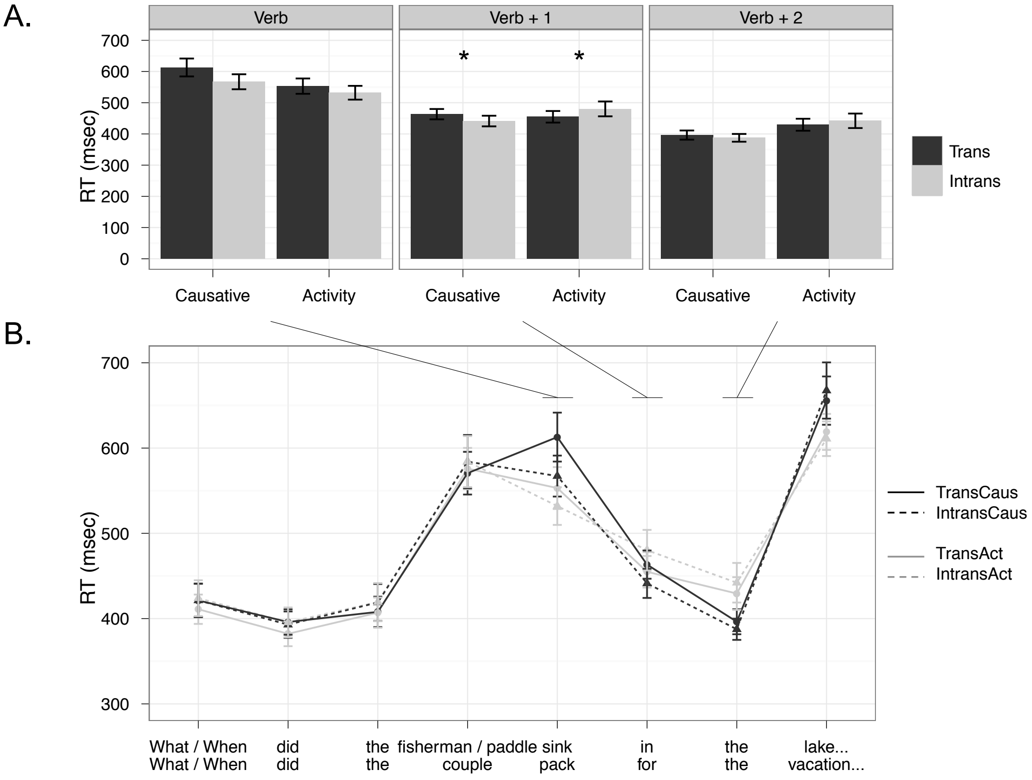

Figure 2: Reading times results from experiment two. (A) Bar-plots showing mean reading times for the verb and the two words immediately following the verb. Asterisks indicate significant pairwise effects in the context of significant interactions between verb type and transitivity. Error bars indicate standard error of the mean. (B) Word-by-word reading times from the beginning of the trial into the spill-over region for Causative (black) and Activity (grey) verbs in the Transitive (solid) and Intransitive (dotted) conditions.

4.3 Experiment 2 Discussion

The results from experiment 2 replicated those in experiment 1, suggesting that the interaction effect was not driven by the contrast in acceptability between transitive and intransitive conditions.

5 Self-Paced Reading Discussion

The results from both experiments support causativization-type analyses of the lexical causative alternation. The causative transitive verbs took longer to process than the intransitive variants in both experiments. Such a contrast was not found in the activity pairs, demonstrating that the number of arguments alone is not driving the distinction.

Although there are differences in the degree of ambiguity of the verb frame at verb presentation, such contrasts would not lead to the results observed. Transitive sentences are clearly disambiguated with respect to transitivity before presentation of the verb, due to the presence of the object wh-phrase at the beginning of the sentence. The intransitive sentences do remain ambiguous at that point, at least to the extent that participants do not discover over the course of the experiment that all adjunct wh-phrase sentences are intransitive. If there were an added cost for the ambiguity of the intransitive verb, this would go in the opposite direction of our effect. Thus if such a cost is present, it may be that it is canceled out by the relative ease of processing the lexical semantics of the intransitive verbs. The delayed processing of the intransitive verbs in the activity pairs may be due to this ambiguity effect in combination with the absence of a lexical semantic advantage. Alternatively, the effect found in the activity pairs could be in part due to the processing of an implicit argument after the verb.

The findings also do not seem compatible with an approach which explains the results as an effect of transitivity expectations. Such an effect would involve a delay in processing the transitive causative condition due to an expectation for the intransitive based on properties of the subject (the only variable phrase preceding the verb other than the wh-word, discussed below). This could occur, for example, if the inanimacy of the subjects in experiment 1 (and for some sentences in experiment 2) creates an unfulfilled expectation of an intransitive reading of the verb. However McKoon and MacFarland (2000) found via corpus study that inanimate subjects are the most common subject type in transitive contexts with change-of-state verbs like the ones in the causative condition investigated here. Thus with this class there should be no expectation that an inanimate subject will be in an intransitive context, and thus no added cost for the combination of an inanimate subject with a transitive verb in the transitive causative condition. We are not aware of any other properties of our subjects that could otherwise lead to such a transitivity bias.

The interaction further does not seem to be driven by factors relating to integration of the wh-phrases. It is plausible that there might be a cost for integrating wh-objects following the verb (Crain and Fodor 1985, Stowe 1986) that is not present for wh-adjunct phrases like those in the intransitive conditions. If intransitive activity verbs induced a cost for integrating an implicit argument, and at the same time wh-object integration slowed both transitive conditions, this could lead to an interaction effect that would be unrelated to the lexical semantic complexity of the verb. Such an interaction, however, would not match the profile of the one observed in experiments 1 and 2. This type of account would predict that no differences would be observed at the verb, contrary to what is found in experiment 1. For experiment 2, while the interaction is not significant at the verb, there is already a pairwise effect at this point between the causative conditions ($\beta = .055, SE = .018, p_{mcmc} < .05$). Although this effect does not survive multiple comparisons due to the lack of an interaction at this point, this pairwise effect is found in both experiments (experiment 1, $\beta = .055, SE = .019, p_{mcmc} < .05$). If the effects were purely due to argument and wh-object integration, no effects would be predicted at the verb. Further, such an account would not predict a difference between the two transitive conditions which was also observed at the verb in both experiments (experiment 1, $\beta = .048, SE = .014, pmcmc < .001$; experiment 2, $\beta = .071, SE = .017, pmcmc < .001$). Finally, the results of the experiment 3 below do not support an account whereby the cost in transitives is due to wh-integration, as will be discussed in section 6.3.

6 Experiment 3

Results from the two reading time experiments show that the zero-derived causatives are associated with increased processing load compared to their intransitive variants, and this effect can not be explained either by differences in number of arguments or acceptability. These data favor a view of causative alternation in English whereby the transitive form is derived from the intransitive (or they are both derived from an underlying root for which the transitive derivation is more involved.) There are several mechanisms by which the causative syntax and semantics might be derived, including a lexical rule that changes the intransitive into a transitive form, the inclusion of one or more unpronounced syntactic elements (e.g. a CAUSE head), or a semantic coercion operation that shifts the meaning to a causative form.

We sought to better understand the underlying mechanism behind the causative derivation by examining the neural signatures associated with processing transitive causative, compared to intransitive, sentences with Magnetoencephalography (MEG). While behavioral measures such as reading times tap into the end-point of incremental sentence processing, the pattern of neural activity elicited by these verbs provides insight into the mechanisms and processes that are engaged internal to the processing system. At present, we do not believe that the understanding of the neural systems underlying language processing offers sufficiently fine-grained mappings from neural signatures to linguistic functions that would be needed to neatly tease out the different hypotheses associated with causativization. As will be described in more detail below, there is a "many to many" mapping between patterns of brain activity and specific language processes. Despite these limitations, we think it is insightful to characterize the pattern of activity associated with processing causativization in relation to results reported by studies that have attempted to elucidate the neural correlates of some of the computations that may be associated with this operation. Such results offer a means to better understand how causativization compares to several other manipulations of morphological, syntactic, and/or semantic complexity. Such data may offer some constraints, particularly as the neural architecture of these processes becomes better understood, on the possible mappings between neural signatures and fine-grained linguistic functions.

What patterns of brain activity might we expect to see associated with causativization under the theories that have been proposed? The hypotheses proposed for causativization narrow down the set of computations to be investigated.

Under a morphological decomposition approach, causatives should differentially engage neural systems associated with decomposing words into component morphemes, with lexical access, and with recombination mechanisms. Several previous studies of morphological decomposition provide clues as to what brain regions may be involved in (some of) these computations. One candidate region is the fusiform gyrus (FG). The left FG has long been associated with letter-reading (e.g.

McCandliss et al. 2003), and it has been shown to be sensitive to the presence of inflectional morphology during visual lexical decision (Lehtonen et al. 2006, Zweig and Pylkkänen 2008); Zweig and Pylkkänen's MEG data show this effect to emerge around 230ms after stimulus onset and they suggest that this activation may reflect the decomposition of the stimulus into its component parts. Lehtonen et al. (2006), using fMRI, report additional activation in the posterior temporal lobe and inferior frontal gyrus. In contrast, the left FG was not found to be sensitive to morphology in a MEG visual lexical decision experiment reported by Vartiainen et al. (2009); instead they report a sustained activation increase associated with inflectional morphology in the posterior superior temporal gyrus between 200 to 800ms after stimulus presentation. Leminen et al. (2011) also found increased posterior temporal (PTL) activation around 200ms for inflectional (but not derivational) morphology using an auditory lexical decision task.

The precise functional role of the observed posterior temporal activation for morphologically complex forms remains poorly understood, but there is evidence that this region plays a crucial role in lexical access from numerous studies demonstrating sensitivity to morphological priming in this region (Gold and Rastle 2007, Devlin et al. 2004, Bozic et al. 2007, Lehtonen et al. 2011), as well as sensitivity around 300-400ms to other factors factors that co-vary with the ease of lexical access, such as lexical frequency (see Pylkkänen and Marantz 2003 for a review). Activity in this time-window was also found to be sensitive to compound word structure by Fiorentino and Poeppel (2007), though no source analysis is reported in that study.

A third region associated with morphological complexity is the inferior frontal gyrus (IFG). Sahin et al. (2009) report sensitivity in the IFG to the presence of zero and overt inflectional (tense) marking in a production task using intracranial electrophysiology. While numerous studies have associated sub-parts the IFG (Broca's Area) with aspects of lexical processing (e.g. Bookheimer 2002, Hagoort et al. 2004, Bedny et al. 2007, Lau et al. 2008), the functional role this region might play in decomposition is not well characterized.

An alternative mechanism for English causativization involves deriving the causative verb via a lexical rule, rather than with a separate morpheme. In a series of studies, Shetreet and colleagues have investigated several different Hebrew argument structure comparisons including unergatives, unaccusatives, optional transitives, and reflexives (Shetreet et al. 2007, 2009b,a, Shetreet and Friedmann 2012), and argued for a division of labor whereby IFG activation is associated with A-movement, as found in, e.g., unaccusatives (Shetreet et al. 2009b, Shetreet and Friedmann 2012), while activation in the PTL was associated with a lexical operation that saturates a thematic role in unaccusatives (Shetreet et al. 2009b) and reflexives (Shetreet and Friedmann 2012); interestingly, activity unique to processing optional transitives in their intransitive form was reported to be localized to the left FG (Shetreet et al. 2009a).

If causativization involves the addition of a syntactically active morpheme, then it would be expected to involve additional syntactic processes compared to intransitives. Numerous studies have linked the left anterior temporal lobe with basic aspects of linguistic composition (e.g. Mazoyer et al. 1993, Stowe et al. 1998, Friederici et al. 2000, Humphries et al. 2006, Pallier et al. 2011, Brennan et al. 2012, Bemis and Pylkkänen 2011; see also the meta-analysis by Ferstl et al. 2008), and researchers have linked this activity with syntactic structure-building (Humphries et al. 2006, Grodzinsky and Friederici 2006) or incremental semantic composition (Stowe et al. 2005, Vandenberghe et al. 2002). Accordingly, a fourth region of interest is the left anterior temporal lobe (ATL).

While many syntactic theories of argument structure assume that thematic role mapping is a consequence of the syntactic structures in which arguments are embedded (perhaps in combination with lexical information from the verb) some theories of sentence processing have posited a role for special mechanisms that map from surface form to thematic role assignments (e.g. the extended argument dependency model, eADM, Bornkessel and Schlesewsky 2006); these mechanisms may be differentially activated in transitives, compared to intransitives, as the latter involve a non-canonical structure in which the surface subject is the thematic theme of the intransitive verb. Processing associated with non-canonical word orders, taken to reflect thematic role assignment, has been found in the IFG, specifically Brodmann's Area 44 (Grewe et al. 2005, 2006, Bornkessel et al. 2005; see Bornkessel-Schlesewsky and Schlesewsky 2009 for a review).

Another hypothesis under consideration connects causativization with coercion, or type-shifting. Coercion from individual to event readings, and between different aspectual classes, has been associated with medial pre-frontal (MPFC) activation peaking approximately 400-450ms after onset of the stimulus that induces the shift in a series of MEG studies by Pylkkänen and colleagues (Pylkkänen and McElree (2007), Pylkkänen et al. (2008), Brennan and Pylkkänen (2008), Brennan and Pylkkänen (2010); see Pylkkänen et al. (2011) for a review). ERP studies have found an N400 effect associated with individual to event coercion (Baggio et al. 2010, Kuperberg et al. 2010). Evidence that this MPFC effect is not specific to coercion operations, but may reflect general semantic compositional operations comes from Bemis and Pylkkänen (2011), who found that anterior medial activity was sensitive to the presence or absence of basic phrase structure, when no type-shifting was required. In contrast to the MPFC localization reported in the above MEG studies, a recent fMRI study by Husband et al. (2011) found that individual-to-event coercion led to increased activity in the IFG.

Anterior midline activity has also been associated with processing lexical semantic features. Behavioral studies indicate that increased numbers of semantic features correlate with processing cost as measure by lexical decision times (e.g. Gennari and Poeppel 2003) and several ERP studies report increases in anterior medial scalp voltages between 200 and 400ms after onset for stimuli that differ with respect to number of semantic features, such as count compared to mass nouns (Steinhauer et al. 2001, Chiarelli et al. 2011) or atelic compared with telic predicates (Malaia et al. 2009). Whether this activation is related to the medial pre-frontal activity associated with coercion is unknown (but see Brennan and Pylkkänen 2010 for some discussion).

Computation	Region	Time	Example Citations
Lexical Decomposition	L FG, R FG	150-300ms	Zweig and Pylkkänen (2008), Lehtonen et al. (2006)
Related to Morphological Complexity	L PTL	200-800ms	Lehtonen et al. (2006), Vartiainen et al. (2009), Leminen et al. (2011), Fiorentino and Poeppel (2007)
Related to Morphological Complexity	L IFG	?	Lehtonen et al. (2006), Sahin et al. (2009)
Lexical-rule application	L PTL	?	Shetreet et al. (2009b), Shetreet and Friedmann (2012)
Lexical rule application	L FG	?	Shetreet et al. (2009a)
Lexical semantic feature processing	MPFC	200-400ms	Steinhauer et al. (2001), Malaia et al. (2009)
Basic composition	L ATL	200-400ms	Mazoyer et al. (1993), Stowe et al. (1998), Brennan and Pylkkänen (2012), Bemis and Pylkkänen (2011)
Thematic role assignment	L IFG (BA 44)	300-500ms	Bornkessel-Schlesewsky and Schlesewsky (2009)
Coercion, Semantic composition	MPFC	400-500ms	Pylkkänen and McElree (2007)
Coercion	L IFG	?	Husband et al. (2011)

Table 7: Summary of computations linked with causativization under different hypotheses and the neural activity that has been associated with these computations.

A summary of computations associated with causativization and the neural signatures that have been previously associated with them is given in Table 7. We examined the neural correlates of causativization against this background of findings. Accordingly, for each brain region and time-window summarized above, we systematically evaluated if that pattern of activity was elicited by causativization in our stimuli. Details of how regions and time-windows were defined are provided below. Restricting our investigation to just these areas of interest that have been motivated by prior work facilitates interpretation of the high dimensional MEG data, as each area represents a particular hypothesis. We avoided conducting a broader "exploratory" analysis as doing so would sharply reduce the statistical power of our analysis.

6.1 Methods

6.1.1 Participants

Seventeen participants were recruited for MEG scanning. Data from one participant was excluded due to a technical error during recording. Participants ranged in age between 19 and 61 years old (Median = 27), including 7 females and 9 males. All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield 1971), and were native speakers of English with normal or corrected-to-normal vision.

6.1.2 Stimuli

Target stimuli in the form of questions were the same as in Experiment 1, yielding 37 sentences per condition. These were combined with 50 semantically anomalous interrogative sentences, leading to a total of 198 trials. Stimuli were presented in a fully randomized order to each participant; all participants viewed all stimuli.

6.1.3 Procedure

Prior to recording, the head shape of each participant was digitized to facilitate source localization (Fastscan; Polhemus, VT). We also digitized the positions of five coils located around the face which were used localize the position of the participants head with respect to the MEG sensor array.

Participants lay supine in a dimly lit magnetically shielded room for MEG scanning. The stimuli were projected in a white courier font, size 36, against a black background onto a screen a screen approximately 50cm above the participant. Sentences were presented word-by-word using Psyscope software (Cohen et al. 1993). Each trial began with a fixation cross, followed by the serial presentation of each word. Each trial ended with the presentation of a question mark prompting the participant to render a binary acceptability judgment to the stimuli with their left hand. Words were presented for 300ms with a 300ms inter-stimulus interval. Before recording began, subjects were presented with five practice trials in order to get them accustomed to the mode of presentation and the task.

Data were recorded continuously from 157 axial gradiometers (Kanazawa Institute of Technology, Kanazawa, Japan) at a sampling rate of 1000Hz with a 200Hz low-pass filter.

6.1.4 Data processing

Environmental noise was attenuated by regressing the data against signals recorded from three orthogonally oriented magnetometers located approximately 20 cm from the recording array using the continuously adjusted least squares method (Adachi et al. 2001). The data were then band-pass filtered from 1 to 40Hz and re-sampled to 200Hz. Channels were excluded from analysis if visual inspection revealed periods of zero signal (saturation) or excessive artifacts relative to neighboring channels (3 channels on average were excluded per subject).

The data were segmented into epochs from -100ms to 800ms around the verb onset. Trials with magnetic field strength exceeding 2.5pT, or that contained artifacts identified via visual inspection, were excluded from further analysis, resulting in the removal of approximately 20% of all trials. Data from one subject was excluded due to behavioral accuracy averaging less than 70% correct and seven outlier items with mean accuracy below 60% were also excluded. Epochs that did not contain artifacts and for which participants registered a correct behavioral response were averaged together by condition for each subject.

6.1.5 Data analysis

Source modeling followed the procedures used in Brennan and Pylkkänen (2012). In brief, the MNE Suite (Martinos center MGH, Boston) was used to estimate neuroelectric current strengths using a cortically-constrained minimum l2 norm source solution based on the recorded magnetic field patterns with a regularization constant of 0.25 (Dale and Sereno 1993, Hämäläinen and Ilmoniemi 1984). The source space was defined using the average brain distributed with Freesurfer software (Martinos center, MGH). Participant head-shapes were co-registered with the averaged cortex using an Iterative Closets Points algorithm and current sources were modeled as sets of three orthogonal dipoles spaced approximately 5mm apart across the cortical surface (Dale et al. 2000), yielding approximately 2500 sources per hemisphere. The lead field was calculated for each source using a single-layer boundary element model (BEM) based on the inner-skull boundary (Hämäläinen and Sarvas 1989).

Anatomical regions of interest (ROIs) were defined using the Desikan-Killiany gyral atlas (Desikan et al. 2006) applied to the average brain with the following modifications: a left posterior temporal region was created by first dividing the inferior, middle, and superior temporal gyri into anterior and posterior portions based on the anterior edge of Heschl's gyrus, and then combining together the three posterior superior temporal and middle temporal regions together with a posterior superior temporal sulcus region. A left anterior temporal region was created by combining the three anterior temporal regions created by this division. For each ROI, we computed the root mean squared amplitude of the three components per source, and averaged these values together within each ROI, yielding a trace of the average estimated neuroelectric amplitude across time in a given ROI for each subject and condition.

Statistical analyses were done using R statistical software (R Development Core Team 2006) and were designed to target the particular activity patterns observed in the prior literature. Our analysis was restricted just to the regions and time-windows discussed above (see Table 7) so as to minimize the chance of false positive results. All statistical tests were performed using linear mixed models implemented in the lme4 package (Bates and Maechler 2009). Models were fit to peak amplitudes and latencies, for transient activity, or to averaged latencies, for sustained patterns, in time-windows of interest with verb-type, transitivity and their interaction as fixed effects, and random intercepts for subjects. For sustained effects, activity was averaged in 100ms bins and a fixed effect of time was also included in the models. The precise time-windows were selected based on prior literature. Effects were evaluated using likelihood ratio tests.

6.2 Results

6.2.1 Fusiform Gyri

Fusiform activity associated with lexical decomposition (Zweig and Pylkkänen 2008) shows a transient pattern peaking between 150 and 300ms. Accordingly, we tested for effects of our manipulation on peak amplitudes and latencies within this region in the left and right fusiform gyri (Figure 3). We observed a significant interaction between verb type and sentence type on peak latency in the left fusiform gyrus, $\chi^2(1) = 3.98, p < .05$. As can be seen in Figure 3, this effect was driven by later peaks in the causative condition, compared to causative intransitives, $\chi^2(1) = 6.14, p < .05$. We did not observe a significant effect of peak amplitude in the left fusiform gyrus, nor were there significant effects of latency or amplitude in the right fusiform gyrus.

6.2.2 Left Posterior Temporal Lobe

Posterior temporal activity, associated with aspects of lexical decomposition (e.g. Lehtonen et al. 2006) or lexical derivation rules (Shetreet et al. 2009b), has been reported as a sustained wave between 200 and 800ms, and so activity in this region, shown in Figure 4, was analyzed in 100ms increments within this time window. We observed a significant interaction between verb type and transitivity during the target interval, $\chi^2(1) = 6.93$, $p < .01$. Inspection of the results shows that this effect was driven by higher amplitudes for causative transitives, compared to causative intransitives and to activity controls, throughout the target interval. While the interaction did not show a statistically significant higher order interaction across time ($p > .5$), post-hoc inspection of the 100ms intervals suggests that the effect was most reliable in two stages, at an early interval between 300 and 400ms ($\chi^2(1) = 7.87$, $p < .01$), and a later interval between 500 and 600ms ($\chi^2(1) = 7.21$, $p < .01$). The interaction effects were driven by increased activity for transitive causatives, both at the 300-400ms window ($\chi^2(1) = 5.9$, $p < .01$) and 500-600ms window ($\chi^2(1) = 8.24, p < .005$).

These results demonstrate a robust increase in activity in the posterior temporal lobe specific

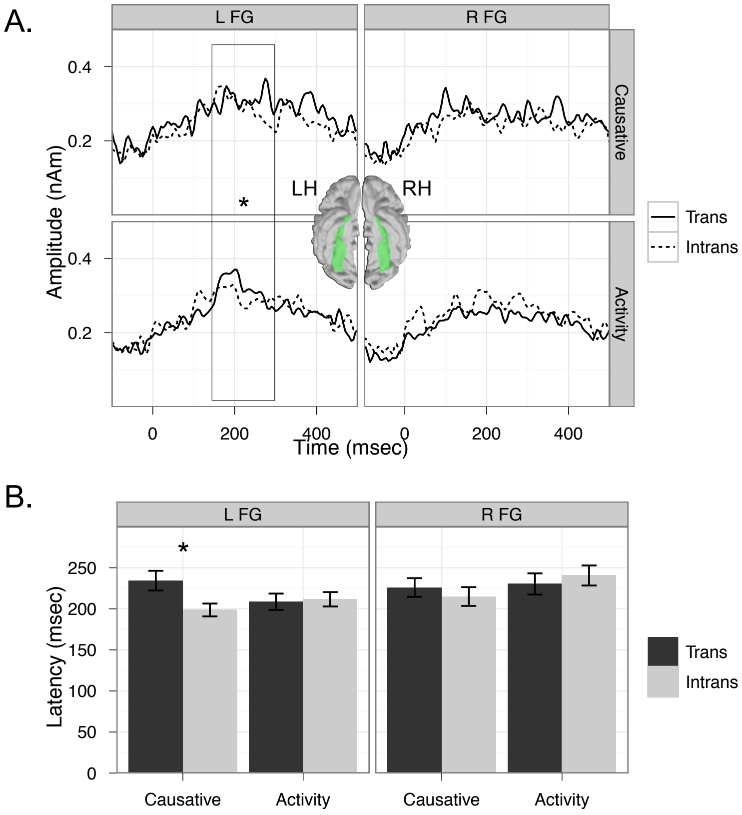

Figure 3: MEG results from the left and right fusiform gyri (L FG and R FG). (A) Average source waves for transitive (solid) and intransitive (dotted) conditions by verb type and region. The box indicates the time-window of interest from 150-300ms; the asterisk indicates a significant interaction between verb type and latency for peak latencies in the L FG. (B) Mean peak latencies between 150 and 300ms in same two ROIs. The asterisk indicates a significant pairwise effect.

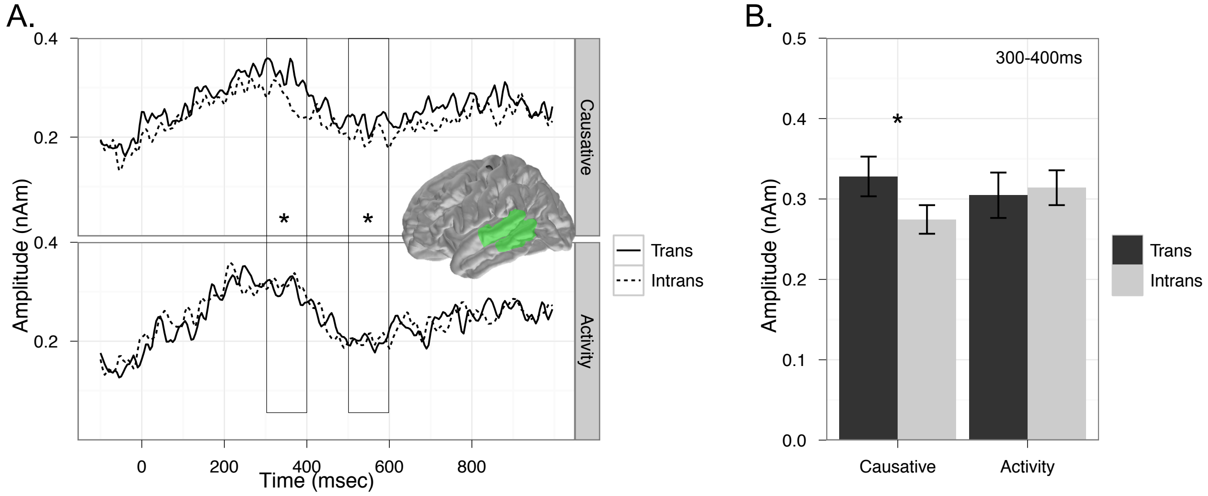

Figure 4: MEG results from the left posterior temporal lobe (L PTL). (A) Average source waves for transitive (solid) and intransitive (dotted) conditions by verb type. Boxes indicate 100ms time-intervals in which there was a significant interaction between verb type and transitivity. (B) Mean amplitudes between 300 and 400ms after verb onset. The asterisk indicates a significant pairwise effect. A qualitatively similar pattern was observed in the 500-600 ms window (not shown).

to causativization, beginning as early as 300ms after stimulus onset.

6.2.3 Left Inferior Frontal Gyrus

A number of researchers have highlighted the possibility of fine-grained sub-divisions within the left inferior frontal gyrus of relevance to a division of labor between short term memory processes, lexical activation, and aspects of syntactic processing such as thematic role assignment or syntactic movement (see Rogalsky and Hickok (2010)). Accordingly, we analyzed three anatomically distinct regions of interest based on the Desikan-Killiany parcellation: the pars opercularis (POp), pars triangularis (PTr), and the pars orbitalis (POr). Our analysis focused on an extended time-window from 200ms to 800ms after verb onset, divided in to 100ms increments. Averaged activity in these regions is shown in Figure 5. We observed a significant interaction between verb and transitivity (POp, $\chi^2(1) = 9.57$, $p < .005$; PTr, $\chi^2(1) = 7.90$, $p < .005$; POr, $\chi^2(1) = 9.98$, $p < .005$). We did not find a three-way interaction between verb type, transitivity, and time, however post-hoc analyses of each 100ms time interval suggests that the interaction effect was

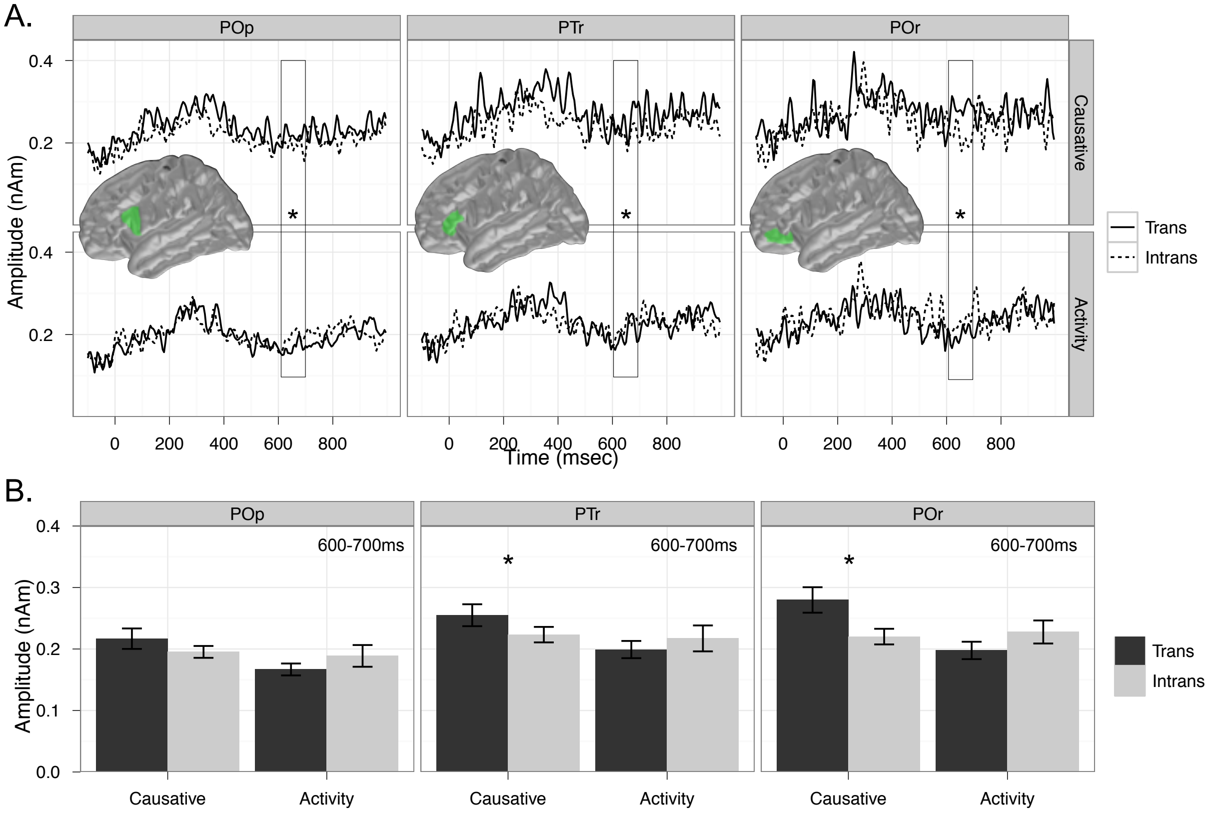

Figure 5: MEG results from three left inferior frontal gyrus ROIs, the pars opercularis (POp), pars triangularis (PTr) and pars orbitalis (POr). (A) Average source waves for transitive (solid) and intransitive (dotted) conditions by verb type and ROI. Boxes indicate 100ms time-intervals in which there was a significant interaction between verb type and transitivity. (B) Mean amplitudes between 600 and 700ms after verb onset. The asterisk indicates a significant pairwise effect.

most prominent in between 600 and 700ms (POp, $\chi^2(1) = 5.42$, $p < .05$; PTr, $\chi^2(1) = 4.16$, $p < .05$; POr, $\chi^2(1) = 11.34$, $p < .001$). The interaction was driven by a combination of increased activity for transitive causatives and decreased activity for transitive activities, compared to intransitives, though the only pairwise comparisons to reach significance in post-hoc testing were between causative transitives and intransitives in the PTr ($\chi^2(1) = 4.04$, $p < .05$) and POr ($\chi(1) = 9.79$, $p < .005$).

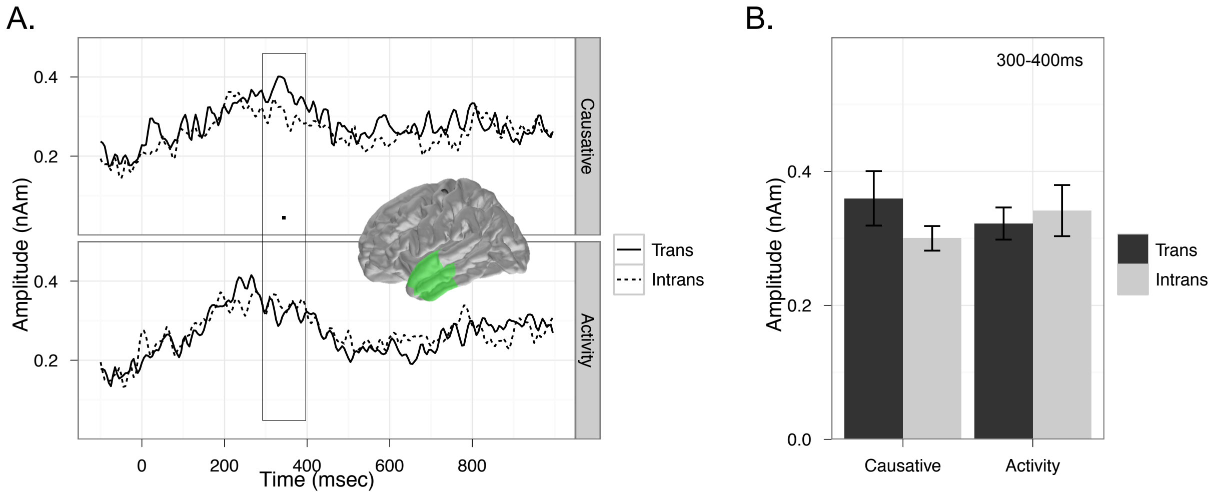

Figure 6: MEG results from a left anterior temporal (L ATL) ROI. (A) Average source waves for transitive (solid) and intransitive (dotted) conditions by verb type. The box indicates the 100ms time-interval in which there was a marginal interaction between verb type and transitivity. (B) Mean amplitudes between 300 and 400ms after verb onset. No statistically reliable pairwise effects were observed.

6.2.4 Left Anterior Temporal Lobe

Activity in the anterior temporal lobe has been associated by a number of researchers with sentence-level composition (see Brennan and Pylkkänen 2012 for discussion), and previous MEG studies suggest that the relevant activity peaks between 200 and 400ms after stimulus onset. We examined activation in a broad anterior temporal ROI in two 100ms time intervals: 200-300 and 300-400ms. As shown in Figure 6, there was a trend towards increased activity in this region uniquely for causative transitives, however the interaction between verb type and transitivity reached only marginal significance in the 300-400ms time-window ($\chi^2(1) = 2.86$, $p < .1$) and there was no pairwise difference within causative verbs in this time-interval.

6.2.5 Medial Prefrontal Cortex

Finally, the medial prefrontal cortex has been associated with semantic type-shifting operations (Pylkkänen et al. 2011) as well as basic semantic composition (Bemis and Pylkkänen 2011). Re-

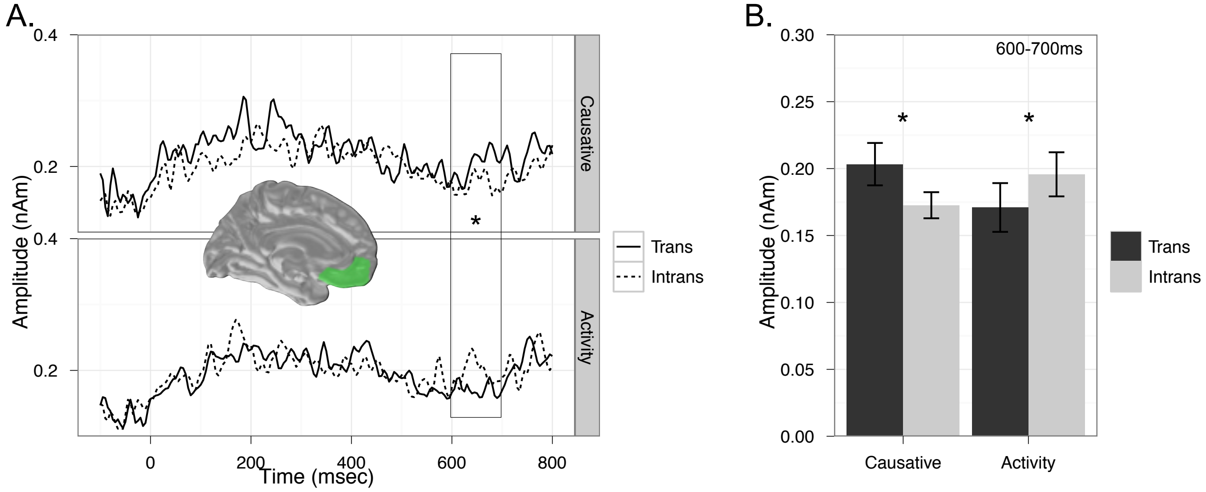

Figure 7: MEG results from a medial pre-frontal ROI. (A) Average source waves for transitive (solid) and intransitive (dotted) conditions by verb type. The box indicates the 100ms time-interval in which there was a significant interaction between verb type and transitivity. (B) Mean amplitudes between 600 and 700ms after verb onset. Asterisks indicate a significant pairwise comparison in the context of a significant interaction.

ports place the peak of this activity around 450ms, and perhaps as late as 700ms after stimulus onset (Pylkkänen et al. 2008). We analyzed a left-lateralized medial orbito-frontal ROI in 100ms increments from 300 to 700ms to test whether this pattern of activity was sensitive to causativization. Results are shown in Figure 7. There was no significant interaction between verb type and transitivity across the whole time window ($p > .2$), but we did find a marginal higher-order interaction with Time, $\chi^2(3) = 6.26$, $p < .1$). Post-hoc tests within each 100ms interval revealed a significant interaction emerging between 600-700ms, $\chi^2(1) = 8.82$, $p < .005$. As with late activation in the inferior frontal gyrus (IFG), this effect was driven by both increased activity for transitive causatives ($\chi^2(1) = 4.94$, $p < .05$), and decreased activity for transitive activities ($\chi^2(1) = 4.93$, $p > .05$), relative to intransitives.

Visual inspection of the MPFC wave-forms identified a suggestive effect for causative transitives in an early time-window, between 200 and 300ms after verb onset, however, post-hoc comparisons within this time window showed no statistically reliable effects.

6.3 Discussion

We used MEG to study the spatio-temporal pattern of neural activity elicited by causativization to gain insight into the computations associated with zero-derived causatives in English. We found reliable effects specific to causativization in the left fusiform gyrus around 200ms after verb onset, and in the posterior temporal lobe around 300-400 and 500-600ms after onset. Increased activity for transitive causatives was paired with decreased activation for transitive activity verbs in later time-windows in several additional regions: the MPFC, and three sub-regions of the left IFG - the POp, PTr, and POr.

Current research does not provide the granularity that would be desirable to neatly distinguish theories of causativization based on brain activity patterns. Our modest goal was to establish a neural profile for causativization in the context of related computations that have been previously investigated. Accordingly, our analysis systematically tested a number of spatial and temporal neural signatures that have been associated with the computations hypothesized for causativization.

One of the most striking aspects of the pattern of results was the effect of causativization on peak latencies in the left fusiform gyrus. This is effect is surprising as this region has been traditionally associated with visual word form processing (see McCandliss et al. 2003, for a review), but our manipulation ensured that the orthographic (and corresponding phonological) forms of the verb were identical across conditions. This is, we believe, the first demonstration of an effect of abstract morphological processing in this region (see also Sahin et al. 2009 for a similar claim about the IFG). The observed effect is left-lateralized, consistent with the region of interest analysis reported by Lehtonen et al. (2006). In contrast, Zweig and Pylkkänen (2008) report bilateral and right-lateralized effects for morphological complexity in a visual experiment. This discrepancy may reflect differences between auditory and visual morphological processing; Zweig and Pylkkänen found that the laterality of their effect was sensitive to whether stimuli contained prefixes or suffixes, leading them to suggest that the visual hemi-field in which the root appeared may have influenced which hemisphere performs early lexical processing in their design.

We observed a posterior temporal effect which also appeared to be specific to causativization;

there was no effect of transitivity for activity verbs on activation in this region. The posterior temporal lobe has long been a core language area, most often related to aspects of phonological to lexical mapping and lexical access (e.g. Hickok and Poeppel 2007). Shetreet and colleagues have also associated activation in this region with lexicon-internal derivational processes (e.g.Shetreet et al. 2009b). Our data is consistent with the view that causativization requires some kind of lexical processing not required for the intransitive variant of causative verbs, but at present it is not clear whether such activation might relate to additional morphological processing, lexical access, or lexical derivations.

While we found robust effects that are plausibly associated with aspects of lexical or morphological processing, neural signatures that have been associated with combinatoric computations, including the left IFG, the left ATL, and the MPFC, showed a mixed pattern of results. IFG effects emerged most reliably in a late time-window, between 600 and 700ms after verb onset. The interaction between verb type and transitivity was reliable across all three sub-regions of this ROI, though the most statistically reliable effects were found in the anterior POr region. Of the computations associated with causativization, the most concrete and explicit predictions come from the the eADM (Bornkessel and Schlesewsky 2006) which associates the IFG with thematic role processing. In that model, the "theme-first" ordering found in our intransitive causative condition, being non-canonical, is predicted to require additional processing compared to the agent-first ordering for the causative transitive condition. However, our results showed an opposite pattern, with increased activation for causative transitives, consistent with an effect for causativization. Sahin et al. (2009) find activation in this region for zero tense morphology using intra-cranial electrodes during a language production task. As our results also involve, by some hypotheses, zero or covert morphology, it might be tempting to draw a connection. However, the relatively late emergence of the effect in this region makes it unlikely to be associated with basic morpho-syntactic operations. Lehtonen et al. (2006) found an effect for overt morphology in the left IFG, but no information about the relative timing of that effect is available in that fMRI study. Thus, while it is intriguing that causatives likewise lead to increased activation in this region, the lateness of the effect, and the numerous functions associated with IFG in the literature make us hesitate to link this activation with a specific computation.

The MPFC and Left ATL have both been associated with sentence-level combinatoric operations. The latter has been associated with basic sentence composition in several recent studies (e.g.Brennan et al. 2012, Bemis and Pylkkänen 2011). While we observed a statistically marginal interaction within the expected 200-400ms window, there was only a non-significant trend in the pairwise comparisons for increased activity for transitive causatives, making a link between causativization and ATL activation tentative at best. The MPFC, a region associated with semantic type-shifting, demonstrated a late interaction effect that emerged between 600 and 700ms. While the timing of our result is in-line with one previous MEG study of coercion (Pylkkänen et al. 2008), it is delayed compared to several other reports (Pylkkänen and McElree 2007, Brennan and Pylkkänen 2008, Bemis and Pylkkänen 2011). Furthermore, this effect was not specific to causativization, as we also observed greater activation for intransitive activity verbs. While it is intriguing that causativization leads to increased activation in a region associated with semantic type-shifting, the similarity between the pattern here and the off-line behavioral results raises the possibility that this activity may reflect processing associated with task difficulty, rather than a language-specific computation. For example, medial frontal regions show increased activation in conditions of increased response competition (Carter et al. 1998).

In sum, while we do not believe that the data are sufficient to rule out specific hypotheses concerning the level of representation at which causativization takes place, we find patterns of activation consistent with additional lexical and/or morphological processing for causativization. In contrast, we find only mixed results with respect to activity that has been associated with compositional processes at the sentence level. As discussed in 5, it is plausible that a processing cost associated with integrating the wh-object in transitive conditions, combined with a cost for processing the implicit argument in activity verbs, could give rise to an interaction effect similar to what we associate with causativization. Under the assumption that movement effects are the same across verb classes, that hypothesis would also predict a main effect of transitivity, however, the activation patterns we observed did not fit this profile, even in regions such as the IFG that have been previously associated with A'-movement (e.g. Ben-Shachar et al. 2004, Santi and Grodzinsky 2007, 2010). Accordingly, we do not believe the neural results we observe are consistent with an explanation in terms of a cost for argument integration. Clearly, future work is necessary to establish a more fine-grained mapping between the relevant linguistic computations and neural activity.

7 General Discussion and Conclusion

The effect of causativity in the reading time data confirms our prediction of a processing cost due to additional semantic complexity for the transitive verbs in the lexical causative alternation in comparison with the intransitive uses. This provides a new kind of data in support of causativization theories of the alternation. The behavioral experiments also demonstrate that this complexity is linguistic in a strict sense and not due to more general conceptual factors which might vary across different verb roots.

Based on the classifications in McKoon and MacFarland (2000), our stimuli include both internally- and externally-caused verbs. For example, they determine that *fade* is externally-caused, while *corrode* is internally-caused based on their criteria. While McKoon and MacFarland (2000, 2002) demonstrate differences in the processing of externally- and internally-caused causative verbs that appear to be independent of the factor of transitivity, here we found an effect that correlated with transitivity (within the alternation, here interpreted as causativity). It is not possible to directly compare our results with those in McKoon and MacFarland's studies, since they studied different dependent variables in their behavioral experiments, measuring the reaction time of end-of-sentence acceptability judgments and sentence reading times. Given that McKoon and MacFarland compare different verbs across conditions, it is possible that the effects that they observe are related to the general conceptual meaning of the roots of the verbs. As discussed in Bhatt and Embick (2003), it is not certain that this conceptual meaning, which leads to tendencies in the morphological realization of lexical causatives across languages (Haspelmath 1993) is present in a distinctly linguistic representation. Thus it may be that McKoon and MacFarland's results demonstrate differences in the conceptual complexity of internally- vs. externally-caused verbs, while our results center on differences in the linguistic representations of transitive and intransitive variants sharing the same root.

Our results are consistent with those of Gennari and Poeppel (2003), who show that differences in event structure lead to differences in processing cost as well. While they show that eventive verbs appear to be more complex than stative verbs, in this study we examine differences between eventive verbs. On standard causativization analyses, the transitive verb contains an extra causative predicate, while both the intransitive and transitive are eventive verbs which encode a change-of-state. Thus our experiments show that there is evidence in processing even at this finer-grained level of distinction between types of eventive verbs. As with experiments in Gennari and Poeppel (2003), our studies further demonstrate that these processing costs can be observed immediately after presentation of the verb. Again, since in our study the comparison was between verbs with the same roots, this also provides further evidence that this distinction is not purely conceptual, but rather has a basis in the specific linguistic realization of the root.

The MEG results suggest that this complexity modulated brain activity in areas associated with lexical and morphological processing, and perhaps in those associated with syntactic and sentence-level semantic processing. By establishing a profile of neural correlates for zero-derived causativity, these findings provide groundwork necessary to bring such data to bear on theoretical hypotheses in this domain in the future.

References

Adachi, Y., M. Shimogawara, M. Higuchi, Y. Haruta, and M. Ochiai. 2001. Reduction of non-periodic environmental magnetic noise in MEG measurement by continuously adjusted least squares method. *Applied Superconductivity, IEEE Transactions on* 11:669–672.

Alexiadou, Artemis, Elena Anagnostopoulou, and Florian Schäfer. 2006. The properties of anti-causatives crosslinguistically. In *Phases of interpretation*, ed. M. Frascarelli, 187–212. Berlin: Mouton.

Baayen, R. H. 2007. *Analyzing linguistic data: A practical introduction to statistics*. Cambridge: Cambridge University Press.

Baayen, R.H., D.J. Davidson, and D.M. Bates. 2008. Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language* 59:390–412.

Baggio, Giosuè, Travis Choma, Michiel van Lambalgen, and Peter Hagoort. 2010. Coercion and compositionality. *J Cogn Neurosci* 22:2131–40.

Bates, Douglas, and Martin Maechler. 2009. lme4: Linear mixed-effects models using S4 classes. R package, version 0.999375-31.

Bedny, Marina, Justin C Hulbert, and Sharon L Thompson-Schill. 2007. Understanding words in context: The role of Broca's area in word comprehension. *Brain Research* 1146:101–14.

Bemis, Douglas K., and Liina Pylkkänen. 2011. Simple composition: A magnetoencephalography investigation into the comprehension of minimal linguistic phrases. *The Journal of Neuroscience* 31:2801–2814.

Ben-Shachar, Michal, Dafna Palti, and Yosef Grodzinsky. 2004. Neural correlates of syntactic movement: Converging evidence from two fMRI experiments. *NeuroImage* 21:1320–1336.

Bhatt, Rajesh, and David Embick. 2003. Causative derivations in Hindi. Unpublished ms., University of Texas and University of Pennsylvania.

Bittner, Maria. 1999. Concealed causatives. *Natural Language Semantics* 7:1–78.

Bookheimer, S. 2002. Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Annual Review of Neuroscience* 25.

Bornkessel, Ina, and Matthias Schlesewsky. 2006. The extended argument dependency model: a neurocognitive approach to sentence comprehension across languages. *Psychol Rev* 113:787–821.

Bornkessel, Ina, Stefan Zysset, Angela D Friederici, D Yves von Cramon, and Matthias Schlesewsky. 2005. Who did what to whom? the neural basis of argument hierarchies during language comprehension. *Neuroimage* 26:221–33.

Bornkessel-Schlesewsky, Ina, and Matthias Schlesewsky. 2009. The role of prominence information in the real-time comprehension of transitive constructions: A cross-linguistic approach. *Language and Linguistics Compass* 3:19–58.

Bozic, Mirjana, William D Marslen-Wilson, Emmanuel A Stamatakis, Matthew H Davis, and Lorraine K Tyler. 2007. Differentiating morphology, form, and meaning: neural correlates of morphological complexity. *Journal of Cognitive Neuroscience* 19:1464–75.

Brennan, Jonathan, Yuval Nir, Uri Hasson, Rafael Malach, David J. Heeger, and Liina Pylkkänen. 2012. Syntactic structure building in the anterior temporal lobe during natural story listening. *Brain and Language* 120.

Brennan, Jonathan, and Liina Pylkkänen. 2010. Processing psych verbs: Behavioral and MEG measures of two different types of semantic complexity. *Language and Cognitive Processes* 25:777–807.

Brennan, Jonathan, and Liina Pylkkänen. 2012. The time-course and spatial distribution of brain activity associated with sentence processing. *NeuroImage* 60:1139–1148.

Brennan, Jonathan, and Liina Pylkkänen. 2008. Processing events: Behavioral and neuromagnetic correlates of aspectual coercion. *Brain and Language* 106:132–143.

Carter, C S, T S Braver, D M Barch, M M Botvinick, D Noll, and J D Cohen. 1998. Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science* 280:747–9.

Chiarelli, Valentina, Radouane El Yagoubi, Sara Mondini, Patrizia Bisiacchi, and Carlo Semenza. 2011. The syntactic and semantic processing of mass and count nouns: An ERP study. *PLoS ONE* 6:e25885 EP –.

Chierchia, Gennaro. 1989. A semantics for unaccusatives and its syntactic consequences. MS, Cornell University.

Cohen, J.D., B. MacWhinney, M. Flatt, and J. Provost. 1993. PsyScope: A new graphic interactive environment for designing psychology experiments. *Behavior Research Methods, Instruments, & Computers* 25:257–271.

Crain, S., and J.D. Fodor. 1985. How can grammars help parsers? In *Natural language parsing*, ed. D. Dowty, L. Kartunnen, and A. Zwicky. Cambridge: Cambridge University Press.

Dale, Anders M., Arthur K. Liu, Bruce R. Fischl, Randy L. Buckner, John W. Belliveau, Jeffrey D. Lewine, and Eric Halgren. 2000. Dynamic statistical parametric mapping: Combining fMRI and MEG for high-resolution imaging of cortical activity. *Neuron* 26:55–67.

Dale, Anders M., and Martin I. Sereno. 1993. Improved localization of cortical activity by combining EEG and MEG with MRI cortical surface reconstruction: A linear approach. *Journal of Cognitive Neuroscience* 5:162–176.

Desikan, R.S., F. Ségonne, B. Fischl, B.T. Quinn, B.C. Dickerson, D. Blacker, R.L. Buckner, A.M. Dale, R.P. Maguire, B.T. Hyman, M.S. Albert, and R.J. Killiany. 2006. An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *Neuroimage* 31:968–980.

Devlin, Joseph T., Helen L. Jamison, Paul M. Matthews, and Laura M. Gonnerman. 2004. Morphology and the internal structure of words. *Proceedings of the National Academy of Sciences* 101.

Dowty, David. 1979. *Word meaning and Montague Grammar: The semantics of verbs and times in generative semantics*. Dordrecht: Reidel.

Ferreira, Fernanda. 1994. Choice of passive voice is affected by verb type and animacy. *Journal of Memory and Language* 33(6):715–736.

Ferstl, EC, J Neumann, C Bogler, and D Yves von Cramon. 2008. The extended language network: A meta-analysis of neuroimaging studies on text comprehension. *Hum Brain Mapp* 29:581–593.

Fiorentino, Robert, and David Poeppel. 2007. Compound words and structure in the lexicon.

Language and Cognitive Processes 1–48.

Friederici, Angela D., M Meyer, and D. Yves von Cramon. 2000. Auditory language comprehension: An event-related fMRI study on the processing of syntactic and lexical information. *Brain and Language* 74:289–300.

Gennari, Silvia, and David Poeppel. 2003. Processing correlates of lexical semantic complexity. *Cognition* 89:B27–B41.

Gold, B.T., and K. Rastle. 2007. Neural correlates of morphological decomposition during visual word recognition. *Journal of Cognitive Neuroscience* 19:1983–1993.

Grewe, Tanja, Ina Bornkessel, Stefan Zysset, Richard Wiese, D Yves von Cramon, and Matthias Schlesewsky. 2005. The emergence of the unmarked: A new perspective on the language-specific function of Broca's area. *Human Brain Mapping* 26:178–90.

Grewe, Tanja, Ina Bornkessel, Stefan Zysset, Richard Wiese, D Yves von Cramon, and Matthias Schlesewsky. 2006. Linguistic prominence and Broca's area: The influence of animacy as a linearization principle. *NeuroImage* 32:1395–402.

Grodzinsky, Yosef, and Angela D Friederici. 2006. Neuroimaging of syntax and syntactic processing. *Current Opinion in Neurobiology* 16:240–246.

Hagoort, Peter, Lea Hald, Marcel Bastiaansen, and Karl Magnus Petersson. 2004. Integration of word meaning and world knowledge in language comprehension. *Science* 304:438–441.

Hämäläinen, M S, and J Sarvas. 1989. Realistic conductivity geometry model of the human head for interpretation of neuromagnetic data. *IEEE Trans Biomed Eng* 36:165–71.

Hämäläinen, Matti, and Risto J. Ilmoniemi. 1984. Interpreting mesured magnetic fields of the brain: Estimates of current distributions. Technical Report TKK-F-A559, Helsinki University, Helsinki.

Harley, Heidi. 1995. Subject, events, and licensing. Doctoral Dissertation, MIT.

Haspelmath, Martin. 1993. Inchoative/causative verb alternations. In *Causatives and transitivity*, ed. Bernard Comrie and Maria Polinsky, volume 23 of *Studies in Language Companion Series (SLCS)*. Amsterdam: John Benjamins.

Hickok, Gregory, and David Poeppel. 2007. The cortical organization of speech processing. *Nature Reviews Neuroscience* 8:393–402.

Humphries, Colin, Jeffrey R. Binder, David A. Medler, and Einat Liebenthal. 2006. Syntactic and semantic modulation of neural activity during auditory sentence comprehension. *Journal of Cognitive Neuroscience* 18:665–679.

Husband, E Matthew, Lisa A Kelly, and David C Zhu. 2011. Using complement coercion to understand the neural basis of semantic composition: evidence from an fmri study. *J Cogn Neurosci* 23:3254–66.

Kuperberg, Gina R, Arim Choi, Neil Cohn, Martin Paczynski, and Ray Jackendoff. 2010. Electrophysiological correlates of complement coercion. *J Cogn Neurosci* 22:2685–701.

Kuroda, S.-Y. 1965. Generative grammatical studies in the Japanese language. Doctoral Dissertation, MIT.

Lakoff, George. 1965. On the nature of syntactic regularity. Doctoral Dissertation, Harvard University.

Lau, Ellen F., Colin Phillips, and David Poeppel. 2008. A cortical network for semantics: (De)constructing the N400. *Nature Reviews Neuroscience* 9:920–933.

Lehtonen, M., V.A. Vorobyev, K. Hugdahl, T. Tuokkola, and M. Laine. 2006. Neural correlates of morphological decomposition in a morphologically rich language: An fMRI study. *Brain and Language* 98:182–193.

Lehtonen, Minna, Philip J. Monahan, and David Poeppel. 2011. Evidence for early morphological decomposition: Combining masked priming with magnetoencephalography. *Journal of Cognitive Neuroscience* 1–14.

Leminen, Alina, Miika Leminen, Minna Lehtonen, Päivi Nevalainen, Sari Ylinen, Lilli Kimppa, Christian Sannemann, Jyrki P Mäkelä, and Teija Kujala. 2011. Spatiotemporal dynamics of the processing of spoken inflected and derived words: A combined EEG and MEG study. *Front Hum Neurosci* 5:66.

Levin, Beth. 1993. *English verb classes and alternations: A preliminary investigation*. Chicago:

University of Chicago Press.

Levin, Beth, and Malka Rappaport-Hovav. 1995. *Unaccusativity: At the syntax-lexical semantics interface*. Cambridge, MA: MIT Press.

Levinson, Lisa. 2012. The morphosemantics of (anti-)causative alternations. Talk presented at the 2012 Linguistic Society of American Annual Meeting, January 2012.

MacDonald, Maryellen C., Neal J. Pearlmutter, and Mark S. Seidenberg. 1994. The lexical nature of syntactic ambiguity resolution. *Psychological Review* 101:676–703.

Malaia, Evguenia, Ronnie B. Wilbur, and Christine Weber-Fox. 2009. ERP evidence for telicity effects on syntactic processing in garden-path sentences. *Brain and Language* 108:145–158.

Mazoyer, B. M., N. Tzourio, V. Frak, A. Syrota, N. Murayama, O. Levrier, G. Salamon, S. Dehaene, L. Cohen, and J. Mehler. 1993. The cortical representation of speech. *Journal of Cognitive Neuroscience* 5:467–479.

McCandliss, Bruce D., Laurent Cohen, and Stanislas Dehaene. 2003. The visual word form area: Expertise for reading in the fusiform gyrus. *Trends in Cognitive Science* 7:293–299.

McCawley, James D. 1968. Lexical insertion in a grammar without deep structure. In *Papers from the Fourth Regional Meeting of the Chicago Linguitsics Society*, ed. B.J. Darden, C.-J.N. Bailey, and A. Davidson. Chicago.

McKoon, Gail, and Talke MacFarland. 2000. Externally and internally caused change of state verbs. *Language* 76:833–858.

McKoon, Gail, and Talke MacFarland. 2002. Event templates in the lexical representation of verbs. *Cognitive Psychology* 45:1–44.

Oldfield, R.C. 1971. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9:97–113.

Pallier, Christophe, Anne-Dominique Devauchelle, and Stanislas Dehaene. 2011. Cortical representation of the constituent structure of sentences. *Proceedings of the National Academy of Sciences* 108:2522–2527.

Parsons, Terence. 1990. *Events in the semantics of English*. Cambridge, MA: MIT Press.

Pesetsky, David. 1995. *Zero syntax: Experiencers and cascades*. Cambridge, MA: The MIT Press.

Piñón, Christopher. 2001. Modelling the causative-inchoative alternation. *Linguistische Arbeitsberichte* 76:273–293.

Pylkkänen, Liina, Jonathan Brennan, and Douglas K. Bemis. 2011. Grounding the cognitive neuroscience of semantics in linguistic theory. *Language and Cognitive Processes* 26:1317–1337.

Pylkkänen, Liina, and Alec Marantz. 2003. Tracking the time course of word recognition in MEG. *Trends in Cognitive Science* 7:187–189.

Pylkkänen, Liina, Andrea E. Martin, Brian McElree, and Andrew Smart. 2008. The anterior midline field: Coercion or decision making? *Brain and Language* 108:184–190.

Pylkkänen, Liina, and Brian McElree. 2007. An MEG study of silent meaning. *Journal of Cognitive Neuroscience* 19:1905–1921.

Pylkkänen, Liina. 2002. Introducing arguments. Doctoral Dissertation, MIT.

R Development Core Team. 2006. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.

Rappaport Hovav, Malka, and Beth Levin. to appear. Lexicon uniformity and the causative alternation. In *The theta system: Argument structure at the interface*, ed. M. Everaert, M. Marelj, and T. Siloni. Oxford, UK: Oxford University Press.

Reinhart, Tanya. 2002. The theta system – an overview. *Theoretical Linguistics* 28:229–290.

Rogalsky, Corianne, and Gregory Hickok. 2010. The role of Broca's Area in sentence comprehension. *Journal of Cognitive Neuroscience* 23:1–17.

Sahin, Ned T, Steven Pinker, Sydney S Cash, Donald Schomer, and Eric Halgren. 2009. Sequential processing of lexical, grammatical, and phonological information within Broca's area. *Science* 326:445–9.

Santi, Andrea, and Yosef Grodzinsky. 2007. Working memory and syntax interact in Broca's area. *NeuroImage* 37:8–17.

Santi, Andrea, and Yosef Grodzinsky. 2010. fMRI adaptation dissociates syntactic complexity dimensions. *NeuroImage* 51:1285–1293.

Shapiro, Lewis P., Edgar Zurif, and Jane Grimshaw. 1987. Sentence processing and the mental representation of verbs. *Cognition* 27:219–246.

Shetreet, Einat, and Naama Friedmann. 2012. Stretched, jumped, and fell: An fMRI investigation of reflexive verbs and other intransitives. *NeuroImage* 60:1800–1806.

Shetreet, Einat, Naama Friedmann, and Uri Hadar. 2009a. Cortical representation of verbs with optional complements: The theoretical contribution of fMRI. *Human Brain Mapping* .

Shetreet, Einat, Naama Friedmann, and Uri Hadar. 2009b. The neural correlates of linguistic distinctions: Unaccusative and unergative verbs. *Journal of Cognitive Neuroscience* .

Shetreet, Einat, Dafna Palti, Naama Friedmann, and Uri Hadar. 2007. Cortical representation of verb processing in sentence comprehension: Number of complements, subcategorization, and thematic frames. *Cerebral Cortex* 17:1958–1969.

Shibatani, Masayoshi. 1976. The grammar of causative constructions: A conspectus. In *The grammar of causative constructions*, ed. Masayoshi Shibatani, volume 6 of *Syntax and Semantics*, 1–40. New York: Academic Press.

Steinhauer, Karsten, Roumyana Pancheva, Aaron J. Newman, Silvia Gennari, and Michael T. Ullman. 2001. How the mass counts: An electrophysiological approach to the processing of lexical features. *NeuroReport* 12:999–1005.

Stowe, L A, C A Broere, A M Paans, A A Wijers, G Mulder, W Vaalburg, and F Zwarts. 1998. Localizing components of a complex task: Sentence processing and working memory. *Neuroreport* 9:2995–2999.

Stowe, L.A. 1986. Parsing wh-constructions: Evidence for on-line gap location. *Language and Cognitive Processes* 2:227–246.

Stowe, Laurie A., Marco Haverkort, and Frans Zwarts. 2005. Rethinking the neurological basis of language. *Lingua* 115:997–1042.

Vandenberghe, R., A. C. Nobre, and C. J. Price. 2002. The response of left temporal cortex to sentences. *Journal of Cognitive Neuroscience* 14:550–560.

Vartiainen, J., S. Aggujaro, M. Lehtonen, A. Hultén, M. Laine, and R. Salmelin. 2009. Neural dynamics of reading morphologically complex words. *NeuroImage* 47:2064–72.

Zweig, E., and L. Pylkkänen. 2008. A visual M170 effect of morphological complexity. *Language and Cognitive Processes* 24:412–439.